

Technical-Environmental-Economical Evaluation of the Implementation of a Highly Efficient District Heating System in China

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Implementation of a Highly Efficient
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PREFACE AND THESIS OUTLINE

This thesis is submitted as a partial fulfilment of the requirement for the Degree of Doctor of Philosophy based on an Industrial PhD project for China entitled “Technical-Environmental-Economical Evaluation of the Implementation of a Highly Efficient District Heating System in China”. The research reported here was carried out with support from the Danish Agency for Science, Technology and Innovation (DASTI), and from Danfoss A/S.

The thesis is conceptually divided into two parts, one focused on space heating (SH) systems, and the other focused on domestic hot water (DHW) systems. Part I is dedicated to reducing heat loss caused by excess heat supply and achieving hydraulic balance, while at the same time improving the level of indoor comfort provided by Chinese building heating systems. The technical approaches investigated involved the use of appropriate control devices to adjust the hydraulic flow and indoor temperature. Part II focuses on the technical feasibility of integrating DHW into District Heating (DH) systems by applying flat stations in China’s multi-storey and high-rise buildings. Under the precondition of such technical feasibility, the economic and environmental superiority of the flat substations concept over the DHW technologies currently in use is emphasized.

The thesis is based on three ISI articles. The thesis reports only the main findings and the full-length articles can be found in the Appendix.

The first article focuses on the challenges related to achieving hydraulic balance in Chinese multi-storey building heating systems.

- Method for achieving hydraulic balance in typical Chinese building heating systems by managing differential pressure and flow. Lipeng Zhang, Jianjun Xia, Jan Eric Thorsen, Oddgeir Gudmundsson, Hongwei Li, Svend Svendsen. Published in Building Simulation in 2016. (See Article I of Appendix)

The second paper studies how the efficiency of typical Chinese district heating systems can be improved by applying the flow and temperature control measures. The results from IDA-ICE simulation and a field test in Beijing of China are presented.

- Method for reducing excess heat supply experienced in typical Chinese district heating systems by achieving hydraulic balance and improving indoor air temperature control at the building level. Lipeng Zhang, Oddgeir Gudmundsson, Jan Eric Thorsen, Hongwei Li, Svend Svendsen, Xiaopeng Li. Published in Energy in 2016. (See Article II I of Appendix)

The third paper investigates the technical feasibility of integrating DHW into existing Chinese DH systems by applying flat stations. The economic and environmental superiority of flat stations concept over the use of individual water heaters is also analysed.

- Technical, economical and environmental investigation of preparing domestic hot water via district heating in Chinese multi-storey buildings. Lipeng Zhang, Oddgeir Gudmundsson, Jan Eric Thorsen, Svend Svendsen, Hongwei Li. Accepted by Energy in September 2016. (See Article III of Appendix)

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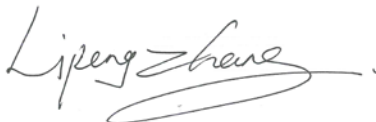
My deepest gratitude goes to my husband for consistently backing me up and taking care of our two children, so that I have been able to complete my academic journey at DTU; to my children, who are always the sources of my strength, perseverance and courage; and to my parents, my parents-in-law, and my twin sister for always being there and cheering me up.

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Sønderborg, 15th July 2015

Lipeng Zhang

A handwritten signature in black ink, reading 'Lipeng Zhang' with a stylized flourish at the end.

ABSTRACT

Over the past 30 years, China has experienced unprecedented urbanization, modernization, and economic development. In the last two decades, China has become one of the largest DH markets in the world, with a total DH production in 2013 amounting to 3,197,032 TJ. This number is still increasing steadily due to the process of rapid urbanization, expansion of the building area, enhancement of building services, and increases in comfort level. The fast pace of urbanization brings out significant challenges to the building heating and water supply in the cities. Therefore, the appropriate technical approaches are urgently needed to improve the efficiency of the DH systems, and create maximum synergy between energy security and air pollution abatement.

The main hypothesis of this industrial PhD project was that by comparing Danish and Chinese DH systems it is possible to learn from the Danish experience and transfer state-of-the-art DH technologies to China and thus improve efficiency, economic operation, and environment protection in Chinese DH systems.

There were three sub- hypotheses in this research. The first two sub-hypotheses focused on SH systems to improve the efficiency of Chinese DH systems. The third sub-hypothesis focused on integrating DHW supply into DH systems to improve the overall efficiency of Chinese DH systems.

A typical issue in Chinese DH systems is that the DH plant has to provide much more heat than the consumers actually need. The main reason for this is the lack of flow control and temperature control at the end-users, which has resulted in significant amounts of energy being wasted. The first and second sub-hypotheses therefore focused on hydraulic control and thermal control, respectively.

The first sub- hypothesis was that hydraulic balance can be achieved in multi-storey building heating systems if the appropriate flow and pressure control devices are applied to the terminal heat emitters. The basic configuration of the technical approach is to apply Thermostatic Radiator Valves (TRV) with pre-setting function to radiators, and apply differential pressure controllers to the apartment loops or the risers. The analysis used a mathematic hydraulic model developed by the author to investigate the hydraulic performance of multi-story buildings. With hydraulic conditions calculated from the hydraulic balance model, the building's thermal performance under design condition was simulated using IDA Indoor Climate and Energy 4.6.2. The results show the hydraulically balanced heating system achieves 16% heat savings and 74% pump electricity savings.

The second sub-hypothesis was that indoor comfort can be improved by activating the thermostatic sensors of TRV. At present, heating is still billed as a fixed charge based on the floor heating area. This gives heat consumers no incentive to save heat and results in a lack of energy-saving consciousness. Consequently, consumers emit heat into the atmosphere by opening the window when indoor temperatures are higher than the comfort level. A building model was developed based on a real case, and real weather data were used in the simulation in IDA Indoor Climate and Energy 4.6.2. The building model simulation verified that indoor temperature can be controlled around a constant level by setting thermostatic sensors. At the same time, heat consumption and pump power consumption were quantified and shown to be much reduced compared to the situation with no indoor temperature control. The simulation results showed that system-wide use of TRV can reduce heating consumption by 17% and pump electricity consumption by 42% compared to the situation without TRV control. Furthermore, the use of TRV enables a constant room temperature and changes the system from constant flow to variable flow.

The third hypothesis was that the efficiency of China's district heating systems could be improved by changing the current situation with regard to domestic hot water (DHW) applications. The vast majority of DH systems in China only provide SH and do not produce domestic hot water. DHW is mainly produced by individual water heaters powered by fossil fuels, which puts pressure on air pollution and energy supply security. To solve this problem, the hypothesis was developed that DHW production can be integrated into DH systems by using the flat stations concept. A multi-storey building with standard apartments was modelled to investigate the technical feasibility of this approach. On the premise of technical feasibility, an economic evaluation was made using net present value (NPV) to compare the annualized cost of using individual water heaters and flat stations. Environmental impacts were considered in terms of particle and CO₂ emissions when various fuels are used to produce DHW. The results show that flat substations solutions are technically feasible if a few technical measures are implemented. The flat station approach is also more economically beneficial than individual water heaters and has less environmental impact.

Chinese DH systems are characterized by low efficiency. There is a large margin for system improvement when compared with Danish DH systems. The thesis evaluates Chinese DH systems from the technical, environmental and economical points of view. The major issues in current Chinese DH systems are addressed through the three sub-hypotheses stated above. The thesis demonstrates that the efficiency of Chinese DH systems can be significantly improved if good solutions can be found for their hydraulic and thermal balances and the supply of DHW.

RESUME (DANISH)

Titel: Teknisk, miljømæssig og økonomisk evaluering af implementering af fjernvarmesystemer med høj effektivitet i Kina

Gennem de seneste 30 år har Kina oplevet en urbanisering, modernisering og økonomisk udvikling uden fortilfælde. I de seneste to tiår er Kina blevet et af de største fjernvarmemarkeder i verden med en samlet fjernvarmeproduktion i 2013 på 3,197,032 TJ. Dette tal er stadig støt stigende på grund af den hurtige urbanisering, udvidelse af bygningsarealet, forbedring af bygningsinstallationer og øgede komfortniveauer. Den hurtige urbanisering afstedkommer betydelige udfordringer til forsyningen af byernes bygninger med rumopvarmning og varmt vand. Derfor er der et akut behov for udvikling af passende tekniske løsninger til forbedring af effektiviteten af fjernvarmesystemer og til at skabe den maksimale synergi mellem energiforsyningssikkerhed og reduktion af luftforurening.

Hovedhypotesen i dette industri-Ph.d.-projekt var, at det er muligt – ved sammenligning af danske og kineske systemer – at lære af de danske erfaringer og overføre de nyeste fjernvarmeteknologier til Kina og dermed forbedre kinesiske fjernvarmesystemers effektivitet, økonomiske drift og miljøbeskyttelse.

Der var tre subhypoteser i denne forskning. De to første sub-hypoteser fokuserede på rumvarmesystemer til forbedring af effektiviteten kinesisk fjernvarme. Den tredje subhypotese fokuserede på integration af levering af varmt brugsvand i fjernvarmesystemer med henblik på at forbedre den samlede effektivitet af kinesiske fjernvarmesystemer.

Et typisk problem i kinesiske fjernvarmesystemer er at fjernvarmecentralen er nødt til at levere mere varme end forbrugeren faktisk har behov for. Den største grund til dette er manglen på kontrol af flow og temperatur hos slutbrugeren, hvilket har resulteret i tab af betydelige mængder af energi. Den første og anden sub-hypoteser fokuserede derfor henholdsvis på hydraulisk og termisk kontrol.

Den første sub-hypotese var at hydraulisk balance kan opnås i etagebygningers varmesystemer, hvis en passende flow- og trykreguleringsenhed bliver anvendt til kontrol af varmeafgifterne. Den basale udformning af teknikken er at anvende radiatorventiler med forindstilling på radiatorerne og differenstrykregulatorer på varmekredsen i lejlighederne eller i stigstrengene. Til analysen af de hydrauliske forhold i varmesystemerne i en etagebygning blev benyttet en matematisk hydraulisk model udviklet af forfatteren. De hydrauliske forhold, beregnet med modellen for hydraulisk balancering af systemer, blev benyttet til simulering af den termiske funktion af bygningen i IDA Indoor Climate and Energy 4.6.2. Resultaterne viser, at det balancerede varme anlæg opnår en besparelse på 16 % til varme og på 74 % til el til pumper.

Den anden sub-hypotese var at indeklimaet kan blive forbedret ved at benytte termostatiske radiatorventiler. For nuværende bliver varmemeforbrug afregnet med en fast pris baseret på gulvarealet. Dette giver ikke kunden nogen tilskyndelse til at spare på energien og resulterer i en mangel på bevidsthed om energibesparelser. Som en konsekvens heraf udleder forbrugeren varme til omgivelserne ved at åbne vinduerne når rumtemperaturen er højere end komfortniveauet. En beregningsmodel af et konkret eksempel på en bygning blev opstillet og beregninger udført med aktuelle vejrdata ved simulering i IDA Indoor Climate and Energy 4.6.2. Simuleringsberegningerne underbyggede at rumtemperaturerne kan holdes på et konstant niveau ved at indstille termostatiske følere. Samtidigt blev varmemeforbruget og elforbruget til pumper bestemt og eftervist at være meget

mindre end i rum uden temperaturstyring. Simuleringsresultaterne viste at systematisk generel anvendelse af termostatventiler på radiatorer kan reducere varmekonsumet med 17 % og el til pumpning med 42 % sammenlignet med en situation uden termostatventiler. Desuden gør termostatventilerne det muligt at holde en konstant temperatur og ændre systemet fra konstant flow til variabelt flow.

Den tredje sub-hypotese var at effektiviteten af de kinesiske fjernvarmesystemer kunne forbedres ved at ændre på den nuværende situation med hensyn til anvendelse af varmt brugsvand. Det store flertal af fjernvarmesystemer i Kina leverer kun rumvarme og ikke varmt brugsvand. Det varme brugsvand bliver hovedsageligt fremstillet med individuelle vandvarmere baseret på fossile brændsler, hvilket presser forureningen og energiforsynings sikkerheden. For at løse dette problem, blev der opstillet følgende hypotese: opvarmningen af varmt brugsvand kan integreres i fjernvarmesystemer ved brug af konceptet med decentrale fjernvarmeunits i hver lejlighed. En etagebygning med typiske lejligheder blev modelleret for at undersøge den tekniske egnethed af denne løsning. Under forudsætning af at teknikken var anvendelig blev der udført en økonomisk vurdering baseret på en sammenligning af nuværdien af udgifterne ved anvendelse af individuelle vandvarmere og decentrale fjernvarmeunits. Miljøbelastningen blev vurderet på grundlag af emissionen af partikler og CO₂ ved anvendelse af forskellige brændsler til fremstilling af varmt brugsvand. Resultaterne viser at decentrale fjernvarmeunits er økonomiske fordelagtige, hvis nogle få tekniske løsninger benyttes. Den decentrale fjernvarmeunit er også mere økonomisk fordelagtig end individuelle vandvarmere og har mindre miljøbelastning.

Kinesiske fjernvarmesystemer er karakteriseret ved lav effektivitet. Der er store muligheder for forbedring af systemerne sammenlignet med danske fjernvarmesystemer. Afhandlingen vurderer kinesiske fjernvarmesystemer ud fra tekniske, miljømæssige og økonomiske synsvinkler. De største problemer i de nuværende kinesiske fjernvarmesystemer er behandlet gennem de tre sub-hypoteser nævnt ovenfor. I afhandlingen vises det, at kinesiske fjernvarmesystemer kan forbedres signifikant, hvis der kan findes gode løsninger til hydraulisk og termisk balancering og til forsyning af varmt brugsvand.

LIST of PUBLICATIONS

Article I

Method for achieving hydraulic balance in typical Chinese building heating systems by managing differential pressure and flow. Lipeng Zhang, Jianjun Xia, Jan Eric Thorsen, Oddgeir Gudmundsson, Hongwei Li, Svend Svendsen. In Build Simulation 2016. DOI: 10.1007/S12273-016-0307-2

Article II

Method for reducing excess heat supply experienced in typical Chinese district heating systems by achieving hydraulic balance and improving indoor air temperature control at the building level. Lipeng Zhang, Oddgeir Gudmundsson, Jan Eric Thorsen, Hongwei Li, Xiaopeng Li, Svend Svendsen. In Energy 2016, vol. 107, pp. 431–442.

Article III

Technical, economic and environmental investigation of using district heating to prepare domestic hot water in Chinese multi-storey buildings. Lipeng Zhang, Oddgeir Gudmundsson, Jan Eric Thorsen, Svend Svendsen, Hongwei Li. Accepted by Energy in September 2016

Article IV

Comparison of district heating systems used in China and Denmark. Lipeng Zhang, Oddgeir Gudmundsson, Hongwei Li, Svend Svendsen, in International Journal of Sustainable and Green Energy, Volume 4, Issue 3, pp.102-116, DOI: 10.11648/j.ijrse.20150403.15

Article V

Comparison of district heating systems used in China and Denmark. Lipeng Zhang, Oddgeir Gudmundsson, Hongwei Li, Svend Svendsen, Euroheat and Power (English Edition) 2013, Vol.10 (4), pp. 12-19

Conference International articles

Article I

Comparison of district heating systems used in China and Denmark. Lipeng Zhang, Oddgeir Gudmundsson, Hongwei Li, Svend Svendsen. Proceedings of 8th Conference on Sustainable Development of Energy, Water and Environment Systems, Dubrovnik

Article II

Technical comparison of domestic hot water system which used in China and Denmark. Lipeng Zhang, Oddgeir Gudmundsson, Jan Eric Thorsen, Hongwei Li, Svend Svendsen. Proceeding of 6th International Conference on Applied Energy, Taipei City, Taiwan, China, 30/05/14 - 02/06/14. Energy Procedia 2014, pp. 2509-2513

Article III

Optimization of China's centralized domestic hot water system by applying Danish elements. Lipeng Zhang, Oddgeir Gudmundsson, Jan Eric Thorsen, Hongwei Li, Svend Svendsen. Proceeding of 6th International Conference on Applied Energy, Taipei City, Taiwan, China, 30/05/14 - 02/06/14. Energy Procedia 2014, pp. 2833-2840

Article IV

China's Anshan project: a good example to implementing Scandinavian DH technology and environmentally friendly heat source to upgrade the DH system. Lipeng Zhang, Lianzhong Li, Oddgeir Gudmundsson, Jan Eric Thorsen, Hongwei Li, Svend Svendsen. Proceedings of the 14th International Symposium on District Heating and Cooling 2014, Stockholm, Sweden, 07/09/14 - 09/09/14, pp. 104-113.

NOMENCLATURE

List of abbreviations

DH	District Heating
SH	Space Heating
DHW	Domestic Hot Water
TRV	Thermostatic Radiator Valves
SHOB	Space Heating only boiler
DP controller	Differential Pressure controller
GHG	Greenhouse Gas
PM	Particulate Matter
AQI	Air Quality Index
USEPA	U.S. Environmental Protection Agency
CHP	Combined Heat and Power
4GDH	4 th Generation District Heating
LTDH	Low Temperature District Heating
NPV	Net Present Value
CNY	Chinese Yuan
DCW	Domestic Cold Water

List of Symbols

ΔP	differential pressure (bar)
l	pipe length (m)
d	pipe diameter (mm)
q_v	volume flow rate (m ³ /h)
k_v	flow coefficient (m ³ /h/(bar) ^{1/2})
k_h	Hourly variation coefficient
f	Coincidence factor

Greek symbols

λ	friction factor
ζ	local resistance coefficient
ρ_w	water density (kg/m ³)
η	Efficiency

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1 Introduction

1.1 Objective of Research

The objective of the thesis is to investigate the major technical issues in Chinese DH system and identify solutions to improve the system efficiency. By comparing the difference between Chinese and Danish DH systems, the Danish DH experience and technology know-how are transferred to the Chinese framework in order to improve the energy efficiency, reduce excess heat loss and pollutant emissions and increase cost saving.

From the technical feasibility perspective, the research took into consideration both existing buildings and new buildings with different levels of heat demands.

1.2 Scope

The lessons learned and experience gained from Scandinavian/Danish DH systems can be transferred to Chinese DH systems. DH systems are complex, so this topic alone could involve a great number of research directions but it is impossible to be covered within a thesis. A typical DH system consists of a heat source (the heat generation part), transmission/distribution pipelines (the heat transportation part), heat consumers (the heat demand part), and substations which indirectly connect the heat source with heat consumers. The essence of the Scandinavian DH concept and technology is to create a balance between heat supply and heat demand by utilizing comprehensive adjustment and control devices to minimize the gap between energy demand and supply, thus maximizing the efficiency of the entire system. In China, indoor heat installations lack control devices, so there is a big difference between the heat supplied to buildings and the real heat required by consumers, which has resulted in substantial heat waste. This thesis, therefore, focuses on the heat demand side, represented by multi-storey and high-rise building heating systems in China.

The assumptions and limitations of this research can be summarized as:

- District heating systems mentioned in this research refer to the SH only systems; DHW is prepared via on-site DHW installations like individual water heaters or natural gas water heaters (Figure 1.1).
- The research mainly focuses on multi-storey or high-rise building heating systems that obtain the heat from a large-area substation or SH only boilers (SHOBs). In such buildings, the heating entrance is the interface connecting the large-area substation or SHOBs to each building's heating system. It is equipped with the necessary pipe connections and valves (Figure 1.1).
- The SH system is a two-pipe radiator heating system, and each apartment has its own heating loop.
- The weather data and relevant parameters and standards for heating systems and buildings in two representative cities, Beijing and Harbin, were used to make the investigation.
- The research did not cover the heat generation and heat transmission parts; the results reference recently published studies.

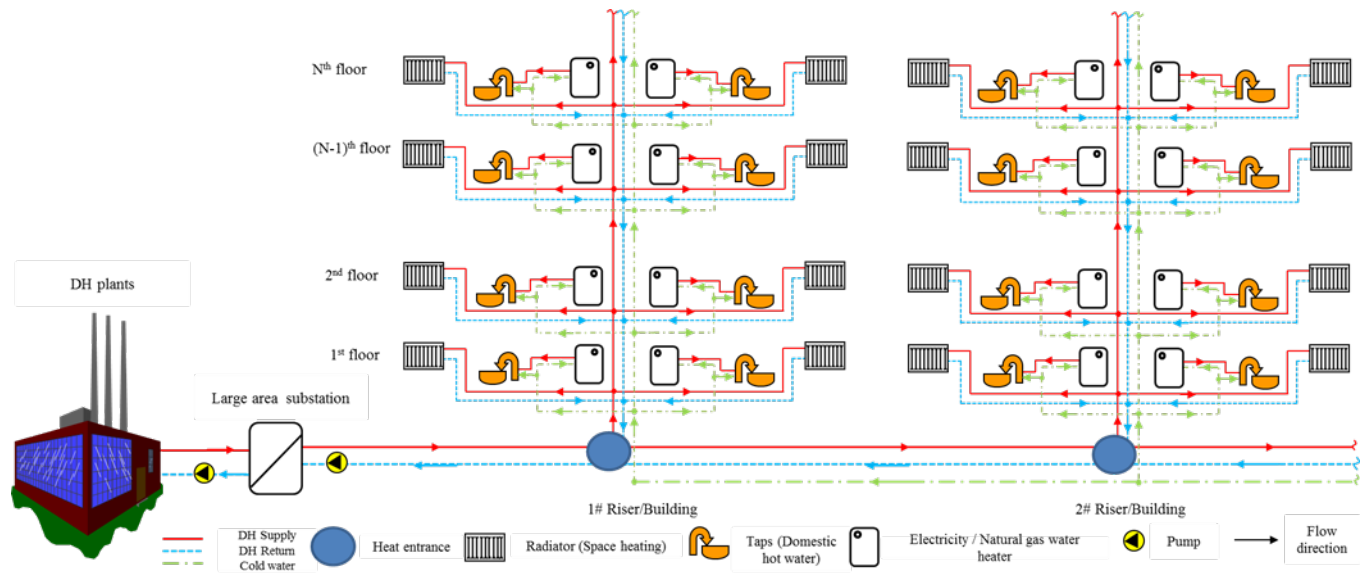


Figure 1.1. Typical DH system in China

1.3 Hypothesis

The main hypothesis of this research was that it is technically feasible to reduce the energy consumption by applying the control devices in building SH installations and by supplying DHW through flat stations from DH. Since coal is dominated fuel for DH plants and power plants in China, the energy consumption reduction implies the reduced fuel consumption, also the emission reduction. Consequently, the technically feasible proposals bring out the positive economic and environmental impacts.

In China, all its energy statistics typically are converted into “metric tons of standard coal equivalent” (tce). One tce is equal to 29.31 GJ and 8140 kWh[1]. Furthermore, burning 1 ton Chinese standard coal (29.3GJ/tce) releases about 2600 kg CO₂, 24 kg SO₂, 7kg NO_x [2].

The main hypothesis can be divided into three sub-hypotheses (see Figure 1.2):

- 1) The first sub-hypothesis aims to improve the hydraulic condition of typical building heating systems in China. Currently, there is generally hydraulic imbalance in Chinese heating systems due to the failure to use control devices. The hypothesis is that hydraulic balance can be achieved in multi-storey building heating systems if appropriate flow and pressure control devices are applied to the terminal heat emitters, which are generally radiators. Through this study, the concept that controllers can control efficiently if design flows go through the radiators when the heating system is operating in design conditions is emphasized. The main idea of the sub-hypothesis is that, with the appropriate technical approach, the flow distribution among the terminal heat emitters (radiators) will be in balance. This means the flows will be adjusted to correct values in design conditions. Avoiding insufficient flows in design conditions makes sure that insufficient flows will be avoided in all other normal conditions. In this way, hydraulic balance is achieved at the level of terminal heat emitters.

- 2) The second sub-hypothesis aims to improve the indoor thermal comfort of Chinese buildings by applying temperature control devices. The currently most common method of indoor temperature control in Chinese DH systems is to adjust the secondary supply temperatures (after large-area substation) to the building heating system manually. This inevitably results in man-made errors, notably excessive heat supply. In addition, heating is still billed based on a fixed charge per square metre of floor heating area in China. This results in heat consumers not being motivated to develop energy-saving consciousness. Consequently, heat is emitted into the atmosphere by opening the window when indoor temperatures are higher than the comfort level. The second hypothesis is that indoor comfort can be improved by using control device, namely activating the thermostat, and that, correctly set, the thermostat can achieve considerable energy savings.
- 3) The third sub-hypothesis aims to integrate DHW production into DH systems by using the flat station concept. Currently, the vast majority of China's DH systems are SH only and do not supply DHW. DHW is mainly produced by individual water heaters powered by fossil fuels. This puts pressure on both air pollution and energy supply security, which are the two most important challenges China faces today. The sub-hypothesis is that the flat station concept will allow the preparation of DHW via the DH network. A multi-storey building model of Beijing is developed to investigate the concept's technical feasibility. Its economic feasibility was analysed by utilizing NPV to compare the annualized cost of individual water heaters versus flat stations. Environmental aspects were considered in terms of particles and emissions when the various fuels are burned to produce DHW. The results show that flat stations are technically feasible if just a few technical measures are implemented and that they are more economically beneficial than individual water heaters and have less environmental impact. This means that using flat stations to prepare

DHW in China's multi-storey buildings is more sustainable than using individual water heaters.

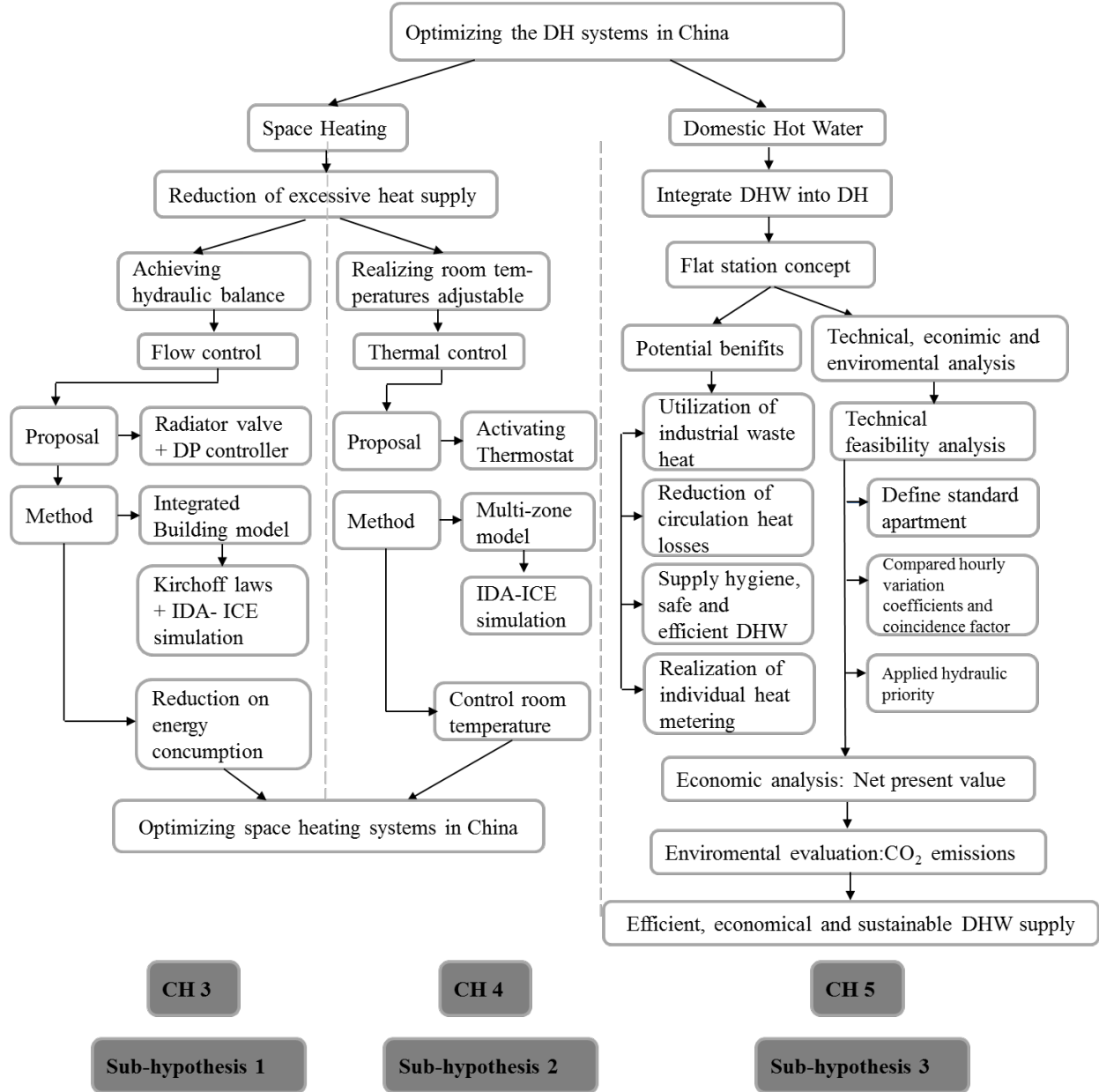


Figure 1.2. The relationship between the hypotheses

2 Background

Chinese DH technologies are derived from the Soviet Union. Currently, approx. 90% of DH systems only supply SH, without DHW. Geographically, China is divided into five climate regions: 1) Severe Cold regions, 2) Cold regions, 3) Hot-Summer and Cold-Winter regions, 4) Hot-Summer and Warm-Winter regions, and 5) Temperate regions. The cities located in severe cold and cold climate regions are legally required to provide SH. These two types of climate region cover almost two thirds of China's territory, account for 43% of all residential and

commercial buildings in China, and accommodate 550 million inhabitants [3]. Conceptually, the heating degree days of these regions based on 18 °C (HDD18) are around 2000~6000 °C·d [4]. The heating period is fixed in wintertime. Its average length is around 150 days, generally from November to March of the following year. Correspondingly, the standard design indoor temperature is 18 °C, and the air exchange rate is 0.5 h⁻¹ [5].

The development of DH in China has gone hand in hand with rapid urbanization and economic growth in the last ten years. China's urban building areas maintain an average annual growth rate of almost 11.1%, and reached 21123.4 million square metres in 2010 [6]. The rapid growth of the total number of heating square metres means the annual energy consumption is rising rapidly at an average annual growth rate of nearly 8.2%. Statistics indicate that the total DH production in 2013 amounted to 3,197,032 TJ [7]. Moreover, the 12th Five-Year guideline requires the usage of DH in the northern heating area to achieve nearly a 65% share of the heat market during 2011-2015 [8].

Moreover, air pollution and security of energy supply have become the two most important challenges China faces today [9]. Building heating energy consumption in China per square metre is almost twice that of developed countries at the same latitude [10][11]. To create a more sustainable relationship between energy consumption and economic growth, the Chinese government is demanding a more energy-efficient way forward. For instance, the key direction of DH reform was defined in 2006. The Renewable Energy Law was launched in January 2006 and stipulates more sustainable energy will be utilized by 2020. In March 2011, China adopted the "12th Five-Year Plan for National Economic and Social Development". This plan calls for a reduction in energy intensity per unit of GDP of 16% and a reduction in CO₂ emissions per unit of GDP of 17% compared to 2010 by 2015 [12]. A more energy efficient way and more renewable energy are also required in the DH sector.

2.1 Current situation

2.1.1 Heat sources

In China, the main heating production facilities are the coal-fired boilers and Combined Heat and Power (CHP) plants. Statistics show, in 2013, 48% of DH came from coal-fired boilers, 42% CHP plants, 8% gas-fired boilers, and the remaining 2% came from scattered and individual heating facilities[13]. Furthermore, coal is the dominant DH fuel in China. Statistics show that 91% of the total energy supply to DH systems came from coal in 2008[14].

2.1.1.1 Dominated DH fuel and environmental challenges

In China, DH relies heavily on coal as fuel. The DH sector accounts for about 5.3% to 6.1% of the total coal consumption in China. Statistics indicate that the heating sector consumed 145.4 million tons of raw coal in 2008, which accounted for 91% of the total energy supply to the DH sector [15]. Coal is the dominant fuel in the DH sector, and this will remain so in the coming years. This means that one of the challenges could be supply security: China has the world's third largest coal reserves at 114 billion tonnes, but became the world's largest importer of thermal coal in 2010 [16]. Moreover, heavy reliance on coal presents a number of environmental, health, and economic challenges [17]. China overtook US as the world's largest consumer of energy in 2010, which makes it the largest emitter of greenhouse gas (GHG) emissions [18]. CO₂ emissions from DH have an average annual growth rate of 10.3%, which represents 4.4% of China's total CO₂ emissions in 2009 [19]. The pressure on the Chinese government to reduce CO₂ emissions is increasing due to the committed target: a

reduction in CO₂ emissions of 40% to 45% per GDP unit from 2005 levels by 2020 at the UN climate change conference in Copenhagen in 2009 [20]. Furthermore, the combustion of coal leads to emissions of SO₂, CO₂, CO, NO_x, black carbon, and PM (particulate matter), etc.

PM₁₀ are the particles between 2.5 and 10 micrometres in diameter. PM_{2.5} refers to particles 2.5 microns in diameter and smaller, including black carbon, which is formed through an incomplete combustion of fossil fuels. PM_{2.5} particulates can penetrate deeper into lungs than typical dust, and are the single most damaging threat to public health [3]. In 2011, annual PM_{2.5} concentrations reached 80-100 µg/m³ in northern China, which is significantly higher than the U.S. environmental Protection Agency (USEPA) maximum of 15 µg/m³. High annual PM₁₀ and PM_{2.5} concentrations now occur more frequently than high SO₂ concentrations and affect the air quality of many Chinese cities. Uncontrolled coal-fired boilers and sources are often significant sources of SO₂, PM and black carbon. During the winter time, heating is one of the main sectors causing smog and haze pollution [21].

The following Data obtained in 2013 and 2014 heating seasons in Beijing indicates the relationship between air pollution and DH industry; explains the current situation in terms of air pollution during the heating season.

The Air Quality Index (AQI) is a non-dimensional index for the quantitative description of air quality. The major pollutants measured to evaluate the air quality are PM₁₀, PM_{2.5}, SO₂, NO₂, O₃ and CO, a total of six items [22]. There are six levels to the Chinese AQI index, with corresponding influences on the environment and human health. The higher the AQI index, the higher air pollution level and the more obvious the implications for human health [23].

The daily AQI data and outdoor temperatures of Beijing city from November 2013 to mid-April 2014 (Figure 2.1), and in the same period for 2014-2015 (Figure 2.2) were collected. This period is the heating season of Beijing (15 November to 15 March of the following year), so the data reflects the relationship between the air quality and outdoor temperatures in Beijing city during the heating period. Lower outdoor temperatures generally correspond to higher AQI levels, i.e. high air pollution levels. Figure 2.3 illustrates the day's percentages at different levels during these two periods. For 2013-2014, a total of 164 days, the number of days with a daily AQI higher than 100 accounts for 51%, and the number of days with a daily AQI higher than 300 accounts for 7%. For 2014-2015, a total of 165 days, the corresponding numbers are 49% and 2% respectively. The data from these two years both indicate that the air quality during the heating season is unsatisfactory.

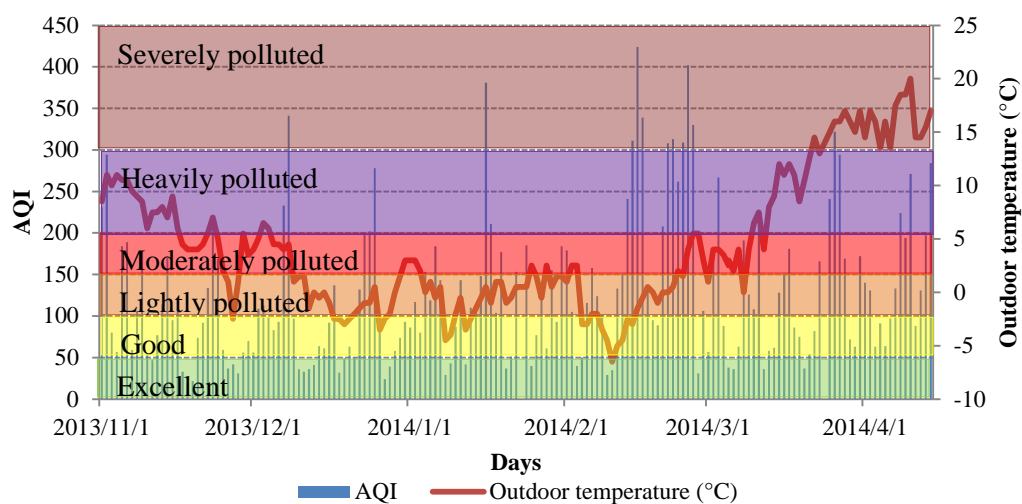


Figure 2.1. AQI and outdoor temperature in the period 11/01/2013-14/04/2014

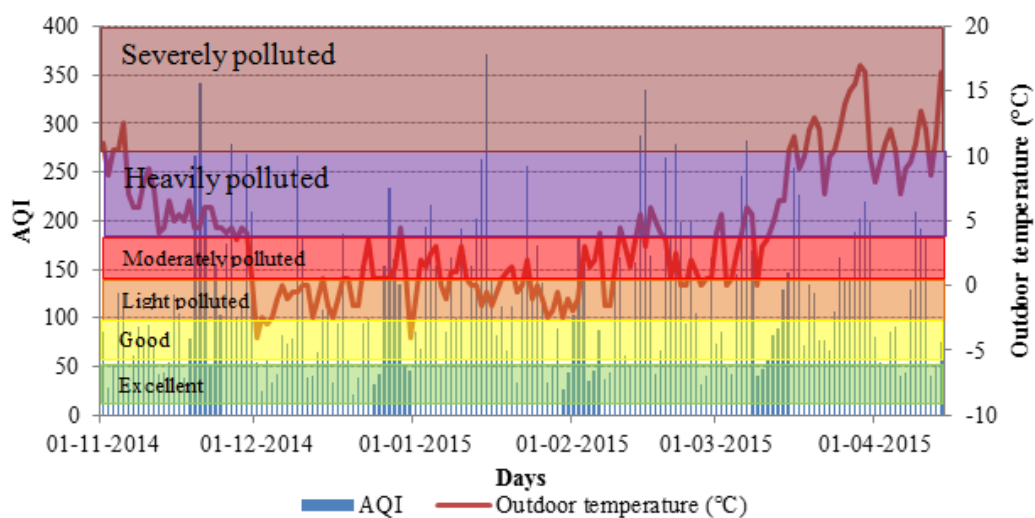


Figure 2.2. AQI and outdoor temperature in the period 11/01/2014-14/04/2015

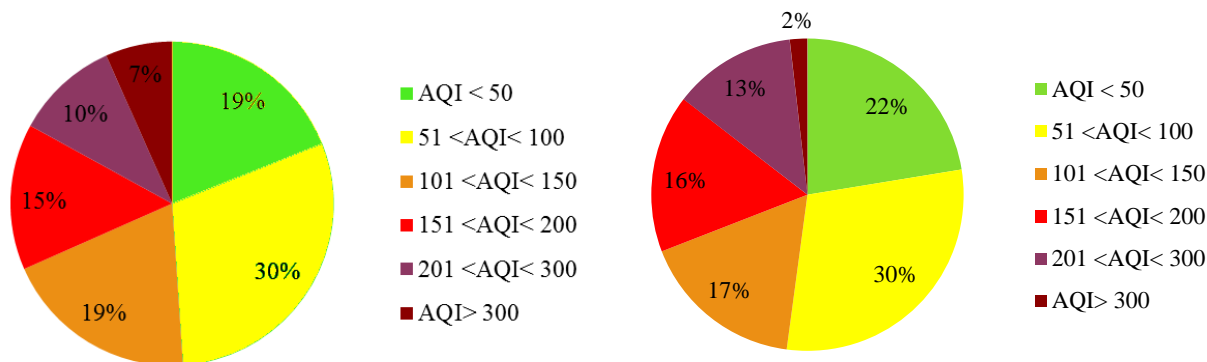


Figure 2.3. % of different daily AQI levels: 11/01/2013-04/14/2014 (left) and 11/01/2014-04/14/2015 (right)

2.1.1.2 Fuel conversion and potentials of industrial waste heat in China

One of the measures proposed for coping with air pollution is the implementation of fuel conversion from coal to natural gas. Since natural gas emits lower levels of pollutants than burning coal, some energy experts have proposed greater reliance on natural gas as a way to slow down global warming and reduce the impact of energy use on the environment. Major cities in China, including Beijing, Tianjin and Taiyuan, are currently planning to restrict new heating plants to gas-fired technology. For instance, under the 12th Five-Year Plan, gas heating will cover 51% of the heating areas in Beijing [24]. However, as a long-term solution to deal with the pollution problems, fuel conversion also faces some challenges. One of the barriers is the high capital cost. For example, the cost of the equipment and installation of gas boilers is much higher than for coal-fired boilers. This is in contrast to Europe where the cost of a natural gas boiler would be around 40% lower than a coal-fired boiler [25].

Another, even more environmentally friendly DH fuel is the waste heat from industrial processing. Research has shown that industrial surplus waste heat could cover up to 70% of the heat demand in northern China's legally mandatory heating regions. Moreover, a lot of surplus heat from industrial processes is available within 30 km of the cities [26]. Figure 2.4 shows the top five energy-intensive industrial sectors in China, and reflects the industrial waste heat utilization potential [15]. Table 2.1 lists the available industrial waste heat capacity from 13 cities around Beijing, together with each city's DH heat load. It is clear that some heavily industrial cities like Tianjin, Zhangjiakou, Tangshan, and Handan have sufficient waste heat capacity to supply the city's DH systems. In other cities, waste heat is also available to some degree. Tsinghua University has proposed the integration of available industrial waste heat around Beijing and surrounding cities within a radius of 200km to be used as the district heating source for these areas [27]. The research results indicate that the existing industrial waste heat in Beijing, Tianjin and Hebei Province could be used as the energy resource to power the DH systems of those areas during the winter for the next 10 years. The study also shows the utilization of industrial waste heat is better than coal-to-gas fuel conversion with regard to economic investment and environmental emissions.

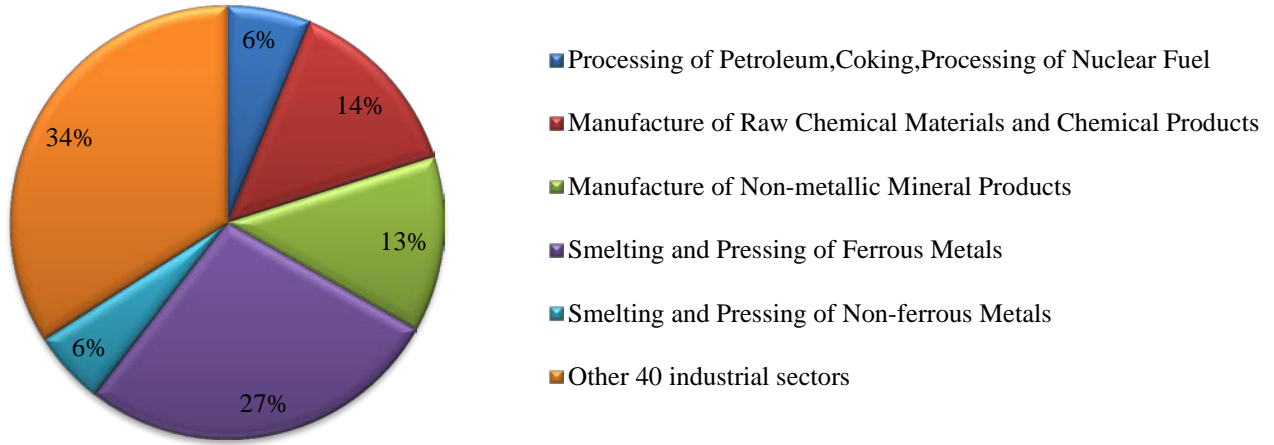


Figure 2.4. Top five energy-intensive industrial sectors in China

Table 2.1. DH heat load and waste heat available in 13 cities around Beijing [27]

	City	A: City heat load (MW)	B:Industrial waste heat capacity (MW)	Ratio A to B
1	Beijing	45666	8951	20%
2	Tianjin	15780	17515	111%
3	Shijiazhuang	13172	12729	97%
4	Chengde	3439	2435	71%
5	Zhangjiakou	5024	7556	150%
6	Qinhuangdao	3634	1988	55%
7	Tangshan	9859	16320	166%
8	Langfan	5415	2028	37%
9	Baoding	11112	4784	43%
10	Cangzhou	7457	5936	80%
11	Henshui	4244	2027	48%
12	Xingtai	7278	2405	33%
13	Handan	10204	11050	108%
	Total	142284	95724	67%

2.1.2 DH network scale and temperature level

Structurally, a typical Chinese DH system is that pressurized hot water as the heat medium is produced in the central heat source. The heat is transported to large-area substations via transmission pipelines. This is the primary side of the DH system. The secondary side is from the large-area substation to its connected heating areas through the distribution pipeline.

A typical DH primary network is shown in Figure 2.5, the heat source is coal-fired space heat only boilers with 37 large area substations, and the covered total heating area is 2.44 million m².

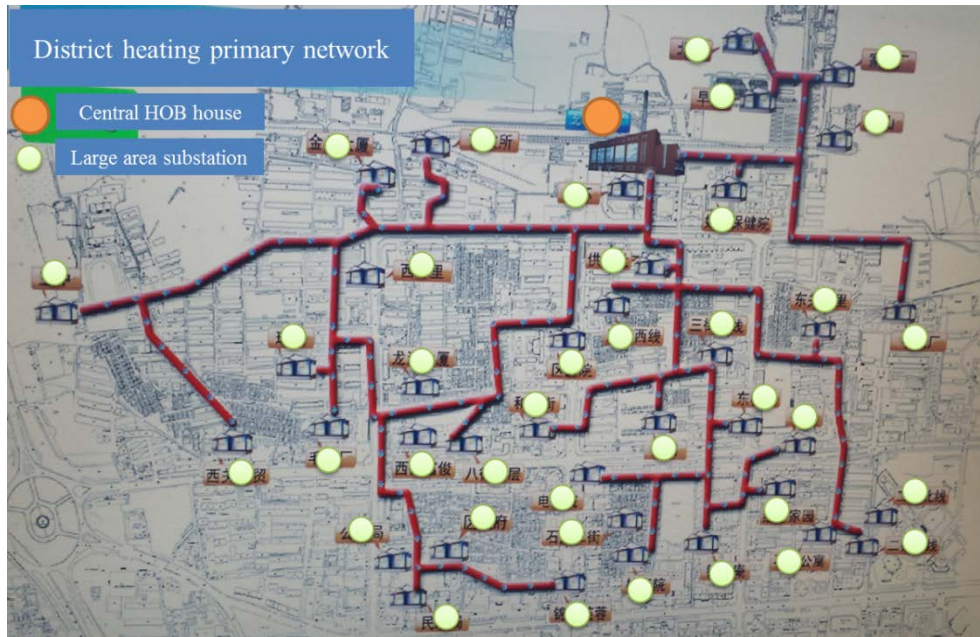


Figure 2.5. District heating primary network

Theoretically, the primary design supply temperature is recommended as 115-130 °C, and the return temperature is 50 ~ 80°C according to design code: JGJ26-2010 [4]. The traditional DH systems in China operate with a constant flow rate and variable secondary flow water temperature. Reducing the primary return temperatures as low as possible can not only achieve the large temperature difference that will ensure the high efficiency of the heat source, but also helps absorb low-grade heat. Because efficiency of heat source is the ratio of heat output to fuel heat input, while the heat output from heat source is proportional to the flow of the energy carrier and to the temperature difference between supply and return. Table 2.2 lists primary supply and return temperatures on the coldest day from the DH systems of various cities to show the temperature levels of the DH primary side.

Table 2.2 DH supply and return temperatures on the coldest day in 10 cities in northern China

City	DH primary supply temperature (°C)	DH primary return temperature (°C)	Temperature difference (°C)
Jinan	92	50	42
Taiyuan	107	48	59
Shijianzhuang	88	58	30
Yinchuan	85	65	20
Baotou	83	48	35
Fuxin	85	47	38
Chifeng	96	52	44
Yanji	96	49	47
Jilin	95	40	55

Harbin	92	46	46
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2.1.3 Substations

In contrast to the building-level substations which are usually applied in European countries, large-area substations are the common case in China. Each large substation supplies heat to a large number of high-rise or multi-storey buildings. According to studies from Tsinghua University, most area substations supply heating areas of between 100,000 m² and 200,000 m². The areas covered by substations in the DH systems of two cities are presented in Figure 2.6. For these two cities, the area substations covering more than 50,000 m² heating area account for 82% and 74% respectively.

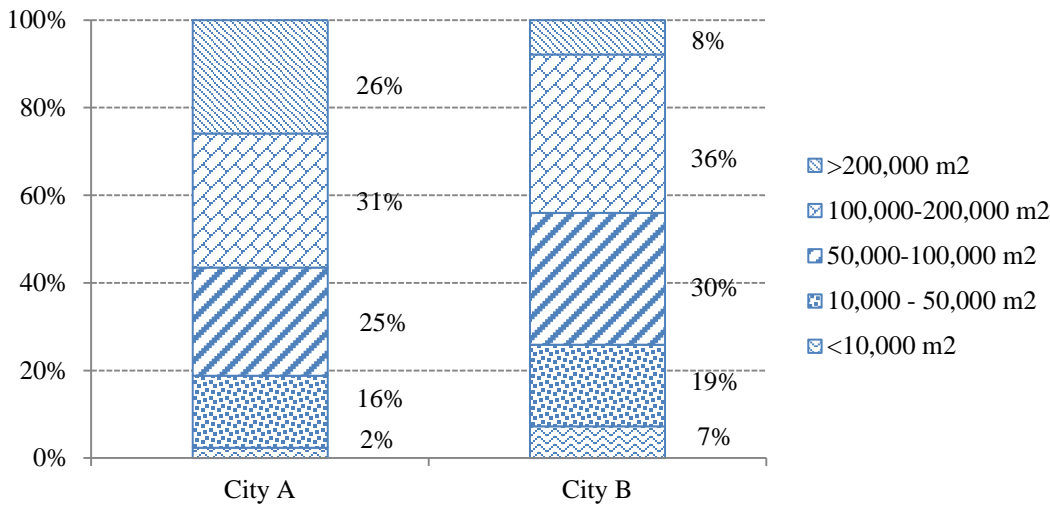


Figure 2.6. Area served by substations in City A and City B [28]

The current Chinese DH system connections by using large-area substations have the following problems:

- When the building types are different, e.g. residential buildings and commercial buildings are mixed in a same DH system, there is generally no individual control for each building, so the heat supplied to the commercial building when it is not occupied is wasted.
- When the building heat systems require different supply temperatures, e.g. radiator heating systems and floor heating systems are mixed in a same DH system, the flow temperature cannot be adjusted flexibly in accordance with the real demand. To ensure the critical building obtains sufficient heat to fulfil the heat demand, some of buildings are overheated. To compensate for this, the pipes have sometimes been designed as oversized from the beginning.
- High initial investment cost for the pipelines due to the long-distance heat transportation line and large heat supply radius, as well as for the oversized pipes.

2.1.4 Heat end-users

The Chinese government has been implementing heat reforms since 2003, when the key direction of DH reform was clearly defined. To reduce the energy use in DH, four main tasks are emphasized in the “Heat Reform Guidelines”:

- 1) Commercialization of DH in cities;
- 2) Promotion of technical innovation of heating systems;
- 3) Application of energy-saving building construction;
- 4) Improvement of living standards.

In terms of the commercialization of urban heating, the main idea is to change heat from an item of welfare into a commodity in the heat market. By 2012 there were 4.92 billion m² of heating area in China. The area retrofitted for heat-metering was 0.805 billion m² in northern China, which accounts for approx.16% of the total heating area in China [29]. It is predicted that there will be a continuous expansion of the heating area with heat-metering in the coming years.

Under this circumstance, currently the majority of indoor heating systems in China have not yet installed thermal adjustment devices, so the end-users cannot adjust the indoor temperatures. Moreover, the heating is billed based on a fixed charge according to the floor area, which brings out heat end-users have no motivation to save heat and lack energy-saving awareness. When a room is too hot, they open the window to dissipate heat, which results in 15-25% a building’s thermal requirement is wasted according to general statistics [30].

2.2 The state of the art

To modernize Chinese DH systems, the successful experiences from traditional mature DH countries, such as Denmark could be inspiration for China. Figure 2.7 compares the basic information on the two countries and their DH systems. It shows the much higher DH penetration rate in Denmark than in China even the country area of Denmark is much smaller than China.

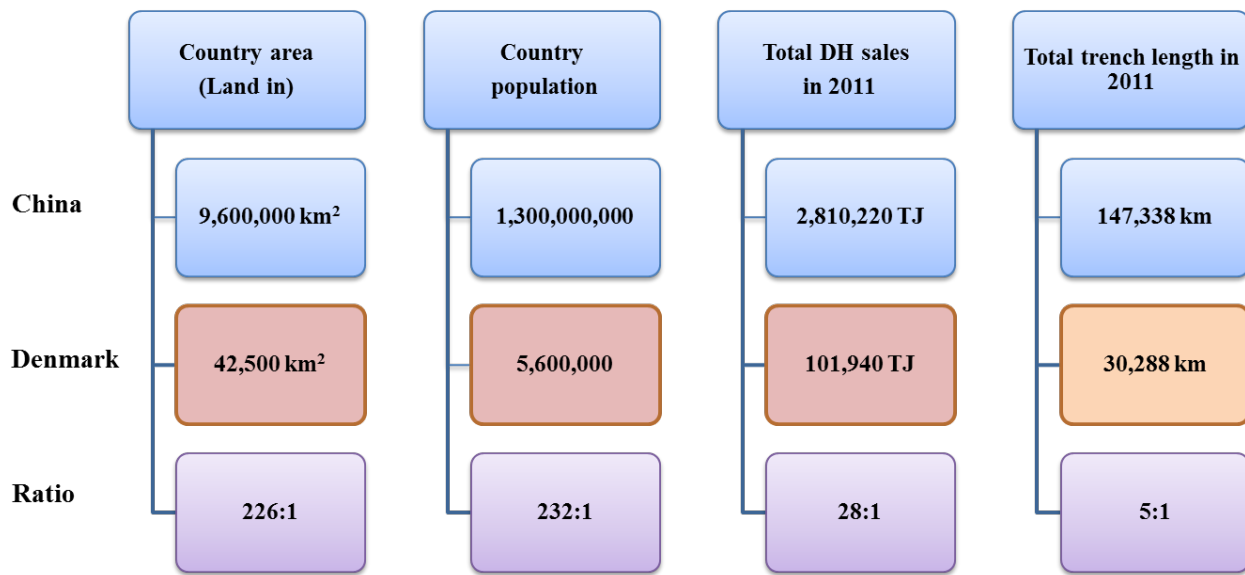


Figure 2.7 Basic information on China and Denmark and their DH systems

Denmark is one of the most energy-efficient countries in the world. A wide range of pro-active, energy-saving measures have reduced energy consumption by increasing the use of renewable energy and technological developments. Since the 1980s, Denmark's energy consumption has remained steady, while the economy has continued to grow. The widespread use of DH and combined heat and power (CHP) has made a major contribution to Denmark's drive towards efficiency and energy self-sufficiency [31]. The country's DH systems combine SH and DHW and run continuously throughout the year. Denmark is developing diverse heat generation technologies, powered by renewables and otherwise wasted energy [32][33][34][35], as well as gradually reducing its use of fossil fuel. Furthermore, the well-oriented and supportive policies of the Danish government have resulted in technical success. Commercial companies have carried out the research and development of DH-relevant products and solutions, along with universities, consultancies, and trade associations, all have made substantial contributions to the revolution in DH technologies.

2.2.1 Using local fuels that otherwise would be wasted

The fundamental idea of DH is to use local fuels that would otherwise be wasted to fulfil the heat demands of local heat consumers via a local distribution network. All these three elements are local, which is essential to minimize investment costs and keep the distribution pipeline as short as possible [36].

In Danish DH plants, the original oil or coal boilers were converted to natural gas or renewables such as biomass, wood-chip or waste, or only used as backup. The boiler design is very flexible with respect to fuels, and the boilers can burn various types of straw, wood chips, wood pellets, etc. In fact, biomass currently accounts for approximately 70% of renewable-energy consumption in Denmark, mostly in the form of straw, wood and renewable wastes [37].

Figure 2.8 shows the fuels that were used to produce DH in Denmark in 2010 [38], including local fuels such as biomass, Solar thermal, Geothermal. The main trend is that fossil fuels will be phased out in the next two

decades in Denmark and gradually replaced by renewable energy under the direction of energy policy. Renewable energy can help Denmark achieve its energy target in the heating sector by 2035. The Danish government's aim is that Denmark should use 100% renewable energy in the energy and transport sectors by 2050, and be completely fossil-free in the heating sector in 2035[35]. This energy policy means that renewable energy will play an ever more important role in Denmark's energy supply structure in the coming years.

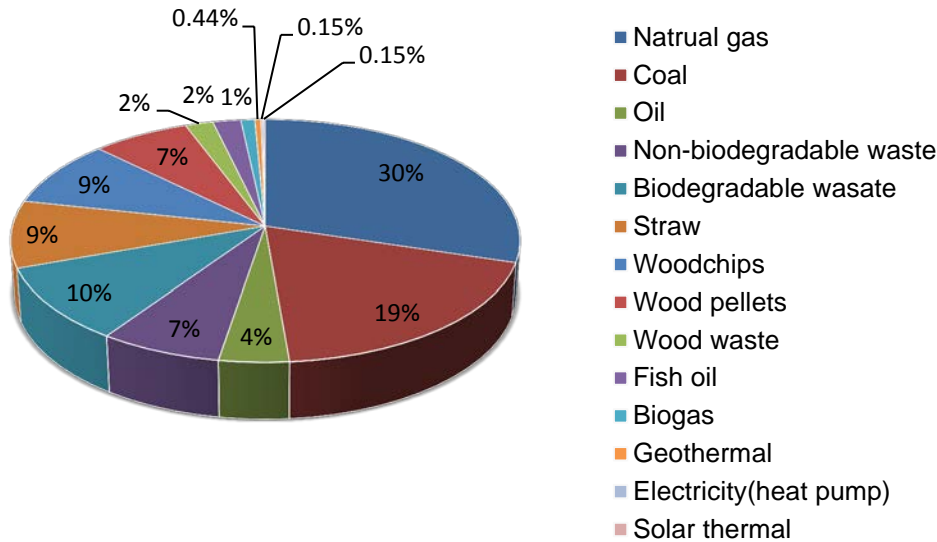


Figure 2.8. District heating fuels in Denmark in 2010

2.2.2 Pre-insulated pipes

In terms of distribution network, the concept of pre-insulating steel pipes and covering the insulation with a water-resistant casing was invented in Denmark in 1960. The concept became a major success and a huge number of kilometres of pipes have been installed in Denmark and other countries, creating the basis for modern cost-effective DH systems [36].

Today, pre-insulated pipes are buried directly under the ground, and fitted without the use of compensators or other stress-releasing methods. Pre-insulated steel pipe is now commonly used in heat transmission and distribution networks, and for the final service pipe between the street and the building, it is common practice to use plastic pipes with insulation. The trend in Danish DH pipes to reduce heat losses has been to use twin pipes as much as possible. The benefit of twin pipes with regard to heat losses is that the return pipe is inside the supply pipe heat flux, which limits heat losses from the return pipe. Further decreases in the heat losses can be achieved if the pipes are situated within the heat flux of each other [39]. Heat loss savings of 37% and investment cost reductions of 12% can be achieved by using twin pipes instead of two single pipes [40]. It has also been shown that placing the return pipe closer to the earth surface, i.e. on top of the supply pipe, gives the best results [36][39]. To minimize water losses in the distribution, two alarm wires for surveillance are embedded under the outer casing of the piping. If leakage occurs, the resistance of the wires changes and leakage can be detected [41]. The various DH pipe systems are presented in Figure 2.9. From left to right, the pipes are: (A).single pipes with a thin insulation layer; (B).single pipe with a thick insulation layer; (C) an egg-shaped twin

pipe; (D) a vertical twin pipe with a large diameter; (E) a vertical twin pipe with a small diameter; (F) and triple pipe. The differences between these pipes have been investigated in [39].

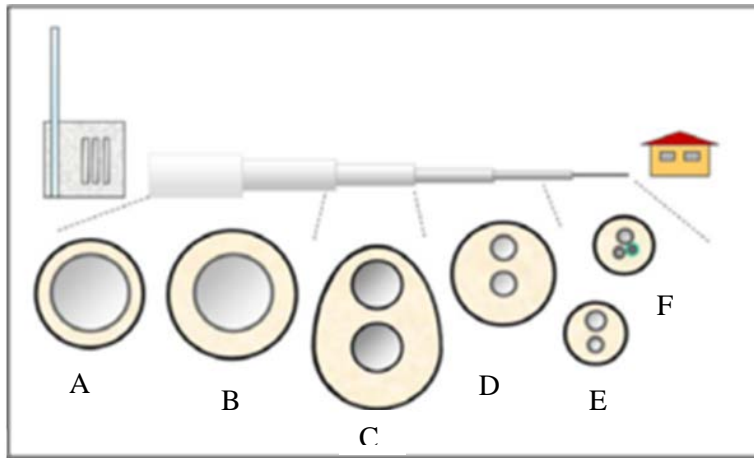


Figure 2.9. District heating pipe systems in Denmark

2.2.3 Heat exchanger in a building level substation or flat station

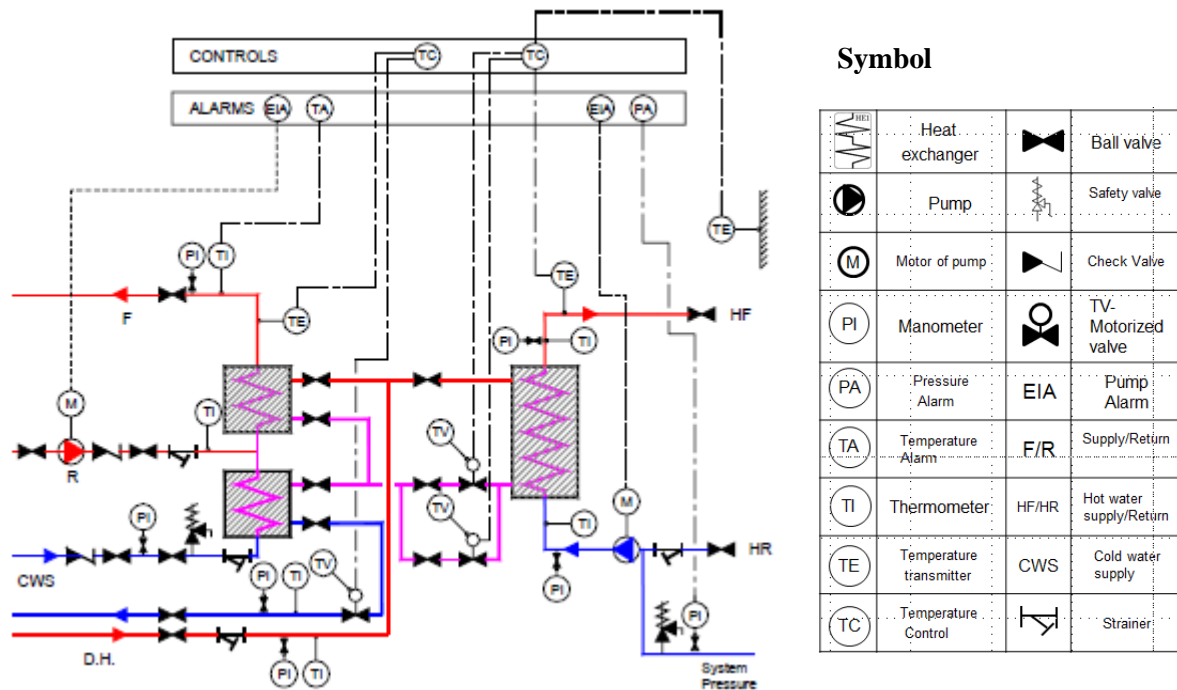


Figure 2.10. Schematic of a heat exchanger substation [42]

Plate heat exchangers are widely used in Denmark. Heat exchanger substations are located at building level or even in individual apartments (flat stations). The prescribed heat exchanger substation is compact in size, and it is easy to find space to install it within the building.

The substation is equipped with comprehensive controllers to ensure the efficient operation of the DH system, see Figure 2.10. For example, the secondary side of the hot water is often designed so that the supply temperature varies according to the outdoor temperature. This control method reduces energy costs and helps to optimize conditions for the control valves, because a certain minimum flow is maintained. A temperature transmitter in the secondary supply pipe measures the process value, and this value is compared with a specified set point condition in the control system.

2.2.4 Individual heat-metering and billing

In Denmark, it is mandatory to pay for heat according to consumption. All DH installations are equipped with energy meters. The installation of heat meters does not in itself bring energy savings. It is the consumer's awareness of his own consumption that motivates the consumer to consider how energy can be saved. Often simple measures are taken by the consumers to reduce heat consumption, such as closing the TRV) instead of opening the window, and avoiding excessive use of supplied heat. More applied technologies on individual heat metering and billing in Denmark are introduced in Chapter 4 of this thesis.

2.2.5 4th generation district heating (4GDH) in Denmark

State-of-the-art DH technology refers to the 4th generation in the development of the technology. In terms of supply temperature level, the 1st to 3rd generation DH technologies are characterized by steam-based systems (1st generation) with the temperature higher than 100 °C, high-temperature water systems ($T_{\text{supply}} > 90$ °C, 2nd generation), and medium-temperature water systems ($70^{\circ}\text{C} \leq T_{\text{supply}} \leq 90$ °C, 3rd generation). Figure 2.11 shows the temperature features of 1st ~ 4th generation DH systems. What is remarkable in the development of DH technology is that the DH temperature level is gradually getting lower. For the 4th generation DH, the DH supply temperature can be lower than 60°C. E.g. during the summer operation of DH system, the DH supply and return temperatures of 50/25 °C are used and instead of 70/40 °C in 3rd generation DH systems.

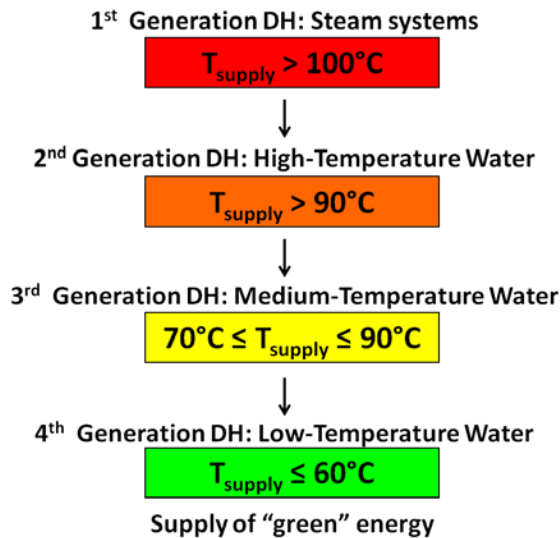


Figure 2.11. Temperature features of 1st ~ 4th generation DH systems [43]

The first generation of DH systems uses steam as the heat carrier and represents an outdated technology due to high heat loss, and high operating and maintenance costs. It is also restricted to heat generation units which can

produce high temperature steam. The second generation switched to pressurized hot water as the heat carrier. The heat carrier of the third generation of DH systems is still pressurised water, but supply temperatures are lower and often combined with the use of the twin pipe system and plastic media pipes where possible.

The 4th generation of DH systems is characterized by strategies to achieve low energy use. In the context, 4th generation of DH systems also are called low temperature DH (LTDH) technologies, but the introduction of the low-temperature characteristics is needed to put together energy efficiency at building and network level with heat sources based on low-grade heat and renewable and then achieve a long-term, integrated and holistic concept. Moreover, the 4th generation DH technologies can firm the competitive position of DH in low heat density area in Nordic countries; meanwhile propagate the advantages of DH. Therefore, the idea of designing the new generation of DH is to develop a flexible, smart and secure energy supply, transmission and distribution system with effective integration of energy efficient buildings and energy efficient DH networks[44][45][46].

Denmark has an ambitious energy policy aimed at achieving 100% renewable energy in the heating sector by 2035[35]. A wide range of energy-saving measures have been taken to reduce the heat demand through more stringent building codes and retrofitting of the existing building stock. The European Union's Energy Performance of Buildings Directive prescribes "nearly zero energy buildings" from 2020 [43]. The development of community energy systems in Europe includes taking them into areas with lower heat density than before, which promotes the integration of more renewables and the more frequent application of low-temperature surplus heat than before. One of the solutions is LTDH, which can be used in low heat density areas. During the transition from 3rd DH to 4th DH systems, heat demand per unit area, the DH temperature level, and distribution heat losses have all been correspondingly reduced in Denmark, see Table 2.3

Table 2.3.DH system reductions during the transition from 3rd to 4th generation

	3 rd generation	4 th generation
Heat demand of DH systems	75-150 kWh/m ²	40 kWh/m ²
Design DH temperatures (winter)	70/40 °C	55/25 °C
Design DH temperatures	60/40 °C	50/25 °C
Distribution heat losses	15-30%	15-20%

The future trend in Danish DH is expected to be towards 4GDH [47], characterized by smart thermal grids utilizing low-quality energy like renewables, with optimized combinations of heat sources to supply appropriate lower temperatures to low-energy demand buildings through a high-efficiency DH network [48].

2.3 The potential for Chinese DH systems in looking at Danish DH systems

Table 2.4 looks at the obvious technical differences by comparing the main elements of DH systems in Denmark and China. The aim is to identify the potential in the Chinese DH systems and opportunities for the integration of Danish DH technologies.

Table 2.4. Comparison of District Heating systems used in China and Denmark

Items	Denmark	China	Potentials for China DH
District Heating system	<ul style="list-style-type: none"> - Both for SH and DHW). - Available the whole year 	<ul style="list-style-type: none"> - SH-only DH systems are common and operate during the heating season. - Only about 5% of DHW is prepared via DH in northern China: individual water heaters are the dominant technology for producing DHW. 	Integrate DHW production into DH systems.
Linear heat density ¹ [49]	<ul style="list-style-type: none"> - Linear heat density was equal “3.4” in 2011; - In 2011, total DH sales were 101,940 TJ; - Trench length of DH pipeline system was 30,288 km [7]. 	<ul style="list-style-type: none"> - Linear heat density was equal “19.1” in 2011; - In 2011, total DH sales were 2,810,220 TJ; - Trench length of DH pipeline system was 147,338 km [7]. 	
Heat generation	<ul style="list-style-type: none"> - DH generation methods: in 2011, CHP supplied 77% of the heat, with the remaining 23% being supplied by various other heat-only devices [50]; - In 2011, the energy supply composition for DH source was composed of: recycled heat, including indirect use of renewables 69.8%, direct renewables 19.3%, and others 10.9% [51]. 	<ul style="list-style-type: none"> - DH generation methods: in 2013, CHP supplied 42% of the heat, coal-fired boilers supplied 48%, gas-fired boilers supplied 8%, others 2% [13]. - In 2008, about 91% of the total energy supply of the heating sector was coal, with 5% petroleum products and 4% natural and other gas [12]. 	Renewable energy, waste energy, etc. clean energy technologies
Distribution network	<ul style="list-style-type: none"> - In transition from 3rd generation DH to 4th generation DH, namely low-temperature DH (LTDH), with DH supply/return changed from 70/40 °C to 50/25 °C [47]; - Reduction of heat loss from distribution pipeline based on multiple techniques, such as pre-insulated twin-pipes. 	<ul style="list-style-type: none"> - DH typical design supply/return temperature is 130/70 °C; - Real DH supply/return temperatures for typical cities are listed in Table 2.2. - Distribution pipes generally have large dimensions due to high heat density; - Pre-insulated pipes are being used more and more to reduce the heat loss, but single pipes are normal. 	Improve the efficiency of DH system by achieving hydraulic balance to reduce heat loss from distribution pipelines.
Substation technology	Building level substations or flat stations in each apartment. Single-family houses and multi-storey buildings are typical.	Large substations serve a group of buildings. High-rise buildings and multi-storey buildings are typical.	Improve the automatic control level and apply building level and apartment level substation concept.
Indoor Comfort and heat billing mechanism	<ul style="list-style-type: none"> - Indoor temperatures are adjustable by using the available adjustment devices, such as TRV; - Heat bills charged based on actually consumed energy; - Heat bills include variable cost, fixed cost, subscription fee and tax. 	<ul style="list-style-type: none"> - Lack of adjustable devices results in the non-adjustable indoor temperature; legal minimum indoor temperature is 18 °C. - Heat billing is based on floor heating area. - Heat reform is going on in China and aims to build an incentive mechanism to meter and bill heat based on real consumption. 	Retrofit for heat-metering and temperature regulation of heating systems: Regulation devices , control components as well as systematic solution

More details can be seen in Article IV of Appendix.

¹ Linear heat density is defined as heat sold annually (GJ) divided by the trench length of the piping system (m), with the unit GJ/m. This ratio indicates the level of DH distribution system utilization and is a good indicator of the ratio of revenue to distribution cost.

3 Part I: Optimizing space heating systems in China by achieving hydraulic balance

3.1 The hydraulic balance issue in heating systems

3.1.1 Definition of hydraulic balance in heating systems

According to the definition of path of least resistance, natural process will go the way with the least resistance. In a pipe system, flow resistance increases with increased flow rate, so the flow rate can change the path of least resistance if no flow control devices are implemented. This means that establishing hydraulic balance in a heating system is often a matter of controlling the differential pressure in the circulation loop and thus regulating the flow rate in each individual branch and the end-heat-emitters to the desired level. To achieve this, differential pressure control devices for managing the flow distribution and pressure profile are needed in the system.

A heating water distribution system is called ‘balanced’ when the supplied flow rate is equal to the required flow rate for each heating device in the whole heating system. This can be achieved when the flows are adjusted to the correct values in design conditions, so avoiding inadequate flow in design conditions makes sure that inadequate will be avoided in all other normal conditions. On the other hand, the lack of flow and pressure control in the heating system inevitably causes hydraulic imbalance. If the correct balancing of the system is not established, this will result in unequal distribution of the flow, so that there will be an excess effect in some of the terminal units, while other terminal units will get insufficient flow distribution. Usually, hydraulic imbalance presents as insufficient supply pressure and therefore poor heat supply in the distal parts of the heating network, or as excessive supply pressure and therefore overheated rooms and waste of energy.

3.1.2 The consequence of hydraulic imbalance in Chinese district heating systems

The most direct consequence of hydraulic imbalance is excessive heat supply. A typical Chinese DH system in China can be described as a centrally located heat source supplying pressurized hot water to a few large area substations (the primary side of the DH system). Each area substation serves a number of multi-storey or high-rise buildings (the secondary side of the DH system). Usually, there are no automatic flow control devices in the secondary-side systems, i.e. from the substation to the buildings. Without flow control, buildings close to the pumps receive more flow than needed and therefore are overheated, whereas buildings located in distal parts of the network may receive less flow than is required to fulfil their heat demands. To achieve the minimum indoor air temperature of 18 °C required under the Chinese building code [5], DH utilities usually increase the circulation flow until the critical consumers achieve this minimum indoor air temperature. This often results in the systems operating with large volume flow and small temperature differences between the supply and return pipes. These small temperature differences also lead to higher power consumption in the circulation pumps. At the same time, high return temperatures compromise the efficiency of the heat plant.

3.2 Methods

To reduce the excessive heat supply and achieve the hydraulic balance in the DH systems, the main idea of the method is to give individual flow and pressure control to the terminal units. Two-pipe radiator heating systems are recommended by the Chinese national standard [5], so two-pipe radiator heating systems were investigated in this study. The configuration of the technical approach was to combine pre-set radiator valves with automatic balancing valves. Pre-set radiator valves were used to control the flow through the radiator and maintain it within

a range around its design level, and a differential pressure (DP) controller of the automatic balancing valves can maintain the differential pressure across the radiator valves during operation, giving good regulation of the radiator valve in all conditions. Moreover, the automatic balancing valves can separate a controlled loop as an individual hydraulic zone.

The hypothesis was that this technical approach would allow hydraulic balance to be achieved in Chinese multi-storey or high-rise building heating systems. An integrated model was developed to verify the hypothesis theoretically, and a field test was implemented to verify its technical feasibility in practical terms.

3.2.1 Two key elements in the technical approach

Radiator valves with the pre-setting function and the automatic balancing valves are the two key elements in this technical approach. The flow through each radiator can be easily maintained within a range around its design level using the pre-setting function. The pre-setting values correspond to the scales marked on the radiator valve and the range is from 1 to 7 and N, which represent gradually increasing maximum flow limits, see Figure 3.1 (right). The pre-setting values can be set in accordance with the requested design flow through the radiator and the pressure drop across the valve. To ensure the optimal regulation of the radiator valve and quiet operation, it is important to achieve the desired differential pressure across the valve. According to EN 215[52], a differential pressure setting of 10 kPa is commonly used for radiator applications. For example, the design flow through the radiator is 35 l/h, and the pressure drop across the valve is 0.1 bar (10 kPa), the presetting valve is 3 accordingly, see Figure 3.1(left) [53].

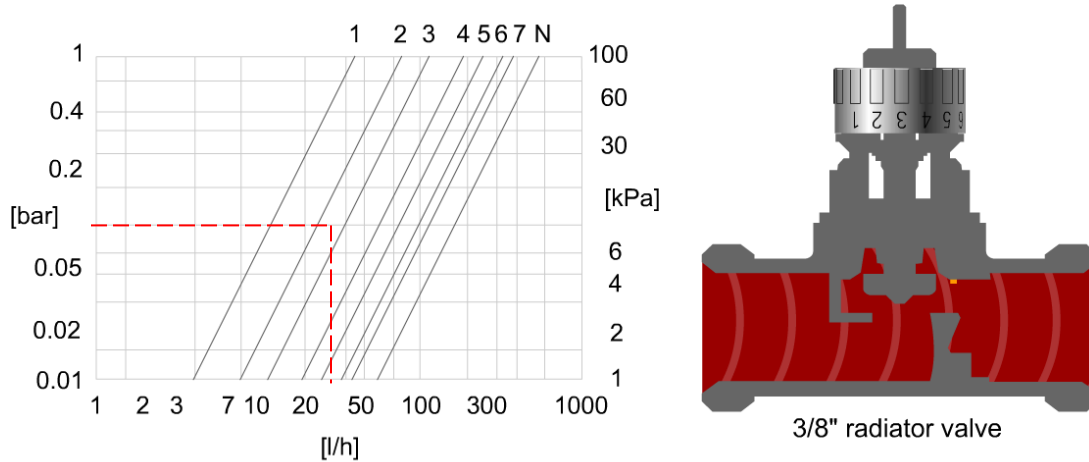


Figure 3.1. Pre-set radiator valve and pre-setting values

The automatic balancing valves can ensure that the desired flow rate is achieved at all times irrespective of any pressure changes within the system. Automatic balancing valves consist of a self-acting DP controller and an associated partner valve, which are mounted in the return and supply pipes respectively of the controlled loop. The valves are linked to each other via a capillary tube. Inside the DP controller, there is a control diaphragm (7) internally connected with the reference spring (4), pressure in the return pipe acts on the underside of the diaphragm, and pressure in the supply pipe acts on the top of diaphragm via an impulse through the capillary tube (5) which connects to the partner valve. Changes in the external differential pressure will be offset by stretching and compressing the spring. If the pressure differential tends to become greater than this setting, then the DP controller immediately reacts and keeps the pressure differential constant, see Figure 3.2. In this way, the flow in the controlled loop does not increase due to any system load changes. Moreover, the installation of automatic balancing valves turns all the controlled loops into pressure-independent zones. This eliminates any problems caused by high or excessive system pressures, including noise from the valves, which might result in poor control of room temperature.

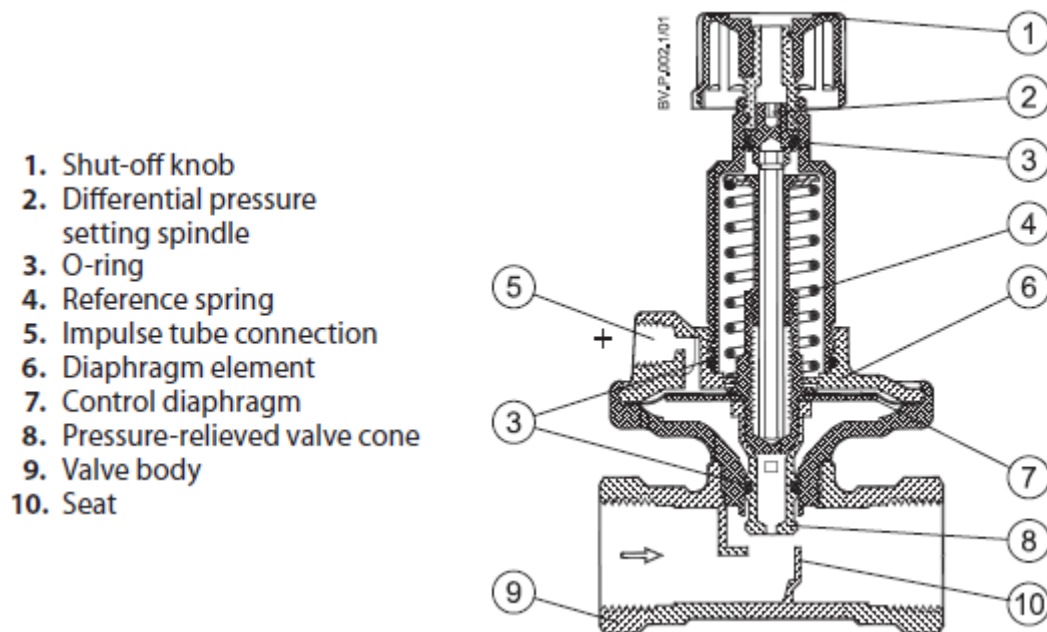


Figure 3.2. Internal structure of ASV-PV [56]

3.2.2 The integrated model

An integrated model was used to investigate the hydraulic performance and the heat performance of the building heating system with pressure and flow either controlled or not controlled. The building model from which the building heating system was derived was developed in commercial software IDA Indoor Climate and Energy (IDA-ICE) 4.6.2 [54]. Based on the heating system, the physical properties of the hydraulic model were known and a mathematical hydraulic model developed by the author was built based on Kirchhoff's laws. Where a DP controller was used, either at the riser level or at apartment level (Figure 3.3), the available differential pressure ΔP (bar) of the controlled loop was kept constant.

For this integrated model, the numerical hydraulic model can be used as a hydraulic calculation tool to find out the degree of openness in the control devices that can achieve the required flow under design conditions, and the differential pressure level that needs to be set by DP controller to ensure good regulation of the control devices and achieve hydraulic balance in the heating system. Based on the balancing flow distribution at terminal units, obtained from the hydraulic model, the required flow for each radiator is known and taken as input to the IDA-ICE building model to find out the indoor temperatures, pump power consumption, and heat consumption of the heating system with and without control devices applied in the heating system.

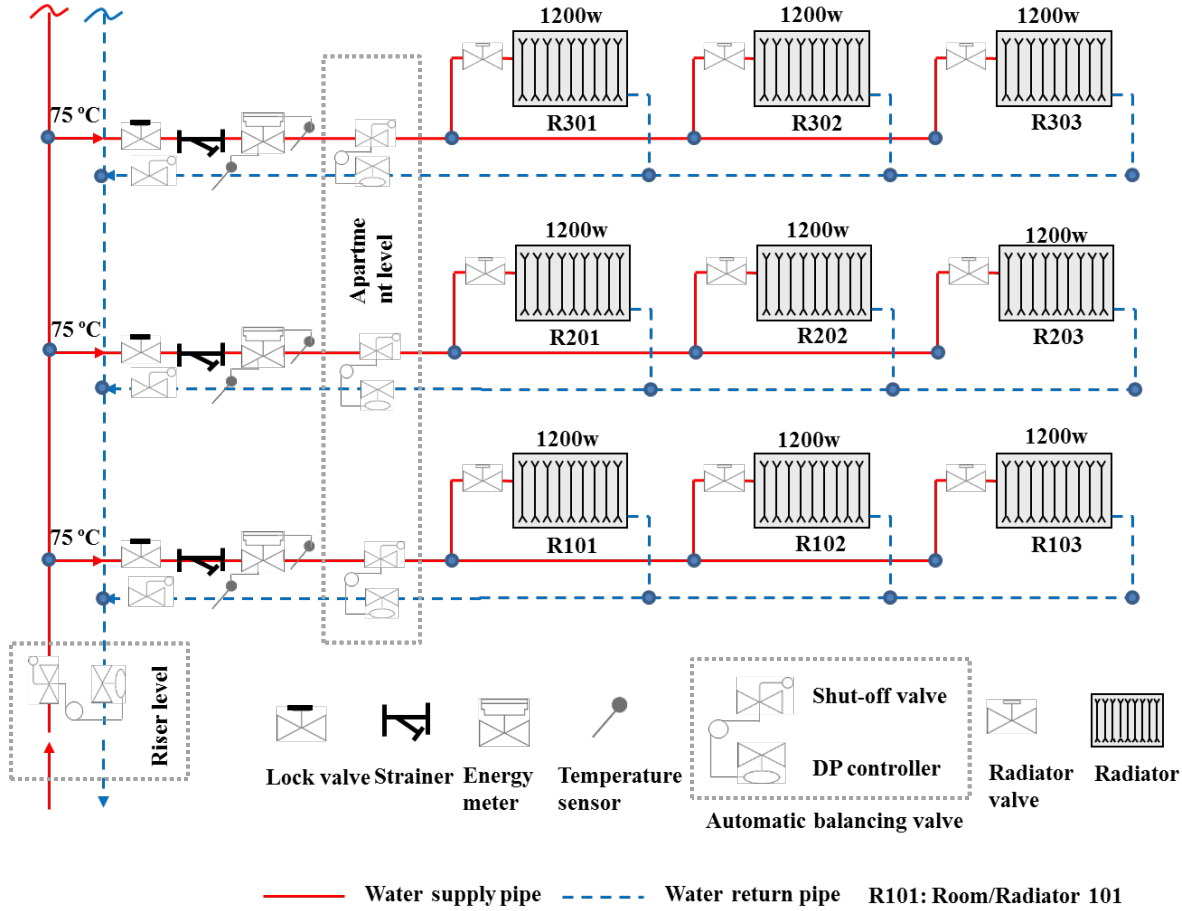


Figure 3.3. Schematic layout of the integrated model

3.2.2.1 Mathematic hydraulic model

3.2.2.1.1 Flow coefficient

According to the Darcy-Weisbach equation, the relationship between flow and pressure drop in a given pipe i can be expressed by Equation (2.1):

$$\Delta P_i = \left(\frac{\lambda_i}{d_i} l_i + \sum_{n=0}^n \zeta_n \right) \frac{1}{900^2 \pi^2 d_i^4 20 \rho_w^2} q_{v,i}^2 \quad (2.1)$$

Moreover, k_v is defined as the flow rate that goes through the valve under a pressure drop across the valve of 1 bar. The actual flow, q (m³/h), through the valve for a given pressure drop, ΔP (bar), across the valve can be calculated using Equation (2.2):

$$q = k_v \sqrt{\Delta P} \quad (2.2)$$

Changes in the throttle section of a control valve change the k_v value. Pipes without control devices have a constant k_v value. It can be said that changing the k_v value of certain pipes, which can be done by pre-setting the radiator valves, consequently changes the flow distribution in the heating system, and that flow control can therefore be achieved. However, for any given k_v value, the differential pressure across the valve also influences the flow through the valve, so a constant differential pressure across the valve is also required to ensure the good regulation of the radiator valve.

3.2.2.1.2 Theory of the hydraulic model

Water-flow in the heating network follows Kirchhoff's laws. According to Kirchhoff's first law, at any node in a hydraulic network, the sum of water-flow into that node is equal to the sum of water-flow out of that node, and this can be expressed as Eq. (2.3):

$$\sum_{n=1}^m q_{v,n} = 0 \quad (2.3)$$

where $q_{v,n}$ (m³/h) is the volume flow of branch n. Whether $q_{v,n}$ is a positive or negative value depends on whether the flow is into or out of the node.

According to the Kirchhoff's second law, the directed sum of the differential pressure around any closed network is zero. This can be expressed as Eq. (2.4):

$$\sum_{n=1}^m \left[\left(\frac{q_{v,n}^2}{k_{v,n}^2} \right) - \Delta P_n \right] = 0 \quad (2.4)$$

For a system of pipelines connected in series, the pressure drop for the whole loop, ΔP_S , is the sum of the pressure drop in each pipeline, ΔP_n . This can be expressed as Eq. (2.5). Based on Eq. (2.2), the equation also can be expressed by $k_{v,S}$ for the whole loop, and $k_{v,n}$ for the each pipeline, see Eq. (2.6).

$$\Delta P_S = \sum_{n=1}^m \Delta P_n \quad (2.5)$$

$$\frac{1}{k_{v,S}^2} = \sum_{n=1}^m \frac{1}{k_{v,n}^2} \quad (2.6)$$

For a system of pipelines connected in parallel, the volume flow for the whole loop, $q_{v,s}$ is equal to the sum of the volume flow through each branch pipe, $q_{v,n}$, see Eq. (2.7). Moreover, $k_{v,s}$ of the whole loop and the resistance characteristic coefficient for each pipe ($k_{v,n}$) is expressed in Eq. (2.8).

$$q_{v,s} = \sum_{n=1}^m q_{v,n} \quad (2.7)$$

$$k_{v,s} = \sum_{n=1}^m k_{v,n} \quad (2.8)$$

3.2.2.1.3 Mathematical model

Based on the schematic layout of the integrated model (Figure 3.3), both the whole building heating system (with three apartments) and each apartment heating system (with three radiators) can be considered as a heating system with three loops (Figure 3.4).

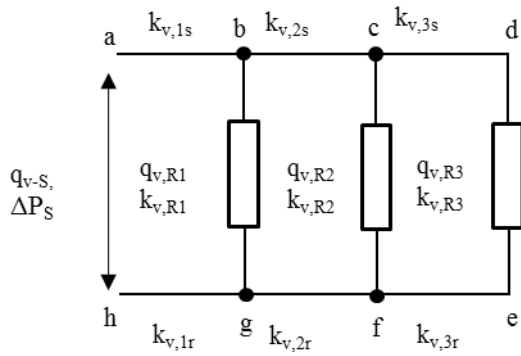


Figure 3.4. Mathematical model of the hydraulic model

According to Kirchhoff's laws, and the series connection and parallel connection of the pipelines, the group of equations for this mathematical model can be written as Eq. (2.9) – Eq. (2.15)

$$\frac{1}{(k_{v-cdef})^2} = \frac{1}{k_{v,3s}^2} + \frac{1}{k_{v,3r}^2} + \frac{1}{k_{v,R3}^2} \quad (2.9)$$

$$\frac{1}{(k_{v-bcdefg})^2} = \frac{1}{k_{v,2s}^2} + \frac{1}{k_{v,2r}^2} + \frac{1}{(k_{v,R2} + k_{v-cdef})^2} \quad (2.10)$$

$$\frac{1}{(k_{v-abcdefgh})^2} = \frac{1}{k_{v,1s}^2} + \frac{1}{k_{v,1r}^2} + \frac{1}{(k_{v,R1} + k_{v-bcdefg})^2} \quad (2.11)$$

$$\Delta P_s = \left(\frac{q_{v,s}}{k_{v-abcdefgh}} \right)^2 \quad (2.12)$$

$$q_{v,S} = \sum_{i=1}^3 q_{v,Ri} \quad (2.13)$$

$$\frac{q_{v,R1}}{q_{v,R2} + q_{v,R3}} = \frac{k_{v,R1}}{k_{v-bcdefg}} \quad (2.14)$$

$$\frac{q_{v,R2}}{q_{v,R3}} = \frac{k_{v,R2}}{k_{v-cdef}} \quad (2.15)$$

When the available DP for this system ΔP_S has been determined, and the $k_{v,1s}$, $k_{v,1r}$, $k_{v,R1}$, $k_{v,2s}$, $k_{v,2r}$, $k_{v,R2}$, $k_{v,3s}$, $k_{v,3r}$, and $k_{v,R3}$ values for each pipe are known, the volume flow, $q_{v,R1}$, $q_{v,R2}$, and $q_{v,R3}$, for each branch pipe can be found based on Eq. (2.9) – Eq. (2.15).

3.2.2.2 Scenarios

To verify the application effects when radiator valves are pre-set and combined with the DP controller, four scenarios were developed which refer to radiator valves pre-set or not, and DP controller applied at riser level or apartment level. The reference case was with no control devices applied in the heating loop at all, see Table 3.1. The flow distribution for the reference and the four scenarios can be calculated by using the hydraulic model. These data were then input into the IDA-ICE model to simulate the heat consumption, pump power consumption, and the deviation from the design indoor temperatures and design return temperatures.

Table 3.1. The reference and the four scenarios

Control conditions	No DP controllers, just pipes	Apply DP controllers		No radiator valves, just pipes	Apply radiator valve	
		Riser level	Apartment level		No pre-setting	With pre-setting
Reference	√	-	-	√	-	-
Scenario 1	-	√	-	-	√	-
Scenario 2	-	-	√	-	√	-
Scenario 3	-	√	-	-	-	√
Scenario 4	-	-	√	-	-	√

3.2.3 A field test for flow control

3.2.3.1 Introduction to the devices used in the field test

The field test was carried out to verify in practical terms the hypothesis that the distributed flow to each radiator can be kept within a range around the design flow value by utilizing the pre-set radiator valves on radiators combined with automatic balancing valves at each apartment heating loop. During the field test, the thermostats mounted on the apartment radiators tested were all removed.

This field test was carried out in a new 18-storey high-rise residential building in Beijing, see Figure 3.5 (left).

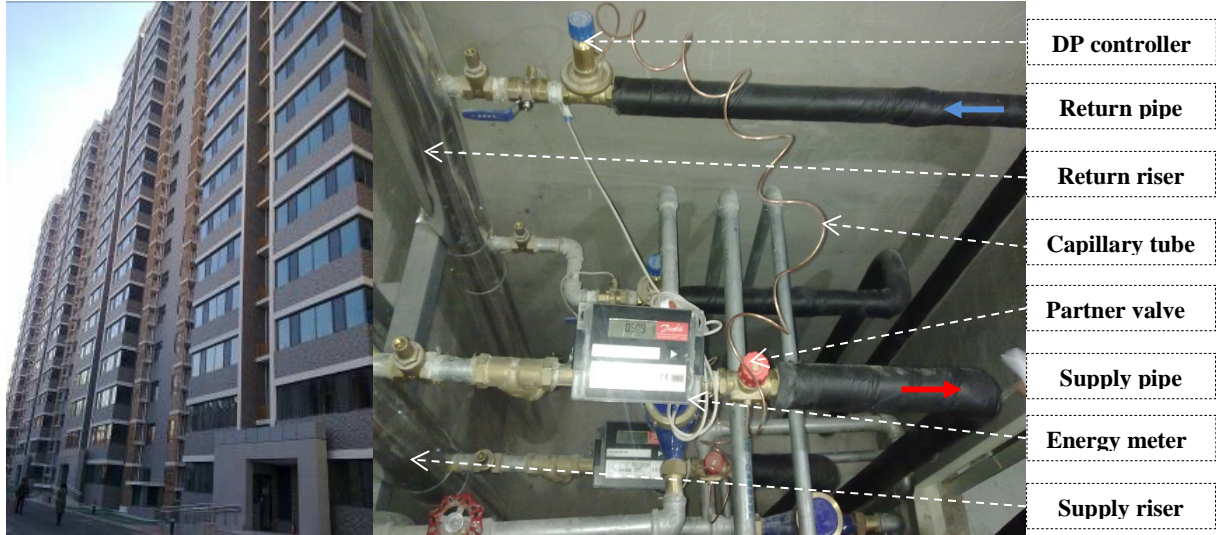


Figure 3.5. Real test case for the flow control approach

The heating installation configuration for each apartment was as follows: the radiator valves with integrated pre-setting were of the type RA-N [53], dimension DN15; the thermostatic sensors type RTW4600 were removed during the test [55]; automatic balancing valves and an ultrasonic energy meter were installed at the heating entrance of the apartment building heating system (Figure 3.5). The hot water from the area substation was distributed to individual apartments via the staircase risers. The risers connected two apartments per floor.

The pre-setting values of RA-N valves can be adjusted on a scale ranging from 1 to 7 and N, and each level corresponds to a maximum flow limit [53], see Table 3.2. From 1 to 7, the maximum flow limit gradually changes from small to large; at N, the valve is fully open.

Table 3.2. K_v -values for RA-N type radiator valves sized DN15 [21]

Pre-setting values	1	2	3	4	5	6	7	N
k_v -max (m^3/h at $\Delta p=1$ bar)	0.04	0.08	0.14	0.21	0.31	0.37	0.47	0.53

The setting on the DP controller, ASV-PV, can be changed by turning the setting spindle. In this case, the differential pressure range was 5-25kPa and turning the spindle a number of times, as described in Table 3.3, sets the DP controller.

Table 3.3. Setting the DP controller, ASV-PV, sized DN20 by turning the spindle [56]

Number of turns (n)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Settable pressure range 5-25 kPa	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5

3.2.3.2 Implementation of the field test

The field test consisted of two parts: Test I and Test II. During the entire test, the heating systems of the other apartments in this building were operating normally.

Test I focused on the pressure control function of the DP controller, and three apartments with identical heating areas but located on different floors were considered as test objects. The loop flows were measured for apartments 201, 202, and 1701 with the DP controllers set at 5, 10, 15, 20, and 25 kPa respectively to investigate

- whether the hydraulic imbalance along the vertical pipe could be reduced by controlling the differential pressure of three loops at the same set values; and
- whether the loop controlled by the DP controller is a hydraulically separated zone, by changing the set-points of the DP controller at random or by completely shutting off the loop flow of the other two apartments to observe the flow changes in the case of the third apartment loop.

Test II considered one apartment with five rooms as the test object and focused on the flow limitation function of the radiator valve integrated pre-setting. A schematic configuration of the apartment heating loop is shown in Figure 3.6. Basic information about the apartment is listed in Table 3.4. On the basis of the desired flow of each radiator and the 10 kPa setting of the DP controller in the apartment loop, the k_v value of the radiator valve was chosen and is listed in Table 3.4.

The set-point of the automatic balancing valves was adjusted to 10 kPa, and then the loop flow, supply and return temperature, and indoor temperature were measured when each radiator valve was pre-set or not pre-set.

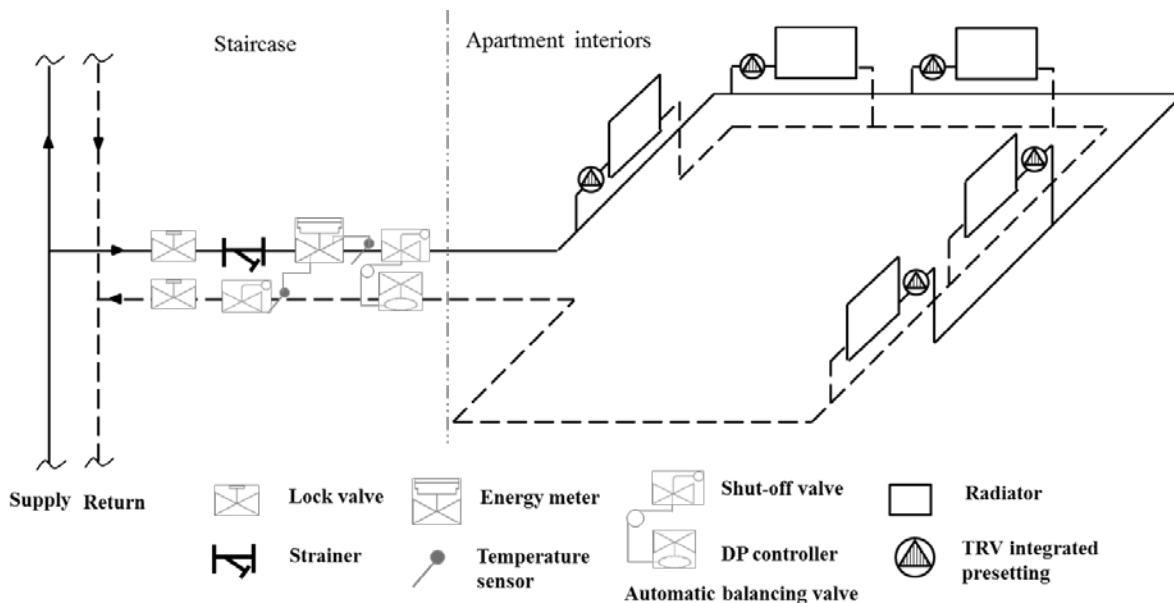


Figure 3.6. Schematic configuration of the apartment heating loop

Table 3.4. Basic information about the apartment tested

Room name	Floor area (m ²)	Heat load (W)	Desired operating temperature difference (°C)	Desired flow (l/h)	Pre-setting values (10kPa)
Living Room	18	810	15	46.4	3
Bedroom A	14.5	654	15	37.5	2.5
Bedroom B	8.7	391	15	22.5	1.5
Bathroom	3.4	168	15	9.6	1
Kitchen	4	180	15	10.3	1
Total	48.6	2203		126	

3.3 Results

3.3.1 The results obtained from the integrated model

3.3.1.1 Flow distributions and room temperatures

Based on the calculation results of the hydraulic model and the IDA ICE simulation results when radiator valves were not pre-set, the flow distribution among the radiator is uneven, and the heating system is in hydraulic imbalance. The situation changed when radiator valves were individually pre-set. The average excess flows were significantly reduced no matter whether the DP controller was applied at riser level or apartment loop level, and when the heating system is in hydraulic balance, the room temperatures are much closer to design values (Table 3.5). More details about the results can be found in Article I: Method for achieving hydraulic balance in typical Chinese building heating systems by managing differential pressure and flow.

Table 3.5. Comparison of the simulation results for the reference and the four scenarios

Control conditions	Hydraulic balance	Average excess flow (%)	Average room temperature (°C)	Deviation from design room temperature (°C)
Reference	NO	321%	26.3	8.3
Scenario 1	NO	44%	20.4	2.4
Scenario 2	NO	33%	20.1	2.1
Scenario 3	YES	10.2%	19.4	1.4
Scenario 4	YES	8.5%	19.3	1.3

3.3.1.2 Pressure head diagrams

In terms of the pressure distribution of the 3rd floor apartment heating loop, when a DP controller was set to provide 5 kPa differential pressure, the available differential pressures was 5 kPa in all four scenarios. But when no DP controller was applied, i.e., in the reference case, the pressure head of the 3rd floor loop needed to be 28 kPa to ensure that Radiator 303 obtained sufficient flow, see Figure 3.7 . This high pressure head meant high

power consumption by the pump, and the excessive pressure drop in the heating system increased the flow rate in the pipes, which can cause noise. Furthermore, a high flow rate can easily lead to more impurities and cause blockages. It can therefore be concluded that using a DP controller maintains a constant pressure drop across the radiator valves, which safeguards their good regulation and quiet operation.

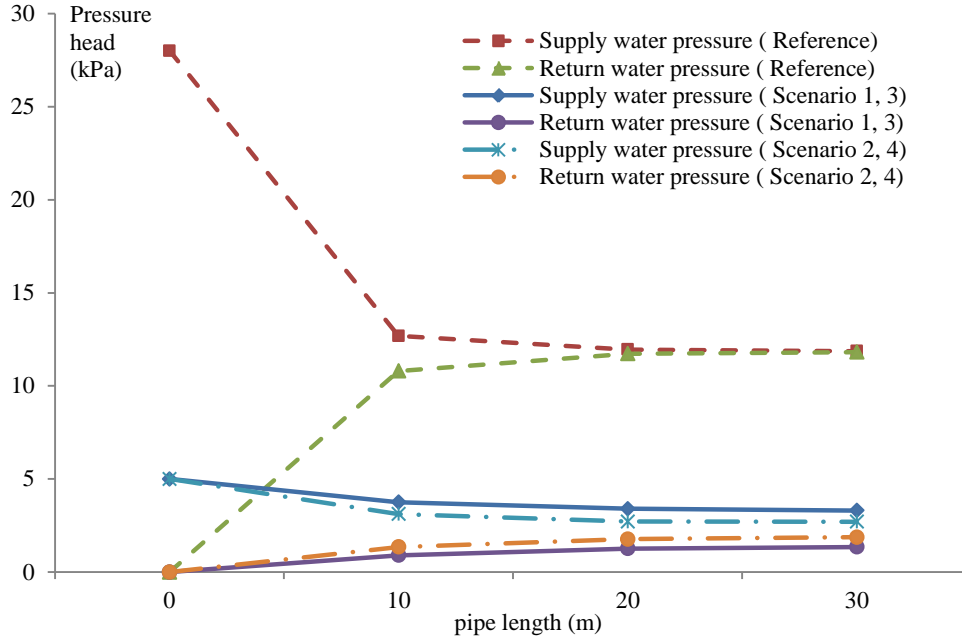


Figure 3.7. Pressure profile of the integrated model

3.3.1.3 Energy consumption and return temperatures

Table 3.6. Comparison of energy consumption and return temperatures for the reference and the four scenarios

Control conditions	Heat consumption	Pump power consumption	Return temperature (°C)
Reference	100%	100%	63
Scenario 1	89.2%	34.9%	56.6
Scenario 2	88.1%	32.2%	54
Scenario 3	84%	24.2%	52.3
Scenario 4	83.8%	23.7%	52.1

Table 3.6 compares the reference and the four scenarios with regard to heat consumption, pump power consumption, and return temperatures. The simulation results show that Scenario 4 had the least heat consumption, the least pump electricity consumption, and the lowest return temperature, closest to the design

return temperature of 50 °C. Scenario 3 had similar simulation results to Scenario 4, which implies that whether the DP controller is applied at riser level or apartment level makes no big difference on energy consumption. So it is wise to find a balance between the cost of the initial product investment and the later operating costs of the heating system. Nevertheless, applying DP controllers at apartment level provides some additional benefits for the system: some risks can be effectively avoided, such as man-made changes or misuse of the initial pre-setting of radiator valves, which might be fully opened and cause hydraulic imbalance, which would affect other loops and perhaps the whole riser heating system as well as causing noise and probably blockage issues.

3.3.2 The results obtained from the field test

Test I gave the following results:

- When the DP controllers of the three apartments loop were given the same set-point (separately set at 5, 10, 15, 20, and 25 kPa), the three loops had a similar volume flow, as expected.
- The deviation of the individual loop flow from the average flow of all three loops at the same set points was within $\pm 15\%$. This shows that the hydraulic imbalance along the vertical riser was reduced after the installation of the DP controllers.
- Moreover, this result also verified that automatic balancing valves are able to separate each heating loop into an independent pressure zone because, when the differential pressure of the other two tested heating loops was changed or the loops were completely shut off, the flow of the first loop was not affected.

For Test II, the test object was one apartment. Table 3.7 compares measurements when the radiator valves were pre-set and when they were not pre-set.

Table 3.7. Comparison of measurements with and without pre-setting in Test II

Parameter of tested apartment loop	No pre-setting	Pre-setting
Total flow rate of apartment loop (l/h)	557	181
Supply temperature (°C)	62.6	62
Return temperature (°C)	53.6	44.7
Delta T (°C)	9	17.3
Average indoor temperature (°C)	22.6	22
Outdoor temperature (°C)	-4	-4

The results show that after the radiator valves were pre-set:

- The total loop flow rate was reduced by 68%: from 557 l/h without pre-setting to 181 l/h with pre-setting. The flow rate with pre-setting is much closer to the design flow rate of 126 l/h, so the excessive flow rate condition was largely ameliorated and excess flow avoided.
- The supply temperatures were similar (62.6 °C and 62 °C) in the two cases, but the return temperature was reduced from 53.6 to 44.7 °C.

- The temperature difference of the controlled loop was increased by nearly 200% from 9 °C to 17.3 °C with pre-setting. The room temperature went down slightly from 22.6 °C to 22 °C within the two hours measurements were made.

3.4 Conclusions

The proposed approach of combining the use of radiator valves with integrated pre-setting and automatic balancing valves has been shown to be both effective and feasible, both in theoretical analysis and in practical terms.

The simulation results based on the integrated model indicate that a technical approach of combining DP controllers with radiator valves will significantly improve the hydraulic conditions compared to there being no pressure or flow control. This technical approach will help achieve a fair flow distribution among the radiators, bring room temperatures and the temperature difference between supply and return close to design values, and result in 16% heat savings and 74% pump electricity savings.

For given application, there can be small differences in heat performance and energy consumption between applying the DP controllers at apartment level or at riser level in combination with pre-setting radiator valves. Both control solutions can achieve hydraulic balance in the heating system. In terms of financial factors, it is important to take into account both the initial investment cost and the potential increase in operating costs in the event of the misuse of radiator valves with DP controllers applied at the riser level and the increased complexity of commissioning this solution.

The field test showed that pre-setting radiator valves combined with automatic balancing valves can achieve the hydraulic balance in the building heating system. Using a DP controller ensures a constant differential pressure in the controlled loop and turns it into a separate pressure zone. At the same time, it protects the good regulation of downstream radiator valves. Pre-setting of the radiator valves reduced the flow rate by 2/3, and the temperature drop in the loop increased by nearly 100% from 9 °C to 17.3 °C.

These results verify that the hypothesis is valid and the solution is feasible: hydraulic balancing can be achieved based on the terminal units with the combined application of pre-set radiator valves and automatic balancing valves. The solution optimizes the flow distribution in the building's heating system so that it provides the intended indoor room temperature with optimum energy efficiency and at minimum operating cost. In this way, room thermal comfort can be improved and heat loss due to excessive heat supply can be reduced. All these benefits will help improve the efficiency of Chinese heating systems.

4 Part II: Optimizing space heating systems by controlling indoor temperature

4.1 Specific background for thermal control of district heating systems

4.1.1 Current heat-metering situation in China and in Denmark

4.1.1.1 China

The current fixed heating charge based on floor area is to be replaced with heat-metering and consumption-based billing, so as to promote the energy-saving consciousness of the end consumers. Under the guiding policy of the heat reform, several heat-metering measures have been investigated and applied in China in an effort to find a fair billing method for the diverse heating systems currently applied in typical multi-storey/high-rise buildings in China.

Table 4.1 lists four main heat-metering methods that have been recommended by the national industry standard “JGJ173-2009 Technical specification for heat-metering of DH system” [57]. The general philosophy is heat consumption is metered for a whole building and then distributed to each unit of this building by applying one of methods listed in Table 4.1.

Table 4.1. Four main heat-metering methods applied in China [57]

Heat-metering methods	Method Description
1. Calorimeter method	A primary calorimeter is installed at the heat entrance of a building; secondary calorimeters are installed at the heat supply pipe to each household, and TRV installed on each radiator to regulate room temperatures.
2. Heat allocator method	A heat allocator is installed on each radiator. The proportion of heat emitted by each radiator to total heat consumption of the whole building can be worked out by reading the allocator.
3. Flow volume and temperature method	Constantly measuring the differential temperature between the inlet and outlet of radiator, and using the flow ratio of each household to the whole building to distribute the heat consumption of the whole building to each unit.
4. On-off time and floor area method	An on-off valve is installed at the heat entry point of each household. The hot water circulation is controlled using the on-off method to maintain the room temperature and the cumulative on-time is measured. The total heat consumption of the whole building is distributed according to the on-time and floor area of each household.

When evaluating which method would be optimal, principles of fairness are important to ensure the method adopted can be accepted by the majority. Multi-storey and high-rise buildings are common in China, see Figure 4.1. This kind of building geometry will always require more heating in some apartments than others, due to

their location within the building. As expected, the most critical apartments are located in the corners, and at the top or bottom of the building, because they have more exterior walls. The extra exterior walls in these apartments can result in 2-3 times higher heat demand than apartments that are located in the middle of the building. Furthermore, if adjacent apartments are not being heated, heating costs can increase by an additional 20-30%, because of heat lost to those apartments that normally would not be the case [10]. Of the four metering methods, the 1st and the 4th method, calorimeter method and heat allocation according to the on-off ratio, is currently used most.



(a) Typical existing buildings in China

(b) Typical new buildings in China

Figure 4.1. Typical existing and new residential buildings in China

As part of all four heat-metering measures, TRV are always applied to the radiators. As the essential and basic control device, the TRV are becoming popular in China. The expected role for TRV in the heat reform is that people will reduce heat consumption by closing the radiator valve instead of opening the window to avoid excessive heat. Over the last decade, TRV have been installed in a great number of new and renovated buildings, see Figure 4.2. However, neither the heat users nor the utility companies fully understand the flow control and thermal control functions of TRV. For instance, instead of setting the thermostat at correct points, many heat consumers just put the set-point at maximum then keep the windows open. The pre-setting function, which is used to control the maximum flow through the radiators for system hydraulic balance, has not been widely used.



(a) Old radiators equipped with TRV in China



(b) New radiators equipped with TRV in China



Figure 4.2. Old and new type radiators equipped with TRV in China

Moreover, the heat reform also encounters barriers due to

- Underestimation of the difficulties when diverse heating systems are under heat-metering renovations;
- The lack of access, knowledge and incentives for control methods;
- The lack of uniform standards and consensus on heat pricing.

The heat reform has been going on in China for the last 10 years, yet there is still a long way to go before a heat-metering and billing mechanism based on actual consumption can be truly realized.

4.1.1.2 Denmark

In Denmark, individual heat-metering of all households is prescribed by law. It is mandatory to pay for heat, just like water and electricity, according to consumption.

One way of measuring the heat consumption of a multi-storey building is to install a heat meter at the point of heat supply to the building, and place heat allocators on the radiators in the apartments. This method is used where the heating circuit does not allow the installation of heat meters, for example in large buildings with a vertical heating system and a large number of apartments. With one heat meter covering the entire building and a heat allocator mounted on every radiator to measure the total heat output of the individual radiator, it is possible to calculate a consumption-dependent share of the total heat consumption for each apartment. Heat cost allocators nowadays allow the logging and remote-reading of data.

Another common way is to install heat meters at building level, building unit level, and apartment level. A heat meter consists of 3 sub-assemblies: a volume flow meter; a pair of resistance thermometers that measure the temperature difference between inlet and outlet pipes; and a calculator that integrates the two measurements over a period of time or an amount of volume flow and accumulates the total heat transfer in units of kWh, MWh or GJ.

In Denmark, TRV are undoubtedly integrated in heating systems as the standard assembly. TRV were invented in Denmark and introduced in the 1970s as a cheap and easy way of controlling zoned temperatures. Nowadays, TRV are also widely used in apartment buildings all over Europe. The replacement of a manual heating control with TRV has been estimated to save at least 280 kilograms CO₂ per year [58]. By 2012, electronic TRV were becoming available using electronic temperature sensing. These are generally programmable so that individual radiators can be programmed for different temperatures at different times of the day. Such increased control allows even greater energy and CO₂ savings [59].

Moreover, modern energy-metering systems in Denmark have been provided with facilities for remote reading. The meters with transmitters are equipped in each household, this makes the data of the meters can be transmitted to internet via wireless connection. Real-time reading can be realized on demand or at certain intervals of time. Remote reading also allows the consumer to follow their consumption via the internet. Consumers can see their own data presented in a graph or in real figures on a web server, it is well protected against unauthorized access. The data reading is done with less manpower and without the need to access the premises and therefore without disturbing the privacy of individual consumers. A schematic diagram of real-time automatic meter-reading is shown in Figure 4.3 [60].

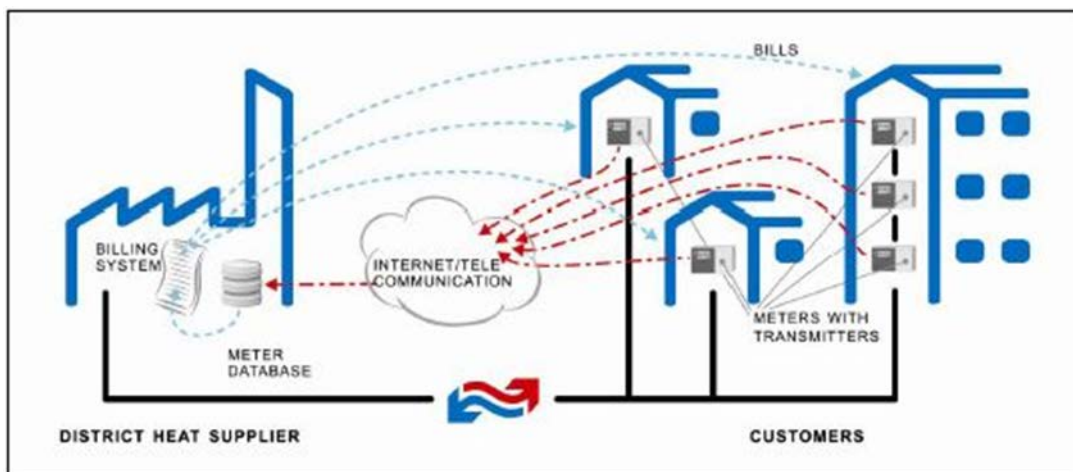


Figure 4.3. Schematic diagram of automatic meter-reading

4.1.1.3 European Union (EU)

The EU has introduced relevant policies to promote individual heat-metering in Europe. The experience and know-how based on studies and pilot cases from member countries like Denmark, Poland, Germany and the Netherlands have shown the energy savings achieved with heat-metering are on average 20%. It has been proved that individual metering and billing is a cost-effective and quick way to reduce emissions, improve energy security and competitiveness, and make energy more affordable for consumers. Against this background, Articles 9(1) and (3) of the Energy Efficiency Directive (EED) of European union state that “in multi-apartment and multi-purpose buildings with a central heating/cooling source or supplied from a DH network or from a central source serving multiple buildings, individual consumption meters shall be installed by 31st December 2016” [61]. The aim is to measure the consumption of heating or cooling and hot water for each unit. At the

same time, it also explains that an energy-metering system is most useful when installed prior to the identification and installation of energy conservation measures. It is more realistic that the first step should be the implementation of a cost-effective energy-metering system using a consolidated process which provides guarantees of success.

Ultimately, the installation of heat meters is a way of making consumers aware of their own consumption and encouraging them to consider how energy can be saved. Energy reduction is a result of changes in the habits of end-users. Therefore, it is important to remember that energy savings are initiated by consumers being aware of their consumption, while the thermostat is the all- important interface device between heat consumers and the real heating systems.

4.1.2 The function of thermostat

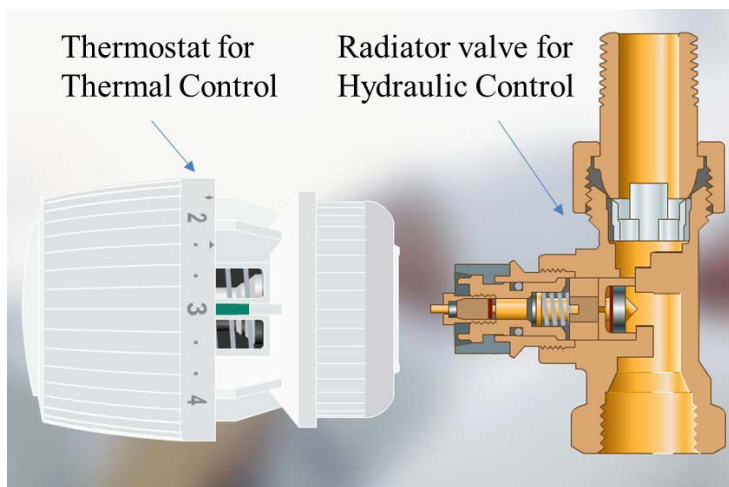


Figure 4.4. Thermostat and Radiator Valve

TRV is the abbreviation of Thermostatic Radiator Valves. TRV consists of a thermostat and a radiator valve (Figure 4.4). The radiator valve is mounted in the pipe-work at the individual heat emitters (usually radiators). The thermostat, namely thermostatic sensor, is mounted on the radiator valve. They are two individual components, but they work as one unit. A radiator valve is a flow control device for limiting the maximum flow through the radiator. The valve opening is controlled by the thermostat, which reacts to changes in the room temperature. The heart of the thermostat is a bellow. The bellow is a closed capsule which contains a medium (gas, wax or liquid). The medium contracts when it is cold and expands when it is warm.

For different rooms, the desired temperatures are often different. It must be possible to differentiate temperatures between the rooms. Typically, the user wishes the bathroom to be warmer than the bedroom. To achieve the temperature desired in each room it must be possible for the users to define or set the temperature in each room. This means that heating system needs individual room temperature controls. Once the desired temperature has been set, the TRV automatically adjusts to changes in the ambient temperature, which saves energy. Table 4.2 lists the recommended settings for different rooms and the corresponding temperatures.

Table 4.2. The recommended settings of the thermostat and the corresponding temperatures

Recommended settings	Dial	Corresponding temperature (°C)
Frost protection	*	7
Staircases and halls	1	13
Bedroom	2	17
Living room	3	20
Bathroom	4	23
Max setting	5	26

The temperature range of the thermostat is 7 to 26 °C. To avoid incorrect settings that will waste energy, the limits of the thermostat can be prepared by releasing 2 pins from the back of the thermostat to limit the setting points to between the desired maximum and minimum values. In *Figure 4.5*, the limit markers indicate where the block pins can be inserted.

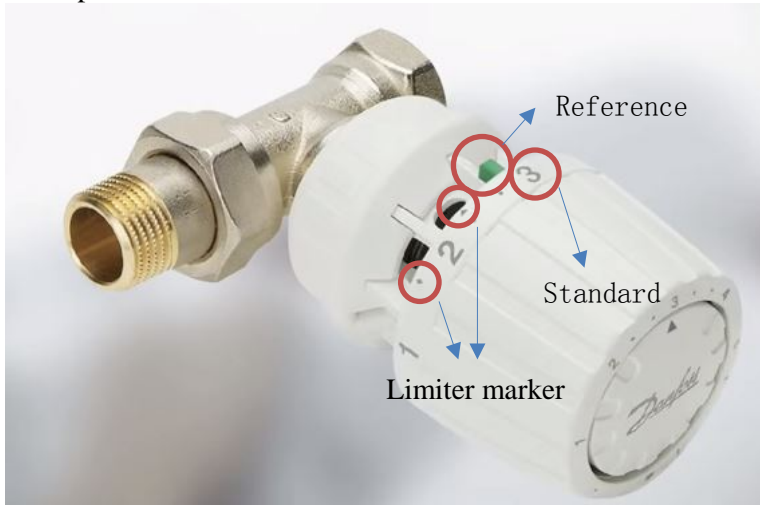


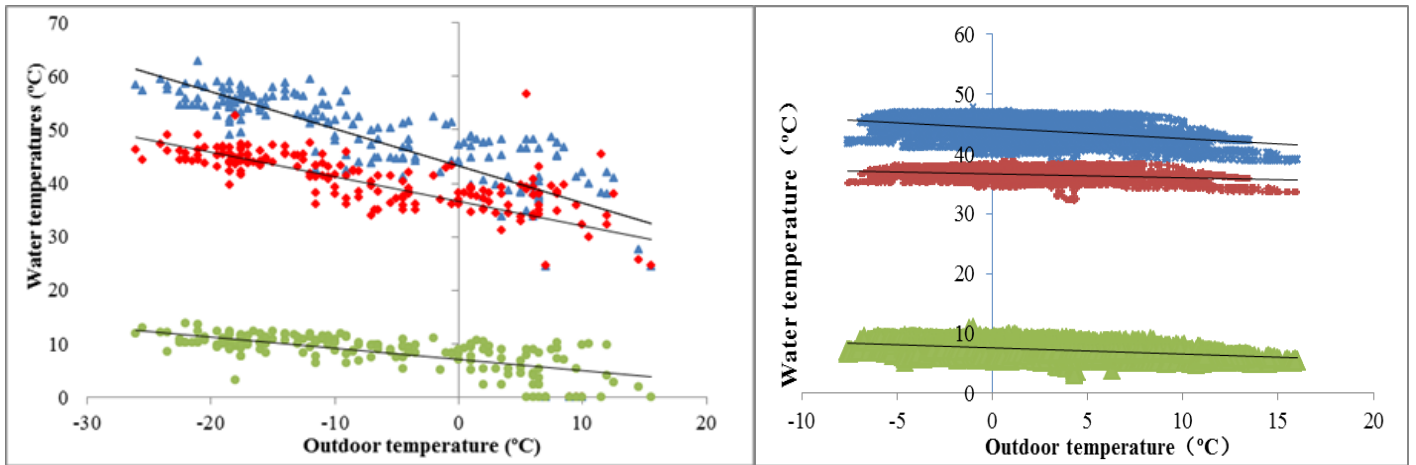
Figure 4.5. Setting limits to the thermostat

4.1.3 Real case studies

4.1.3.1 Cases in China and Europe

TRV installed in the heating systems have not played much of a role in China because bills for heating have not been based on the actual consumption, and quite a large number of buildings have yet to apply TRV, so most Chinese DH systems generally operate with constant flow. This makes it necessary to adjust the secondary supply temperature to reflect the heating demand of the heating area covered by the area substation or heat-only boilers.

Two real cases, Cases A and B, were studied to investigate the supply temperature of DH systems in China. Case C, from Finland, is introduced to make it possible to see the difference between China and European countries in terms of supply temperature. The supply (blue) and return (red) temperatures measured during the heating season for Cases A and B are illustrated in Figure 4.6, together with the temperature differences (green). The supply and return temperatures measurements for Case C are presented in Figure 4.7.



(a) Daily average supply and return temperatures for Case A in the period 20/10/2013-20/04/2014

(b) Real time supply and return temperatures at 5min. intervals for Case B, 15/01/2015-15/03/2015

Figure 4.6. Temperature control situation from Cases A and B

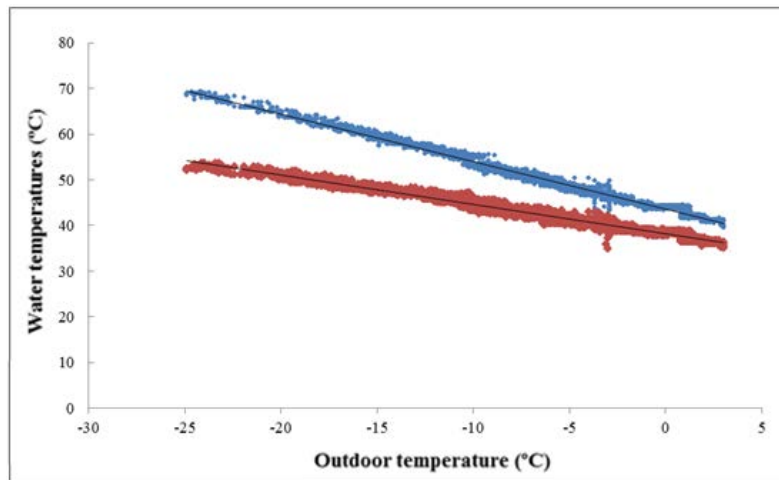


Figure 4.7. Supply and return temperatures for Case C, 24/12/2012-23/01/2013 [13]

Data from Cases A, B, and C are listed in Table 4.3. Those make it possible to compare the information with regard to temperature controls and see the differences between them. It is clear that the supply temperature control in China is less precise and lacks automatic control devices, so that the systems get overheated, especially at both ends of the heating season. For Case C, weather compensation control and automatic flow and temperature control measures benefit the heating system, so that the expected outcomes could be that heat outputs are in line with the heat demands.

Table 4.3 Comparison of Cases A, B and C in terms of temperature control in SH systems

Case name	Case A	Case B	Case C
Case location	China, Harbin city	China, Beijing city	Finland
Figure	Figure 4.6 (a)	Figure 4.6 (b)	Figure 4.7
Reflected information	<ul style="list-style-type: none"> • Supply/return temperatures are not linearly related to outdoor temperatures; • When outdoor temperatures are above 0 °C, the supply/return temperatures are higher than they should be. • The temperature difference curve is relatively flat, which means it is almost constant. 	<ul style="list-style-type: none"> • Supply and return temperatures, as well as temperature differences are relatively constant, no matter what the outdoor temperatures 	<ul style="list-style-type: none"> • Supply and return temperatures are linearly related to outdoor temperatures; • The temperature difference gets smaller with increasing outdoor temperatures
Temperature control situation	<ul style="list-style-type: none"> • The supply temperature is manually adjusted in accordance with the weather forecast even though weather compensation facility is available. • No automatic flow or temperature control measures for the heating network itself • TRV is not applied at terminal radiators. • SH only system, without DHW. 	<ul style="list-style-type: none"> • The supply temperature is manually adjusted in accordance with the weather forecast. • No automatic flow or temperature control measures are applied. • TRV installed but do not work well due to the incorrect usage, i.e. TRV is fully opened or windows opening. • SH only system, without DHW. 	<ul style="list-style-type: none"> • Individual weather-compensated flow and temperature control in substation • Differential pressure control on DH connections • Automatic balancing control on all risers • TRV on radiators • SH and DHW both supplied

4.2 Methods

4.2.1 IDA-ICE simulation for indoor temperature control

For the temperature control investigation, an eight-storey residential building model was developed using the commercial software IDA-ICE 4.2.6 [54]. Detailed information from one of the buildings in Case A (in Harbin) was used to develop this model. One of the apartments in the building was selected as a multi-zone model; each room was modelled as a separate zone. The layout of the multi-zone model is shown in Figure 4.8.

With an outdoor heating design temperature of -26 °C for Harbin and an indoor design room temperature of 18 °C, the building model derived the heat demand of each zone under the most unfavourable weather conditions.

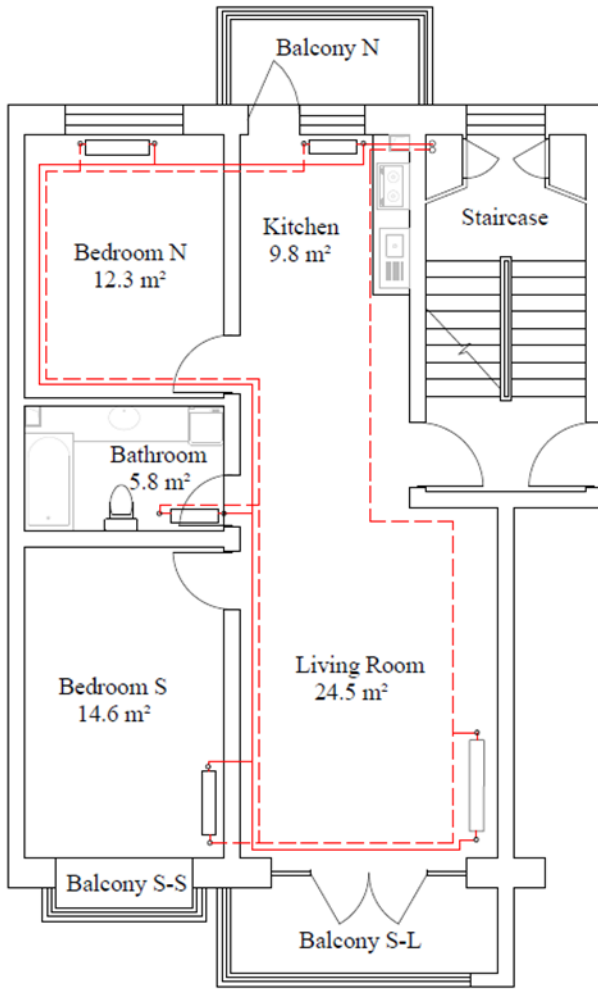


Figure 4.8. Multi-zone model and the building plan

The supply temperature to the SH system was chosen in accordance with the linear relationship between the outdoor temperature and the supply temperature shown in Figure 4.6 (a). To simulate realistic conditions, the internal heat gains were considered to be constant at 5.0 W/m^2 [62]. The model was used to estimate the energy consumption for heating using real weather data from Harbin city in 2014 [63] in two scenarios: 1) without TRV fitted to the radiators, which is the most common situation in Chinese SH systems, and 2) with TRV fitted to the radiators to adjust the indoor temperature by setting the thermostat. The return temperatures of the SH system, the room temperature of each zone during the heating period, and the energy consumption including heat consumption and pump electricity consumption during the entire heating period were all compared on the basis of the simulation results.

4.3 Results

4.3.1 Model validation

In the multi-zone model, the radiator heating system was designed in accordance with the Chinese design standard and combined with real data from Case A (CASE-Harbin). This model could then be used to investigate the energy-saving potential generated by room temperature control while remaining applicable to the real case. The model was used to run a year's simulation to obtain the predicted return temperatures from the SH system shown in Figure 4.9. The simulated return temperatures were compared with the linear return temperatures from CASE-Harbin; the results showed that the deviation between the simulation results and the linear return temperatures from CASE-Harbin was on average about 2 °C. The deviation between the model outputs and the measured return temperatures was therefore considered to be acceptable and the model was considered valid.

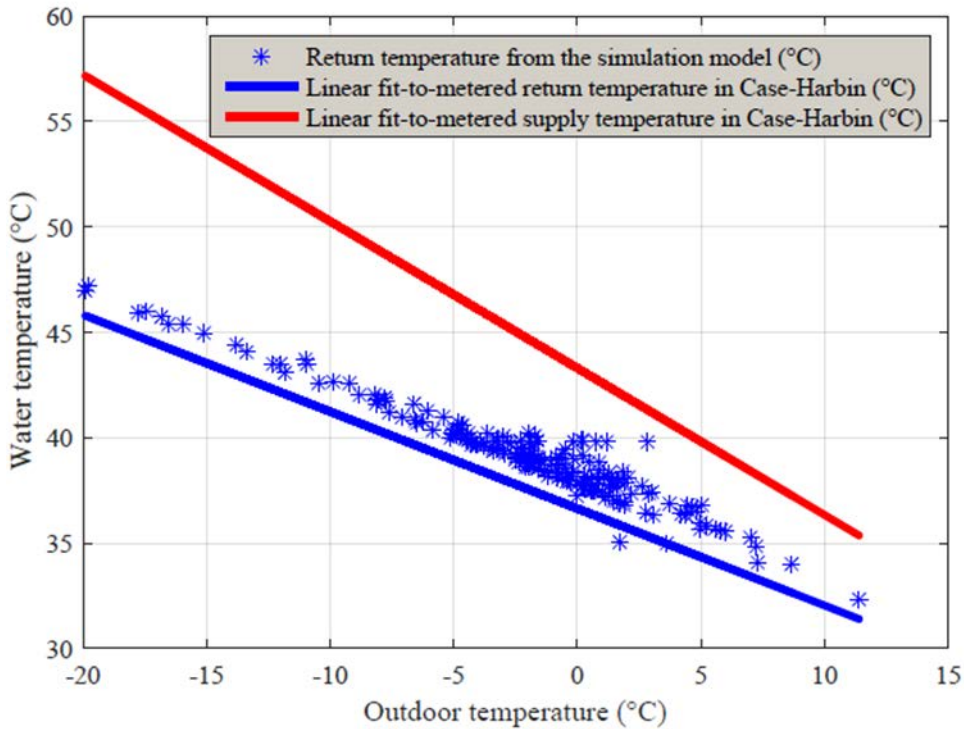


Figure 4.9. Supply and return temperatures for the model of the SH system

4.3.2 IDA-ICE simulation results

After confirming that the multi-zone model was valid, simulations were performed concentrating on the 180-day heating period in Harbin (20th October to 20th April of the following year) in two scenarios: the radiators without TRV and with TRV. The results show that without the TRV the room temperatures in all the zones are above 18 °C and neither stable nor constant. During the entire heating period, the average room temperatures in all five zones were around 22 °C. When TRV control was applied and the thermostatic sensors of the TRV were set to 18 °C, the room temperatures in all the zones were constant at around 18 °C, with only minor deviations between the set temperature and the simulated room temperature due to the 0.5 °C proportional band (P-band).

In Figure 4.10, the northern room ‘Bedroom N’ and the ‘Living Room’, the largest room in this multi-zone model, are two examples to illustrate the indoor temperature changes with and without TRV control. The figure shows clearly that without TRV control the indoor air temperatures of both Bedroom N and the Living Room fluctuated with the outdoor air temperature. For a few days at the beginning and towards the end of the heating period, the indoor temperatures were quite high because of the relatively high outdoor temperatures. It can also be seen that the indoor air temperature lagged a few hours behind changes in the outdoor temperatures. When the TRV was used and the set-point was 18 °C, temperatures in both rooms were more constant during the heating period.

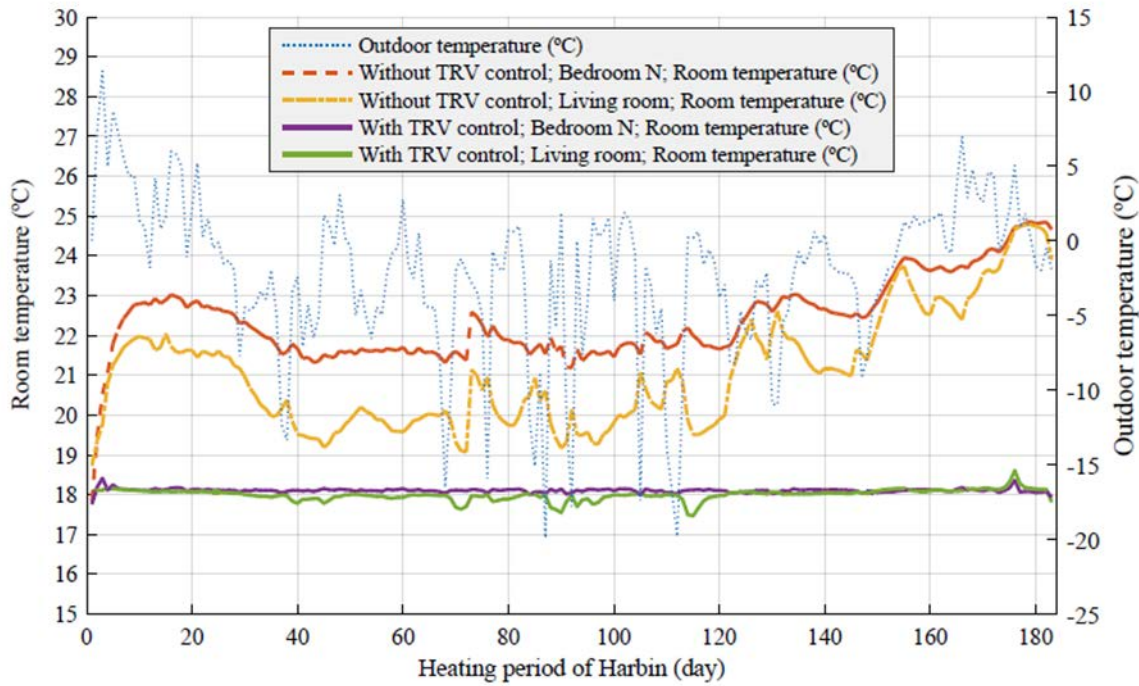


Figure 4.10. Zone room temperature for Bedroom N and the Living Room during the heating period

The results show that the application of TRV will reduce heat energy consumption by 17% and pump electricity consumption by 42.8%. With regard to the system’s operation, it is important to note that the application of TRV changes the SH system from constant flow to variable flow. More details can be found in Article II of the appendices.

4.4 Conclusions

This part focuses on the differences between China and Denmark in term of the topic of heat-metering. After comparing the national policies, current situation, applied technologies and real case studies, the gap between China and the state-of-the-art technology of heat-metering becomes clearly visible. It can be seen that individual heat-metering is a quick and easy way to achieve China’s energy-saving targets. TRV is the all-important interface between heat consumers and the DH systems and can help heat consumers to develop an energy-saving habit.

The investigation of a real case in Harbin in China reveals that the potentials for energy saving in existing heating systems can be achieved only when the thermostatic valves are used and set correctly. TRV can improve thermal comfort by allowing the setting and achievement of the desired room temperature; they convert the heating system from constant flow into variable flow; they effectively reduce the return temperature; and they increase the temperature difference between supply and return. Such advantages considerably improve the efficiency of the heating system: power consumption for pumps is reduced by 42.8% and heat consumption is reduced by 17%.

5 Part III: Optimizing Chinese domestic hot water systems

5.1 Specific background for domestic hot water applications in China

5.1.1 The potential of DHW application in China

Over the past 30 years, China has experienced unprecedented urbanization, modernization and economic development. According to World Bank reports, 54% of the total population lived in urban areas in 2014, a rate that rose from 34% in 1996 [3] (Figure 5.1). In the coming 20 years, it is estimated that 350 million Chinese currently living in rural areas will move into cities [29]. It is projected that about 70% of China's population, about 900 million people, be living in cities by 2025 [64]. The fast pace of urbanization will bring significant opportunities and challenges in building water supply, heating and other public utilities in the cities.

Over the last decade, the popularity of individual DHW systems has led to a substantial increase in DHW consumption. From 1996 to 2011, hot water consumption in Chinese urban areas has increased significantly along with the urbanization process (Figure 5.1) [26]. In 2011, the total energy consumption for residential DHW was 426 PJ, which is 9.5% of the total residential energy consumption in China. Moreover, the annual average DHW consumption for each urban household in 2011 reached 1.8 GJ and had increased by almost 8-fold compared to 1996 [65]. This growth trend makes the gap between China and the developed countries on DHW consumption is getting smaller. For instance, a standard household in Denmark yearly consumes 8.28 GJ for DHW.

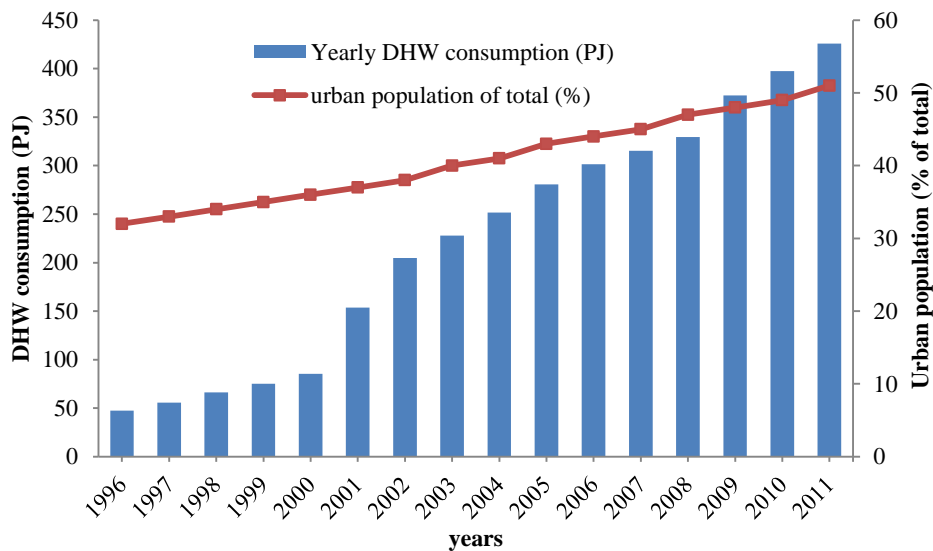


Figure 5.1. China's annual urban residential DHW consumption (PJ) and urbanization % in 1996-2011

Based on the experience and trends in other countries, it can be expected that the share of DHW consumption in urban building energy consumption will keep growing over the next decades in China. For instance, a wide range of energy-saving measures have been implemented in Denmark which have considerably decreased the unit energy consumption for buildings, while energy consumption on DHW has been relatively constant irrespective of building type. As a result, the proportion of DHW consumption in building energy consumption is

gradually rising. The annual energy consumption per unit area on DHW, SH and EL, as well as the proportions of each in different types of building are shown in Figure 5.2 [66]. In addition, according to residential building energy requirements in Denmark, class 2 building stands for the low-energy building class with annual heat consumption $50+1600/\text{HFS}$ (kWh/m^2). (Here HFS means the building's heated floor space in m^2) [67]. This gives a good illustration of probable future development trends for DHW applications in China.

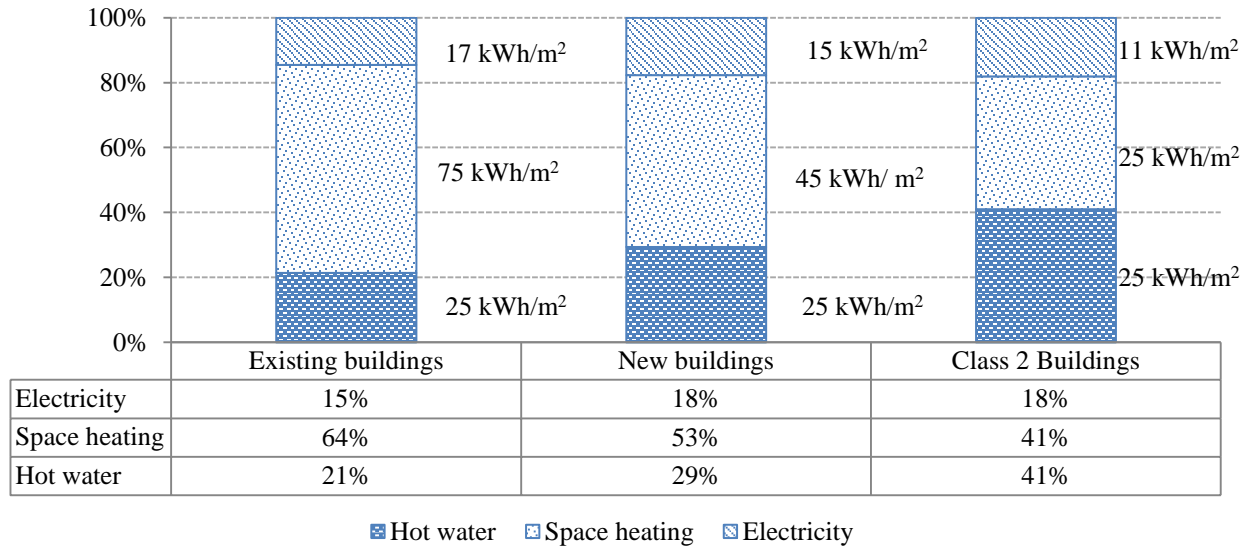


Figure 5.2. Annual energy consumption in buildings in Denmark

5.1.2 The existing DHW preparation technologies in China

Currently, individual water heaters are the dominant technology for producing DHW in Chinese households. The typical individual water heaters used in China are storage-type electric water heaters, natural gas water heaters, and solar water heaters, see Figure 5.3. DHW prepared via DH systems is uncommon. An investigation made in 2011 reveals the share of different DHW technologies in the Chinese DHW market in northern China and southern China (Figure 5.4). It reflects the difficult situation of centralized DHW systems in China.



(a) Storage-type electric water heaters (b) Natural gas water heaters



(c) Solar water heaters

Figure 5.3. Individual DHW preparation technologies applied in China

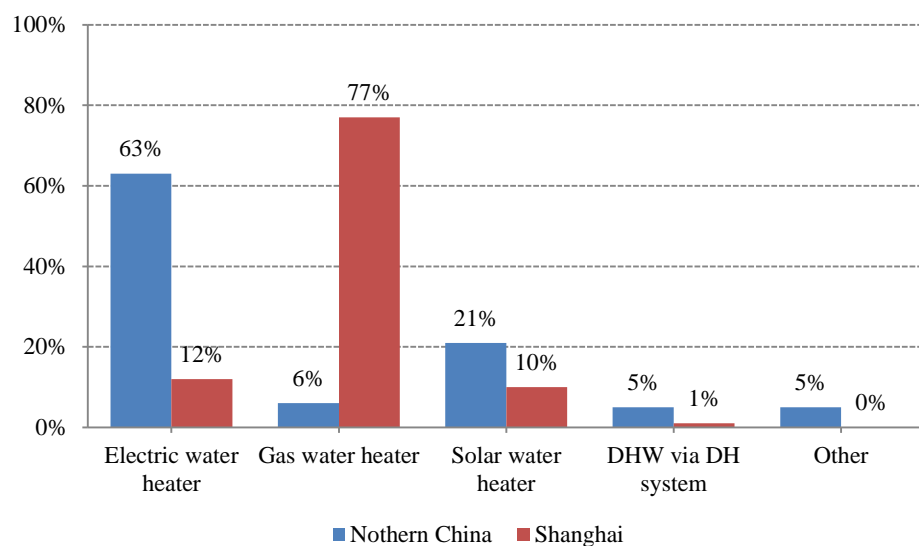


Figure 5.4. DHW preparation technologies in northern and southern China (Shanghai)

Table 5.1. Comparison of various DHW preparation technologies in Beijing of China

DHW solution	DHW preparation	User satisfaction degree evaluations		
		Advantages	Disadvantages	Satisfaction
Centralized DHW systems	DH plants	<ul style="list-style-type: none"> • Convenient; • Safety; 	<ul style="list-style-type: none"> • High DHW unit price • Long wait-time where circulation pipes do not reach to taps 	90%
	Heat-only boilers			
Individual water heater	EL water heater (Storage-type)	<ul style="list-style-type: none"> • Easy to install; • Compact size; • Easy to adjust temperature; 	<ul style="list-style-type: none"> • Heats water slowly • High electricity consumption, • Easily forms lime 	80%
	Natural gas water heater	<ul style="list-style-type: none"> • Heats water fast; • Easy to install; • Compact size; 	<ul style="list-style-type: none"> • Risks of gas emission • Risks of explosion 	70%
	Solar water heater	<ul style="list-style-type: none"> • Low cost; • Environmentally friendly; 	<ul style="list-style-type: none"> • Insufficient amount of DHW • Limited using time • Need to drain off null water • Unstable water temperature • Limitations on floor position 	73%

Table 5.1 lists comparisons between the various DHW preparation technologies. The user satisfaction degree evaluations are based on a questionnaire sent to a user group for each of the DHW preparation methods. The results show that centralized DHW systems have the highest satisfaction degree evaluation, but account for less than 5% of the market share for DHW solutions [66].

5.1.3 The reasons why most DHW is not prepared via DH systems in China

There are four main reasons for the small market share of centralized DHW systems in China.

1. High heat losses from distribution and circulation pipes.

In centralized systems, hot water is produced, distributed, circulated by pumping back to the generation site. During this process, energy loss is inevitable. When the efficiency of a centralized DHW system is defined, Eq. (5.1) is used:

$$\eta_{DHW} = \frac{Q_1}{Q_1 + Q_2 + Q_3 + Q_4} \quad (5.1)$$

Where Q_1 is the energy consumption for heating the cold water to hot water; Q_2 is heat loss from hot water pipes and circulation; Q_3 is heat loss from hot water heaters, heat exchangers, and associated piping and valves; and Q_4 is the electricity consumption of the circulation pump. The efficiency of the centralized system is stated as Q_1 divided by the total energy consumption, i.e. the sum of Q_1 , Q_2 , Q_3 and Q_4 . To improve the efficiency of centralized DHW systems, it is necessary to reduce the heat losses Q_2 , Q_3 , Q_4 as much as possible.

The efficiency of centralized DHW systems in Denmark has been found to be 30%-77% in apartment buildings and between 8% and 46% in office buildings and schools [68]. A lot of the energy demand for DHW is lost in the circulation system, so a number of new types of circulation lines are being considered in Denmark, such as concentric pipes or twin pipes, prefabricated vertical pipes, which may reduce pipe heat losses considerably [66].

The efficiency of Chinese centralized DHW systems has been found to be 26% to 55% for residential buildings, based on actual measurements for a few centralized DHW systems in Beijing [69]. The range of efficiency variation is determined by the circulation and distribution pipeline scale between China and Denmark. In China, large area substations are the usual case. In Denmark, building level substations are more common.

The traditional DH system for DHW supply in China normally uses a large area substation or central DHW-only boilers to supply hot water to a number of multi-storey buildings or high-rise buildings via a large-scale distribution pipeline. The traditional DH system supplying both SH and DHW is illustrated in Figure 5.5. In such a system, large circulation pipes are necessary to keep hot water circulating to ensure the appropriate hot water tapping temperature in terms of hygiene and comfort. Chinese design code GB50015-2009 [70] states that the hot water temperature should be 60 °C. This implies that the centralized DHW systems need to supply 60 °C water to the furthest consumers. This temperature is higher than the standard in Denmark, which says the DHW temperature could be 55 °C for 3rd generation DH systems, and 45 °C for 4th DH systems [71]. The higher supply temperature in China leads to substantial heat losses from distribution and circulation pipelines, which result in inefficient and uneconomic DHW production.

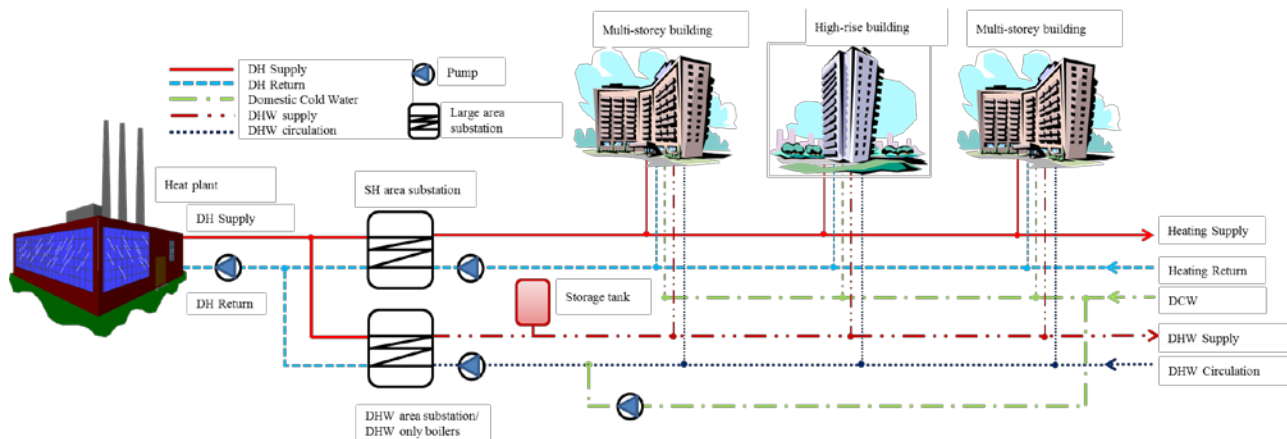


Figure 5.5. Existing DHW systems combining SH and DHW

2. High DHW unit price compared to individual water heaters

Moreover, the pool of customers shrinks because of the high DHW unit price compared to using individual water heaters. For instance, in Beijing, the DHW consumption from the DH network is metered and billed based on cubic metres. To heat 1 ton of water from 10° C to 40° C consumes 125.6MJ. If we assume the efficiency of electric and natural gas water heaters is 88%, and the heat value of natural gas is 35.84MJ/m³, the DHW production cost of using electric and natural gas water heaters is respectively 19.8 Chinese Yuan (CNY) and 9.1 CNY, i.e. 14% and 60% lower than 23 CNY/m³ unit price of centralized DHW (*Table 5.2*). The relatively lower unit prices of electricity and natural gas make the customers favour individual electric/natural gas water heaters.

Table 5.2. Energy consumption and cost when separate water heaters heat 1 ton of 10 °C cold water to 40 °C

Individual water heater type	Energy consumption	Efficiency	Energy consumption	Energy unit price in Beijing (CNY)	DHW production cost (CNY)
Electric water heater	125.6 MJ	88%	39.6 kwh (electricity)	0.5/kWh	19.8
Natural gas water heater	125.6 MJ	88%	3.98 m ³ (natural gas)	2.3/m ³	9.1

3. Initial investment limitation downgrades the DHW comfort level

For Danish centralized DHW systems, the national standard DS439:2009 [72] stipulates that, to avoid wastage of water, DHW systems should be designed so that hot water at a flow rate of 0.2l/s reaches the taps within the acceptable waiting time, approximately 10 seconds, with a temperature never below 50 °C. This specification consequently requires that the circulation pipes are arranged to reach to each tap, as shown in *Figure 5.6 (b)*. However, to limit the initial investment for DHW preparation via DH networks in China, the circulation pipes in some cases do not reach each tap (*Figure 5.6 (a)*). With circulation pipes arranged as in *Figure 5.6 (a)*, the result is that a large amount of cooled water has to be drained off before hot water with the desired temperature is obtained, but the drained-off cold water is still charged at the hot water price.

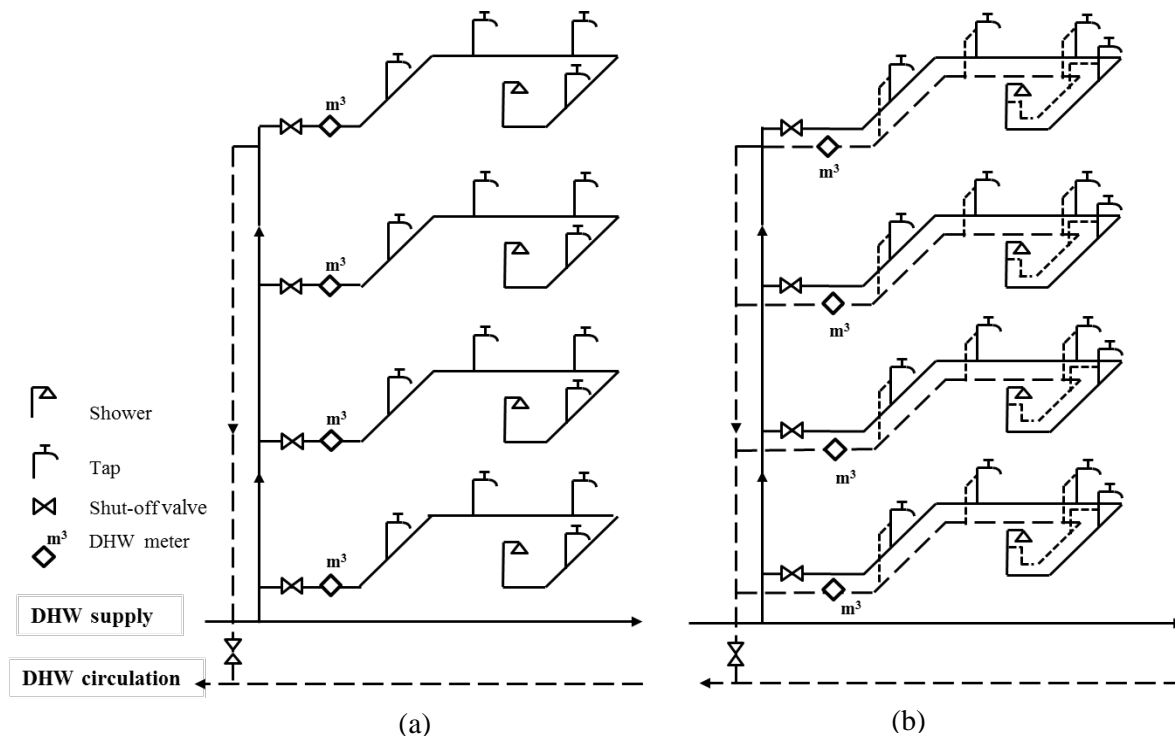


Figure 5.6. Two different circulation pipe arrangements

4. Hot water consumption amount

Some studies state that the daily hot water consumption in Chinese DHW systems is only 1/5 of the daily hot water consumption in some developed countries, such as Spain 200 litres/apartment per day, United State 270 litres/apartment per day, Japan 300 litres/apartment per day [69]. Data obtained from 7 centralized DHW systems in Beijing in 2012 show the average hot water consumption is 45~133 litres per apartment per day. The data from Danish DHW measurement projects show the consumption of cold water for DHW varying between 47 and 143 litres per apartment per day [68], and the standard apartment in Denmark contains 3.5 occupants. In general, for centralized DHW systems, the greater the amount of hot water consumed, the more obvious the economic benefits.

The above-mentioned factors influence each other and form the main barriers for the development of centralized domestic hot water systems in China.

Based on the analysis above, it can be found that the production and distribution of DHW will constitute a major share of building energy consumption in both present and future energy design requirements. It is essential for China to find a sustainable DHW preparation technology to cope with the current challenges of security of energy supply, environmental issues, and efficiency improvement. Against this background, the experience and technology from Denmark could be useful. Among the various possible solutions, the flat stations solution proposed is to integrate DHW into the existing DH systems and use the power from local available waste as DH fuels.

5.2 Methods

The flat stations are integrated into the existing heating system and replace the existing DHW systems, such as traditional centralized DHW systems and individual water heaters. A flat station is a complete individual heat transfer unit. The energy is supplied from a central energy source and a flat station is installed in each apartment or single-family house. The configuration of the renovated heating system is that the primary side of flat station is connected to the building riser and the secondary side is connected to the indoor DHW system. SH is still directly connected to the existing apartment heating system: see Figure 5.7.

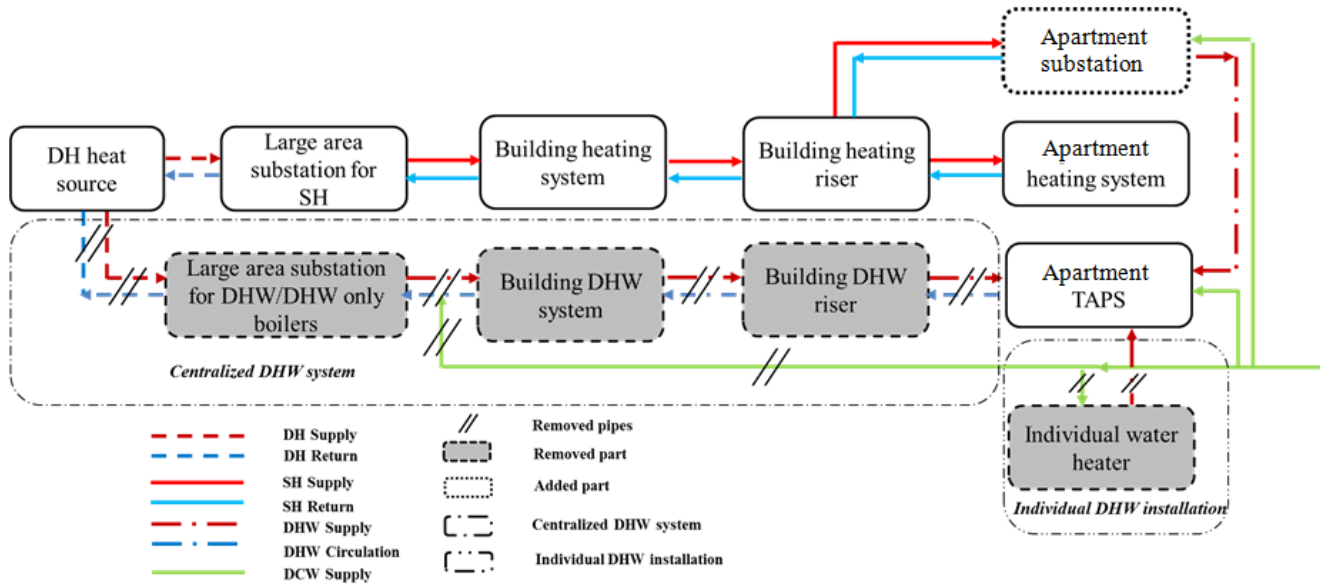


Figure 5.7. Renovating the existing DH system by integrating flat stations

5.2.1 The benefits of flat stations over the existing DHW production technologies in China

Flat stations concept is proposed for the renovation of the existing DHW technologies in China, because the numerous advantages flat stations have are significant for coping with the challenges which China is facing today.

1. Security of energy supply and environmental issues

Individual water heaters, such as electric and natural gas water heaters, are the most common technologies used for DHW preparation in China. Coal is the most common fuel for Chinese power plants, and burning coal is one of the main causes of air pollution [19]. Moreover, the fuel conversion policy from coal to natural gas, which is currently being implemented in major cities of China to cope with air pollution, has highlighted the question of natural gas supply security. The situation makes the central government want to use renewables as DH fuels: e.g. considering the fundamental idea from Denmark of using local energy that would otherwise be wasted as a heat source for DH [73][74].

Surplus waste heat from industrial processing could be a sustainable DH heat source. Studies have shown that in most cases this kind of resource can be found within a 30 km radius of cities in northern China and can meet

almost 70% of the heat demand of northern China [26]. In fact, according to Fang et al. [6], if just 34% of the industrial waste heat available in 2009 had been recovered, it would have been enough to meet the whole DH heat demand that year. Industrial waste heat is a great pollution-free resource for fulfilling residential heat demand in China today. This kind of waste energy can only be used by centralized DH systems.

Furthermore, compared to the individual water heaters, recovering waste heat for DH use could considerably reduce environmental impacts and the consumption of fossil fuels.

2. Circulation distribution heat loss

With flat stations in multi-storey buildings the DHW distribution pipes are moved into the apartments, and vertical circulation pipes are eliminated completely. The traditional 5- pipe system (SH supply and return, DHW supply, circulation and domestic cold water (DCW) supply) is replaced by 3-pipe flat stations (SH supply and return and cold water supply). This reduction implies not only 40% less pipes, also a corresponding 8-16% heat loss reduction, as mentioned above [75].

On the other hand, it also implies that the supply and return pipelines on the primary side of flat stations are extended to the apartments. During the winter time, DH systems supply both SH and DHW, while DHW is supplied all year, but the proportion of DHW to the total DH supply is very small. Since a large area substation usually connects a number of multi-storey or high-rise buildings in China, the heat losses are much lower with flat stations than with the traditional centralized DHW systems.

3. Hygienic, safe and efficient DHW supply

Legionella growth range is from 20 °C to 45 °C, so the hot water temperature generally required to ensure hygiene is 55 °C, which also avoids the risk of scalding and lime deposits, which occur if the temperature is higher than 60 °C. Moreover, German standard W 551 [76][77] states that DHW systems with less than 3 litres are considered to be safe irrespective of the DHW temperature. Flat stations minimize the risk of Legionella, because the distance from the point of DHW preparation to the point of usage is considerably shortened, and the water in the pipe is flushed out with each tapping and replaced with fresh hot water. During non-tapping periods, the water cools down to room temperatures, typically below or at the lower end of the growth range for Legionella. Since the DHW is prepared instantaneously and circulation pipes are eliminated, hygienic, comfortable and efficient DHW becomes a reality.

4. Individual heat-metering and billing

One of the most important targets of DH reform in China today is to create an individual heat-metering and billing mechanism based on actual consumption. This is another advantage of the flat station concept, because it enables comprehensive control at the level of the apartment, which makes energy consumption measurement at this level simple. In Germany, for instance flat stations are growing in popularity in residential buildings, because the metering and billing of the heat consumption of each household is mandatory in Germany. Data obtained from Danish DH systems show that individual metering and billing can bring 15-30% savings [60]. This shows that apartment flat station solutions could help China smooth the DH reform process, and the existing heat-metering and billing methods, namely a heating fee charged by floor area and a DHW fee charged

by cubic meter could be replaced. This would motivate the energy-saving consciousness of end-consumers, eventually energy consumption and emission reductions can be achieved.

5.2.2 Verification of technical feasibility

A building model was developed and a standard flat was defined to verify the technical feasibility of the proposed flat stations solution in this study. Comparison of the calculations used for sizing centralized DHW systems in China and Denmark showed that differences exist in the hourly variation coefficients. Therefore, coincidence factors from Danish DHW systems were used to correct the errors when determining the pipe sizes.

Table 5.3. Comparison of the DHW calculation methods used in China and Denmark

Comparison items	China	Denmark
Main building types	Multi-storey buildings	Single-family houses/multi-storey buildings
Definition of standard apartment	3 occupants with 95 m ² floor area	3.5 occupants with 137 m ² floor area
DHW heat demand per apartment	21 kW to meet the DHW demands of the shower and hand sink simultaneously	32.3 kW the taps for kitchen washing (14.7 kW) and shower (17.6 kW) simultaneously
Important factors to determine the size of centralized DHW system	K_h , Hourly variation coefficient,	f , Coincidence factor,
Definitions	K_h is defined as the ratio between the maximum hourly water consumption in the peak load day, q_{hr} (l/h) and the average hourly water consumption, q_T (l/h).	f is an estimate of the number of apartments that will use hot water at the same time
Relationship between K_h and f	According to the International Electro technical Commission, the coincidence factor is identical to the reciprocal of the diversity factor [78]	
Define the DHW system	$Q_{DHW-CN} = K_h \frac{mq_r C(T_h - T_c) \rho_w}{3600t}$ m is the number of DHW consumers; q_r (l/person · day) is the DHW usage quota and recommended as 60 ~100 l/person · day [70]. T_h, T_c are the temperatures of hot water and cold water (60 °C and 10 °C), respectively. ρ_w (kg/l) is the density of water, and t is DHW daily supply hours (24 hours here)	$Q_{DHW-EU} = n * f * \phi_{DHW}$ n is the number of apartments in which DHW is required, f is the coincidence factor for DHW, and ϕ_{DHW} is DHW demand per apartment

The comparison of coincidence factors (f) when the number of apartments is less than 100 is shown in Figure 5.8. To confirm the reliability of the coincidence factor, data from Germany and Sweden are also shown.

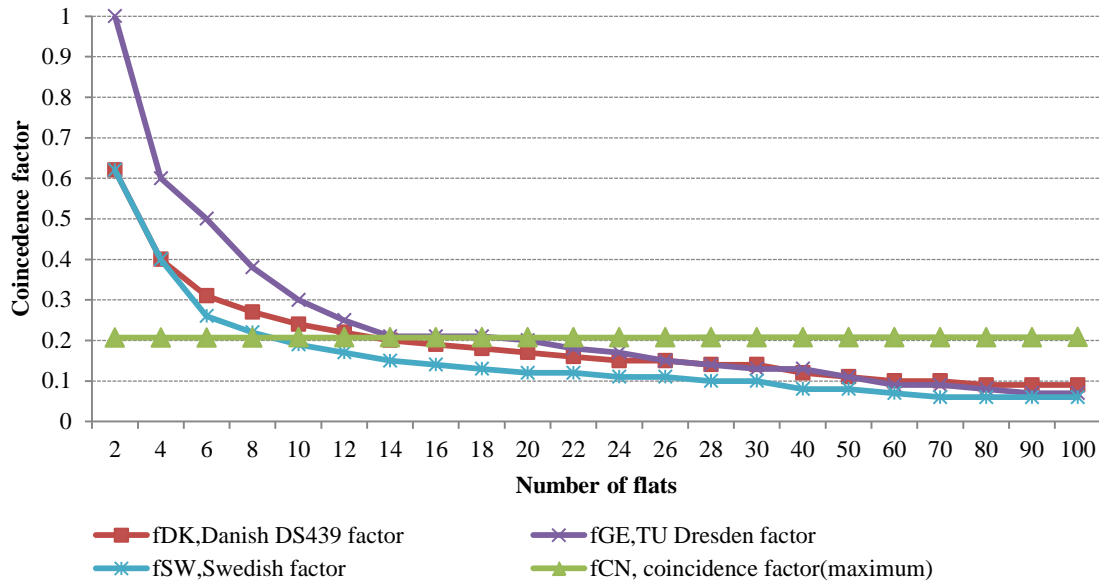


Figure 5.8. Comparison of the coincidence factors used in different countries

The comparison results show that K_h cannot be used to calculate the DHW capacity when the number of apartments is less than 12, i.e. one building unit. The reason is that high-rise and multi-storey buildings are the main types of building in China, so a low simultaneous DHW usage probability is considered from the economic point of view. Whereas in European countries, single-family houses and multi-storey buildings are the main building types, so that the coincidence factors have detailed values when the number of apartments is small to take comfort into account. On the other hand, the K_h values stated in the Chinese design code are empirical data originally derived from Soviet DHW systems, so there may be errors arising from differences between the design and real conditions due to the lack of actual measurements from Chinese DHW systems [70].

Therefore, when determining the DHW capacity for a single building riser, the coincidence factors of Denmark were used to make the calculation. Moreover, when checking the pipe sizes of the existing heating systems to see if they can meet the required flow rate when DHW is integrated, the philosophy of DHW priority was applied. That means that the required flow rate of the pipe is determined based on the DHW demands. If the existing pipe capacity is smaller than the DHW peak load, bigger pipes are needed. Otherwise, no change will be made to the pipe dimensions, because in this case the pipes can take the flow to fulfil either the DHW demands based on DHW priority or simultaneously fulfil the DHW and partial SH heat demands under non-DHW peak load conditions.

DHW priority can be implemented electronically in the multi-functional self-acting controller, type Evoflat FSS [79], which is embedded in the flat station. Evoflat can meet the requirements of the technical approach, indirectly connecting the DHW system and directly connecting the SH systems. At the same time, along with the increasing number of connected apartments, the SH demands dominate the heating system, and are greater than DHW demands. So when DHW demands occur, the system can meet the DHW and partial SH demands, and in most cases the SH demand can be 100% met because the coincidence factor value is lower, when more apartments are connected.

5.3 Results

Based on the coincidence factors drawn from Danish DHW systems, the renovated pipe sizes were dimensioned, and only the pipes located in the top two storeys of the 6-storey building model need to be replaced; the others can stay as they are, as shown in Figure 5.9. Using the philosophy of DHW priority, the technical feasibility of the flat station solution has been verified.

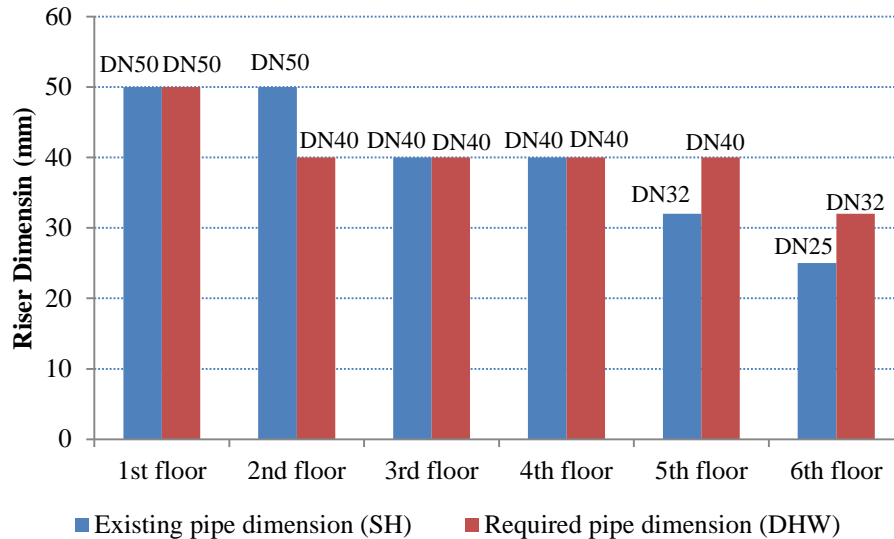


Figure 5.9. Comparison of existing SH pipe dimensions with the pipe dimensions required for DHW

Having established the precondition of technical feasibility, the flat station solution was compared with individual water heaters in terms of economic evaluation. The results show that flat stations have the lowest annualized heat cost of 0.442 CNY/kWh compared with electrical water heaters at 0.772 CNY/kWh and natural gas water heaters at 0.448 CNY/kWh, when industrial waste heat is assumed as the DH heat source.

In terms of the CO₂ emission issue, the environmental impact was also quantified. Using flat stations can reduce CO₂ emissions by 1273 kg per flat per year compared to using electric water heaters, and by 753 kg per flat per year compared to using natural gas water heaters.

More details on the methods used in economic and environmental impact evaluation can be found in Article III.

5.4 Conclusions

This part analysed the current situation of DHW applications in China by using real data and summarized the main reasons why centralized DH systems are not widely used to supply DHW in China. The DHW systems used in China and Denmark were compared to determine the differences in technologies and concepts. The flat station solution integrated into the existing DH systems to produce DHW instantaneously was shown to be a technically feasible approach for renovating China's centralized DHW systems. The flat stations have a series of technical advantages that make it possible to solve the problems existing in China's traditional centralized DHW systems.

The important assumption to promote the utilization of flat station to produce DHW in China is to utilize renewable or waste heat as DH fuels. The development of DH in China's highly populated and cold-climate regions is an environmentally friendly and energy-efficient strategy. Moreover, fuel conversion have been implemented in China in DH field, from coal to natural gas conversion will be gradually replaced by the conversion from coal to renewables. And available industrial waste heat is important local resource and has huge potential to be developed as DH fuels in the coming years.

The coincidence factors used in Danish DHW systems can be used to correct the hourly variation coefficients used in Chinese DHW systems. Moreover, the philosophy of DHW priority can be applied electronically using the multifunctional controller installed in the flat stations. Furthermore, the annual heat cost of the flat stations compared to individual water heaters was evaluated using the Net Present Value method, which showed the economic benefits of applying flat stations. On the assumption that flat station solutions can utilize industrial waste heat as heat source, the environmentally friendly impact of flat stations was quantified and compared with individual water heaters.

A reliable and sufficient supply of DHW for daily use has become an important factor influencing life quality in China against the background of the accelerating urbanization and modernization of Chinese society. On the other hand, air pollution and security of energy supply are derivative challenges, which could compromise the rapid development of the whole of society. The flat station solution presented in this study provides a sustainable alternative solution for DHW preparation in China.

6 General conclusions

Sub-hypothesis 1: hydraulic balance can be achieved in Chinese heating systems by utilizing flow control devices at the level of the terminal heat emitter.

This hypothesis is true. This hypothesis was verified as feasible in the field test and the energy-saving effects were quantified in the simulations.

Sub-hypothesis 2: it is possible to improve the indoor thermal comfort of Chinese buildings by applying temperature control devices.

This hypothesis is true. The experience from Danish DH systems shows that using thermostats correctly will help heat consumers to develop energy-saving awareness and habits. A building model based on IDA ICE simulation and derived from the real case of a northern Chinese city was used to investigate and demonstrate the potential for energy savings in the correct use of thermostats.

Sub-hypothesis 3: it is possible integrate DHW into DH systems by using the flat station concept. Installing a substation in each apartment instead of the existing individual water heaters is technically feasible.

This hypothesis is true. Using the multi-functional controller embedded in the flat station to apply the philosophy of DHW priority means that the integration of flat stations into existing DH systems is technically feasible if some pipe renovation is implemented based on the initial calculations. At the same time, industrial waste heat is a potential and realistic DH fuel source, and individual heat-metering and billing will be required in the coming years and will necessitate the application of a flat station solution. Based on NPV concept, the economic benefits

of flat stations are greater than those of individual water heaters, and it is apparent that if waste heat is the heat source of the flat stations, the environmental impacts will be lower than for individual water heaters using fossil fuels.

Main hypothesis: Chinese district heating systems can be optimized by using technology and experience from Denmark's DH systems.

The hypothesis is true. China and Denmark are different countries with different national conditions and cultures. Denmark has gone through the first, second, and third generation DH technologies, and is currently implementing 4th generation DH systems. Some of the technical solutions are suitable for China when specific application conditions are taken into account. Excessive heat supply, hydraulic balance, and DHW supply are key problems in current Chinese DH systems that urgently need to be solved. Based on the investigations reported in this thesis, all three issues can be solved by using technology and experience from Danish DH systems, technical renovations thus bring out the environmental and economical benefits.

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APPENDICES

Article I

Method for achieving hydraulic balance in typical Chinese building heating systems by managing differential pressure and flow

Article II

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Article I

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Method for achieving hydraulic balance in typical Chinese building heating systems by managing differential pressure and flow

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Abstract

Hydraulic unbalance is a common problem in Chinese district heating (DH) systems. Hydraulic unbalance has resulted in poor flow distribution among heating branches and overheating of apartments. Studies show that nearly 30% of the total heat supply is being wasted in Chinese DH systems due to a lack of pressure and flow control. This study investigated using pre-set radiator valves combined with differential pressure (DP) controllers to achieve hydraulic balance in building distribution systems, and consequently save energy and reduce the emissions. We considered a multi-storey building modelled in the IDA-ICE software, along with a self-developed mathematical hydraulic model to simulate its heat performance and hydraulic performance with various control scenarios. In contrast to the situation with no pressure or flow control, this solution achieves the required flow distribution and close-to-design room temperatures, as well as 16% heat savings, 74% pump electricity savings, and proper cooling of supply water. The energy consumption savings would therefore have positive environmental impacts, and be reflected in seasonal reductions of 2.1 kg/m² CO₂, 0.02 kg/m² SO₂, and 0.01 kg/m² NO_x for 3rd step energy efficiency buildings in Beijing.

Keywords

district heating,
hydraulic balance,
differential pressure controller,
pre-set radiator valve,
pressure and flow control,
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1 Introduction

1.1 Background

Research studies have indicated that DH (district heating) has a key role to play in society's goal of achieving an effective and sustainable energy system (Xia et al. 2016; Lund et al. 2010, 2014; Yang et al. 2016). With its rapid growth in urbanization and industrialization, China has become one of the largest DH markets in the world in the last two decades. Statistics indicate that the total DH production in 2013 amounted to 3 197 032 TJ (EURO HEAT & POWER 2013). This number is still increasing steadily due to the process of rapid urbanization, the expansion in the total building area, the enhancement of building services, and increases in requirements for comfort. The development of

DH in high-population and cold climate regions has become an environmentally friendly and energy-efficient strategy for ensuring energy supply security and air pollution abatement, which are the two most important challenges facing China today (Hong et al. 2013; Lin and Liu 2015; Chen et al. 2013). Enhancing the efficiency of DH systems by modernizing them is particularly critical. One of the main issues influencing the efficiency of Chinese DH systems is the energy wasted due to hydraulic unbalances in the systems. The failure to install control devices to enable pressure and flow control in the DH network has resulted in poor flow distribution among heating branches, and consequently nearly 30% of the total heat supply is being wasted through excess flow and overheating of apartments (Building Energy Research Center of Tsinghua University 2011; Yan et al. 2011).

Multi-storey and high-rise buildings are typical in China.

Pressurized hot water as the heat medium is produced at a heat source and is directly transmitted to a number of high-rise or multi-storey buildings via heat entrances. In some cases, area substations indirectly exchange the heat from the primary network (from heat source to area substations) to secondary network (from area substation to buildings), which then enters the building heating systems via the heat entrance. The heat entrance is the interface between the DH system and the building heating system and is generally equipped with shut-off valves, a strainer, thermometers, pressure gauges, a heat meter, etc. Moreover, the national design code emphasizes a two-pipe radiator system, with each apartment having its own heating loop, as the primary form of SH (space heating) system in future multi-storey buildings in China (Liu et al. 2015).

Establishing a hydraulic balance is a matter of controlling the DP (differential pressure) to the required level, thereby controlling the flow rate in individual branches. In practice, the most common adjustment devices in current Chinese DH systems are the manual balancing valves installed at building heat entrances to limit the flow through the buildings. They are relatively inexpensive to install, but the system-commissioning work is complex and time-consuming. On the other hand, against the background of the implementation of heat reforms in China, the application of TRVs (thermostatic radiator valves) in DH systems has become more common (Xu et al. 2008). For instance, in 2006, 16% of the total heating area in China was given a heat metering retrofit (Zhang et al. 2013) to install TRVs. However, the use of TRVs transforms a constant flow heating system into a variable flow system. This can cause problems in systems that continue to use manual balancing valves, because they rely on static conditions and cannot cope with the system changes introduced by the TRVs. This means that an effective solution that uses appropriate control devices to achieve hydraulic balance in multi-storey building heating systems is urgently needed.

There have been a lot of studies on improving the efficiency of Chinese DH systems that have focused on various DH elements (Fang et al. 2013a,b; Sun et al. 2012; Wang et al. 2011a,b; Jing et al. 2014; Jie et al. 2012, 2015; Jiang et al. 2014; Cao et al. 2014). Some studies have investigated the control strategies used in relation to hydraulic balance issues in Chinese DH systems (Yan et al. 2013; Ma and Wang 2009). For instance, Yan et al. (2013) proposed improving hydraulic performance by using variable speed distributed pumps on the primary side of indirectly connected DH systems. Moreover, with the implementation of heating reform in China, research has also been carried out on TRV application in Chinese heating systems (Xu et al. 2008, 2009, 2013, 2014; Li et al. 2009; Yan et al. 2011; Liu et al. 2011). Xu et al. (2009) investigated how the regulation of TRVs

and the opening of windows influenced the hydraulic performance and energy consumption of a DH system. Xu et al. (2008) studied the thermal and hydraulic behaviour of SH systems that use TRV-controlled radiators in multi-family buildings. Xu et al. (2014) carried out a survey of district heating systems in northern China and verified the fact that hydraulic unbalance due to poor levels of control and monitoring in DH systems results in wasted energy or excessive heat supply.

However, when we examine the previous research mentioned above, there is still a lack of expertise or knowledge on how building heating systems can be optimized by correctly using flow control and temperature control and, not least, their inherent relationship with energy savings and indoor temperature improvement.

This paper presents a technical concept that combines the use of DP controllers and pre-set radiator valves to control the pressure and flow in two-pipe multi-storey building heating systems. The current popularity of TRVs in China makes it possible to adjust individual local radiators, but the flow pre-setting function of radiator valves and the benefits of DP controllers are not well understood. A clear understanding of the technical concept will help to further support and promote relevant policies targeted at enabling and improving the energy efficiency of buildings in China. This could give enhanced understanding and guidance for renovating future Chinese DH systems.

1.2 Current situation from a real case

To make it possible to understand the current hydraulic situation in Chinese multi-storey building heating systems, we present data from a real heating system in Beijing, China (CASE-Beijing). These data were used to analyse the hydraulic performance of this actual heating system. They were not used in the later simulation.

1.2.1 Basic information

The CASE-Beijing heating system supplies heat to 25 multi-storey/high-rise residential buildings, with a total heating area of nearly 278 000 m² (Fig. 1). As the heat-carrying medium, hot water is produced at central gas-fired boilers and transported to those 25 buildings via 31 heat entrances. Manual balancing valves are installed at the heat entrances to manage the water flow into the connected buildings. DH utilities usually use a flow index to determine the required volume flow to each building in accordance with the heating area served. The manual balancing valves are set at the beginning of the heating season in accordance with this estimated flow and the DP across the controlled loop. After this initial commissioning, the settings of these manual balancing valves are kept for the complete heating season,

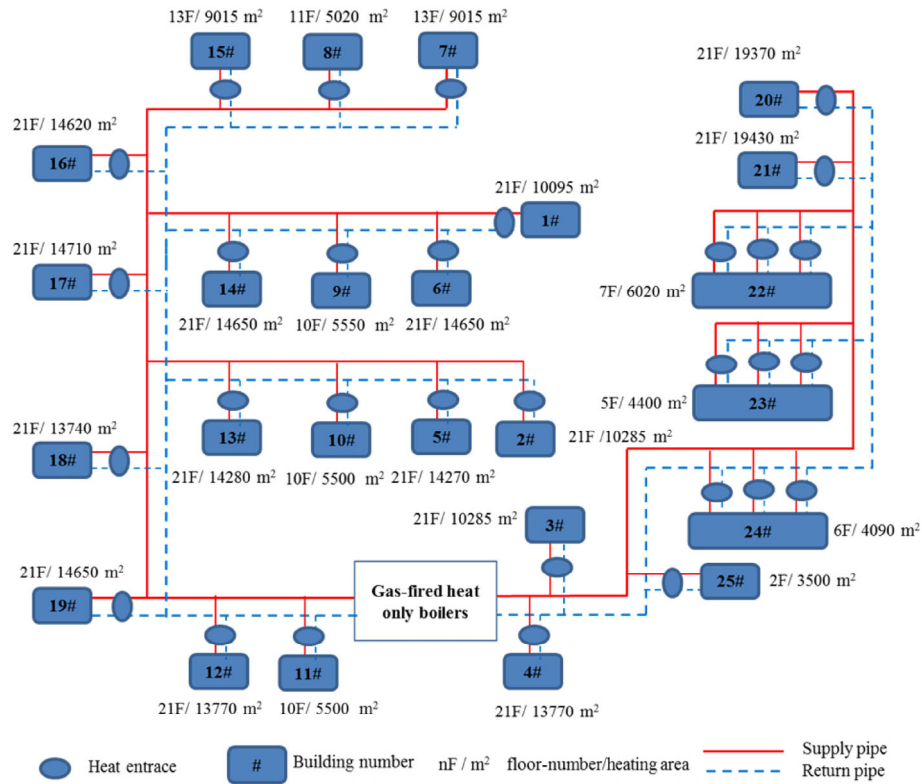


Fig. 1 Heating system layout of CASE-Beijing

except for minor adjustments. Moreover, no control devices are applied to regulate the flow distribution between the apartments within the building.

All the buildings in this area were built in 2005 with the same exterior envelope materials. The buildings meet the requirements of the 3rd step of the energy efficiency building standard for Beijing. According to this standard, the peak heat load of those buildings is required to be no more than 32 W/m^2 under a design outdoor temperature of -9°C for the heating period, and the average heat loss index is required to be no more than 14.15 W/m^2 under an average outdoor temperature of 0°C during the heating period of 120 days (Zhang et al. 2015). This implies the seasonal heat consumption per square metre of the buildings in CASE-Beijing is 0.15 GJ/m^2 . For this case, the initial design temperatures for the radiator heating system were $75/50/18^\circ\text{C}$ (supply/return/indoor temperature), while the system operates as constant flow. This means that the design flow rate per m^2 can be calculated to be $1.1 \text{ kg}/(\text{m}^2\cdot\text{h})$.

1.2.2 Data analysis

First, the mass flows were measured using an ultrasonic flow meter. The mass flows per square metre for all 31 heat entrances can be calculated based on the heated area. The results are shown in Fig. 2. These data reflect the water flow through the 31 heat entrances and into the 25 connected

buildings via the horizontal pipelines.

Since the interior envelopes of all the buildings were characterized as having the same insulation properties and the heating system operates on the constant flow principle, the unit mass flow should theoretically be numerically equal or similar for all the heat entrances. Compared to the design unit mass flow, 27 out of 31 heat entrances are in a state of excess flow, and the unit mass flow through all 31 heat entrances is uneven. These data show that there is hydraulic unbalance in the DH distribution network.

Next, to investigate the vertical flow distribution, one of the high-rise buildings was selected for measurement of the mass flows along the internal vertical riser. The building chosen was #3, with 21 stories. Figure 3 illustrates the mass flow per square metre along the low-pressure riser at the 1st, 6th, and 13th floors, and along the high-pressure riser at the 14th, 18th, and 21st floors.

The water-flow direction is from the bottom to the top, and the mass flow rate per square metre gradually drops along the water supply direction; the top floor receives the lowest flow rate, even though the top floor could be expected to have a greater heat demand than the others due to its greater exterior surface. The data shows that the flow supply per square metre to each floor is unequal; moreover, the flow is higher than the design value of $1.1 \text{ kg}/(\text{m}^2\cdot\text{h})$ even on the top floor.

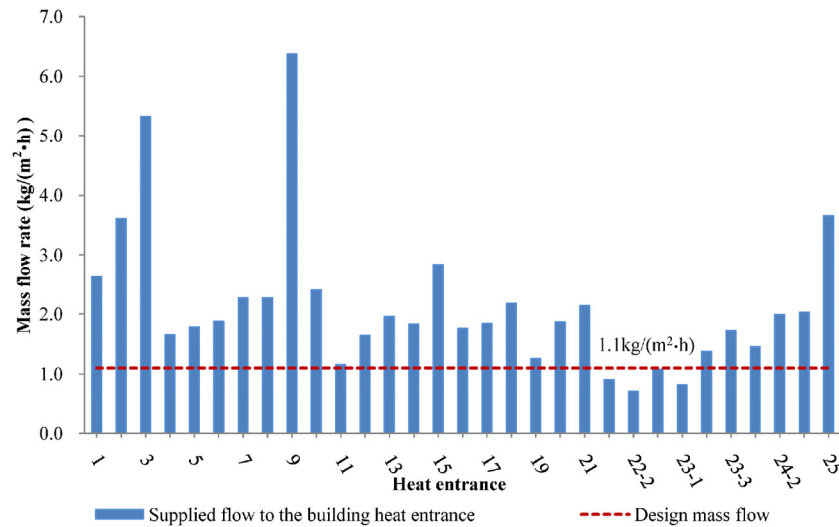


Fig. 2 Mass flow of the 31 heat entrances of CASE-Beijing

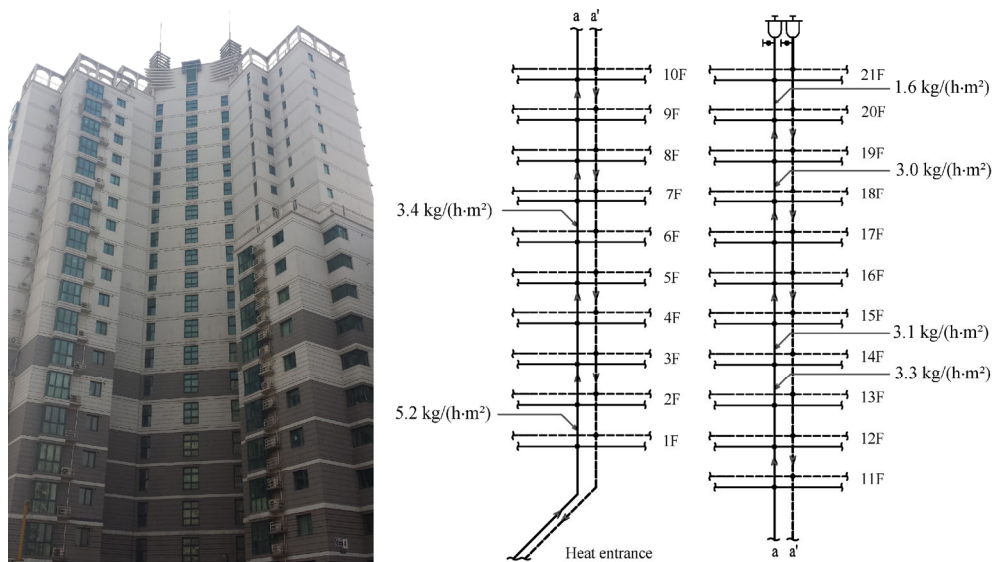


Fig. 3 Building #3's appearance and the mass flow along one of the vertical riser supplies (Zhang et al. 2016)

In summary, CASE-Beijing showed that the heating system was in hydraulic unbalance, both in the DH distribution network and in the building distribution system. CASE-Beijing reflects the general hydraulic situation of Chinese heating systems. Hydraulic unbalance occurs mostly due to the lack of appropriate control devices in the heating system. Given that the whole building receives the design heat demand, any hydraulic unbalance in the building will lead to overflow condition in some rooms and underflow condition in others, leading to that some rooms cannot reach 18 °C room temperature. This results in that the heat supply is increased until the critical users achieve 18 °C, which further aggregates the overflow condition and its inevitable consequences on the system efficiency. Consequently, the heating system is operating under large flow with small

temperature differences. In addition, by the nature of the Chinese district heating system any heat supply that results in higher than standard room temperature is essentially a heat loss. Due to the constant flow principle and inherently transportation delay in the distribution system, hydraulic unbalance will in general terms then add to the overheating of the buildings and consequent open window heat regulation.

2 Methodology

In view of the problems mentioned above, the main purpose of this study was to clarify how the technical approach presented in this study can manage the pressure and flow in multi-storey buildings and thus achieve hydraulic balance and reduce the energy consumption. The aim of this analysis

was to simulate the typical Chinese building heating systems, unlike western district heating systems, they usually operate as constant flow system throughout the heating season. The constant flow nature of the Chinese heating systems is a result from the fact that there are no automatic balancing controls applied in the systems. Due to this fact, the central hypothesis of this study rests on the philosophy that the design flow must pass through each radiator at design condition to build the hydraulic balance. Once the flows through the radiators are controlled, both excess flow and insufficient flow can be effectively avoided in all the radiators. The flow distribution in all the branches is even, and hydraulic balancing is achieved in all conditions, under both peak load and partial load conditions. To verify that the proposed approach can give the heating system hydraulic balance in an unfavourable situation, this research was carried out based on the design condition. The research object in this study was a typical multi-storey building heating system, in which the heat from the DH network is supplied to the interior of the building via a heat entrance, and then distributed to a number of apartments located on different floors along the vertical riser. Each apartment has its own two-pipe heating loop.

2.1 Control devices

TRVs and automatic balancing valves are the two key components that are integrated in this technical approach.

TRVs consist of a thermostatic sensor and a radiator valve. An important function of radiator valve is the integrated pre-setting function, which can adjust the flow through the valve to the required value by changing the opening of the valve, namely by adjusting the pre-setting levels.

Generally, the k_v value is used to describe the flow capacity of the valve, and depends on the degree to which the valve is opened. When the valve is fully open, the specific k_v obtained is called the k_{vs} , which is defined as the maximum flow rate that goes through the valve under a pressure drop across the valve of 1 bar (Frederiksen and Werner 2013). The actual flow, q (m^3/h), through the valve for a given pressure drop, ΔP (bar), across the valve can be calculated using Eq. (1):

$$q = k_v \sqrt{\Delta P} \quad (1)$$

Some specific radiator valves, e.g. a type RA-N radiator valve (Danfoss 2014a) with no pre-setting, have a k_{vs} of 0.53 ($\text{m}^3/(\text{h} \cdot \text{bar}^{1/2})$) when the valve is fully open. If a radiator valve has an integrated pre-setting function, this means the k_v value of the valve can be adjusted in a discontinuous, level-by-level way. For instance, a type RA-N radiator valve with a pre-setting function has pre-setting scales ranging from 1 to 7 and N. Each scale corresponds to a maximum flow

coefficient; at N, the valve is fully open. The pre-setting of the radiator valve is done in accordance with the expected available DP across the valve and the required design flow through the valve.

A radiator valve with no pre-setting means the valve can be either fully open or fully closed, unless a thermostatic sensor is mounted on the radiator valve. Some misunderstanding exists that the installation of radiator valves that do not have an integrated pre-setting function, can ensure hydraulic balancing is obtained automatically, because the function of radiator valve is to adjust the flow through the radiator to the correct values. In fact, the radiators in an apartment generally have various heat loads, but the same size radiator valves are usually installed on all radiators. The pressure drop on the radiator can be negligible, so the same flow will go into all the radiators. This flow rate might suit one of the radiators, but it means excess flow or insufficient flow for other radiators. To achieve the hydraulic balance it is therefore important to apply radiator valves with integrated pre-setting functions. The purpose of the pre-setting function is to limit the maximum flow rate through the radiator valve in accordance to the peak demand of the radiator. Once pre-setting of the radiator valve has been performed hydraulic balance has been achieved at design conditions.

Based on Eq. (1), it is easy to see that the flow through the radiator valves will be influenced when the pressure drop across the valves changes. Since excess of differential pressure on the valves could cause noise and the increased flow rate might carry impurities so that the risk of clogging is high, the pressure drop across the radiator valve needs to be controlled to ensure good adjustment effects. Good regulation of the radiator valve requires a constant DP across the valve. This constant DP can be created and maintained by using a DP controller. The constant DP protects downstream control valves from excessive pressure and offsets the effects of pressure variations caused by the movement of control valves in other branches. For radiator valves, the maximum pressure drop should not exceed 30 – 35 kPa, and most radiator applications use a DP range of 5 – 25 kPa (British Standards Institution 2004). With the installation of a DP controller, all of the controlled loops also become pressure-independent zones. This eliminates any problems caused by high or excessive system pressures, including noise from the valves and poor control of room temperatures.

The DP controller and the radiator valve are the two key control devices used in this study. With these two control devices, terminal units (radiators) can achieve rational flow allocation, so that the entire building heating system is kept in hydraulic balance under all load conditions.

2.2 The integrated model

An integrated model was used to investigate the hydraulic performance and the heat performance of the building heating system when the pressure and flow are either controlled or not controlled. Figure 4 shows a schematic layout of the heating system. The model consisted of two parts: a building model and a hydraulic model. The building model was developed using the commercial software Indoor Climate and Energy (IDA-ICE) 4.6.2 (EQUA 2015), from which the building heating system was derived. Based on the heating system, the physical properties of the hydraulic model were known, and we developed a mathematical hydraulic model based on Kirchhoff's laws.

2.2.1 Building model

The simplified building model consisted of three floors of a multi-storey building in Beijing. Each floor had an apartment with three rooms. All the rooms were identical, with a heating area of 37.5 m² and a height of 3.0 m. The building was to meet the 3rd step of the energy efficiency standards for Beijing. This implies that the design heat load per room was 1200 W under design conditions. Moreover, the construction envelope properties and the thermal characteristics for the building model, including external/internal walls, internal floors, roof and ground, windows and doors, window glazing, etc., as well as thermal bridges

and the window-to-wall ratio, were all as specified in China's design standard (Ministry of Housing and Urban-Rural Development of China 2010). The building was modelled as a multi-zone model, which means that each room was modelled as an individual zone. Because the model was used to investigate the heat performance of a multi-storey building under design conditions, synthetic weather data were used: the outdoor ambient temperature was constant and kept at -9°C . Furthermore, to simulate this most unfavourable situation, the influence of solar radiation and mechanical ventilation on indoor temperatures was disregarded.

For the SH installation, the design was carried out in accordance with (Lu 2008). The design heat load for all rooms was 1200 W. The design temperatures of the radiator heating system were $75/50/18^{\circ}\text{C}$ (supply/return/indoor temperatures). Firstly, the pipeline layouts of the building heating system were arranged. To keep things simple, the horizontal pipe length between the riser and the radiator, and between one radiator and the next were all simply considered to be 10 metres. The riser height for each floor was 3 m. Secondly, the design flow rates of the radiators were determined in accordance with the peak heat load and design temperatures. The radiators were KORADO "Type 22" panel steel radiators (KORADO 2014). Thirdly, a hydraulic calculation of the building heating system was made. The dimensions of pipes were defined in accordance with

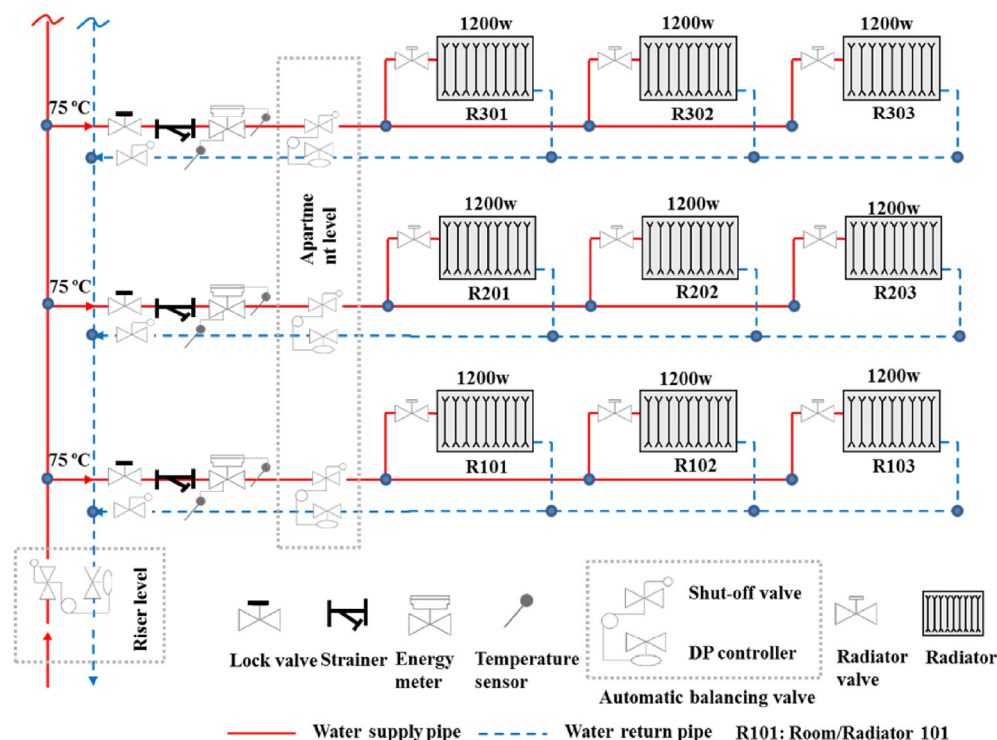


Fig. 4 Schematic layout of the integrated model

(Jing et al. 2014). On this basis, the dimensions of all indoor heating pipes were DN15, and the riser pipe sizes on the 1st, 2nd, and 3rd floors were DN25, DN20, and DN15, respectively. Accordingly, the DPs of these three apartment heating loops were calculated and all were less than 5 kPa under the design flow rates. RA-N-type radiator valves with a dimension of DN15 were therefore used (Danfoss 2014a). As DP controllers, an ASV-PV (Danfoss 2014b) was applied in the return pipe, and its associated partner shut-off valve ASV-M (Danfoss 2014b) was applied in the supply pipe. The ASV-PV and ASV-M were linked to each other with a capillary tube; together they are known as automatic balancing valves. They were located in the staircase hall, which is also where the heat entry point of the apartment heating loop was located.

2.2.2 Hydraulic model

2.2.2.1 Flow coefficient

According to basic fluid mechanics, the pressure drop for a given length of circular pipe is caused by friction along the length of the pipe, and by local resistance from pipe fittings, valves, forks, bends, etc. Furthermore, in the light of the Darcy-Weisbach equation, the relationship between flow and pressure drop in a given pipe i can be expressed by Eq. (2):

$$\Delta P_i = \left(\frac{\lambda_i}{d_i} l_i + \sum_{n=0}^n \zeta_n \right) \frac{1}{900^2 \pi^2 d_i^4 20 \rho_w^2} q_{v,i}^2 \quad (2)$$

where ΔP_i (bar) is the pressure drop in pipe i ; λ_i is the friction factor of pipe i ; d_i (mm) is the diameter of pipe i ; l_i (m) is the length of pipe i ; ζ_n is the n -th local resistance coefficients in pipe i ; ρ_w (kg/m³) is the water density; and $q_{v,i}$ (m³/h) is the volume flow through pipe i .

Changes in the throttle section of a control valve change its k_v value. Pipes without control devices have a constant k_v value. It can therefore be said that changing the k_v value of certain pipes, which can be done by pre-setting the radiator valves, changes the flow distribution in the heating system, and thus flow control can be achieved. On the other hand, for any given k_v value, the DP across the valve also influences the flow through the valve. A constant DP across the valve is therefore required to ensure good regulation of the radiator valve.

Once the heating system was designed and the piping configuration was determined, so that the design flow, the pipe dimensions, pipe lengths, and local resistance coefficients were known, the pressure drop for each pipe could be calculated using Eq. (2). Subsequently, the k_v values of the pipes were calculated in accordance with Eq. (1). When the radiator valve was pre-set or fully open, the k_v values of the radiator branch pipes were changed correspondingly.

2.2.2.2 Mathematical model for a simplified case

Water flow in the heating network follows Kirchhoff's laws. According to the First Law of Kirchhoff, at any node in a hydraulic network, the sum of the water flow into that node is equal to the sum of the water flow out of that node, which can be expressed as Eq. (3):

$$\sum_{n=1}^m q_{v,n} = 0 \quad (3)$$

where $q_{v,n}$ (m³/h) is the volume flow of branch n . $q_{v,n}$ has a positive or negative value depending on whether the flow is into or out of the node.

According to the Second Law of Kirchhoff, the directed sum of the DP around any closed network is zero. This can be expressed as Eq. (4):

$$\sum_{n=1}^m \left[\left(\frac{q_{v,n}^2}{k_{v,n}^2} \right) - \Delta P_n \right] = 0 \quad (4)$$

For a system of pipelines connected in series, the pressure drop for the entire loop, ΔP_s , is the sum of the pressure drop in each pipeline, ΔP_n . This can be expressed as Eq. (5). Moreover, based on Eq. (1), the equation can also be expressed by $k_{v,s}$ for the entire loop, and by $k_{v,n}$ for each individual pipeline, as in Eq. (6).

$$\Delta P_s = \sum_{n=1}^m \Delta P_n \quad (5)$$

$$\frac{1}{k_{v,s}^2} = \sum_{n=1}^m \frac{1}{k_{v,n}^2} \quad (6)$$

For a system of pipelines connected in parallel, the volume flow for the entire loop, $q_{v,s}$, is equal to the sum of the volume flow through each branch pipe, $q_{v,n}$, as expressed by Eq. (7). This can also be expressed in k_v values, as in Eq. (8).

$$q_{v,s} = \sum_{n=1}^m q_{v,n} \quad (7)$$

$$k_{v,s} = \sum_{n=1}^m k_{v,n} \quad (8)$$

2.2.2.3 Mathematical model

Based on the schematic layout of the integrated model (Fig. 4), both the whole building heating system (with three apartments) and each apartment heating system (with three radiators) can be considered as a simple heating system with three loops (Fig. 5).

According to Kirchhoff's laws, and the series connection and parallel connection of the pipelines, the set of equations

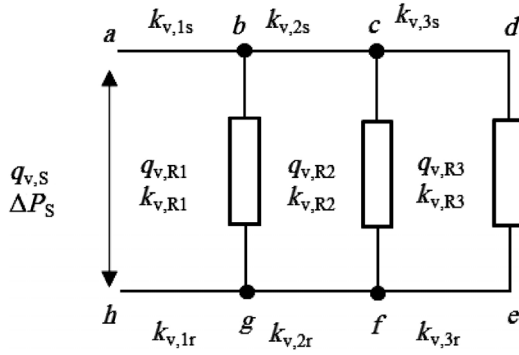


Fig. 5 Mathematical model of hydraulic model

for this mathematic model can be written as Eqs. (9)–(15):

$$\frac{1}{(k_{v-cdef})^2} = \frac{1}{k_{v,3s}^2} + \frac{1}{k_{v,3r}^2} + \frac{1}{k_{v,R3}^2} \quad (9)$$

$$\frac{1}{(k_{v-bcdefg})^2} = \frac{1}{k_{v,2s}^2} + \frac{1}{k_{v,2r}^2} + \frac{1}{(k_{v,R2} + k_{v-cdef})^2} \quad (10)$$

$$\frac{1}{(k_{v-abcdefgh})^2} = \frac{1}{k_{v,1s}^2} + \frac{1}{k_{v,1r}^2} + \frac{1}{(k_{v,R1} + k_{v-bcdefg})^2} \quad (11)$$

$$\Delta P_s = \left(\frac{q_{v,s}}{k_{v-abcdefgh}} \right)^2 \quad (12)$$

$$q_{v,s} = \sum_{i=1}^3 q_{v,Ri} \quad (13)$$

$$\frac{q_{v,R1}}{q_{v,R2} + q_{v,R3}} = \frac{k_{v,R1}}{k_{v-bcdefg}} \quad (14)$$

$$\frac{q_{v,R2}}{q_{v,R3}} = \frac{k_{v,R2}}{k_{v-cdef}} \quad (15)$$

When the available DP for this system ΔP_s is determined, and the $k_{v,1s}$, $k_{v,1r}$, $k_{v,R1}$, $k_{v,2s}$, $k_{v,2r}$, $k_{v,R2}$, $k_{v,3s}$, $k_{v,3r}$, and $k_{v,R3}$ values for each pipe are known, the volume flow, $q_{v,R1}$, $q_{v,R2}$, and $q_{v,R3}$, for each branch pipe can be calculated based on Eqs. (9)–(15). From the mathematical model, the flow distribution between the radiators and the apartment heating loops is known, and the hydraulic performance of the heating system is clarified. The volume flows obtained

from this mathematical model were used as inputs into the IDA-ICE building model; subsequently, the room temperatures, i.e. the temperatures of each zone, could be simulated, and the heat performance of the model determined.

2.3 Scenarios

To test the effects of this integrated approach, four scenarios were developed. The reference was the distributed design flow with no pressure or flow control measures. In the four scenarios, the DP controllers and radiator valves had different applications (Table 1). Because the calculated pressure drop in the three floor loops is the same and less than 5 kPa under the design conditions, when the DP controller was at the apartment level, the available DP for each loop was set to 5 kPa. When the DP controller was at the riser level, the available DP ensured that the 3rd floor apartment loop obtained 5 kPa. The heat consumption, pump electricity consumption, indoor temperature, and return temperature in the building heating system were compared for the four scenarios. The units for heat consumption and pump electricity consumption were unified as kWh and temperatures are presented in °C to facilitate comparison of the scenarios and determine the optimum approach.

3 Results and discussion

3.1 Validation of building model

The building model was developed in accordance with “Industry standard JGJ 26-2010” (Ministry of Housing and Urban-Rural Development of China 2010), the standard according to which the buildings in the network were built. The thermal characteristics of the building that was modelled, which is representative of all the buildings in the network, are an indoor air temperature of 18 °C and a heat demand of 32 W/m² at an outdoor design temperature of −9 °C. The radiator heating system is designed to be able to maintain the room temperature around 18 °C, given a 75 °C supply temperature, and to cool the return to 50 °C.

Table 1 The reference and the four scenarios

Control conditions	No DP controllers, <u>Apply DP controllers</u>			No radiator valves, <u>Apply radiator valve</u>		
	just pipes	Riser level	Apartment level	just pipes	No pre-setting	With pre-setting
Reference	√	—	—	√	—	—
Scenario 1	—	√	—	—	√	—
Scenario 2	—	—	√	—	√	—
Scenario 3	—	√	—	—	—	√
Scenario 4	—	—	√	—	—	√

With the outdoor temperature at $-9\text{ }^{\circ}\text{C}$ and the supply temperature of the heating system at $75\text{ }^{\circ}\text{C}$, we ran the model in IDA-ICE 4.6.2; the simulation results showed the mean air temperature for all zones was around $19\text{ }^{\circ}\text{C}$ (Fig. 6). The specific room temperatures for the zones are listed in Table 2. The average indoor temperature was $18.8\text{ }^{\circ}\text{C}$, and the deviation from the minimum design indoor temperature of $18\text{ }^{\circ}\text{C}$ was less than $1\text{ }^{\circ}\text{C}$, which is reasonable and acceptable. Moreover, the room unit heat demand for all zones was $31.5 - 32\text{ W/m}^2$, and the return temperature of the heating system was $50\text{ }^{\circ}\text{C}$. Therefore, the heat demand of the building model and the heat supplied by the radiator heating system were consistent under design conditions. The building model with the derived heating system was developed in IDA-ICE and was used for the investigation.

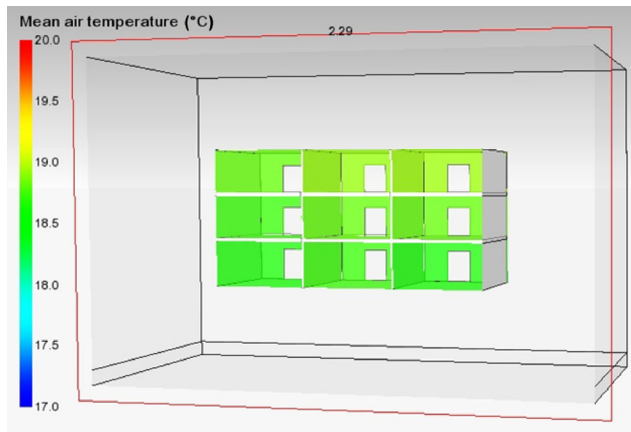


Fig. 6 Mean air temperatures of all zones

3.2 Scenarios

3.2.1 Flow distributions and room temperatures

Using the hydraulic model and the building model, we investigated the flow requirements and heat delivery when the pressure and flow control measures were adopted or not, and the results are listed in Table 3. First, it is clear that with no flow or pressure control (i.e., the reference case), there was a hydraulic unbalance in the entire heating system, as well between the radiators for each apartment loop. In order for the critical Radiator 303, which is the last radiator in the 3rd floor apartment loop, to receive sufficient flow to achieve the standard room temperature, the excess flow of

the whole heating system was 321%. Moreover, the first radiators for each floor, namely Radiator 101, Radiator 201, Radiator 301, encountered severe excess flows of 870%, 778%, and 686%, respectively. Correspondingly, the room temperatures were well beyond the design level, probably forcing the opening of windows and ultimately wasting energy. This result is also very clear.

On the other hand, when pressure and control measures were employed in the heating system (in the four scenarios), the excess flow was much more controlled, and the deviation in indoor temperature between the simulated results and the design values became smaller as well. Looking at the four scenarios, when radiator valves with no pre-setting were used with DP controllers at the riser level or the apartment level (Scenarios 1 and 2, respectively), the average excess flows of the heating system were more than 15%, there was hydraulic unbalance in the heating system, and the room temperatures were uneven and deviated from the design values. When radiator valves with pre-setting were used and were pre-set in combination with the DP controllers at the riser level or the apartment level (Scenarios 3 and 4, respectively), the average excess flows of the heating system were controlled within 15%, the heating system was in hydraulic balance, and the room temperatures were even and close to the design values, averaging $18.8\text{ }^{\circ}\text{C}$. In terms of flow distribution and room temperatures, Scenario 4 had a slightly smaller average excess flow than Scenario 3. The deviation from the design flow occurred because the radiator valve with pre-setting is a discontinuous controller, so it is not always exact. The average room temperature for Scenario 4 ($19.3\text{ }^{\circ}\text{C}$) is also just slightly closer to the design average indoor temperature of $18.8\text{ }^{\circ}\text{C}$ than Scenario 3 ($19.4\text{ }^{\circ}\text{C}$).

The simulation results show that the lack of appropriate flow and pressure management inevitably causes hydraulic unbalance. To achieve the standard room temperature for the critical end users, DH suppliers increase the flow, creating more hydraulic unbalance and excess flow in the system. This means hydraulic unbalance is related to overheated rooms, unsatisfactory indoor thermal comfort, windows being opened, and much more pump electricity consumption than under conditions of hydraulic balance. All this implies higher energy consumption and lower operating efficiency, all of which threatens China's energy security and air pollution abatement policy.

Table 2 The design flows and indoor temperatures for the building model

Items	Radiator 101	Radiator 102	Radiator 103	Radiator 201	Radiator 202	Radiator 203	Radiator 301	Radiator 302	Radiator 303	Total flow (kg/h)
Design flow (kg/h)	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	371.3
Room temperature ($^{\circ}\text{C}$)	18.7	18.8	18.7	18.8	18.9	18.9	18.9	19.0	19.0	

Table 3 Comparison of the simulation results for the reference and the four scenarios

Control conditions	Items	Radiator 101	Radiator 102	Radiator 103	Radiator 201	Radiator 202	Radiator 203	Radiator 301	Radiator 302	Radiator 303	Total flow (kg/h)	Average excess flow (%)
Reference	k_v value	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28		
	Flow (kg/h)	400.5	125.1	50.7	362.6	113.2	45.9	324.6	101.4	41.1		
	Room temperature (°C)	27.4	23.4	20.1	27.2	23.2	19.5	27.0	23.0	18.8	1565.1	321%
	Excess flow (%)	870%	203%	23%	778%	174%	11%	686%	146%	0%		
Scenario 1	k_v value	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52		
	Flow (kg/h)	80.6	59.0	52.4	74.9	54.8	48.7	69.2	50.6	45.0		
	Room temperature (°C)	21.2	20.5	20.0	21.1	20.4	19.9	21.1	20.3	19.8	535.2	44%
	Excess flow (%)	95%	43%	27%	81%	33%	18%	68%	23%	9%		
Scenario 2	k_v value	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52		
	Flow (kg/h)	69.2	50.6	45	69.2	50.6	45	69.2	50.6	45	494.4	33%
	Room temperature (°C)	20.8	20.0	19.4	20.9	20.1	19.6	20.9	20.2	19.7		
	Excess flow (%)	68%	23%	9%	68%	23%	9%	68%	23%	9%		
Scenario 3	k_v value	0.21	0.27	0.27	0.27	0.27	0.31	0.27	0.31	0.31		
	Flow (kg/h)	41.8	48.0	46.3	48.8	43.0	47.2	45.6	45.4	43.4	409.5	10.2%
	Room temperature (°C)	19	19.4	19.3	19.4	19.3	19.5	19.4	19.5	19.4		
	Excess flow (%)	1%	16%	12%	18%	4%	14%	10%	10%	5%		
Scenario 4	k_v value	0.27	0.31	0.31	0.27	0.31	0.31	0.27	0.31	0.31		
	Flow (kg/h)	45.6	45.4	43.4	45.6	45.4	43.4	45.6	45.4	43.4	403.2	8.5%
	Room temperature (°C)	19.2	19.3	19.1	19.3	19.4	19.2	19.4	19.5	19.4		
	Excess flow (%)	10%	10%	5%	10%	10%	5%	10%	10%	5%		

3.2.2 Energy consumption and return temperatures

Figure 7 compares the reference and the four scenarios on heat consumption, pump power consumption, and return temperature. The simulation results show that Scenario 4 has the least heat consumption at 83.8% of the reference, the least pump electricity consumption at 26.3% of the reference, and the lowest return temperature at 52.1 °C. This means that having DP controllers at the apartment level, combined with pre-set radiator valves (Scenario 4) achieved hydraulic balance in the heating system, brought room temperatures close to the design level, and reduced the return temperature of the heating system. Furthermore, this solution dramatically reduced the electricity consumption of the pumps by nearly 74%, and gave a 16% heat consumption saving.

As mentioned before, the seasonal heat consumption per square metre of the buildings in CASE-Beijing is 0.15 GJ/m², so a 16% heat consumption saving implies a heat reduction of 0.024 GJ/m² during the heating season. Furthermore,

coal is the dominant DH fuel in China (You and Xu 2010). Statistics show that 91% of the total energy supply to DH systems came from coal in 2008 (Baeumler et al. 2012). Therefore, any reduction in consumption will lead to reduced emissions. Burning one ton Chinese standard coal (29.3 GJ/tce) releases about 2600 kg CO₂, 24 kg SO₂, 7kg NO_x (Price et al. 2011). Consequently, a seasonal heat consumption reduction of 0.024 GJ/m² implies a reduction of 2.1kg /m² CO₂, 0.02 kg/m² SO₂, and 0.01 kg/m² NO_x for CASE-Beijing. If the proposed controls are applied in Chinese DH systems, appropriate energy consumption savings would be achieved which would consequently have positive environmental impacts.

These results show that a well-balanced building hydronic circuit can be achieved under design conditions by applying the technical approach proposed. This approach ensures the flow through each radiator never exceeds the required maximum value, which limits the excess flow for all radiators under any conditions. At the present time, most Chinese building heating systems are operated as constant

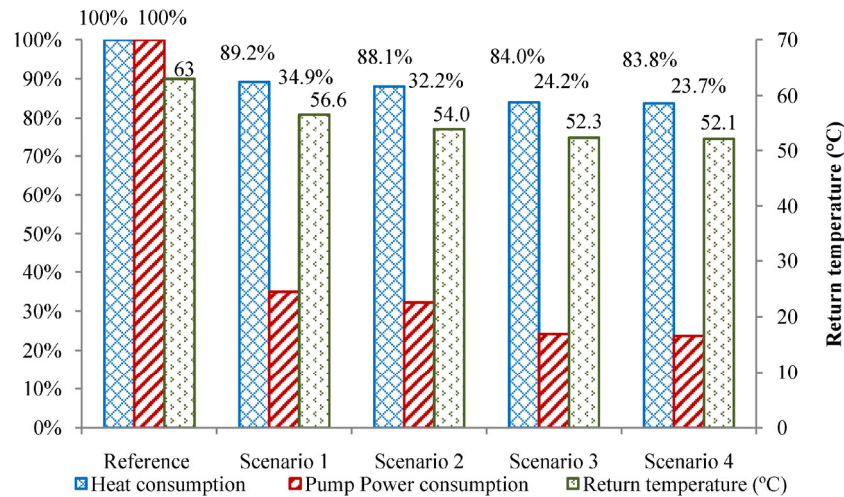


Fig. 7 Comparison of the reference and the four scenarios

flow systems: the flow rates are fixed so the hydraulic situation remains balanced under various load conditions; and the varying heating loads are met by varying the supply temperatures. On the other hand, these are good preconditions for mounting thermostatic sensors on the radiator valves. As the thermostats are activated, the flows into the radiators will be limited and even completely closed depending on the desired room temperatures. That will transform the heating system from constant flow to variable flow and allow the return temperature to be further decreased. Reducing the return temperature as low as possible will allow subsequent improvements in heat source efficiency. Furthermore, once the thermostatic sensor has been installed further energy savings can be achieved as it will prevent the inherit oversupply experienced in constant flow systems when the outdoor temperatures are higher than the design value. This approach not only makes the necessary technical preparation, but will also create hydraulic balance when the application of TRVs becomes more widely used in Chinese heating systems in the coming years.

Nevertheless, it is worth noting that the differences between Scenario 3 and Scenario 4 are limited in terms of both energy consumption and indoor temperatures. Therefore, it is wise to find a balance between the cost of initial product investment and the later operating costs of the heating system. However, applying DP controllers at the apartment level provides some additional benefits for the system:

Some risks can effectively be avoided, such as man-made changes or misuse of the initial pre-setting of the radiator valves, which might be fully opened and cause hydraulic unbalance, affecting other loops and perhaps the whole riser heating system, as well as causing noise and probably blockage issues.

Furthermore, applying DP controllers at the apartment level can make the commissioning work easy and rapid. Multi-storey buildings usually have the same layout on every floor, so the rooms located on different floors but in the same vertical position usually have the same heating area and heat demand, and radiators located on different floors but in the same vertical position could have the same pre-setting value. In contrast, applying DP controllers at the riser level is more complex because the pressure drop for apartment loops on different floors is different, so that the pre-setting work in high-rise buildings might become relatively complicated due to the building's height.

4 Conclusions

An integrated model for the simulation of the heat performance and hydraulic situation of a two-pipe multi-storey building heating system in China has been developed, validated, and applied to analyse pressure and flow conditions. The simulation results indicate that the technical approach of combining DP controllers with radiator valves will significantly improve the hydraulic conditions, as compared with no pressure or flow control.

Without pressure and flow controls, increases in the flow rate to ensure sufficient room temperatures to distal or critical rooms result in considerable hydraulic unbalance, large flow rates, and high pump electricity consumption. In contrast, combining DP controllers at the apartment level with pre-set radiator valves achieves a fair flow distribution, room temperatures that are close to design values, 16% heat savings, 74% pump electricity savings, and a difference between the supply and return temperatures that is close to the design value. These results verify that the hypothesis presented in the paper is valid: hydraulic balancing optimizes the flow distribution in the building's heating system so that

it provides the intended indoor room temperature at optimal energy efficiency and minimal operating cost.

For the appropriate application, there are small differences in heat performance and energy consumption between applying the DP controllers at the apartment level or at the riser level in combination with pre-setting radiator valves. Both control solutions achieve hydraulic balance in the heating system. In terms of financial factors, it is important to take into account both the initial investment cost and the potential increase in operating costs in the event of misuse of radiator valves with DP controllers applied at the riser level, as well the increased complexity of commissioning this solution.

The technical approach proposed here fits the current constant flow principle in heating systems, but also makes technical preparations for the future when TRVs become widely used and heating systems are transformed from constant flow to variable flow.

The approach proposed could help decision-makers and stakeholders to plan new or renovated DH projects to be more energy-efficient and cost-effective. It would make a considerable contribution to energy supply security and air pollution abatement for Chinese society by giving smart control to heating systems.

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Article II

Method for reducing excess heat supply experienced in typical Chinese district heating systems by achieving hydraulic balance and improving indoor air temperature control at the building level

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Method for reducing excess heat supply experienced in typical Chinese district heating systems by achieving hydraulic balance and improving indoor air temperature control at the building level

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ABSTRACT

A common problem with Chinese district heating systems is that they supply more heat than the actual heat demand. The reason for this excess heat supply is the general failure to use control devices to adjust the indoor temperature and flow in the building heating systems in accordance with the actual heat demand. This results in 15–30% of the total supplied heat being lost. This paper proposes an integrated approach that aims to reduce the excess heat loss by introducing pre-set thermostatic radiator valves combined with automatic balancing valves. Those devices establish hydraulic balance, and stabilize indoor temperatures. The feasibility and the energy consumption reduction of this approach were verified by means of simulation and a field test. By moving the system from centrally planned heat delivery to demand-driven heat delivery, excess heat loss can be significantly reduced. Results show that once the hydraulic balance is achieved and indoor temperatures are controlled with this integrated approach, 17% heat savings and 42.8% pump electricity savings can be achieved. The energy savings will also have a positive environmental effect with seasonal reductions of 11 kg CO₂, 0.1 kg SO₂, and 0.03 kg NO_x per heating square meter for a typical case in Harbin.

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1. Introduction

Research has shown that DH (district heating) is playing an important role in the societal goal of realizing an effective and sustainable energy system [1–5]. Along with the rapid growth of urbanization and industrialization, China has become one of the largest DH markets in the world in the last two decades. Statistics indicate that the total DH production in 2013 amounted to 3,197,032 TJ [6]. This number is still increasing steadily due to the process of rapid urbanization, expansion of the building area, enhancement of building services, and increases in comfort level. On the other hand, according to a World Bank report in 2012, the consumption of heating energy in China per square metre of floor

area is almost twice that in developed countries at the same latitude. Nevertheless, the resulting room thermal comfort in China is still unsatisfactory [7]. Furthermore, the 2011 Annual Report on China Building Energy Efficiency [8] reports that 15–30% of the total heat is being lost due to excess heat supply in northern China's DH systems. These high losses are primarily due to a failure to use control devices to control the heating supply in accordance with the actual heating demand. There is an urgent need to apply appropriate technical approaches to improve the Chinese DH efficiency to create the maximum synergy between energy supply security and air pollution abatement, which are the two most important challenges for China today [9].

Chinese DH systems are very different from European DH systems. Structurally, a typical Chinese DH system is like this: pressurized hot water as the heat medium is produced in the central heat source and distributed to a few area substations (the primary side of the DH system). Each area substation then serves a number of multi-storey or high-rise buildings (the secondary side of the DH system). The heat entrance is the interface connecting the large-

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area substation to the building heating system (see Fig. 1). It is usually equipped with shut-off valves, and measurement devices like thermometers, pressure gauges and heat meters, etc. [10].

In terms of temperatures, China's national design code [11] states that the DH primary side network should be designed with supply temperatures of 115 °C–130 °C and return temperatures of 50–80 °C. The design code does not state any minimum design temperature difference. For the radiator SH (space heating) systems, the design supply/return temperatures are recommended as 75/50 °C or 80/60 °C [12]. In practice, DH systems generally operate with different temperatures based on various conditions for the particular DH systems.

In terms of heat sources, the main heating production facilities are the coal-fired boilers and CHP (combined heat and power) plants. For instance, in 2013, 48% of DH came from coal-fired boilers, 42% CHP plants, 8% gas-fired boilers, and the remaining 2% came from scattered and individual heating facilities. Furthermore, coal is the dominant DH fuel in China [13]. Statistics show that 91% of the total energy supply to DH systems came from coal in 2008 [14].

Moreover, unlike European DH systems where DH supply covers both SH and DHW (domestic hot water), approx. 90% of Chinese DH systems supply SH without DHW [15].

These important characteristics make it possible to understand why excess heat supply occurs in typical Chinese DH systems.

From the perspective of temperature control, room temperature regulation and control functions are not available in approx. 84% of the total heating area in China [16]. According to the national code [12], 18 °C is the standard room temperature for heat consumers in northern China to evaluate whether the heating effect is up to the required standard. The DH utility usually increases the secondary circulation flow rate until at least critical consumers attain this standard, which often results in the systems operating with large volume flow and small temperature differences between the supply and return streams. Moreover, once the heat demands of the critical consumers are fulfilled, the secondary flow rate often remains constant, with the varying SH demand being met by adjusting the secondary side supply temperature. Furthermore, there is a lack of automatic weather compensation control in some cases at substation level. Manual adjustment may be applied, e.g., tentatively adjusting the opening of the control valve installed on the primary side of the DH system, which is eventually reflected in changes in secondary supply temperatures. Such manual operation is based on the experience of past years and the level of complaints from critical users of the system, and the purpose of adjusting the supply temperature is to correlate the heat supply with the outdoor

air temperature. Consequently, when the supply temperature to the SH system is higher than required, consumers will open windows to get comfortable indoor temperatures. In some cases, TRVs (thermostatic radiator valves) are installed in the DH systems. However, they are typically left fully open. Due to the fixed heating charges based on heating area, not actual heat consumption, there is no incentive for consumers to consciously reduce the TRV settings in an oversupply situation. They would generally regulate the indoor temperature by opening the windows. All these factors mean that consumers are either unable to control their room heating supply or lack motivation for energy conservation, which means excess heat supplied is wasted.

From the perspective of flow control in the secondary DH network and at building level, there are no automatic flow control devices, which results in an uneven flow distribution in the secondary-side DH network. Buildings close to the substation receive more flow than needed and become overheated, whereas buildings located in distal parts of the network receive less flow than required and are unable to fulfil their heating requirements. There is a lack of hydraulic balance inside the buildings. Specifically, the secondary side of Chinese DH systems generally operates on a constant flow and pressure basis. The pressure head at the pump is controlled to maintain constant differential pressure at area-substations. In addition, the constant flow operation principle makes the pumps run at constant speed. Although there are some variable-speed pumps, they are mainly used to correct the deviation between the design and operation conditions in terms of the pressure head and flow rate. Large volume flow leads therefore to higher than necessary electricity consumption in circulation pumps, small temperature differences, high return temperatures, and network heat losses.

In summary, it can be said that the general failure to use temperature and flow control devices in Chinese DH systems is the direct cause of excess heat loss, which subsequently compromises the efficiency of Chinese DH systems.

Studies have investigated how to improve the efficiency of Chinese DH systems by focusing on various DH elements [17–28]. With the heat reform in 2006 in China, 16% of the total heating area in China was given a heat metering retrofit [16] to install TRVs (thermostatic radiator valves) by the year 2012. A lot of research has been carried out on TRV application in Chinese heating systems [29–35]. For instance, Xu et al. [33] investigated how hydraulic performance and energy consumption in individual apartments and the whole system were influenced when TRVs were regulated and when windows were opened. Xu et al. [34] developed a dynamic model and simulated the thermal and hydraulic behaviour of

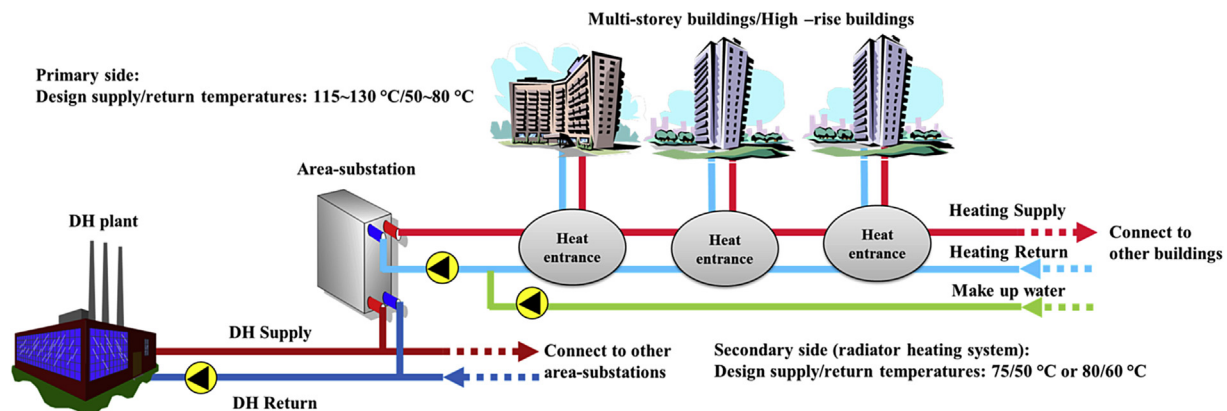


Fig. 1. Typical district heating system used in China.

SH systems employing TRV-controlled radiators in multi-family buildings. Liu et al. [35] analysed the heat metering methods currently available in China and proposed a new method for metering the heat consumption of individual households in accordance with the accumulated on-time as well as the floor space of each household.

However, when we examine the previous research mentioned above, there is still a lack of expertise or knowledge on optimizing building heating systems by correctly using the flow control and temperature control functions of TRVs, including their inherent relationship with energy consumption reduction and indoor temperature improvement.

In this paper, an integrated approach has been developed and applied to a real project in northern China. The technical feasibility is shown and the advantages are quantified. This could give enhanced understanding and guidance for renovating future Chinese DH systems.

2. Methodology

The research objects in this study were the building heating systems. The central hypothesis of this study rests on the idea that the flow and temperature control functions of TRVs combined with differential pressure management can reduce the excess heat supply experienced in current Chinese DH systems while reducing their energy consumption. This idea is reflected in the research question: how large is the potential for reducing excess heat consumption by using temperature and flow control in the heating system of buildings?

Chinese energy statistics usually use the unit “metric tons of standard coal equivalent” (tce) because the primary energy source for DH systems in China is coal, and one tce equals 29.3 GJ. Burning 1 ton Chinese standard coal (29.3 GJ/tce) releases about 2600 kg CO₂, 24 kg SO₂, and 7 kg NO_x [36]. If the proposed controls were applied in Chinese DH systems, energy consumption reduction would be achieved which would have considerable positive environmental impacts due to the heavy reliance on coal as DH fuel in China.

To show the inter-relationship between excess heat supply, overheating of rooms, and the hydraulic imbalance, we analysed the data from two real cases, Case-Beijing-A and Case-Harbin, and proposed a technical approach to solve the excess heat supply.

We performed a two-step analysis. Firstly, a field test was made to demonstrate the technical feasibility of the approach. The field test was carried out in a high-rise building in Beijing (Case-Beijing-B), which is structurally similar to Case-Beijing-A. Secondly, simulations for scenarios analysis were carried out using building simulation software: IDA Indoor Climate and Energy [37]. The prototype of the building model is one of the multi-storey residential buildings in Case-Harbin. The linear fit-to-metered secondary supply temperatures from Case-Harbin were used as input for the model to run the simulation. The flowchart shown in Fig. 2 illustrates the integrated design approach in this paper.

2.1. Current situation from real cases

First, the data from two real cases were analysed to present the excess heat supply experienced in Chinese DH systems.

Case-Beijing-A refers to a DH system in Beijing. The data from a residential high-rise building heating system were used to indicate the link between hydraulic imbalance and excess heat supply. Case-Harbin refers to a DH system in Harbin. The data from the secondary side of one substation were obtained to verify the causal link between overheated rooms and excess heat loss.

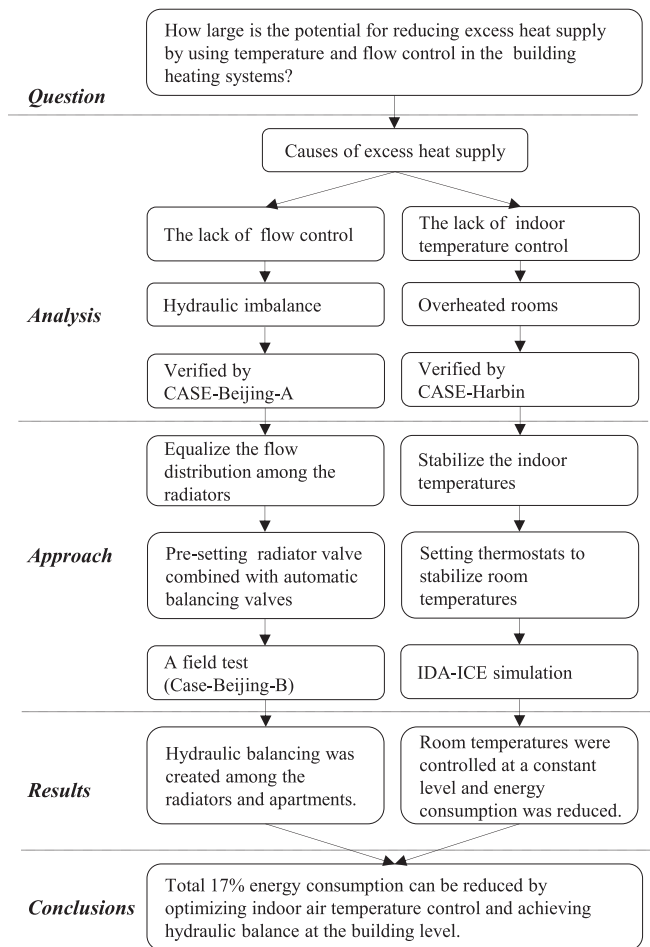


Fig. 2. Flowchart of methods used in the study.

2.1.1. Case-Beijing-A: hydraulic imbalance and excess heat loss

To understand the hydraulic situation in high-rise building heating systems, the volume flow data from a 21-floor residential building in Case-Beijing-A were obtained. The DH water from an area substation flows into the building via the heat entrance, where manual balancing valves are used as the only flow control device to manage the flow distribution among the connected buildings. DH utilities usually use a flow index to determine the required volume flow of each building in accordance with the heating area served. The manual balancing valves are set at the beginning of the heating season according to the estimated flow and differential pressure across the controlled loop. After initial commissioning is finalized, the setting values of these manual balancing valves are kept for the whole heating season, except for minor adjustments.

In this high-rise building, each floor had the same heating area. The instantaneous volume flows per square metre along one of vertical supply risers were measured by using a hand-held ultrasonic flow meter. The volume flows along the risers were measured on the 1st, 6th, and 13th floors and on the 14th, 18th, and 20th floors, as shown in Fig. 3. The results show how the volume flow per square metre decreased along the supply water direction.

The top floor should have a higher heat demand because of its larger exterior surface, but in reality, it was supplied with the least volume flow. Even though the volume flow per square metre on the top floor was less than 1/3rd that of the first floor, few thermal comfort complaints were reported. As a complaint over the phone is the most common way for Chinese heat consumers to inform the



Fig. 3. Flow measurement of a high-rise building in Beijing.

DH utilities about the heat effects, it can therefore be assumed that the floors below the top floor were receiving a higher volume flow than they actually required. These floors would be overheated. This case illustrates the excess heat supply caused by hydraulic imbalance in a building heating network where no flow control devices were used.

2.1.2. Case-Harbin: overheated rooms and excess heat supply

To understand the relation between the overheated rooms and excess heat supply, the data from one of the area-substations of Case-Harbin were obtained. The data included the supply and return temperatures of the area substation and the corresponding outdoor temperatures. The data covered the entire heating period from 20 October 2013 to 20 April 2014. This area substation supplied heat to 14 multi-storey buildings with a heating area of 124,150 m².

The control situation in this case was that no indoor temperature control devices were applied in the SH system. In addition, automatic weather compensation control was not available at the substation, and the system was operating under constant flow rate. The secondary supply temperature was manually adjusted based on the average daily outdoor temperatures from metrological data and past years' experience in relation to the level of complaints from heat consumers.

The data presented in Fig. 4 reveals the relationship between the supply temperature and outdoor air temperature being scattered when the manual control was applied. For the same outdoor temperature, the temperature differences between supply and return varied a lot. According to the records of the DH utility, very few complaints were received from the occupants during the heating period, and this implies that most consumers had room temperatures above 18 °C. This also implies that, for a given outdoor temperature, the lowest temperature difference has met the heat demand. All other temperature differences higher than the lowest values imply the buildings were overheated, since the constant flow principle was being applied in the secondary DH network. All heat supplied in excess of the lowest value can be regarded as heat loss due to excess heat supply. Due to the lack of the individual control for the indoor terminal heat units, overheated rooms inevitably leads to window opening, which also explains why

several different temperature differences exist under the same outdoor temperature.

2.2. The proposed approach

To reduce the excess heat supply, an integrated approach was introduced that included the control devices: TRVs with pre-setting function, and automatic balancing valves. The SH systems considered in this paper are two-pipe radiator systems, and all the apartments have their own heating loops. A schematic configuration of the apartment heating loop applied in the integrated approach is illustrated in Fig. 5. The number of the radiator might be different based on the particular apartment.

TRVs consist of a thermostat and a radiator valve. The radiator valve is a flow control device. The degree of valve opening determines how much water flows through the valve into the radiator. This is controlled by the thermostat, which reacts to changes in room temperature.

The radiator valve with integrated pre-setting is a flow-limiting device that is fitted into the valve body to pre-set the maximum water flow through the radiator. The pre-setting values correspond to the scales marked on the radiator valve and the range is from 1 to 7 and N, which represent gradually increasing maximum flow limits [38], see Fig. 6. The pre-setting values can be set in accordance with the requested design flow through the radiator and the pressure drop across the valve. To ensure the optimal regulation of the radiator valve and quiet operation, it is important to achieve the desired differential pressure across the valve. According to EN 215 [25], a differential pressure setting of 10 kPa is commonly used for radiator applications. Automatic balancing valves were therefore also applied in this approach to ensure the optimum operation of the radiator valve.

Automatic balancing valves consist of a self-acting DP (differential pressure) controller and an associated partner valve. The valves are linked to each other by a capillary tube. In this case, the partner valve was designed to shut off the pipe flow, and the DP controller was designed to maintain a constant differential pressure across a loop. The constant differential pressure across the controlled loop protects downstream control valves from excess pressures and offsets the effects of pressure variations caused by

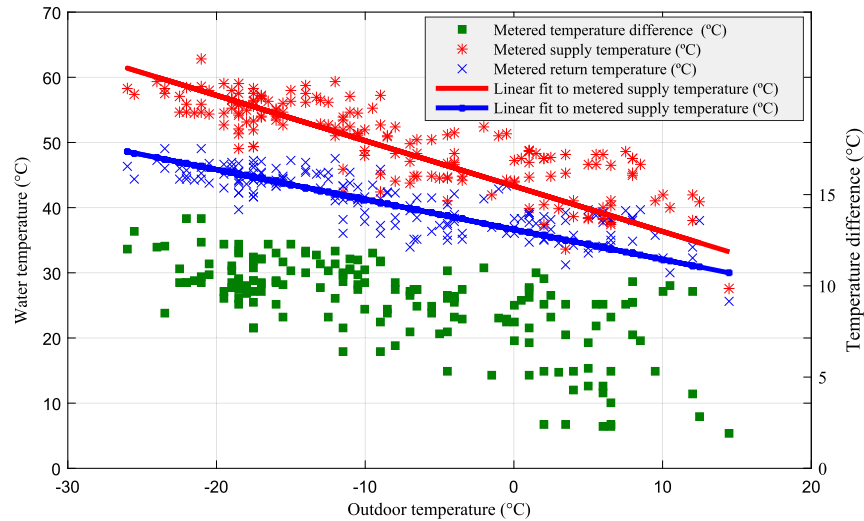


Fig. 4. Supply and return temperatures of a substation in Case-Harbin during the 2013–2014 heating period.

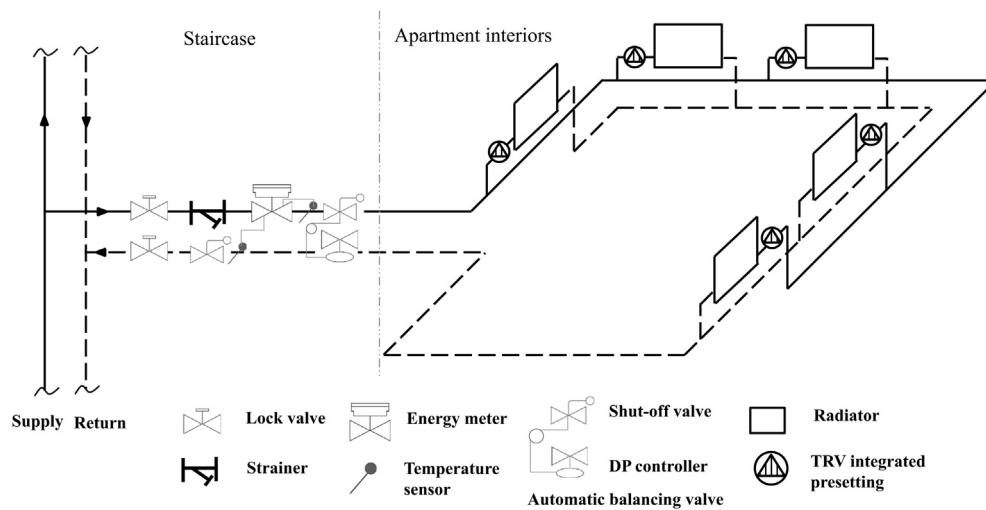


Fig. 5. Schematic configuration of the apartment heating loop.

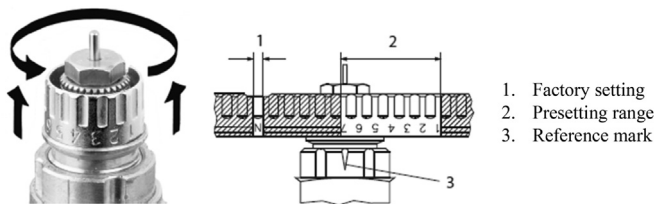


Fig. 6. Pre-setting scales of radiator valve [38].

the movement of the control valves in other branches. By installing automatic balancing valves, all the controlled loops become pressure-independent zones [39]. This eliminates any problems caused by high or excess system pressures, including noise from the valves and poor control of room temperature.

Pre-setting radiator valves combined with automatic balancing valves equalize the flow distribution among the radiators and establish hydraulic balance at peak load. The thermostat function stabilizes the indoor temperature with regard to weather variations and free heat gains. By moving the system from centrally planned

heat delivery to demand-driven heat delivery, the excess heat supply can be reduced, which can consequently reduce the energy consumption of Chinese DH systems and lead to positive environmental impacts.

2.3. Verification of the proposed approach

The technical feasibility of this approach and the improvements in indoor temperature control were verified by means of a field test (Case-Beijing-B) and building simulation software IDA Indoor Climate and Energy (IDA-ICE) 4.6.2 [37].

2.3.1. Field test in Beijing for flow control

The basic idea of the field test was to examine the flow control effect of using the radiator valve in combination with automatic balancing valves. With these two devices, the hydraulic balance is established and the flow distributed to each radiator can be controlled around the design value.

2.3.1.1. Configuration of the field test. This field test (Case-Beijing-B) was carried out in a new 18-storey high-rise residential building in

Beijing, which is structurally similar to Case-Beijing-A. The building's appearance is shown in Fig. 7 (left). The heating installation configuration for each apartment is illustrated in Fig. 7 (right). Details of the devices used are listed in Table 1. It should be mentioned that the radiator valves and the automatic balancing valves either need to be pre-set, or set during commissioning when the heating season starts, so that the radiators can achieve the required design flow under peak load. The set values of these two devices would be kept throughout the heating season or slightly adjusted if necessary. This field test focuses on the flow control effect of using these two devices, so the thermostats were removed for the experiment. In addition, automatic weather compensation control was applied at substation level for Case-Beijing-B to control the supply temperature, and variable speed pumps were available on the secondary-side of this DH system.

2.3.1.2. Implementation of the field test. The field test consisted of two parts: Test I considered three apartments as test objects and focused on the pressure control function of the DP controller. Test II considered one apartment as the test object and focused on the flow limitation function of the radiator valve pre-setting function. Throughout the test, the other apartments' heating systems in this building were operating normally.

In Test I, three apartments with identical heating areas were chosen as the test objects. They were located on the right-hand side of the 2nd floor (201), the left-hand side of the 2nd floor (202), and the right-hand side of the 17th floor (1701). During the test, all the radiator valves were pre-set to N, i.e. the radiator valves were fully open.

The apartment loop flows were measured for apartments 201, 202, and 1701 when the DP controllers were in turn set at 5, 10, 15, 20, and 25 kPa. The ultrasonic energy meter of each apartment was used to measure the flow and investigate: 1) the hydraulic situation along the vertical pipe; 2) the flow changes in one apartment loop resulting from changing the set points of the DP controller at random or completely shutting off the loop flow of the other two apartments.

In Test II, one of the apartments was chosen as the test object. The aim of Test II was to investigate how the pre-setting function of the radiator valve controls the flow rate of the heating system. This apartment had five rooms with their own radiators and was located on the 2nd floor. Basic data about the apartment are given in Table 2. Each radiator was equipped with a radiator valve with pre-setting function. Test II was performed with the DP controller set at 10 kPa in accordance with EN 215 [25]. The design parameters of this heating system (supply/return/indoor temperature) were 75/

60/18 °C. The design flow for each radiator could therefore be calculated and is given in Table 2. Based on the pressure drop of the heating loop and the design flow of the radiator, the pre-set scales of the radiator valve were determined and are listed in Table 2. The schematic configuration of the apartment-heating loop is illustrated in Fig. 5. A Testo 925 [40] was used for measuring the indoor temperature.

2.3.2. IDA-ICE simulation for indoor temperature control

For the indoor temperature control investigation, a simulation model of an eight-storey residential building was developed using IDA-ICE 4.2.6 [37]. To develop this building model, the building layout and building materials of one of the buildings in Case-Harbin were used. The building envelope properties and the thermal characteristics were as specified in China's energy conservation design standard JGJ26-95 [41]. One of the apartments was modelled as a multi-zone model. Each room in the apartment was a separate zone. The room height was 2.7 m. This multi-zone model contained five heated zone areas: Bedroom N (north), Bathroom, Bedroom S (south), Kitchen, and Living Room, as well as three non-heated balconies and a non-heated staircase/hall (see Fig. 8). The outdoor heating design temperature was −26 °C for Harbin and the indoor design room temperature was 18 °C. Based on the information, we run the multi-zone model equipped with ideal radiators, and obtained the peak heat load of each zone.

We dimensioned the radiators in accordance with Chinese standard [10]. In each zone, an M132-type radiator [42] was modelled as the room heating unit as in Case-Harbin. The design parameters of the SH system were the same as those for Case-Harbin: 80/60/18 °C (supply/return/indoor air temperatures). Correction factors were derived to correct for the actual output of each radiator. Accordingly, the maximum power of each radiator was determined, and the design flow limitation through the radiators and the design heat load for the SH system were defined.

Linear fit-to-metered supply temperatures were chosen in relationship to the outdoor temperatures shown in Fig. 4. Here the secondary supply temperature is assumed to have been optimized by applying the weather compensation control at the substation and variable speed pumps in the secondary network of this system. To reflect the real conditions, an internal heat gain of 5.0 W/m² was considered [41]. Real weather data in Harbin city in 2014 was used to estimate the energy consumption for heating using EnergyPlus [43]. Two scenarios were considered: 1) without TRVs fitted to the radiators, which is the most common situation in Chinese SH systems; and 2) with TRVs fitted to the radiators to adjust the indoor temperature by setting the thermostat of the TRVs. The room



Fig. 7. Real test case for the flow control approach.

Table 1

Details of the relevant devices installed in tested apartment.

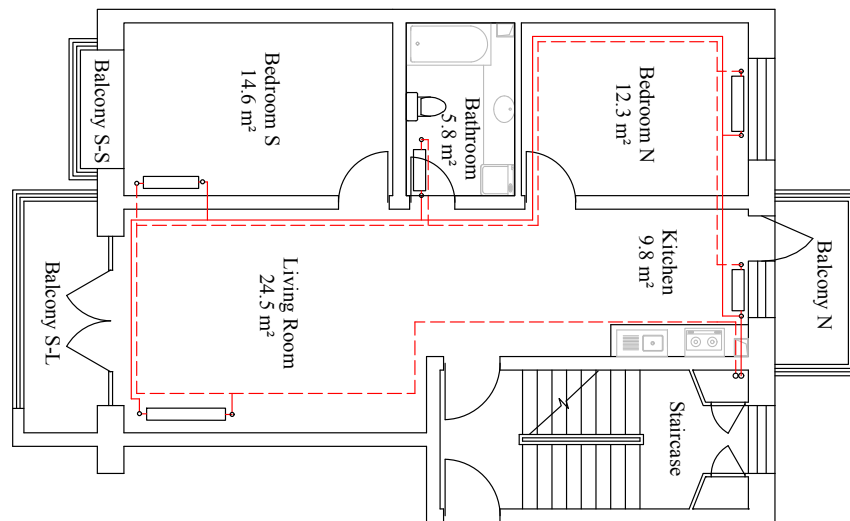
Device name	Type	Dimension (mm)
Radiator valve	RA-N [21]	DN15
Auto balancing valves	ASV-PV [23]	DN20
	ASV-M [23]	DN20
Ultrasonic energy meter	SONOMETER 1100 [24]	DN20

The radiator valves were mounted on the radiator pipework. All the other devices mentioned above were installed in the staircase/hall (see Fig. 7 (right)), which was the location of the heat entry point for the apartment heating systems.

Table 2

Basic information about the apartment tested.

Room name	Floor area (m ²)	Heat load (W)	Desired operating temperature difference (°C)	Desired flow (l/h)	Pre-set values of the radiator valve
Living Room	18	810	15	46.4	3
Bedroom A	14.5	654	15	37.5	2.5
Bedroom B	8.7	391	15	22.5	1.5
Bathroom	3.4	168	15	9.6	1
Kitchen	4	180	15	10.3	1
Total	48.6	2203		126	

**Fig. 8.** Multi-zone model.

temperature of each zone, the energy consumption including heat consumption, and the electricity consumption of the pumps as well as the volume flow of the heating system were all compared based on the simulation results.

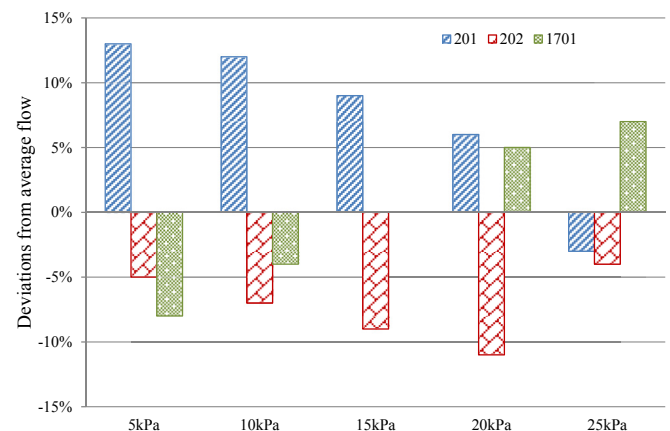
3. Results and discussion

3.1. Field test in Beijing

3.1.1. Test I: differential pressure control of the apartment heating loop

The test objects for Test I were three apartments 201, 202, and 1701.

The first aim of the investigation was to test whether the three test heating loops had the same distributed flow when the set points of the DP controllers were the same. The measurement results are shown in Fig. 9. When the DP controllers of the three apartments loop were given the same set point (separately set at 5, 10, 15, 20, and 25 kPa), the three loops had a similar volume flow as expected. The deviation of the individual loop flow from the average flow of these three loops at the same set points was within

**Fig. 9.** Deviations from the average flows of 201, 202, and 1701 at various set values of the DP controllers.

$\pm 15\%$ (see Fig. 9). This deviation can be considered as acceptable, because the set points of the DP controllers were adjusted by manually turning the spindle and there were no pressure gauges in the supply and return pipes to measure the pressure drop of the loops directly. Moreover, mechanical hysteresis influences the variations and causes a difference in the measured flow rates. The 2nd floor and 17th floor have identical floor heating areas, so theoretically the distributed flow could be the same. It can therefore be concluded that the hydraulic imbalance along the vertical riser was reduced after the installation of the DP controllers.

The second aim of Test I was to test whether one of the heating loops was pressure-independent when the differential pressure of the other two heating loops changed. The results show that when the differential pressure of the other two tested heating loops was changed by adjusting the set points of the DP controllers or by completely shutting off the loops, the other apartments' heating systems kept operating normally and the flow of the third tested loop was not influenced or changed. This means that the automatic balancing valves were able to separate each heating loop as an independent pressure zone, and maintain the constant differential pressure in the controlled loop. It also implies that the DP controller controls the differential pressure across the controlled loop, which will ensure an optimal differential pressure across the downstream control valves. In this way, the flow within the controlled loop would not be affected by any system load changes, and noise would be avoided.

3.1.2. Test II: the pre-setting function of the radiator valves

For Test II, the test object was one apartment.

The apartment loop's mass flow, the supply and return temperatures, and the indoor temperature were measured with the set point of the DP controller at 10 kPa. The measurements were first carried out without radiator valves pre-set, and after that with them all pre-set. The mass flow measurement results (see Table 3) showed that after the radiator valves were pre-set, the total flow supplied to the apartment was reduced to 1/3, from 557 l/h with no pre-setting to 181 l/h with pre-set. This implies that the flow rate through each radiator was limited dramatically by the pre-setting function. The flow rate in the case of pre-setting was close to the design flow rate of 126 l/h. This indicates that flow control by pre-setting the radiator valves on the terminal heat units is effective. The temperature measurement results showed that the temperature difference of the controlled loop increased by nearly 100% with the radiator valves pre-set, changing from 9 °C to 17.3 °C. Test II focused on the hydraulic control effect of pre-setting the radiator valves. The results clearly show that the large flow and small temperature difference problem which is typical in Chinese DH systems has been significantly relieved. This is the most important result that the test aimed to get. It also reflects the great energy-saving potential if the excess flow can be controlled.

In addition, at the start of the test, when there was no pre-setting of the radiator valves, the room temperature was 22.6 °C (see Table 3), with heating power of 5.8 kW. The design capacity is

2.2 kW for -9 °C outdoor air temperature. Due to lack of individual controls, the tenants regulate the room temperature by opening windows, which explains why the room temperature was no higher. After the pre-setting of the radiator valves, the delivered capacity was 3.6 kW and the room temperature went down to 22 °C within two hours. A further decrease might be expected, but the 3.6 kW would be more than enough to sustain 18 °C room temperature, seen in relation to the design capacity.

The field test showed that pre-setting radiator valves combined with the automatic balancing valves could control the loop flow close to the design level. Within the apartment loop, pre-setting the radiator valves limited the maximum flow of each radiator and created the right balance among the radiators. Flow limitation for each terminal heat unit prevented insufficient flow at distal units and excess flow at proximal ones. It reduces the total supplied flow and consequently the pump electricity consumption.

The differential pressure limitation of the automatic balancing valves provided the appropriate pressure drop over the radiator valves. The hydraulic imbalance along the vertical riser was reduced, and it guaranteed to set the thermostat properly to adjust the indoor temperature. At the same time, the noise from the radiator valves was avoided. Further adjustments of the room temperature towards the desired temperature could be achieved by adding a thermostat to the radiator valve, which would adjust the valve depending on the deviation from the set-point temperature of the TRVs.

In this field test, a dynamic hydraulic balance was created in the heating system by using pre-set radiator valves combined with automatic balancing valves. Every loop received the required flow and excess flow and insufficient flow were avoided. Every room received the required heat. Flow limitation improved the efficiency of the pump, and increased the temperature drop across the radiator. This field test indicates that the excess heat loss can be reduced through establishing dynamic hydraulic balancing in the building heating system.

3.2. IDA-ICE simulation

3.2.1. Model validation

The radiator heating system in the multi-zone model was designed in accordance with the Chinese design standard. The "linear fit-to-metered supply temperature" from CASE-Harbin (see Fig. 4) defined the supply temperatures of the simulated heating

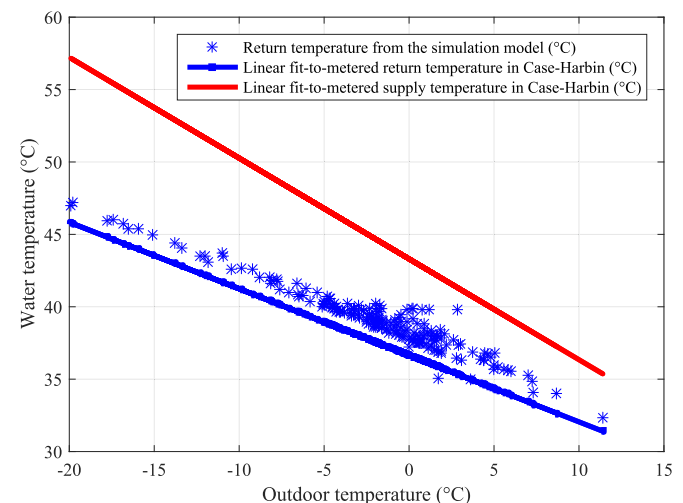


Fig. 10. Supply and return temperatures for the model of the SH system.

Table 3
Temperature measurement comparison between with and without pre-setting in Test II.

Parameter of tested apartment loop	No pre-setting	Pre-setting
Total flow of apartment loop (l/h)	557	181
Supply temperature (°C)	62.6	62
Return temperature (°C)	53.6	44.7
Delta T (°C)	9	17.3
Average indoor temperature (°C)	22.6	22
Outdoor temperature (°C)	-4	-4

system during the heating period. As shown in Fig. 10, the simulated return temperatures were compared with the linear fit-to-metered return temperatures from Case-Harbin. The results show that the deviation between the simulation results and the linear fit-to-return temperatures from Case-Harbin was on average about 2 °C. It should be mentioned that the measurements from Case-Harbin were acquired at the area substation and were the average return temperatures from all the connected buildings. The deviation between the model outputs and the measured return temperatures were therefore considered to be acceptable and the model was considered valid.

3.2.2. IDA-ICE simulation results

A simulation was carried out for the heating period in Harbin for two scenarios: radiators without TRVs and with TRVs. Several factors were considered in the simulation: room temperatures, heat consumption, pump electricity consumption, and the flow rate in the heating system.

Firstly, in terms of the room temperatures, the general results showed that without TRVs the room temperatures in all the zones were much higher than 18 °C except for a few hours at the beginning of the heating period. The average room temperatures in all five zones over the entire heating period were around 22 °C. With TRV control, the room temperatures in all the zones were constant at around 18 °C. There are some minor deviations between the set temperature and the simulated room temperature, due to the 0.5 °C proportional band (P-band). Because TRVs are proportional temperature controllers, they respond to any deviation from the set temperature by increasing or decreasing the flow into the radiators until the required room temperature is achieved. Fig. 11 shows the simulation results for two typical rooms in the multi-zone model: the northern room 'Bedroom N' and the largest room the 'Living Room', which reflects these small variations particularly clearly. The indoor air temperature can also be seen to have lagged a few days behind outdoor temperatures changes because of the thermal inertia of the building envelope materials.

As shown in the simulation results, the application of TRVs provides the practical possibility for the room occupants to adjust the room temperature. When the rooms are overheated, the indoor temperature can be adjusted by setting the thermostat rather than opening the windows. Thermal comfort can imply multiple factors

like indoor temperature, humidity, and draught [44]. But in the heating supply context, thermal comfort mainly refers to the indoor room temperature. In an unbalanced system, the thermal discomfort means excess heating for users close to the substation and insufficient heating for users far away from the substation. Through the implementation of the technical approach presented here, the indoor temperatures for rooms in different locations are balanced and close to the design room temperatures. We therefore conclude that the indoor thermal comfort is improved.

Correct use of TRVs has the potential to achieve great energy-saving effects. In some cases, heat consumers might not know how to use the TRVs correctly and might simply use the maximum set point, which will compromise the energy savings potential. The set points can be protected and locked by inserting the pins on the dial, and an energy-saving type of TRV can be used with a maximum set point of 20 °C [45].

Secondly, the monthly heat consumption and pump electricity consumption were compared for the two scenarios, and the results are shown in Fig. 12. Since the heating season is fixed in Harbin city and does not include May to September, no data were collected for those months. In terms of annual energy consumption, which was obtained by accumulating the monthly energy consumption over the heating season, the results imply that applying TRVs can reduce annual heat consumption by 17% and annual pump electricity consumption by 42.8% for this particular apartment. Here it should be noted that the pump energy consumption is very small compared to the heating energy consumption, only 0.1% of the heat energy delivered.

Coal is the dominant DH fuel, and the dominant fuel for Chinese power plants. Burning coal is one of the main causes of air pollution in China [46]. Hydraulic balance can achieve 17% heat savings and 42.8% pump electricity savings. This will result in positive environmental impacts. In Case-Harbin, the total heating area in 2013–2014 heating season was 442,340 m². The measured seasonal heat consumption per m² was 0.7 GJ/m², and the seasonal pump electricity consumption was 2.1 kWh/m². This reflects the currently unbalanced system situation. With hydraulic balance, the simulation results show that the seasonal heat consumption could be reduced by 0.12 GJ/m², and the seasonal pump electricity consumption could be reduced by 0.9 kWh/m². The results imply that the total emission reduction for Case-Harbin could have been 4837

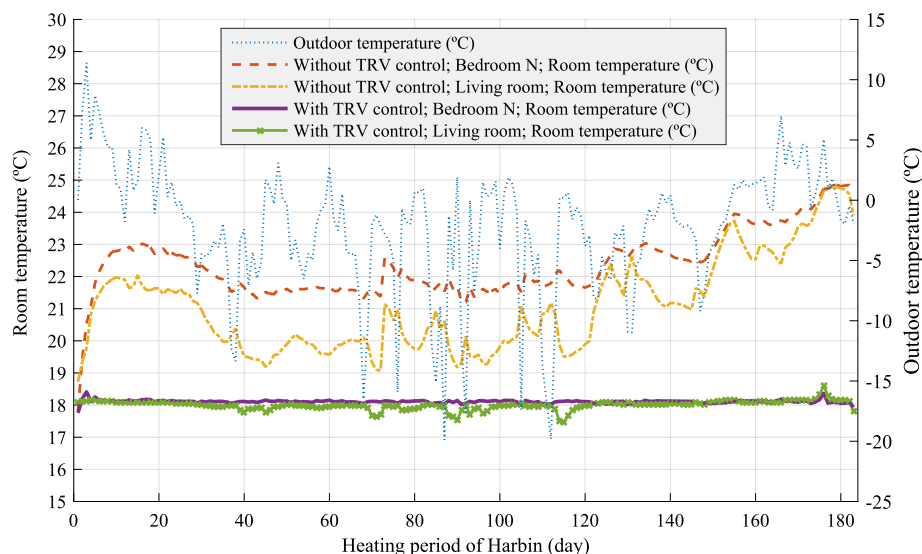


Fig. 11. Zone room temperatures of Bedroom N and the Living room during the heating period.

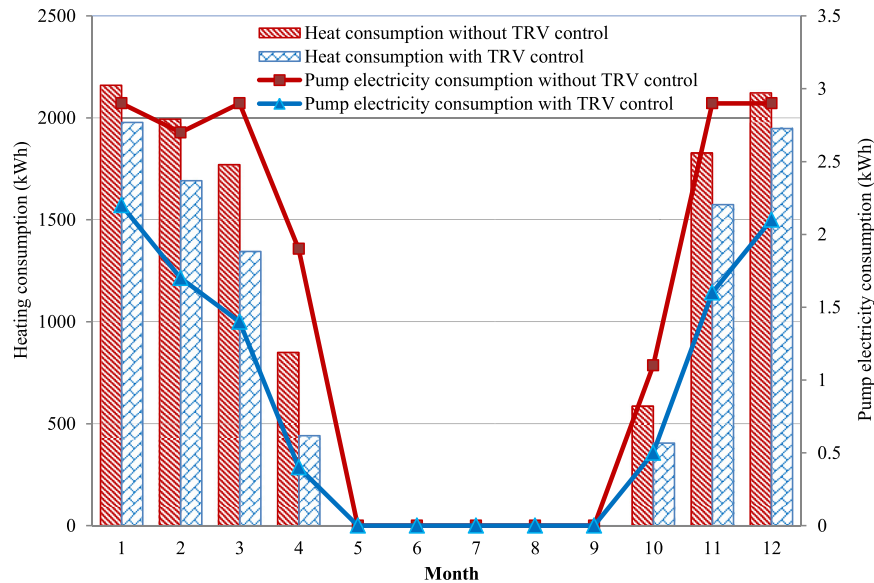


Fig. 12. Comparisons of heat consumption and pump electricity consumption between the scenarios with and without TRV control.

ton of CO₂, 44.7 tons of SO₂, and 13 tons of NO_x in the 2013–2014 heating season if hydraulic balance had been achieved. Therefore, the seasonal environmental impacts would reflect the reduction of 11 kg CO₂, 0.1 kg SO₂, and 0.03 kg NO_x per heating square metre.

Moreover, with regard to the system's operation, it is important to note that applying TRVs changes the SH system from constant flow to variable flow (see Fig. 13).

According to the results from the field test and the IDA-ICE simulation, the excess heat loss can be reduced by achieving hydraulic balance and optimizing indoor air temperature control at the building level.

In this study, the research object was the building heating system. Energy reduction at the building level will inevitably impact the whole DH system, reducing the amount of heat that area-substations have to deliver to a group of buildings and that the heat source plants have to deliver to the area-substations.

Dynamic hydraulic balancing ensures the apartment heating loops distribute the requested flow, with neither excess flow nor

inadequate flow. Moreover, it means that the apartment heating loops are not influenced by each other if adjustments are made. Temperature control stabilizes the room temperature at comfort levels and avoids the room overheating. The integrated technical approach therefore reduces excess heat supply and excess heat loss. This means lower fuel consumption and less polluting emissions due to the fossil fuels heavily used in China. The economic benefits and environmental effects achieved will be considerable.

In the future, along with the energy consumption reduction in space heating systems, it is expected that Chinese DH systems will transition from the current centrally planned heat supply to demand-driven heat generation, which will also give increased comfort for users. In addition to this improvement in quality of life, DHW could also be integrated into DH systems to supply hot water in the future. This would be possible because the reduction in excess heat supply will result in large energy savings.

The high building density in Chinese cities and the continuously expanding heating areas with rapid urbanization mean that there

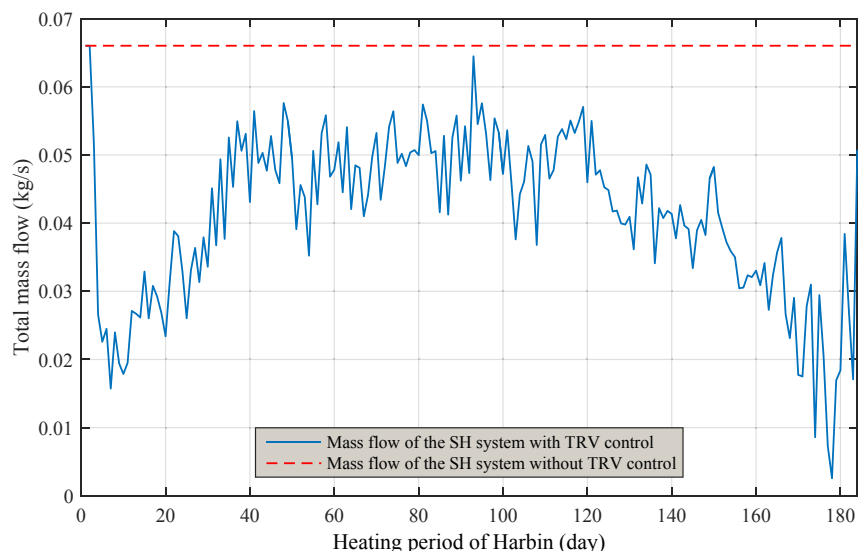


Fig. 13. Total mass flow comparison between scenarios with and without TRV control.

will be significant heat demands that need to be fulfilled. This emphasizes the significance of the kind of reductions in energy consumption in Chinese DH systems discussed in this paper.

4. Conclusions

To conclude, the proposed approach of combining the use of TRVs with an integrated pre-setting function and automatic balancing valves has been shown to be both feasible and effective in practice.

Firstly, a field test showed that pre-setting radiator valves combined with automatic balancing valves can establish dynamic hydraulic balance in a building heating system. Each controlled loop becomes an independent zone. The pre-setting of the radiator valve is an important function to equalize the flow distribution among the terminal heating units. Moreover, automatic balancing valves enable the radiator valves to work at optimum differential pressure level. As a result, the problems of excess flow and insufficient flow are avoided in the heating system. At the same time, the return temperature was decreased, and the temperature drop across the radiator was increased.

Secondly, IDA-ICE simulation results indicate that TRVs stabilize the room temperature. Wide use of TRVs in Chinese buildings can reduce heat consumption by 17% and pump electricity consumption by 42.8%, compared to a scenario without TRV control. In addition, adjusting TRVs transform the system from constant flow to variable flow. Variable speed pumps can be applied with variable flow rate. As coal is the dominant fuel for DH plants and power plants in China, the savings on both heat consumption and pump electricity consumption imply the positive environmental impacts.

Traditional Chinese DH systems seldom have control at the consumer end. By moving the control close to the end users, it is possible to bring the heating supply into line with the heating demand. The integrated assessment method and field test show that a well-balanced DH system can improve consumer thermal comfort and at the same time save significant pumping power. A well-balanced DH system allows heat users to pay less if the heating is charged on the basis of the real consumption. The heat users are satisfied also due to the improved room temperature control. At the same time, it would also be cost-effective for DH utilities, who could increase their profits by avoiding excess heat loss.

The developed integrated approach will help the decision makers and stakeholders to plan new or renovated district heating projects to be more energy efficient and cost effective. It would make a considerable contribution to energy supply security and air pollution abatement for Chinese society by giving smart control to district heating systems.

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Article III

Technical, economic and environmental investigation of using district heating to prepare domestic hot water in Chinese multi-storey buildings

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Technical, economic and environmental investigation of using district heating to prepare domestic hot water in Chinese multi-storey buildings

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Abstract

The development of DH (District Heating) is an environmentally friendly and energy-efficient strategy in China. Currently, the vast majority of DH systems are SH (Space Heating) only and do not provide DHW (Domestic Hot Water). DHW is mainly produced by individual water heaters due to the cost-effective issues of the centralized DHW systems. From the perspective of long-term development, DHW produced via DH systems would be more sustainable because DH is an important precondition for an environmental safe use of domestic waste fuels. This paper presents an approach that uses flat stations meanwhile utilizes the industrial waste heat to prepare DHW via the DH network. A building model of a multi-storey building in Beijing was developed to investigate the technical feasibility. An economic evaluation was made using net present value to compare the annualized cost for individual water heaters and flat stations. The environment impact in terms of CO₂ emission when fossil fuels are used to produce DHW was quantified. The results show that flat stations are technically feasible if a few renovations are implemented, and that the use of flat stations is a more sustainable, economic and environmentally friendly approach than the existing DHW preparation technologies.

Key words: district heating, domestic hot water, flat station solution, hydraulic priority, industrial waste heat, China

1 Introduction

Many international research studies have shown that DH is playing an important role in the societal goal of realizing an effective and sustainable energy system [1][2][3][4]. For China, the development of DH in highly-populated and cold-climate regions is both an environmentally friendly and energy-efficient strategy [5] to cope with air pollution and provide energy supply security, which are the two most important challenges for China today [6]. The 12th Five-Year Guideline requires the use of DH in the northern heating area to achieve a 65% share of the heat market [7]. Currently, the vast majority of DH systems only supply SH without DHW.

Over the past 30 years, China has experienced unprecedented urbanization, modernization, and economic development. According to a report from the World Bank, the proportion of urban population rose from 34% in 1996 to 54% in 2014 (Figure 1) [8]. Over the next 20 years, an additional 350 million people are expected to

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migrate to the cities. The rapid urbanization has resulted in significant pressure to provide DHW that can fulfil hygiene and comfort requirements in an efficient, environmentally friendly and economical way.

Over the last decade, the popularity of private DHW systems has led to a substantial increase in DHW consumption. From 1996 to 2011, hot water consumption in Chinese urban areas increased at a significantly faster rate than can be explained by the urbanization process alone (Figure 1) [9]. In 2011, the total energy consumption for residential DHW was 426 PJ, which accounts for 9.5% of total residential energy consumption in China. Moreover, in 2011 the annual average DHW consumption per urban household reached 1.8 GJ having increased more than 8-fold since 1996. This growth trend means the gap between China and developed countries on DHW consumption is getting smaller. For instance, an average household in Denmark consumes 8.28 GJ per year for DHW [10]. Based on the experience and trends in other countries, it can be expected that the share of DHW consumption in urban building energy consumption will keep growing in the next decades. This means that China urgently needs an efficient and technically feasible solution for producing DHW.

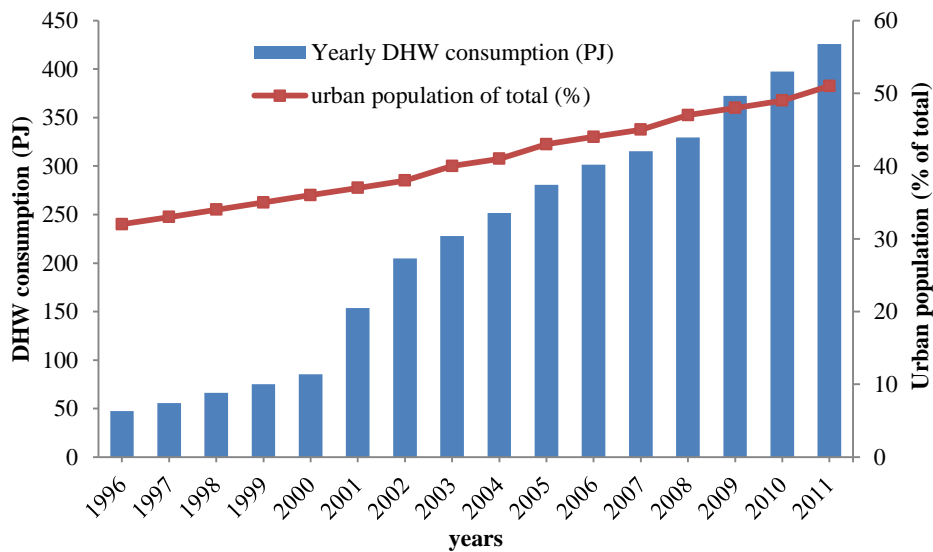


Figure 1. 1996-2011 China's yearly urban residential domestic hot water consumption (PJ)

Numerous studies have focused on producing DHW in an efficient, environmentally friendly and economical way. The 4th generation DH project [2] has studied technology for supplying DHW instantaneously and SH from DH networks with a low supply temperature [10][11][12]. In China, recent DHW research has mainly focused on decentralized DHW systems, such as the use of heat pumps and local renewable energy. For instance, Liu et al. [13] presented a hybrid heat pump system that uses solar energy as the initial heat source for heating shower water in public buildings. An electric heat pump recycles the exhaust heat from the used and drained shower water. Kong et al. [14] analysed the thermal performance of a direct-expansion solar-assisted heat pump water heater to supply DHW throughout the year. Liu et al. [15] studied the production of DHW by recovering the condensing heat from a solar thermoelectric air conditioner. Wu et al. [16] simulated the supply of heating, cooling and DHW combined by using a ground source absorption heat pump. Finally, Luo et al. [17] presented a retrofitted natural gas-based cogeneration system to heat DHW using the waste heat of condensing steam and exhaust gas.

All these studies focused on DHW production in China, but no relevant research has looked into the preparation of DHW using the flat station solution. There are numerous benefits in combining DH supply for SH with the DHW system because the economies of scale in DH make it possible to achieve higher efficiencies in heat plants than can be achieved in individual water heaters. Furthermore, DH can be coupled with environmentally friendly heat sources that cannot be used on an individual basis.

1.1 Background

Currently, individual water heaters are the predominant way of producing and supplying DHW in Chinese households (Figure 2), and DHW prepared via DH systems is rare. A study was made in 2011 to investigate the share of different DHW solutions applied in China, and the results are listed in Table 1 [18].



Figure 2. Individual water heater installations in Chinese households

Table 1. DHW preparation technologies in northern and southern China

DHW preparation technology	Share of total	
	Northern China	Southern China, Shanghai
Electric water heaters	63%	12%
Solar water heaters	21%	10%
Natural gas heaters	6%	77%
District heating	5%	1%
Other	5%	0%

Table 1 shows that electric and natural gas water heaters are the technologies most commonly used for DHW

preparation in China: 69% in northern China and 89% in southern China respectively. DHW supplied via DH systems accounts for less than 5%. Since the individual water heaters can supply hot water with the desired temperature instantaneously, it seems they must be more cost-effective than DHW from the DH network. But from the perspective of long-term development, DHW produced via DH systems would be more sustainable, because DH has the advantage of being a fuel-independent technology, which means it can supply energy from any energy source that is connected to it [19]. Therefore, investigation is essential to work out the most economical way to produce DHW. This study will address the economic comparison.

1.2 Centralized DHW systems in China

Existing traditional DH systems in China that combine SH and DHW generally have large area substations or central DHW-only boilers that supply hot water to a number of multi-storey buildings via the distribution pipeline. The profile of the traditional DH system that supplies both SH and DHW is illustrated in Figure 3.

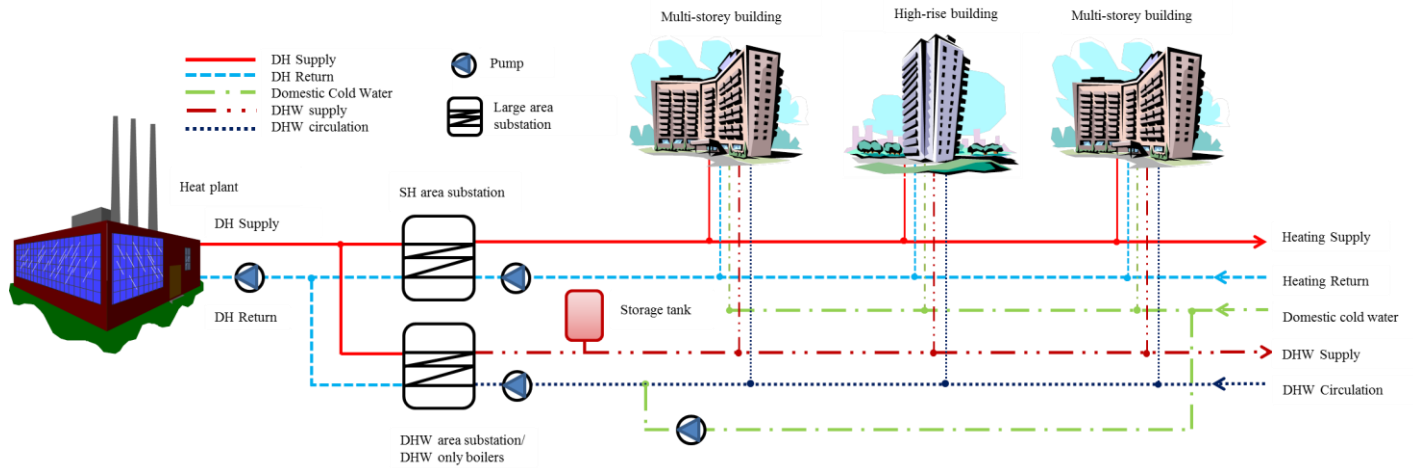


Figure 3. Traditional DH systems that combine SH and DHW supply

These facts have led to the following obstacles to applying DHW preparation via DH:

- High heat losses from the distribution and circulation pipes of centralized DHW systems;
- Unsatisfactory DHW comfort level, due to the arrangement form of the circulation pipes;
- Generally lower hot water consumption per capita than in European countries;
- Historically, SH seen as social welfare is the basis of the DH systems and DHW is excluded.

Figure 3 shows clearly how the central location of the large area substations or DHW-only boilers means that large-scale distribution pipelines are needed to reach all the connected multi-storey or high-rise buildings. Large circulation piping systems are also necessary to keep hot water circulating to ensure the appropriate hot water tapping temperature in terms of hygiene and comfort for DHW usage. Substantial heat losses occur from these distribution and circulation pipelines, which result in inefficient and uneconomic DHW production. Studies have indicated that heat losses from distribution and circulation pipelines account for over 50% of the total heat consumption when DHW is prepared in such a centralized manner [20].

Furthermore, to control costs in the centralized DHW networks, the circulation pipe is commonly only at the staircase level (Figure 4(a)), rather than reaching to each tap (Figure 4 (b)). When circulation pipes are arranged in this way, see Figure 4(a), the result is that a large amount of cold water has to be drained off before the hot water with the desired temperature can be tapped. Nevertheless, the drained-off cold water is still charged at the hot water price.

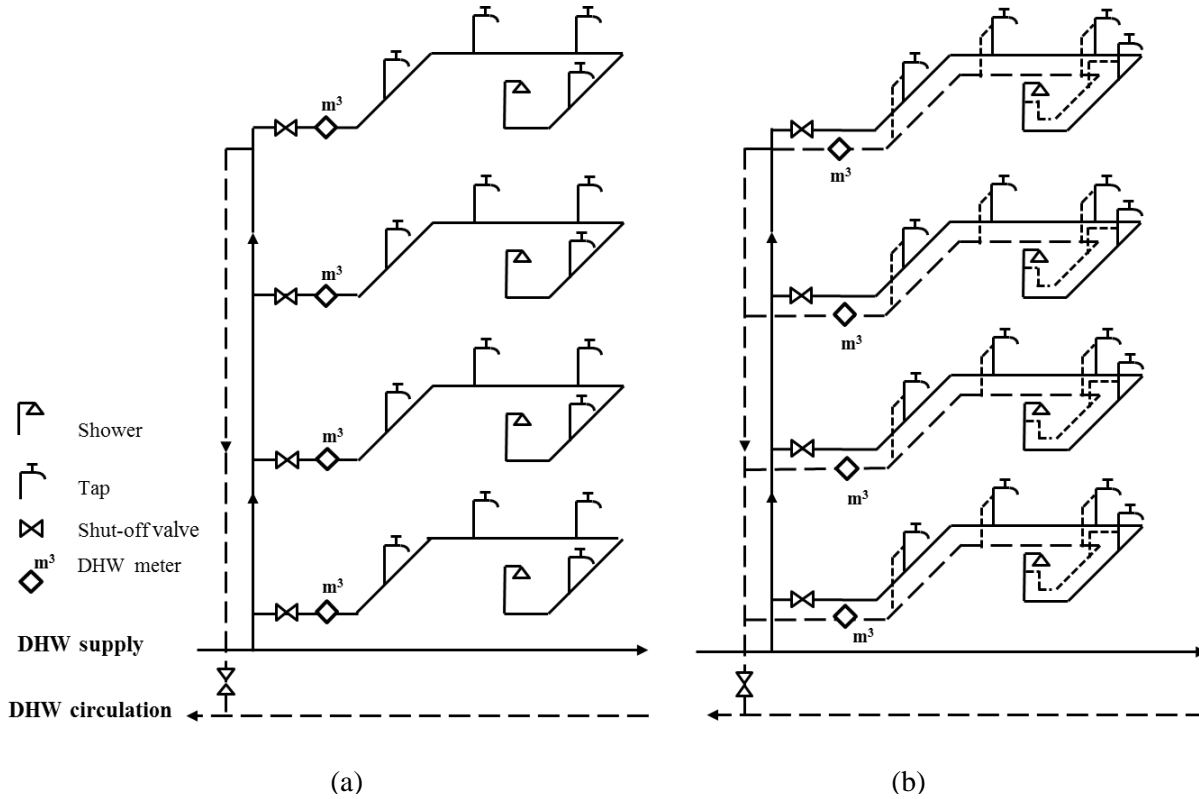


Figure 4. Two different circulation pipe arrangements

Studies show that hot water consumption in China only amounts to 1/5 of the hot water consumption in other countries, such as Spain 200 litres/apartment·day, United States 270 litres/apartment· day, Japan 300 litres/apartment·day [20]. Furthermore, measurements from 7 centralized DHW systems in Beijing in 2012 show that the average hot water consumption is 45~133 litres per apartment per day [18]. With centralized domestic hot water systems, the greater the amount of hot water consumed, the more obvious are the economic benefits.

Historically, DH was originally planned as a social welfare service in China with the aim of only providing SH to urban residents during the winter period, and DHW was excluded from the DH systems. Today, the Chinese government is working towards modernizing DH systems by implementing the heat-metering reform of 2003 [21]. One of the aims is to commercialize or commodify heating in cities. That means that in the long run all heat consumption, both SH and DHW, will have to be paid for on the basis of real consumption in the future.

The above-mentioned issues interact with each other and constitute the main barriers to the development of centralized domestic hot water systems in China.

1.3 Key factors in centralized DHW systems

A hot water temperature of 55 °C is commonly applied in DHW systems. It is sufficient to meet typical household demands. It is also high enough to kill off *Legionella*, which has a growth interval from 20 °C to 45 °C. Higher temperatures than 60 °C are not recommended because they can result in scalding of human skin and lime deposits in heat exchangers and other downstream equipment.

For the sake of health safety, *Legionella* prevention has to be given high priority in DHW systems. Breathing of *Legionella*-contaminated aerosol, which can occur when the water springs out of taps or shower heads, can cause “Pontiac fever” and “Legionnaires diseases”, such as chronic lung disease, immunodeficiency, and can be fatal [22]. European countries have specific stipulations to cope with *Legionella* in DHW systems. For instance, Danish standard [23] states that, if the concentration of *Legionella* in contaminated hot water has reached 1000 cfu/l, sterilization treatments must be initiated. To minimize the risk of *Legionella*, some alternative disinfection methods have been introduced: such as thermal disinfection methods, photochemical (UV light) methods, and physical techniques (ultrafiltration) for pump operation. Other possibilities are to minimize *Legionella* growth potential by system design. According to the German standard w551 [24][25], DHW systems with volumes less than 3 litres are considered to be safe irrespective of the DHW temperature.

The Chinese design code [26] states that the hot water temperature should be 60 °C when considering bacteria and lime precipitation issues. This means that to make DHW hygienically safe the centralized DHW systems need to supply 60 °C to the furthest consumers. This causes high heat losses in the distribution and circulation pipelines. Experience from Denmark’s DH systems could be relevant for China. They normally use building level or flat stations to produce SH and DHW from separate heat exchange units. To avoid the considerable heat losses caused by large-scale distribution pipelines, low DH temperatures are applied, such as 70/40 °C (supply /return temperatures) in 3rd generation DH systems, or even 50/25 °C in 4th generation DH systems [27]. Moreover, pre-insulated pipes are commonly used to minimize building distribution and circulation heat losses [28]. The trend today is to avoid DHW circulation altogether by applying a substation in each flat to prepare DHW instantaneously combined with a low-volume DHW installation. This means that the SH supply temperature can be lowered down to 50 °C and DHW temperatures to 45 °C [29], and that large-scale distribution systems are eliminated. Real flat station applications in Denmark show 8-16% savings can be achieved in terms of the distribution heat loss reduction when flat stations replace the traditional centralized DHW systems [30].

2 Proposed approach

This paper presents the flat station concept for providing both DHW and SH on demand via the DH system to end-users in Chinese multi-storey residential buildings. The flat station is a proven concept. In most European countries, individual heat metering is enforced by law and here flat stations have considerable advantages over vertical DHW riser systems because heat metering can be easily achieved at the same time and with the same heat meter as is used for metering heat consumption for space heating. This study used a building model to analyse the technical feasibility of this concept in a multi-storey residential building in Beijing. We compared the use of flat stations and individual water heaters in terms of both economic benefits and environmental impacts. The aim was to develop a sustainable approach to the production of DHW in Chinese multi-storey residential buildings. The main conclusions from the analyses are: 1) the flat station application is technically feasible in both existing residential building and new buildings; 2) it is economically competitive compared to

existing individual DHW production methods in China; and 3) the utilization of sustainable energy or renewable/waste energy as fuel sources makes this approach environmentally friendly.

2.1 Flat station solutions

The flat station is a complete individual heat transfer unit. The energy is supplied from a central energy source and a flat station is installed in each flat or single-family house. A substation consists of three main elements: instantaneous preparation of DHW, differential pressure control of the heating and DHW system, and metering of the energy consumption. It is installed in the apartment with three centrally connected pipes: a heating supply pipe and a return pipe connected via the DH network to a central heat source, and a cold water supply pipe.

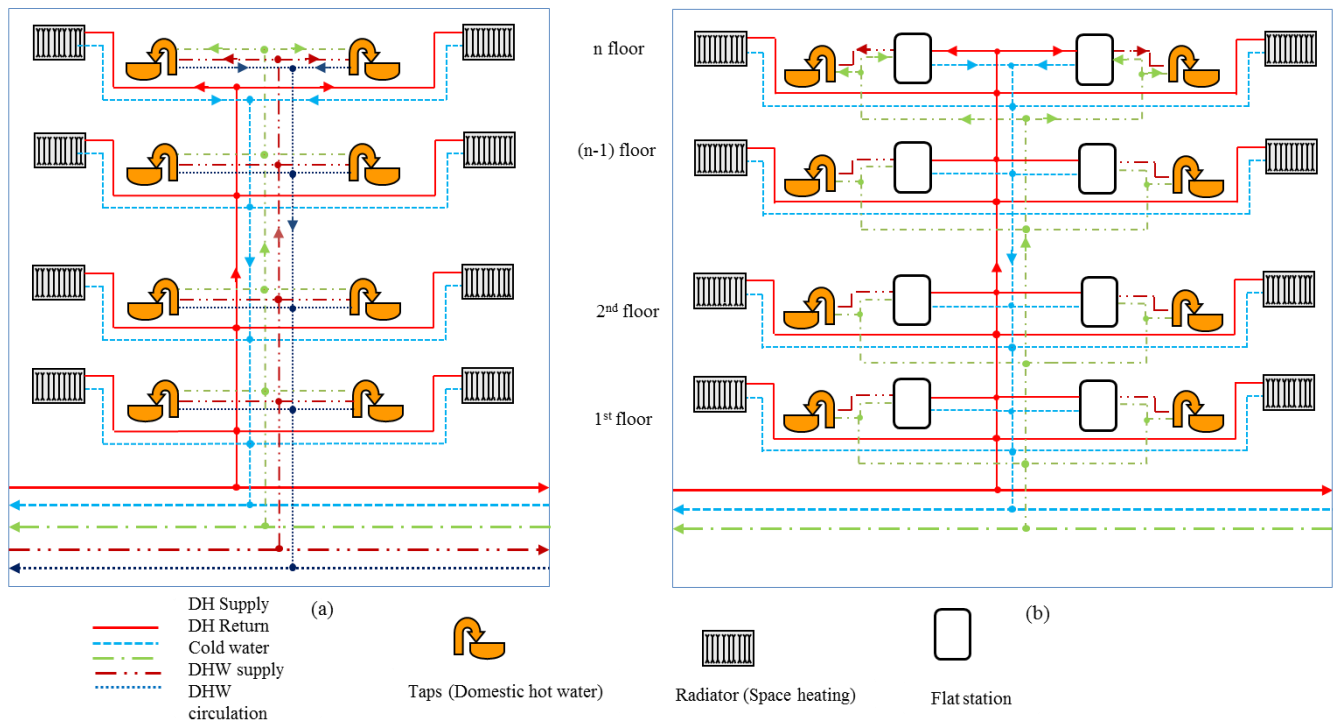


Figure 5. Traditional centralized DHW pipe system (a) and the flat station pipe system (b)

When flat station solutions are applied, the number of vertical pipes in the staircase is reduced. The traditional 5-pipe system (SH supply and return, DHW supply, circulation and DCW supply as shown in Figure 5 (a)) is replaced by 3-pipe flat stations (SH supply and return and cold water supply as shown in Figure 5 (b)). This reduction implies not only 40% less piping, but also 8-16% heat loss reduction.

With regard to Legionella, the flat stations minimize the risk, because the distance from the point of DHW preparation to the point of usage is considerably shortened. Furthermore, with every tapping the water in the pipe is flushed out and replaced with fresh hot water. During non-tapping periods, the water cools down to room temperature, typically below or at the border of the growth zone of Legionella.

Other advantages of the flat station concept are the comprehensive possibilities for individual control and energy consumption measurement at the level of the apartment. As flat station solutions take into account SH and DHW consumption measurements for individual apartments, the existing heat metering and billing methods, namely

heat fees charged by floor area, and DHW fees charged by cubic metre, can be replaced. This could motivate the energy-saving consciousness of end-consumers, resulting in the achievement of reductions in energy consumption and emission [31].

2.2 The proposed approach

The proposed approach in this study is to integrate flat stations into existing heating systems with the aim of minimizing the necessary renovation work, but also taking into account the long-term development possibilities of the heating systems.

By integrating flat stations, the existing combined DHW/SH DH systems are simplified: the distribution and circulation pipes of the traditional centralized DHW systems can be removed (Figure 6). The indoor DHW system indirectly connects to the existing SH system via the heat exchanger embedded in the apartment substation. If the DHW is produced by an individual water heater, it is simply replaced by the flat station (Figure 6). In both cases, the existing SH system becomes the heat source of the flat stations.

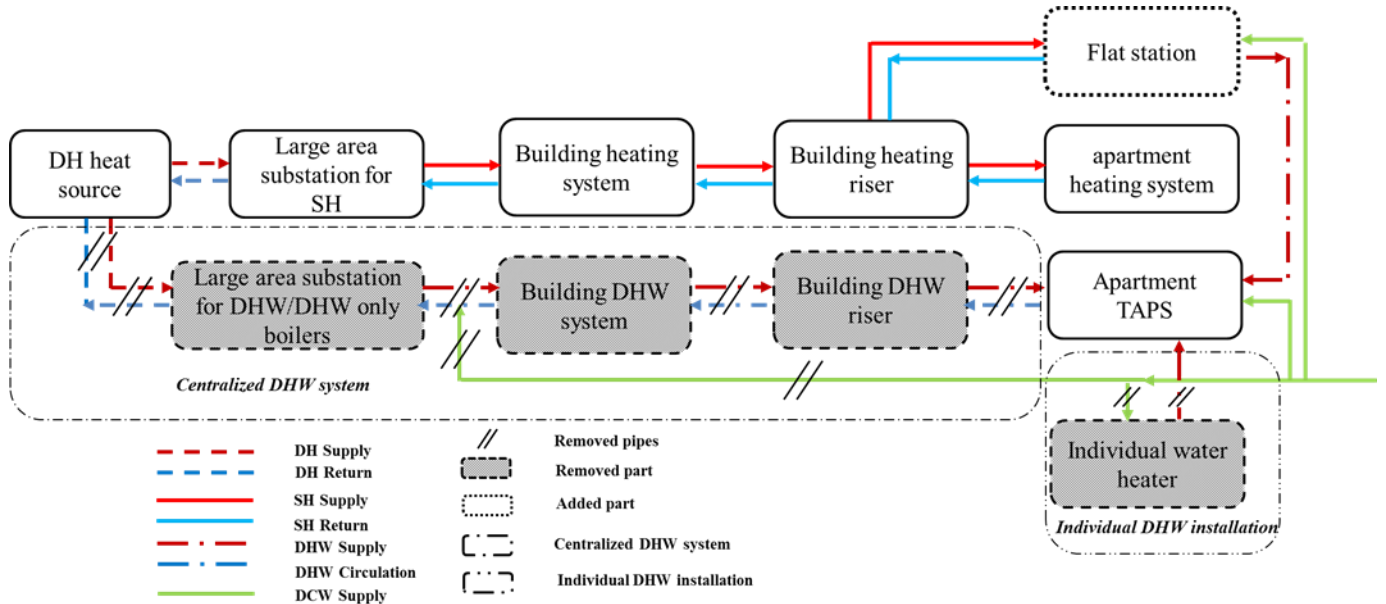


Figure 6. Renovating the existing DH system by integrating flat stations

From the long-term development point of view, the Chinese DH industry looks towards utilizing local renewable energy and surplus heat from industrial processing, which are currently being wasted into the atmosphere or unused as heat sources [32][33]. Moreover, studies have shown that in most cases waste heat from industrial processes can be found within a 30 km radius of cities in northern China that can meet almost 70% of the heat demand of northern China [9]. Table 2 [34] lists the available industrial waste heat capacity from 13 cities around Beijing, together with each city's DH heat load. It is clear that some heavily industrial cities like Tianjin, Zhangjiakou, Tangshan, and Handan have sufficient waste heat capacity to supply the city's DH systems. Tsinghua University has proposed the integration of available industrial waste heat around Beijing and surrounding cities within a radius of 200km to be used as the DH source for these areas [26]. The research

results indicate that the existing industrial waste heat in Beijing, Tianjin and Hebei Province could be used as the energy resource to power the DH systems of those areas during the winter for the next 10 years.

Table 2. DH heat load and industrial waste heat available in 13 cities around Beijing

	City	A: City heat load (MW)	B: Industrial waste heat capacity (MW)	Ratio A to B
1	Beijing	45666	8951	20%
2	Tianjin	15780	17515	111%
3	Shijiazhuang	13172	12729	97%
4	Chengde	3439	2435	71%
5	Zhangjiakou	5024	7556	150%
6	Qinhuangdao	3634	1988	55%
7	Tangshan	9859	16320	166%
8	Langfan	5415	2028	37%
9	Baoding	11112	4784	43%
10	Cangzhou	7457	5936	80%
11	Henshui	4244	2027	48%
12	Xingtai	7278	2405	33%
13	Handan	10204	11050	108%
	Total	142284	95724	67%

In China, the heating season generally has a fixed period, such as from November to the following March. Based on the assumption that industrial surplus waste heat can be utilized or recovered as the heat source for DH systems in China, and that DHW heat demand is significantly lower than that for SH, the industrial waste heat could be used to cover the DHW heat demand during the non-heating period. Moreover, the existing DH pipeline infrastructure, currently mostly used only for SH supply, can now be fully utilized operating for the whole year.

3 Methodology

A model was developed to evaluate the technical feasibility of implementing the flat station solution with instantaneous DHW preparation replacing the traditional centralized DHW system or existing individual water heaters in standard apartments in a multi-story building in Beijing.

3.1 Building model

According to the statistical data of Beijing city in 2014, the three-person family is the most common family size accounting for 30.9% in the urban area [35]. The same data shows that the housing area per capita in Beijing urban area is 31.5 m² [36]. This means that the standard apartment in Beijing can be defined as 95 m² with three occupants.

To accord with design code [26], the minimum pressure head needed to supply DCW (domestic cold water) to 1st storey apartments is 100 kPa. For the second storey, it is 120 kPa. For apartments above the 2nd storey, each storey needs an extra 40 kPa [37]. The DCW pressure head at the building service pipe is generally 300 kPa,

which means the available pressure head is sufficient to deliver water to the sixth storey. So, in this study, we consider the supply pressure of DCW required for a 6-storey high residential building. Higher buildings will need DCW booster pumps. Here we assumed this 6-storey apartment building is attached to a few other building units. In each building unit, each floor has two apartments with the same area. The 12 apartments in each building unit are supplied heat via a common riser. The heating installation structure is shown in Figure 7.

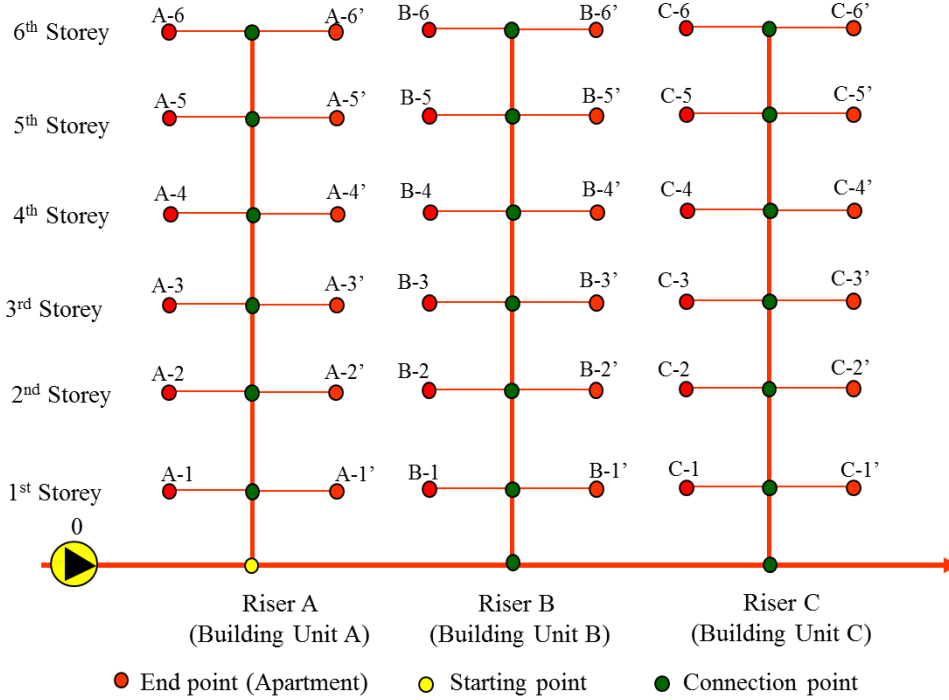


Figure 7. Graphic showing the heating installation structure in the multi-storey building model

3.2 The SH heat capacity and DHW demands

3.2.1 SH heat capacity and DHW demand for a single apartment

The existing buildings referred to in this study are mostly buildings built after 2000 with a two-pipe radiator heating system. Each apartment has its own horizontal heating loop. The peak heat load of the radiator heating system is considered to be 32 W/m^2 with a design outdoor temperature in Beijing of -9°C [38]. Experience shows that many central heating systems are oversized, and were so even in the initial design phase. This was because the heating areas might be increased in the future or indoor thermal comfort might need to compensate for unsatisfactory operation. It is not unusual for the design heat capacity to be around 65 W/m^2 or even higher in some cases. So the design heat load for our standard apartment is 65 W/m^2 , and the heating capacity for the standard apartment with 95 m^2 will be 6.2 kW . The design temperatures for radiator heating systems are usually $75/50/18^\circ \text{C}$ (supply/return/indoor temperature) according to the national design code [39].

A 95 m^2 residential apartment in China usually contains a bathroom and a kitchen. The water installations are designed in accordance with the national design code [26], see Table 3. Here the average DCW temperature is considered 10°C . For DHW installations in a single apartment, the necessary capacity usually meets the DHW

demands of the shower and hand sink simultaneously. So for our standard apartment, the required DHW power is 21 kW.

Table 3. DHW consumption in a standard apartment in China

Item	Unit	Bath	Shower	Kitchen	Hand sink
Water flow	l/s	0.2	0.1	0.14	0.1
Appropriate tap temperature (Mixed water)	℃	40	40	50	30
Capacity demand if $T_{\text{cold water}}=10\text{ }^{\circ}\text{C}$	kW	25.1	12.6	23.4	8.4

3.2.2 China's hourly variation coefficient and European coincidence factors

When a centralized DHW system is dimensioned in China, the hourly variation coefficient K_h is an important factor in determining the hot water flow rate and heat consumption. The hourly variation coefficient is defined as the ratio between the maximum hourly water consumption in the peak load day and the average hourly water consumption: see Eq. (1).

$$K_h = \frac{q_{hr}}{q_T} \quad (1)$$

where q_{hr} (l/h) stands for the maximum hourly water consumption in the peak load day and q_T (l/h) is the average water consumption, which can be calculated as in Eq. (2)

$$q_T = \frac{m * q_r}{24} \quad (2)$$

where m is the number of DHW consumers and q_r (l/person · day) is the DHW usage quota per person per day. For residential buildings in China, the hot water consumption quota per person is recommended as 60 ~100 l/person · day [26].

So the actual K_h value depends on the personal hot water consumption quota, q_r (l/person · day) and the number of DHW consumers, m . The design code [37] states that when the number of consumers is less than 100, K_h is 4.8; and K_h is 2.75 when the number of the consumers is higher than 6000. Intermediate values can be obtained by using the interpolation method [37].

For an all-day DHW supply system in China, DHW demand power, Q_{DHW-CN} (kW) can be calculated by using Eq. (3).

$$Q_{DHW-CN} = K_h * \left(\frac{m * q_r * C * (T_h - T_c) * \rho_w}{3600 * t} \right) \quad (3)$$

where T_h, T_c are the temperatures of hot water and cold water, corresponding to 60 °C and 10 °C respectively, ρ_w (kg/l) is the density of water, and t is DHW daily supply hours (equals 24 here).

In contrast, when a European DHW system is dimensioned, coincidence/simultaneous factors are commonly used to estimate the number of the flats that might use hot water at the same time. Coincidence factors use a probability method to determine the size of centralized DHW systems. Briefly stated, only some of all tap points are used in actual practice, based on a 99.9% coincidence interval in a statistical probability distribution [40]. By using coincidence factors, a centralized DHW demand can be calculated for European countries as in Eq. (4).

$$Q_{DHW-EU} = n * f * \phi_{DHW} \quad (4)$$

where n is the number of apartments that require DHW, f is the coincidence factor for DHW, and ϕ_{DHW} is the DHW demand per apartment.

Coincidence factors are related to the DHW consumption pattern of a “standard flat”, which refers to the number of residents in the average flat. For instance, in Denmark, Germany and Sweden the standard flat is defined as having 3.5 residents, which constitutes the basis for the factors[40]. Deviations can occur if the consumption pattern is atypical and differs from the “standard flat. The curves in Figure 8 show the coincidence factors for DHW systems in Denmark, Germany and Sweden. For these European countries, the coincidence factors have similar values, so that the probability of DHW simultaneous use is less than 0.25 when the number of flats is 12, and less than 0.1 when the number of flats is 100.

According to the International Electrotechnical Commission [41], the coincidence factor is identical to the reciprocal of the diversity factor. This definition means that the Chinese DHW hourly variation coefficient and the European DHW coincidence factor are comparable in terms of centralized DHW system calculation. The comparison is shown in Figure 8, where it can be seen that, for China, the DHW coincidence factors, which are the reciprocal of the hourly variation coefficient K_h , are relatively constant around 0.2 when the number of apartment is less than 100.

The reason that the coincidence factors differ greatly between European countries and China could be that high-rise and multi-storey buildings are the main types of building in China, so a low simultaneous DHW usage probability is assumed from the economic point of view. Whereas in European countries, single-family houses and multi-storey buildings are the main building types, so that the coincidence factors have detailed values when the number of flats is small to take comfort into account. On the other hand, the K_h values stated in the Chinese design code are empirical data originally derived from Soviet DHW systems, so there may be errors arising from differences between the design and real conditions due to the lack of actual measurements from Chinese DHW systems [42].

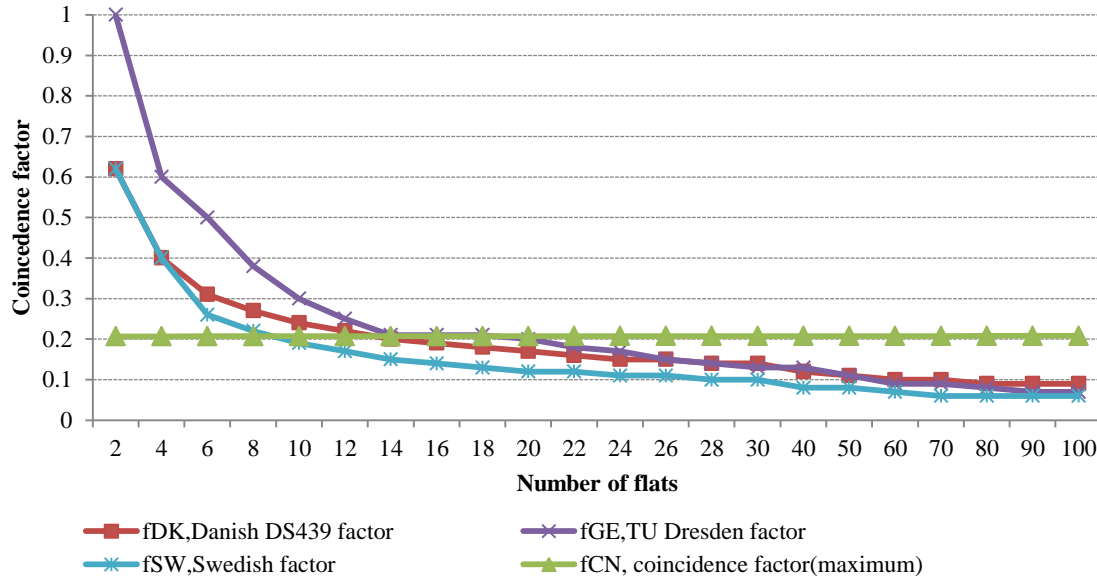


Figure 8. Comparison of coincidence factors used in different countries

Such errors are further confirmed when Eq. (3) is used to input the DHW usage quota, q_r as 100 l/person · day, together with the known data mentioned above, to calculate the DHW demand along the riser in the building model. The calculation results from the building model show that when the number of apartments is less than 6, as when the riser reaches the 4th, 5th and 6th floors, the DHW demand falls below the demand per standard apartment, 21 kW: see Table 4. It is clear that the K_h data are too rough to calculate the DHW demand when the number of apartments is small. To correct the calculation, f_{DK} and Eq. (4) can be used to obtain the accurate required DHW power. The corrected results are listed in Table 4. The SH demands of the building model per floor were calculated and are listed in Table 4 as well.

Table 4. Domestic hot water heat demands corrected by using coincidence factors from Denmark

The number of apartments	Calculation using K_h		Corrected calculation using f_{DK}		SH demands (kW)
	k_h	DHW demand power (kW)	f_{DK}	DHW demand power (kW)	
1	-	21	-	21	6.2
2	4.8	7.0	0.62	26.0	12.4
4	4.8	14.0	0.4	33.6	24.8
6	4.8	20.9	0.31	39.1	37.2
8	4.8	27.9	0.27	45.4	49.6
10	4.8	34.9	0.24	50.4	62
12	4.8	41.9	0.22	55.4	74.4

3.3 DHW hydraulic priority

3.3.1 Philosophy of DHW priority

The philosophy of DHW priority in European DH systems is generally used to dimension the service pipes that run from the street to a single-family house. This means that when the service pipes are designed, only the heat capacity for DHW is considered, because DHW priority assumes that the heat supplied to the SH system can be reduced or suspended during the short periods when DHW is drawn off. In fact, thermal comfort is not considered to be threatened by the lack of SH supply during the period of DHW use, since its duration is assumed not to exceed 10-15 minutes [43]. At a practical level, DHW priority could be achieved using sophisticated hydronic design or, in the case of a substation with electronic control, it can also be implemented electronically.

For this research, the hypothesis was that flat stations can be integrated into existing heating systems to prepare DHW with the minimum of renovation. However, the existing pipelines between the secondary side of the local large area substation and the primary side of the flat stations may need to be adjusted in accordance with the philosophy of DHW priority. Where the existing pipes are smaller than required for DHW, they need to be replaced with DHW size pipes; but where the existing pipes are the same size or bigger, they can be left as they are.

The dimensioning of pipes is determined by maximum flow rates in each section of pipeline. The normal criteria are a certain flow velocity and a certain pressure loss per running metre. In this case, the flow velocity in the pipes is typically less than 1m/s, and the pressure drop per metre has been recommended as 40-60 Pa/m for risers and less than 100 Pa/m for horizontal pipes [44]. The configuration of the renovated heating system is that the primary side of the flat station connects to the building riser, and the secondary side connects to the indoor DHW system. SH is still directly connected to the apartment heating system.

There are two preconditions for applying the philosophy of DHW priority: the first is that the DHW usage time needs to be short, e.g. 10-15 minutes; the second is that the philosophy can be realized at the practical level, in this study, electronically.

3.3.2 DHW usage in northern China

To find out about DHW consumption habits during the heating season on northern China, an investigation was launched using a questionnaire [20]. The questionnaire focused on three items: approximate tapping time, the usual time of day when the person takes a shower, how many times a week. The results show that the tapping time is less than 21 minutes for over 50% respondents; around 59% of the respondents take a shower in the evening; and the majority of respondents, 70%, take a shower once or twice per week (Table 5).

Table 5. Investigation into shower-taking in northern China

1. Tapping time		2. Time of day		3. Frequency of bathing	
< 7 mins	3%	Morning	9%	1-2 times a week	70%
7~ 9 mins	10%	Noon	3%		
9~ 16 mins	28%	Afternoon	14%	3-4 times a week	22%
16~ 21 mins	23%	Evening	59%		

21~ 32mins	17%	Midnight	1%	Every day	8%
> 36 mins	19%	Random	1%	Twice per day	0%

These data indicate that the philosophy of DHW priority is feasible from a realistic point of view. Even though the SH suspension interval could be 21 minutes, the time constant of buildings is typically so large that it would not make a noticeable difference to the indoor temperature.

3.3.3 Implementation of DHW priority

For the standard apartment with a two-pipe heating system considered in this study, a simple flat station like the Evoflat FSS [45] could be used. The Evoflat FSS is a complete unit for direct heating and indirect instantaneous DHW. Figure 9 shows the circuit diagram of the Evoflat FSS. The DHW temperature is controlled by a self-acting multifunctional controller, TPC-M [45], which implements DHW priority by using a zone valve.

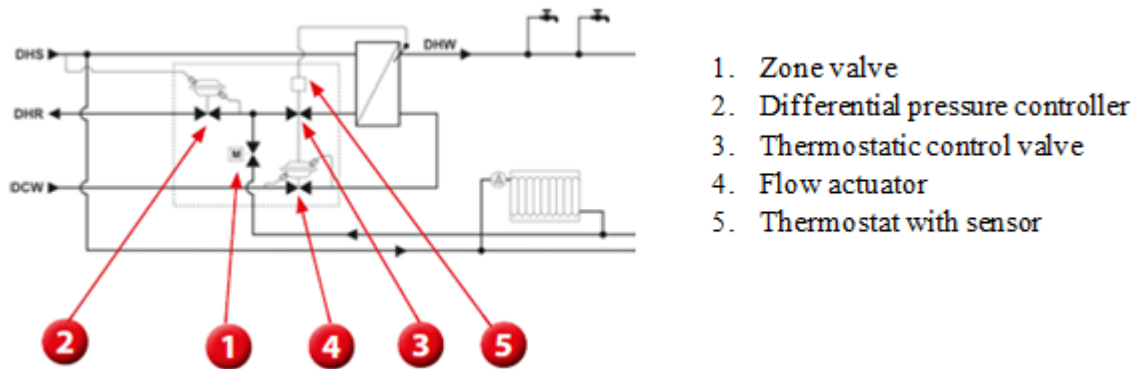


Figure 9. Circuit diagram of Evoflat FSS with self-acting multi-functional controller TPC-M

The TPC-M consists of 5 parts (Figure 9). When a DHW tap opens, the pressure drop that arises at the flow actuator (4) forces the thermostatic valve (3) towards an open position that is related to the flow rate on the secondary side. The desired DHW temperature is achieved by adjusting the opening of the thermostatic valve (3) in accordance with the difference between the desired temperature and the temperature that is measured with the thermostat (5). At the same time, the zone valve (1) ensures DHW priority over SH. There is a flow switch embedded in the secondary side. When a tap is opened, the flow switch detects the flow in the secondary pipe and transmits a “close” signal to the controller, which issues a command to the zone valve to close. When the DHW tapping stops, the flow actuator (4) ensures the immediate closing of the thermostatic control valve (3), and the zone valve (1) opens to allow supply to the SH system. The purpose of the differential pressure controller (2) is to ensure stable and optimum operating conditions for the DHW control valve and that the heating installation is not being affected by the external operation of the DH system. During non-heating periods, the zone valve (1) can be closed manually. In this way, the Evoflat FSS ensures the hydraulic priority of DHW.

4 Results and Discussion

4.1 Technical feasibility

Using the corrected coincidence factors and Eq. (4), the required DHW powers were calculated along the riser of the building model. The vertical DHW riser sizes were dimensioned on the basis of the calculation criteria, i.e. flow velocity less than 1m/s and a pressure drop per metre in the range of 40-60 Pa/m. The results are presented in Figure 10 and compared with the existing vertical SH riser sizes. The figure shows clearly that the riser needs to be replaced with DHW size pipes above the 4th floor, while the rest of the riser can still be used. For the horizontal pipes between the different risers, the required DHW powers are smaller than the SH demands due to the even smaller coincidence factors because of the increasing number of connected apartments. So the existing SH pipe dimensions should be sufficient to supply a flow rate to the buildings that can fulfil the partial SH and DHW demands simultaneously.

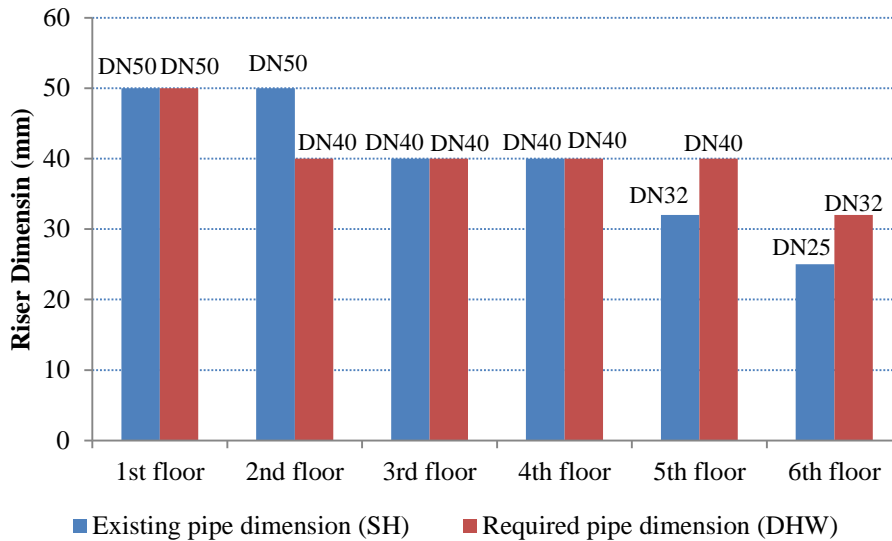


Figure 10. Comparison of existing SH pipe dimension with required pipe dimension for DHW

The philosophy of DHW priority over SH was applied to determine the dimensions of the riser. By explaining the functions of the multifunctional self-acting controller TPC-M, which is installed in the type Evoflat FSS flat stations, we have shown how the substations can implement the philosophy electronically. The other precondition for the application of this philosophy is that the DHW tapping should take no more than 10-15 minutes. Such short periods when SH is suspended will not affect the indoor temperature. The investigation into DHW consumption habits in northern China showed that 70% people take a shower once or twice a week, mostly in the evening, and have less than 21 minutes tapping time. This means that the impacts on indoor temperatures can be ignored. On the basis of these clarifications and data, the integration of flat stations into existing SH systems with the minimum of renovation is therefore technically feasible.

4.2 Economic evaluation

The main idea of economic evaluation is to compare the annual unit energy cost, which depends on the specific DHW preparation technologies, such as flat stations or individual water heaters. This economic comparison is

based on the investment costs, operational costs, fuel costs, efficiency and the expected lifetime of the different DHW preparation units [46]. The calculation flow chart is presented in Figure 11. The uniform currency used in this economic evaluation is the Chinese Yuan (¥).

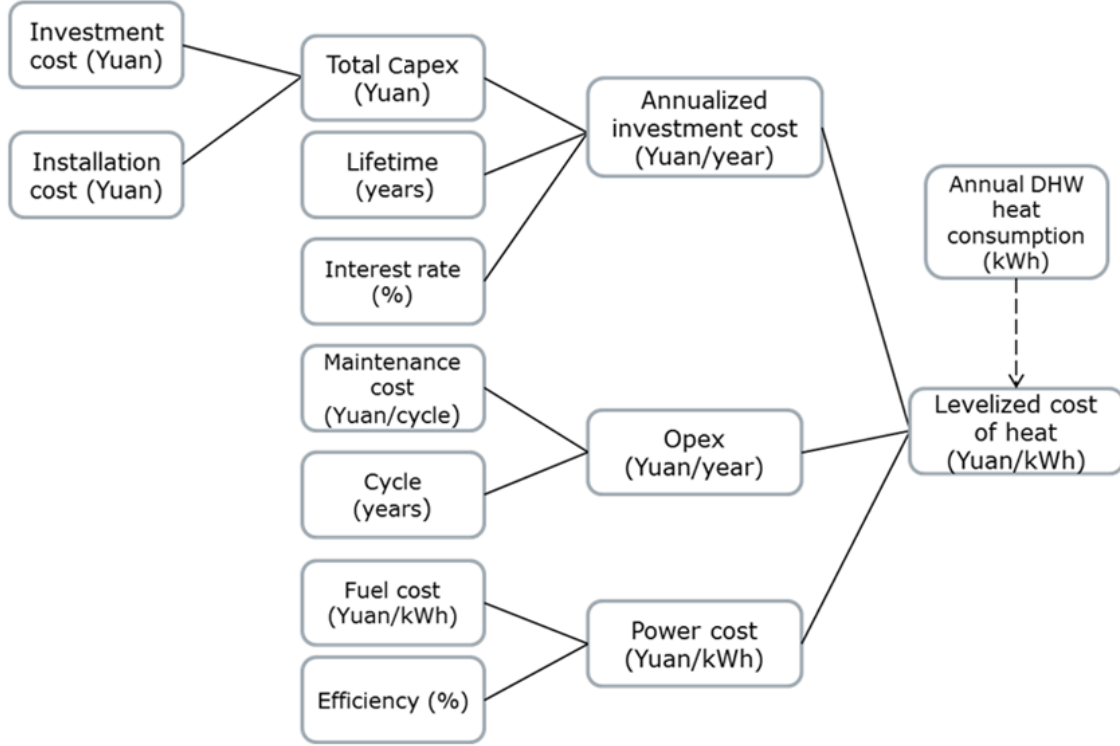


Figure 11. Flow chart to compare the economic evaluations between different DHW production equipment

The total Capex is the sum of investment cost and installation cost. To estimate the annualized investment cost, the net present value (NPV) concept [47] is utilized.

The annualized investment cost can be calculated using the following equation, which is a representation of the NPV concept with the NPV being zero at the end of the payment stream, with the time value and the money interest rate over the lifetime taken into account.

$$\text{Annualized investment cost} = \left(\text{Total Capex} * \frac{\text{Interest rate}}{1 - (1 + \text{Interest rate})^{-\text{Lifetime}}} \right) \quad (5)$$

In Figure 11, Opex means the average annual cost for operating and maintaining the unit in a safe and reliable manner. Fuel cost represents the cost of the energy per kWh used in preparing the DHW. The fuel can be electricity, natural gas or any other fuel suitable for DH systems. The cost of the fuel is used as the actual cost for residential buildings in Beijing. The annualized cost of heat (Yuan/kWh) for different DHW preparation technologies, such as individual water heaters or flat stations, is the sum of the annualized investment cost, Opex per year divided by the annual DHW heat consumption (kWh) and the annual power cost.

The annual DHW heat consumption for a 95 m² apartment in China can be estimated to be 3990 kWh according to [48]. Basic information about the three DHW preparation technologies is listed in Table 6.

Table 6. Economic factors determining the annual cost of heat with different DHW preparation technologies

Items	Natural gas water heater	EL water heater	Flat stations
Annual DHW consumption for a family	3990 kWh	3990 kWh	3990 kWh
Nominal Heat/Electricity Power	21 kW (Heat)	9.5 kW (Electricity)	21 kW (Heat)
Fuels type	Natural gas	Electricity	Local waste heat
Investment cost (Yuan)* ¹	3500	4000	6000
Installation cost (Yuan)	500	500	500
Life time (years) * ²	8	8	12
Interest rate (%)	5.25%	5.25%	5.25%
Maintenance cost (Yuan/cycle)	100	100	100
Fuel cost (Yuan/kWh)	0.23	0.5	0.09
Efficiency (%)	88%	88%	Flat stations:98%; DH heat source 60%; DH distribution pipeline 90%

*Prices are from Chinese local electronic commerce websites. Lifetime data are from the datasheet on DHW preparation units.

Based on the method discussed above, the levelized costs of heat (LCH) from the three DHW preparation technologies were calculated and are listed in Figure 12, which shows the economic advantage of flat stations over electric/nature gas water heaters. Electric water heaters have the highest LCH, and the LCH of flat stations is the lowest when all the economic factors are taken into account, including investment costs, operational costs, fuel costs, efficiency and expected lifetime. Although, only a small economic gap exists between the flat station solution and using a natural gas water heater, it is noticeable that the efficiency of the DH heat source used in flat station solution was estimated to be 60%. This is relatively low and is an average level, but it has great potential to be improved in the future (Table 6).

Convenience and safety are the two most important factors for residential DHW usage. This was shown by a questionnaire survey carried out in northern China [18]. According to the questionnaire interview data, the centralized DHW systems have the highest resident acceptance of 90% due to the convenience and high safety performance. On the other hand, the disadvantages of centralized DHW systems were mainly reflected in the high DHW price and long waiting-time because of the circulation system traditionally used. Moreover, the same questionnaire showed that individual water heaters have relatively low satisfaction compared to a centralized DHW solution: e.g. 80% said that electric water heaters have the disadvantages of high electricity consumption and the fast formation lime scale, 70% said that natural gas water heaters have risks of gas emission and explosion, and 73% said that solar water heaters have limited use time, provide an insufficient amount of DHW, and limitations in installation position. It seems that the disadvantages of both traditional centralized DHW system and individual water heaters can be avoided by applying flat station solution. So the result is positive in terms of the residents' acceptance of the flat station solution.

Under the national policy, the commercialization of heat, the implementation of household heat-metering based on the real consumption, the modernization of DH system, and the integration of more renewable energy into DH systems are imperative. This situation will drive the DH utilities to provide qualified heat to achieve high satisfaction among heat consumers. On the other hand, cost-effective DH applications are sought to expand profits and increase capacity. In these circumstances, the flat station is a win-win solution. Moreover, compared to renovated buildings, the flat station solution is more easily implemented in new buildings, especially if integrated in the initial design phase.

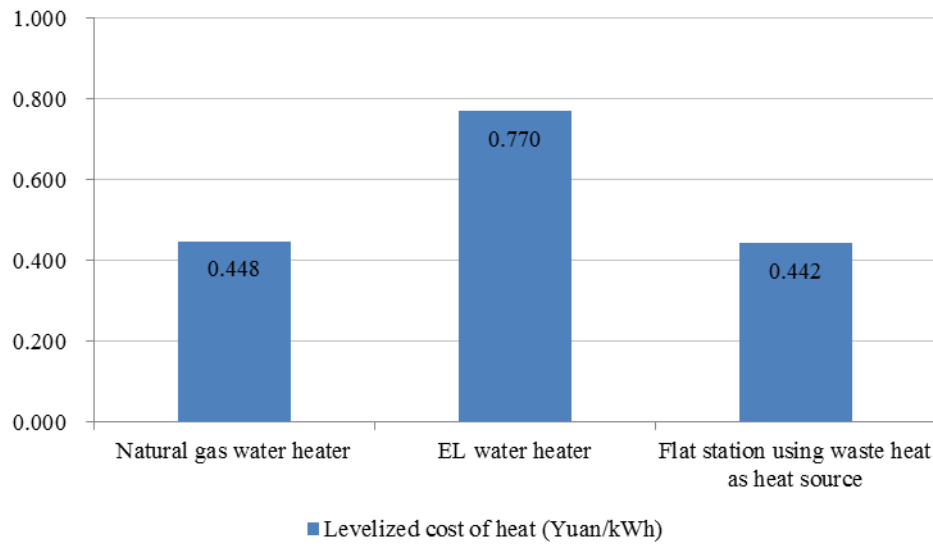


Figure 12. The annualized heat cost comparison between individual water heaters and flat stations

4.3 Quantification of environmental impact

The environmental impact of flat stations compared to individual water heaters can be accessed by considering CO₂ emissions from the different fuels.

China typically converts all its energy statistics into “metric tons of standard coal equivalent” (tce), one tce equal 29.31 GJ (low heat) [49]. In terms of energy equivalence, to generate 1 kWh electricity is equivalent to 0.123 kg standard coal consumption. Regardless of the conversion losses, the corresponding emissions are: 319 g carbon dioxide (CO₂), 2.95 g (SO₂), and 0.86 g nitrogen oxide (NO_x). For natural gas, the two principal combustion products are CO₂ and water vapour. Burning 1 standard cubic metre natural gas with 35.84 MJ/m³ low heat value emits 1.88 kg CO₂. As mentioned above, a standard apartment annually consumes 3990 kWh for the production of DHW. The consumed energy is equivalent to 3990kWh electricity, and 401 m³ natural gas.

Table 7. Emissions when using EL water heater and Natural gas water heater to produce DHW

Annual DHW consumption for a standard flat	Energy consumption		Unit emissions	Annual emissions for annual DHW consumption
3990 kWh	Electricity	3990 kWh	CO ₂ :0.319 kg/ kWh _e	1273 kg CO ₂

3990 kWh	Natural gas	401 m ³	CO ₂ : 1.88 kg/m ³ _{gas}	753 kg CO ₂
3990 kWh	Waste heat	-	-	-

The flat station solution can use a variety of fuels including waste heat from local industrial processing. Moreover, urbanized areas in northern China already have a well-developed DH pipeline infrastructure. Surplus heat from industrial processes is a great pollution-free resource for fulfilling residential heat demand [50]. According to Fang et al. [51], if 34% of available industrial waste heat had been recovered in 2009, it would have been enough to meet the whole DH heat demand that year. So it is entirely realistic for the flat station solution to use industrial waste heat as the heat source. If surplus heat from industries that is currently being wasted is utilized, there will be practically no extra particle or GHG emissions at all.

Based on the annual energy required to produce DHW for a standard apartment, the emissions (mainly CO₂) when electricity and natural gas are the power fuels were calculated. Based on the assumption that flat stations use local waste heat as the heat source, the CO₂ emission reduction could be 1273 kg per flat per year compared to using electricity as the power source and 753 kg per flat per year compared to using natural gas as the power source (see Table 7).

5 Conclusions

In this paper, we have analysed the current situation of DHW applications in China by using real data, and we have summarized the main reasons why centralized DH systems are not the main technology used to prepare DHW. Based on the current circumstances, the technical approach proposed is that flat stations should be integrated into the existing heating systems to produce DHW instantaneously. The technical advantages of the flat station solution can solve the problems in existing traditional centralized DHW systems and the individual water heaters currently in use can be removed.

Based on the model we developed of the building in Beijing, the proposed approach has been confirmed as technically feasible, and the renovation work required is limited to enlarging the riser pipe dimensions. During the technical feasibility analysis, the hourly variation coefficients commonly used to size centralized DHW systems in China were corrected by using coincidence factors from Denmark. Furthermore, we used the Net Present Value method to evaluate and compare the LCH from flat stations with that of individual water heaters, which showed the economic benefits of applying flat stations.

Real data evidences that massive industrial waste heat source is available around Beijing. Utilizing the industrial waste heat as DH fuel, rather than emitting into atmosphere, is a main tendency also an effective way to abatement the air pollution. On the assumption that flat station solutions can utilize industrial waste heat as the heat source, the environmentally friendly influences of flat stations were quantified and highlighted in comparison with individual water heaters.

A reliable and adequate supply of DHW for daily use has become an important factor for increasing life quality in China against the background of the rapid urbanization and modernization of Chinese society. At the same time, air pollution and security of energy supply are derivative challenges that could compromise the rapid development of the whole of society. The flat station solution presented in this study provides a sustainable

alternative for DHW preparation in China; it is wise to have a long-term DHW application to balance the conflict between current opportunities and current challenges. The flat station solution can produce hygienic, comfortable and economic DHW in an environmentally friendly way, thus reducing the burning of fossil fuels and other non-renewable sources of energy and improving the quality of life for residents in China.

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Article IV

Comparison of District Heating Systems Used in China and Denmark

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Comparison of District Heating Systems Used in China and Denmark

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Abstract: China has one of the largest district heating (DH) markets in the world with total district heat sales in 2011 amounting to 2,810,220 TJ. Nevertheless, it still has great potential for further expanding its DH supply, due to rapid urbanization and the demand to improve the quality of life. However, the current DH system in China is in great need of system improvements, technology renovation, and optimization of operations and management. As one of the world's leading countries in terms of DH supply, Denmark has state-of-the-art DH technologies and rich experience in the design and operation of DH systems. Experiences learned from the Danish DH system are useful for improving the current Chinese DH system. This article provides an overview of the technological differences between the two countries, focusing on: a) heat generation, b) the DH distribution network, c) DH network control, and d) the end consumer. The paper looks at the obvious differences between these two countries in terms of DH supply and concludes that there is significant, achievable potential for improvement regarding both energy efficiency and user comfort in the Chinese DH system, through technological advancement and implementing the operational know-how of more modern DH systems.

Keyword: District Heating, Energy Efficiency, Technical Measure, China, Denmark

1. Introduction

Denmark is one of the most energy-efficient countries in the world. A wide range of pro-active, energy-saving measures have decreased energy consumption and increased the use of renewable energy and technological development. Since the 1980s, Denmark's energy consumption has consequently remained steady, while the economy has continued to grow. The widespread use of district heating (DH) and combined heat and power (CHP) has made a major contribution to Denmark's drive towards efficiency and energy self-sufficiency (Dyrelund, 2012). The country's DH system combines space heating (SH) and domestic hot water (DHW) and runs continuously throughout the year. Denmark develops diverse heat generation technologies, powered by renewables and otherwise wasted energy (Lund et al., 2010)(Alberg et al., 2010)(Mathiesen et al., 2012)(Münster et al., 2012), as well as gradually reducing fossil fuel. Furthermore, well-oriented and supportive policies issued by the Danish government have resulted in the technical success. Commercial companies carried out the research and development of DH-relevant products and solutions, along

with universities, consultancies, as well as trade associations—all made substantial contributions to the revolution of DH technology.

The Chinese DH system had developed based on standard Soviet-era technology, which provided only heat, not DHW. There is considerable potential for improving the Chinese DH system and reducing greenhouse gas (GHG) emission. Coal, as the dominant heat source fuel, has resulted in a series of environmental, health, and economic challenges (U.S.Environmental Protection Agency, 2008). Furthermore, this kind of single heat source also heavily highlights issues of supply security, since energy consumption keeps increasing along with rapid urbanization and industrialization. The huge growth of the DH sector has made China the fastest growing DH market in the world. However, heat generation, distribution energy efficiency, heat demands, and fulfillment of user comfort requirements are not comparable with some European DH systems, such as Denmark. In China, heating energy consumption for 1m² is almost 2 times that of developed countries in the same latitude (Liu et al., 2011)(Xu et al., 2009). Currently, China's heat reform is still in process, with the aim of improving

building energy efficiency, updating the overall DH system, as well as establishing new heat metering and billing mechanisms based on actual consumption. Meanwhile, Danish DH experience will be a good resource from which China can learn.

This article looks at the obvious technical differences by comparing the main elements of DH systems between Denmark and China. It aims to identify the potential within the Chinese DH system, along with opportunities for integration of Danish DH technologies. It is important to note that these technical measures, that are essential to the Danish system, are appropriate and feasible for China at a practical level.

1.1. Historical Perspective and Future Prospects

1.1.1. Denmark

Since the first waste incineration and CHP plant-based DH system was built in Denmark in 1903 (DBDH, 2013), the Danish DH supply has gone through moderate development over the past 100 years. In 1973, the worldwide oil crisis tremendously affected the Danish economy, due to nearly 100% importation of foreign oil. The Electricity Supply Act of 1976 implemented the policy that all new power capacity after 1976 had to be CHP and the Heat Supply Act of 1979 ensured the least cost integration of power, heat, gas, and waste sectors in Denmark (Gerlach, 1991). The development of CHP on both a large scale (city-wide) and small scale (communities and institutions) and the associated DH have been booming since the 1980s (Mortensen, 1992). Such measures significantly increased energy supply efficiency and enhanced energy supply security, which has helped Denmark become energy independent since 1997 (Christensen, 2008). In 2012, the Danish government set forth an ambitious energy target: by the year 2035, the electricity and heat supply will be covered 100% by renewable energy and, by the year 2050, all the energy supply in Denmark should be 100% from renewable sources (Danish Energy Agency, 2013). DH once again became one of the key measurements and the share of total DH supply will increase from 60% to 70%, with the rest of the heating demand met by heat pumps (Lund and Mathiesen, 2009).

The future trend of the Danish DH is expected to be towards 4th generation DH (4GDH) (Lund et al., 2014), which is defined by smart thermal grids utilizing low quality energy like renewables, with optimized combinations of heat sources to supply appropriate lower temperatures to low-energy demand buildings through a high-efficiency DH network (Li and Svendsen, 2012).

1.1.2. China

During China's first five-year plan period (1953-1958), the first batch of thermal power plants were constructed, aided by the Soviet Union. In 1958, Beijing established China's first thermal power plant to supply heat to a few public buildings; this was the starting point of China's urban central heating. Afterwards, central heating utilizing CHP as the heat

generation came almost to a standstill for quite a long period, due to unexpected errors related to heat capacity. In the 1970s, the number of CHP plants began to increase again. However, these plants typically belonged to factories and enterprises, mainly meeting their own heat demands (Xu, 2010). During the early 1980s and into the late 1990s, CHP plants grew rapidly. Since the 1980s, CHP units started to supply heat for public, residential and commercial buildings. In 1986, the state council of China released the No. 22 document (Xu, 2000), which set the general direction for the development of CHP. Moreover, the central government increased funding and policy support. In this way, CHP was promoted. After the late 1990s, more and more heat-only boilers (HOBs) were built, gradually equaling CHP as the heat generation units, later even surpassing CHP. Although CHP should be preferred, due to better primary energy usage, there can be certain conditions that favor HOBs when it comes to DH, especially in the starting phase. HOBs played a transition role; after CHPs were built to supply the base load, they can be used efficiently for peak load. In 2007, China's total hot water DH sales amounted to 1,586,410 TJ, central HOBs contributed 1,047,750 TJ and accounted for 66%, and CHP represented 33% at 522,880 TJ (Xu, 2010).

The development of DH in China has gone hand in hand with rapid urban expansion and economic growth over the past ten years. In 2008, out of China's 655 cities, approximately 329 were equipped with DH facilities (Baeumler et al., 2012). The district heated floor space has expanded rapidly from 2.16 billion square meters in 2004 to 4.74 billion square meters in 2011 (China National Bureau of Statistics, 2012). At the same time, CHP more than doubled in capacity between 2001 and 2005, rising from 32 GW to 70 GW (IEA, 2007).

In China's 12th five-year plan report, improving energy efficiency is specifically mentioned as an important issue (Thomson, 2014). The DH sector has received further focus by policies that, among other things, actively promote urban clean energy retrofitting, strengthen building energy-efficiency retrofitting, develop CHP and DH, and eliminate a number of small coal-fired boilers, along with the phasing out of decentralized heating coal stoves in rural areas by encouraging the utilization of renewable energy. A prior policy of eliminating scattered coal boilers by consolidating them into large central heating systems with high energy efficiency and pollution control will continue (Lo and Wang, 2013) (Price et al., 2011).

1.2. Climate and Heating Periods

1.2.1. Denmark

Denmark has a temperate marine climate with mild winters and cool summers. The coldest month is January with average daytime temperatures of 2°C and nighttime temperatures of 2.9°C. During the winter, strong wind can quickly change the outside temperatures (Global Talent, 2013). The theoretical heating period is from October to the following April. Nevertheless, the fact is that an internal building heating system, connected to a DH system, can be

turned on or off according to heat consumers' comfort; actually the heat users can decide for themselves how long the heating period is. In addition, during the non-heating period, the DH supplies water for DHW preparation only.

1.2.2. China

China stretches over a large area with various winter climates classified from warm to severe cold. Figure 1 shows the climate zones map of China (Gao et al., 2014) and Table 1 gives the population information and the proportion of residential and commercial buildings in the different climate zones. Cold and severe cold zones cover about 70% of

national territory and account for 43% of the total residential and commercial buildings in the country (Baeumler et al., 2012). All 13 provinces and cities belong to the cold and severe cold climate zones (Ministry of Construction of China & General Administration of Quality Supervision Inspection and Quarantine of the P. R. China, 2012), which are geographically located north of the Qinling Mountain Range and the Huaihe River. The cold and severe cold zones are defined as having at least 90 days of average outdoor temperature at or below 5°C (the Ministry of Construction of China & State Bureau of Technical Supervision, 1993).

Table 1. Distribution of population, residential and commercial buildings in different climate zones of China[21]

Climate zones	Inhabitants (million)	Residential and commercial buildings ratio
Severe-Cold and Cold zones	550	43%
Hot-Summer and Cold-Winter zone	500	42%
Hot-Summer and Warm-Winter zone	160	12%
Temperate zone	90	3%



Figure 1. Climate zones map of China

Generally, in China, the heating season is specified from October to the following March. Despite being shorter or longer for some areas, the average heating period is around 150 days. Once the heating season is over, the DH supply is turned off, meaning that DHW preparation by heat from DH is uncommon. The common DHW solutions in China are: a) small and decentralized DHW systems, such as HOBs that generate DHW and supply a building block, e.g. gas-fired boilers produce hot water for a residential community or b) individual water heaters that produce hot water in each household, such as solar, electric, or gas water heaters.

2. Methods

In this paper, the technical comparison elaborates four main DH elements: heat production, DH distribution network, DH network control, as well as the end consumer. In addition, the specific DH technologies, successfully

applied in Denmark, are analyzed, having potential for development in Chinese DH systems. However, wholesale adoption of the exact technologies would not be wise, as different national situations must be considered; otherwise the advantages of the technologies would be compromised potentially leading to failure.

2.1. Heat Generation and Fuel Sources

When discussing heat generation technology for DH, it is notable that the technology is independent of the heat source and many different fuels can supply the system, such as renewables, waste to energy, and fossil fuels. The only requirement is that the temperatures of the heat sources are sufficiently high to heat the buildings. This capability both increases the security of supply and allows for optimization of the cost of heat generation, a remarkable advantage with which individual heating solutions cannot compete. Historically, DH has developed in relation to CHP. There is a clear benefit to having a CHP plant supplying the heat to the DH network. If the fuel source for the DH is fossil-based, it has also been shown that the CHP creates the lowest carbon footprint of all fossil-fuel burning plants (Orchard, 2009).

2.1.1. Denmark

In the Danish DH system, heat is supplied from either CHP plants or heating plants. 665 CHP plants include 16 centralized CHP plants in large cities, whereas most decentralized CHP plants are in small cities or for private supply for enterprises or institutions. CHP supplies 77% of the heat, with the remaining 23% (Odgaard, 2013) being supplied by various other heat-only devices, such as biomass boilers, geothermal heat plants, solar plants, and waste heat from industry. A total of 230 DH plants can be found in Denmark (Dansk Fjernvarme, 2013). In 2011, the energy supply composition for DH source was composed of: recycled heat including indirect use of renewables 69.8%,

direct renewables 19.3%, and others 10.9% (EURO HEAT & POWER, 2014).

Figure 2 shows the development of energy source for DH between the years 2001 and 2010 in Denmark (Werner and Frederiksen, 2013). A clear trend of a gradual decrease in the use of fossil fuels is evident in the DH sector; in contrast, the increased usage of renewable energy, such as biomass, waste energy, geothermal and solar energy, provided environmentally friendly heat to the DH network. The inspiration from these examples is that during the progressive establishment of a smart energy consumption pattern, the orientation directives of the Danish government played an important role. They masterfully use the economic levers of taxes and subsidies to set the national energy development direction.

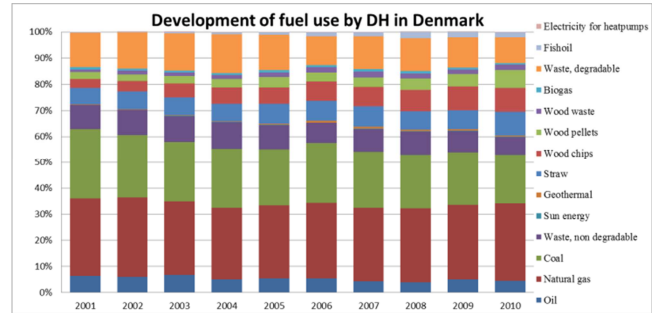


Figure 2. Developement of energy source for DH in Denmark 2001-2010

Biomass accounted for approximately 70% of renewable-energy consumption in 2010, mostly in the form of straw, wood chips, and pellets, while biogas accounted for less (Bertelsen and Tafdrup, 2014). The “Danish Biomass Action Plan of 1993” had forced power plants to use biomass to generate power and heat, a political decision that reoriented biomass energy consumption, resulting in a four-fold increase from 1980 to 2005 (Jørgensen, University of

Copenhagen). The Avedøre 2 CHP plant is known as the world’s largest and most efficient biomass-fuelled CHP plant (Ottosen and Gullev, 2004). Two units in this plant with a total capacity of 810 MW of electricity and 900 MW of heat, run on a wide variety of biomass fuels, as well as less coal, oil, and natural gas. In 2027, the plant is expected to run 100% on biomass (Wikipedia, 2014).

Denmark is at the forefront of the development of large-scale solar DH systems in Europe. Of the top 10 large-scale solar heating plants in Europe, nine are located in Denmark. The number 1 plant, Marstal Fjernvame solar DH system, was established in 1996 (SDH, 2013). This is, so far, the largest solar heating plant in the world, with 33,300m² of ground-mounted flat panel collectors, with a thermal capacity of 23,300 KW. There are two energy systems (new and existing) that, together, have an annual production of 56,000MWh of heat (Extranet, n.d.). Water thermal energy storage systems can provide seasonal and diurnal storage for the energy systems. According to the “solar thermal strategy” of the Danish Energy Agency, in 2030, 10% of Danish DH load will come from solar thermal and in 2050, nearly 40% of the DH load is estimated to come from solar heat generation (Runager and Nielsen, 2009).

There is great potential for developing geothermal DH in Denmark due to the presence of assessed geothermal resources in large parts of the country. In 2012, DH extracted and used about 300TJ of geothermal heat. Table 2 shows three representative geothermal plants in Denmark to demonstrate the development status of deep geothermal. In addition, shallow geothermal will likely expand in the coming years, especially in areas with no DH or natural gas supply. Furthermore, current ground source systems cover more horizontal collectors, as well as a small proportion of borehole heat exchangers, when considering groundwater protection and drinking water quality (Mahler et al., 2013).

Table 2. Three representative geothermal plants utilized deep geothermal energy in Denmark

	Year	Location	Heat capacity	Flow volume	Temp.	Depth	Saline amount
1	1984	Thisted,Denmark	7MW	200m ³ /h	44°C	1.24 km	15%
2	2005	Copenhagen,Denmark	14MW	235m ³ /h	73°C	2.6 km	19%
3	2013	Søderborg,Denmark	12MW	350m ³ /h	48°C	1.2 km	15%

Over many years of policy-making in Denmark, waste has experienced a role reversal from being a health problem in the 1960s to a resource since 2000. Waste incineration is the method for recovering energy from waste. Danish waste incineration plants are connected to the energy grid, providing DH and electricity to the Danish market, while, at the same time, decreasing the volume of waste by up to 70% (Andersen and Mortensen, Copenhagen Cleantech Cluster). Municipal solid waste (MSW) and household waste are an important source of heat for the DH sector. In Denmark, all MSW is incinerated, and household waste is not allowed to go to landfills. Typically, Danish incineration plants generate approximately 2 MWh of heat and 2/3 MWh of electricity from every ton of waste incinerated, that implies that the

operation of waste incineration plants produces nearly 80% heat and 20% electricity (Vestforbrænding, 2013). Therefore, waste incineration plants are well suited as a heat source for DH. Moreover, with a high priority on efficient energy usage, waste heat from industry has also become an important heat source for the DH sector. For example, in the town of Fredericia, the DH network distributes waste heat from local chemical plants to 55,000 households (Eldrup, 2013).

Denmark has achieved a highly efficient energy system based on CHP, which is already widespread and successful in this country, due to consistent prioritization over the past few years. On the other hand, Denmark never stops pursuing renewable heat sources for DH, as well as developing thermal storage technology. In this way, Denmark already

has the foundation stones for delivering high efficiency for its DH systems and, in addition, it will continue to consolidate and optimize over the coming years.

2.1.2. China

There are three main heating production modes in China: 1) CHP plants and DH plants, 2) HOBs, and 3) small, scattered HOBs or individual stoves for single buildings or individual households. Since DH has evident economic benefits in highly populated areas, the first two modes are common in cities, where the fuels are coal, natural gas, or oil. The third mode is the heating solution generally used in suburban and rural areas by burning coal, oil, or crop waste.

Figure 3 shows the proportional change in the trend of heat sources in northern China from 1996 to 2008. The heated area in northern China nearly quadrupled from 2.4 billion m² in 1996 to 8.8 billion m² in 2008, the proportion of individual coal stoves drastically decreased from 50% in 1996 to less than 10% in 2008, and the percent of natural gas gradually rose to 5% of total heating areas in 2008 (China National Bureau of Statistics). The share of the heating supply coming from CHP accounts for one third of the heat supplied in the DH sector, while the remaining heat comes from HOBs, mostly fueled by coal.

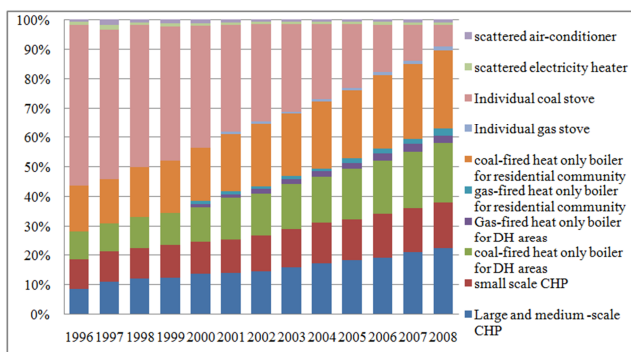


Figure 3. Proportional change in the trend of heat sources in northern China from 1996 to 2008.

For CHP plants, large-scale, high-capacity installations are actively encouraged, in order to realize the goal of saving energy and reducing emissions. This implies that large CHP plants will more easily obtain construction approvals and financial support than smaller ones. Currently, large extraction-condensing steam turbines, namely 200MW, 300MW, and 600MW (Tsinghua University building energy research center, 2011), are the leading type in China. This kind of CHP system can generally offer a 2.0-10.0 heat-to-power ratio and 60%-80% overall efficiency.

Coal is the dominant fuel source in the Chinese heating sector; this situation will continue in the coming years. Burning non-clean coal influences the efficiency of the boilers and causes excessive consumption of coal, as well as environmental pollution. According to the data from China's State Statistics Bureau in 2008, the national heating sector consumed 145.4 million tons of raw coal—about 91% of the total energy supply of the sector, in addition to 5% petroleum products and 4% natural and other gases, of which around one third is used in low efficiency HOBs (China National Bureau of Statistics).

Coal-fired HOBs are reported to have an efficiency of 60-65% (WADE, 2010), which can be considered quite low compared to the efficiency levels experienced in Western Europe. Currently, China's main cities have planned to restrict new heating plants to gas-fired technology. This fuel conversion is a long-term solution to deal with the consistent pollution issues faced today and to improve the efficiency of boilers. For Beijing city, the long-term plan is that gas heating will cover 51% of Beijing's heating areas in 2015. At the same time, heating areas of Beijing will expand from 680 million m² in 2010 to 850 million m² in 2015 (Beijing Heating group, 2011). Beijing has pledged to shut down most coal-fired boilers in central city areas before 2016, as part of its efforts to reduce fine particle pollution, especially during the heating season. This will result in a nearly 5-million-ton reduction in coal use, compared to 26.35 million tons in 2010 ("Beijing shuts coal-fired boilers for clean air," 2013). However, according to Li et al., (2009), this fuel conversion policy would lead to a significant increase in overall costs if building energy efficiency is not simultaneously taken into consideration.

Since coal is the main fuel for CHP plants and HOBs, this brings up a series of challenges for health, the environment, and the economy. On the other hand, the situation will continue in the coming years. At the same time, urbanization and industrialization are speeding up along with the economic growth, such that China faces the great challenge of energy supply security. According to *2011 Annual Report on China Building Energy Efficiency* (Tsinghua University building energy research center, 2011), utilizing the surplus heat from industrial processes as the heat source in DH sector, otherwise discharged into the environment (Ajah et al., 2007), would enable China to realize energy goals and meet the challenges. Table 3 lists available surplus heat from the industrial processes around cities (Tsinghua University building energy research center, 2011).

Table 3. Available surplus heat from industrial processes around cities of China

Code	Available low quality energy	Temp. level	Extractable heat amount
1	Gas emissions from coal and gas combustion	50-180°C	10%-20% of fuel total calories
2	Heat emission from the condenser of power plant	20-40°C	70%-200% of generated electrical energy
3	Surplus heat from industrial production, e.g. industrial furnaces, steel plants, non-ferrous metals plants, chemical plants	30-200°C	30%-80% of consumed energy in the plant
4	Heavy after-sewage water treatment	20°C	Recycled water per ton can release heat of around 12kwh if temperature lowered to 10°C

Fang *et al.*, (2013) introduce a demonstration project and present the huge potential to utilize surplus heat from industrial processes in China's DH sector. Li *et al.*, (2011) introduce a new method for improving energy efficiency and the capacity of the DH system.

2.2. DH Distribution Network

Distribution cost is a critical factor for the profitability of a DH system (Gebremedhin, 2012). Furthermore, heat loss is a major issue for the distribution pipelines. According to Werner and Frederiksen, (2013), annual relative heat loss is influenced by four factors: total heat transmission coefficient from the insulation heat resistance, average pipe diameter, distribution temperature level, and the linear heat density.

2.2.1. Linear Heat Density

In (Persson, 2010), the definition of linear heat density is: Q_s (GJ), heat sold annually in a DH system, divided by the trench length of the piping system L (m), which is symbolized by equation (1), with the unit GJ/m. This ratio indicates the level of DH distribution system utilization, and is a good indicator of the ratio of revenue to distribution cost.

$$\text{Linear heat density} = Q_s/L \quad (\text{GJ/m}) \quad (1)$$

As is well known, most of the cost of a DH system lies in the distribution pipe work. Regions with high linear heat density can allocate more infrastructure costs to DH pipeline, thereby maintaining the competitiveness of DH. In Denmark, 80% of the DH companies face an average heat density within the interval of 1.2 – 5 GJ/m/year (Finn Bruus and Halldor Kristjansson, 2004), while, according to (Baeumler *et al.*, 2012), the average heat load density in China is about 38.88 GJ/m/year. Table 4 shows the annual average linear heat density in Denmark and China based on equation (1) and the data from Euroheat & Power (EURO HEAT & POWER, 2014). China has higher linear heat density than Denmark because densely populated cities with high-rise buildings are always in the DH supplied areas.

Table 4. Linear heat density in Denmark and China in 2007 and 2011

Year	Country	Total DH sales (TJ)	Trench length of DH pipeline system (km)	Linear heat density (GJ/m)
2007	Denmark	94,271	27,851	3.38
	China	2,250,150	102,986	21.85
2011	Denmark	101,940	30,288	3.37
	China	2,810,220	147,338	19.07

2.2.2. Denmark

For a large-scale Danish DH network, the complete pipeline system generally consists of the transmission system, distribution system, and municipal network, with different companies being in charge of each part—a good example is Copenhagen's DH system.

The Danish DH systems have evolved over time by

utilizing innovative methods to reduce distribution heat loss. One of the main contributing strategies has been to operate the distribution network with relatively low supply temperatures and as high a differential temperature between forward and return pipes as possible; this both insures good cooling of the supply and minimizes mass flows in the system, which results in pump savings later on. Currently, the operating temperatures of the DH system are typically 70/40°C during the heating season and 65/25°C during the non-heating period. Moreover, Denmark is in the transition from 3rd generation DH to 4th generation DH, the DH system will be working under 50/20°C in the future, instead of the former 70/40°C (Brand and Svendsen, 2013). An international research center, 4DH, has carried out relevant research work (4DH, 2014.). Further investigation is seeking even lower supply temperatures. Low network temperature increases the quality match between heating demand and supply (Li and Svendsen, 2012), minimizes heat loss in the distribution network, improves the network's economic feasibility, and enables easier adaption to renewable energy (Dalla Rosa *et al.*, 2013)(Dalla Rosa *et al.*, 2011).

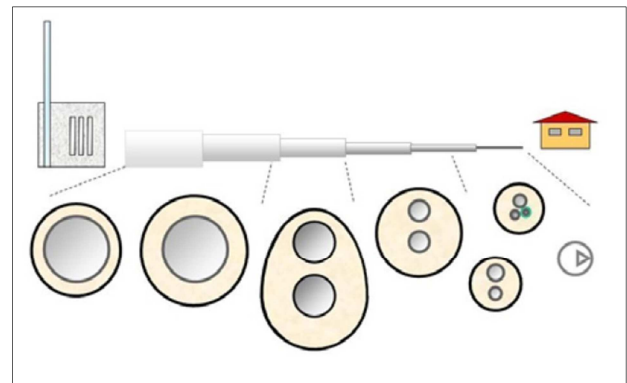


Figure 4. Innovation of DH distribution pipes in Denmark

Another notable contribution is the invention of the concept of pre-insulating steel pipes and covering the insulation with a water-resistant casing. Moreover, the service pipes are designed with optimized geometry (Figure 4), in order to reduce the relatively high heat loss of small pipes and consolidate the competitiveness of DH in low heat density areas, where single-family houses or new energy-efficient buildings are common. Transmission pipes from local CHP/DH plants generally have larger dimensions and use signal piping made of pre-insulated steel. The distribution pipeline from local heating substations likewise uses mainly pre-insulated steel pipe work; if the pipe size is small enough, the twin-pipe structure will be used. For municipal networks, with final distribution based on all plastic pipe work and insulation, twin-pipe or even triple-pipe is used. The triple-pipe is described as two forward lines and one return line, generally combined with a booster pump in the house, not only in order to achieve smaller heat loss than traditional service pipes, but also to provide better hot water comfort. Twin-pipe means that two pipes are located

within a common circular insulation with an outer casing. Twin-pipe is energy-efficient because the return pipe is arranged close to the temperature field generated by the supply pipe. In that case, heat resistance due to coinciding temperature fields becomes greater, resulting in lower heat loss from the return pipe (Werner and Frederiksen, 2013). Heat loss savings of 37% and investment cost reduction of 12% can be achieved by using twin pipes instead of two single pipes (Finn Bruus and Halldor Kristjansson, 2004). In addition, to achieve large differential temperatures and hydraulic balance in a DH system, it is necessary to have high-efficiency heat exchangers and control valves installed in the network.

2.2.3. China

China greatly extended the DH pipelines along with the expansion of heating areas, rapid economic development, and accelerating urbanization. It could be said that large dimensions and high temperature levels are the characteristics of the Chinese DH network. Single pipe is the most common structure. One of the reasons for this is that high heat density in urban areas needs a larger dimension of pipes. In addition, more and more DH transmission systems utilize directly buried pre-insulated pipes, instead of the former concrete trenches where the insulation foam for pipelines was applied on site. Typically, the service pipe is steel and is covered by insulation foam with rigid polyurethane. The outer protection is commonly a glass steel tube or high-density polyethylene tube. A DH temperature range of 115~130°C for supply and 50~80°C for return is typical (Ministry of Housing and Urban-Rural Development of China, 2010).

Heat loss is a big issue influencing the efficiency of a DH network. According to (Yan et al., 2011), around 30% of total supply heat is lost in Chinese DH systems due to hydraulic imbalance and water leakage. Around 30% of total supply heat is lost in Chinese DH system due to hydraulic imbalance and water leakage. Tsinghua University has conducted research to clarify energy loss items by taking a typical Beijing residential building as an example. In order to meet the annual heat demands, 0.30 GJ per square meter is required, whereas heat generation has to produce 0.45 GJ to ensure 18 °C statutory indoor temperature in the heating season (Tsinghua University building energy research center, 2011). That means 33% of total produced heat is lost when heat is delivered from heat generation to end users.

Among the factors, hydraulic imbalance accounts for quite a significant amount of total energy loss, and excess heat supply could be one result. This reflects the general lack of automatic control measures in the Chinese DH system. For the hydraulic balance of the DH network, it is important to have accurate flow control to substations, buildings, and end users, so that the heat demand can be better matched with exact energy consumption. Since in China the common case is one in which a large substation supplies heat to a group of high-rise or multi-story buildings, which contain a number of apartments in a building. For this kind of large and complex

DH system, it is inevitable to have hydraulic imbalance, if there are no control or adjustment devices in the individual branches: proximal end users get more flow than needed, and the distal receive less than required. Moreover, the apartments in a single building are located in different orientations and positions; therefore, the indoor temperature differs from room to room. Under this condition, when the distal end user's basic thermal comfort is met, the proximal user's environment might be overheated. Furthermore, there are no adjusting devices at the ends of the internal building's heating system. Naturally, proximal heat users are likely to open a window to bring the indoor temperature down, as needed, according to their comfort. Additionally, if the supplied heat cannot be adjusted according to the varying weather, the heat could be excessively supplied during the entire heating season. Hydraulic balance in a DH system can be achieved by using the differential pressure of the system to insure an adequate flow through the branches; usually, valves and pumps are the basic components for solving the hydraulic imbalance issue. Boysen and Thorsen, (2007), analyze how to establish hydraulic balance in a DH system. Weather compensation controllers can adjust the produced heat according to weather changes to meet the heat demands.

2.3. DH Substations-Network Control Methods

Since an increasing number of DH experts recommend applying the indirect-connection in modern DH systems (Thorsen and Gudmundsson, 2012), substations play a key role in securing energy-efficiency and no-risk operation. Substations provide hydraulic separation between heat generation and heat consumers, thereby avoiding the contamination of internal building heating systems.

2.3.1. Denmark

When comparing substation technology between Denmark and China, one finds that a large community-level substation is the most common case in China and one substation generally supplies heat to 50,000-200,000 m² floor area (Xu et al., 2009). In Denmark, a substation may be a customer substation, which is installed in each building, referred to as a building-level substation. The sub-station may even be in each flat, apartment, or single-family house, known as a flat station. At the same time, a typical Denmark substation will supply both space heating and DHW. Generally, the closer the control equipment is to the heat consumer the better the network control that is achieved. Moving the control components towards the heat consumers has been a continuous trend in Danish DH systems and has played a crucial role in the increased efficiency and economic performance of the Danish DH industry.

The importance of good control in order to achieve high energy efficiency cannot be stressed enough. As DH is a hydraulic system, the draw off by one consumer will inevitably have consequences for the other consumers, therefore, the closer the control is to the consumer the less affected they become. The optimum control is achieved when all consumers have their own substation (Thorsen, 2010).

Moreover, the additional benefits of utilizing small substations are that they can be pre-manufactured and insulated, and achieve great space savings. Compared to

large substations, building-level substations improve energy efficiency and allow for the application of more advanced solutions.

Table 5. Large substation and building level station based on a real case in China

Heating zone	Heating area (m²)	Scenario 1:Large substation		Scenario 2:Building-level substation		
		Heat capacity	Unit	Heat capacity	Unit	Sum
1#	48390	2900kw	1	200kw	5	11 units, total 3100kw
				250kw	2	
				300kw	1	
				400kw	2	
				500kw	1	
2#	48381	2900kw	1	100kw	1	14 units, total 3100kw
				150kw	1	
				200kw	8	
				250kw	2	
				200kw	5	
3#	48547	2900kw	1	200kw	6	14 units, total 3350kw
				250kw	5	
				300kw	3	
4#	47020	2900kw	1	200kw	9	13 units, total 3100kw
				250kw	2	
				400kw	2	
5#	37600	2300kw	1	150kw	5	14 units, total 2800kw
				200kw	6	
				250kw	2	
				350kw	1	
6#	43068	2600kw	1	150kw	1	6 units, total 2700kw
				200kw	1	
				250kw	2	
				550kw	1	
				1300kw	1	
7#	48773	2700kw	1	100kw	1	12 units, total 2900kw
				150kw	3	
				200kw	5	
				250kw	2	
				900kw	1	
8#	21360	1200kw	1	800kw	1	2 units, total 1300kw
				500kw	1	
Pipes cost		80.28%		58.43%		
Substations cost		19.72%		38.33%		
Total		100%		96.76%		

2.3.2. China

There is a real case in Weihai city in Shandong province of China (Danfoss A/S, 2004), where a total of 343,139 m² heating areas are split into 8 heating zones. Moreover, two scenarios are compared: 8 large substations (Scenario 1) versus 86 building-level substations (Scenario 2), see Table 5. The comparison includes the investment needed for the

substations and primary and secondary pipes. This investment calculation does not include the cost of civil works to any extent, nor the cost of electrical facilities (transformers, cubicles, etc.), network valves, or the power connection needed for the group substations. If these expenses were included, it would increase the total investment of Scenario 1 and make Scenario 2 even more

favorable. The contrast clearly shows that the investment would be lower when using building-level substations, although the total cost of small substations is double compared to that of large substations. Pipeline routing in the primary side can be done more efficiently and with a greater temperature difference, thus reducing the pipe diameter. From a technical perspective, small pipe size and a high differential temperature are helpful for reducing the heat loss of DH pipelines. In addition, Scenario 2 also gives other additional technical benefits, which remarkably influence the long-term operational costs and the total lifetime of the heating system. These benefits could include, but are not limited to, the following:

- an uncomplicated hydraulic system;
- a reduction of pump operation costs;
- Improvement of heat user comfort level;
- Modular design;
- reduced space requirements;
- The possibility to combine DHW system;
- Ability to charge the heating fee based on actual consumption;
- Flexible and smart control.

According to China's industry standard JGJ173-2009 (Ministry of Housing and Urban-Rural Development P.R.China, 2009), the building-level substation is recommended in 4.2.5 because of obvious technical superiorities, which are mentioned above.

Against the background of the heat reform in China, there is an opportunity to upgrade the DH system of China. Small substations can be in line with current DH industry developments. There is great potential for employing this application in the future.

2.4. End Consumer

Heat reforms are ongoing in China. In July 2003, eight central government ministries and commissions jointly issued a Government Circular calling for each of the 16 Northern provinces (in cold and severe cold climate zones) to implement heating system reforms in several pilot municipalities, according to the specified guidelines in the document "Heat Reform Guidelines." The principles of these Guidelines are the commercialization of urban heating, the promotion of technical innovation in heating systems, the application of energy-saving building construction, and the improvement of living standards. In the section on heat consumers, establishing a heat metering and billing mechanism based on actual consumption and improving building energy efficiency are two main tasks.

2.4.1. Heat Metering and Billing

There are some fundamental differences between DH systems in Denmark and China when it comes to the consumers. Two of the differences are heating billing and metering measurement.

Generally, China uses a fixed heating price based on square meters when charging the heating bill. Heat unit price

depends on different factors, such as the type of heat generation (DH plants or HOBs), the type of thermal media (water or steam), building type (residential or commercial). Generally, internal building heating systems follow the constant flow principle, due to the lack of control devices at the end user. The statutory indoor temperature of residential buildings in the heating season is 18 °C. If the temperature is lower than this standard, the customers can refuse to pay the heating fee; if it is higher than this, the heating fee is charged as normal. Under this condition, heat consumers have no incentive to consciously save energy. For this reason, the heat reform aims to install regulation devices at the end of internal building heating systems, thereby making the room temperature adjustable; the heating fee will be charged according to the actual energy consumption. To reach this goal, several technical heat-metering measures have been invented and applied in China. In (Liu et al., 2011), the technical heat metering measures are presented and analyzed according to China's current DH situation. Currently, the heating area in China in 2012 was 4.92 billion m²; the retrofitted area for heat metering was 0.805 billion m² in northern China, which accounted for approximately 66.7% of the total retrofitted area of heat metering devices installed (Ministry of Housing and Urban-Rural Development of China, 2012).

Table 6 lists two households' heating bills from Denmark and China. This seeks to illustrate the differences of heat billing between these two countries, not the price level. As this comparison is not based on the same benchmark, the heating bill of Denmark includes the DHW and SH throughout the year, while the Chinese heating bill contains only the SH fee during the heating season. In Denmark, the cost of DH is split into fixed and variable costs. The fixed cost covers the cost of the distribution network and the variable cost is metered according to actual energy consumption.

In Denmark, regulation devices are mounted at the end of internal heating systems to adjust the thermal flow rate into air heat units, thereby, the heat consumer can take measures to reduce heat consumption, such as closing the thermostatic valve instead of opening the window. In fact, the consumer can have a strong influence over their energy consumption by setting the desired room temperature. Additionally, consumers decide for themselves when their heating season starts or ends. The installation of heat meters and other regulation devices do not, in themselves, save energy. Rather, the energy savings are initiated by the consumers' own awareness. This way of heat billing has shown an average of 20-35% energy savings by the consumers (Drysdale, 2002). Further, modern energy meters are provided with facilities for remote reading. This is not only convenient for the DH companies to monitor the entire heating system, but also facilitates heat users tracking their energy consumption online.

Table 6. Comparison of heating bill between Denmark and China*

Heating bill for a 154 m ² one-family house in Denmark for the whole year (365 days)						
variable cost		Heat meter records		Unit price (exl.tax)	DKK	€
	start	end	consumption			
	258.99 GJ	356.75 GJ	97.76 GJ	80 kr./GJ	7820.8	1048.4
fixed cost	effect contribution	heating area 154m ²		15 kr./m ² /year	2310	309.7
subscription fee					550	73.7
Tax	25%				2670.2	357.9
total					13351	1789.7
Heating bill for a 154m ² apartment in a multi-storey building in Beijing for the heating season (125 days)						
fixed cost	Heating generation types		heating area	Unit price (incl.tax)	Total (Yuan)	€
	Gas-fired boiler		154m ²	30 Yuan/m2	4620	474.8

*1Euro=8.48 Yuan=7.46 kr.

Table 7. Residential building energy requirements in Denmark

Standard	Building class	Kwh/m ² /year	conditions
BR08	Building class 2008	70+2200/HFS*	Minimum requirement in 2006-2010 year
	Low-energy building class 1	35+1100/HFS	Low-energy building class
	Low-energy building class 2	50+1600/HFS	Low-energy building class
BR10	Building class 2010	52.5+1650/HFS	Minimum requirement in 2012 year
	Building class 2015	30+1000/HFS	Low-energy building class
	Building class 2020	20	Low-energy building class

*HFS is the building's heated floor space in m²

2.4.2. Building Energy Efficiency

Building energy efficiency is a key factor influencing the heat load of space heating. Since space heating typically represents a significant share of total building energy consumption, the most beneficial way to implement energy savings is to increase the energy efficiency of stock of houses.

Since the 1970s energy crisis, energy efficiency policies have been implemented in Danish buildings, which is has driven significantly less consumption than is experienced in most other European countries with similar climates (Danish Energy Agency, 2012). Furthermore, Danish authorities' strategy includes announcing future energy efficiency requirements many years in advance. Local municipalities have the power to require new construction to comply with future building requirements. Table 7 lists Danish residential building energy regulations and corresponding heat requirements.

The Chinese residential building sector accounts for approximately 30% of the country's final energy consumption (Richerzhagen *et al.*, 2008). In 2008, heating energy consumption in northern Chinese towns accounted for 23% of total building energy consumption (Tsinghua University building energy research center, 2011). In an effort to reduce heating energy consumption, China began to enforce "Building Energy Efficiency Codes" in 2005 by implementing a three-step approach (Ministry of Housing and Urban-Rural Development of China, 2013).

- Step 1: Residential buildings built in 1991-1999 are

required to achieve 30% energy savings compared to average residential buildings built before 1991.

- Step 2: Residential buildings built in 2000-2004 are required to achieve 50% energy savings compared to average residential buildings built before 1991.
- Step 3: Residential buildings built after 2005 are required to achieve 65% energy savings compared to average residential buildings built before 1991 in that location.

Since China's legal heating areas cover different climate zones, building heat consumption index levels vary from case to case. For Beijing, in the 1980s, standard coal consumption per square meter per heating season was 25.2kg. According to the 3-step energy saving approach, this consumption should be reduced to 17.64kg (30%), 12.4kg (50%), and 8.28kg (65%) respectively. In order to reach those levels, the efficiency of the DH distribution pipeline and the efficiency of the boiler are improved accordingly, as well as the building's envelop insulation performance. Consequently, building heat consumption per square meter per heating season is decreasing; see Table 8, with calculations based on equation (2).

$$q_c = 24 * Z * q_H / (H_c * \eta_1 * \eta_2) \quad (2)$$

The heating season in Beijing (Z) is 125 days and H_c stands for the calorific value of the standard coal equivalent, 8140wh/kg. Table 7 and 8 contain building energy-consumption requirements in Denmark and in China. However, it is illogical to make a simple comparison, since

Danish regulations try to promote long-term thinking concerning energy-efficiency investments. For instance, Danish regulations include requirements for overall building energy demand: SH, ventilation, cooling, DHW, and non-residential lighting. This has encouraged innovation towards more comfortable buildings that have lower overall energy demands. In the case of China, building energy efficiency exclusively focuses on the energy consumption of SH. After the third step energy savings are achieved, the heat consumption of Beijing residential buildings are 43.5kwh/m²/year; this is slightly higher than 40kwh/m²/year in BR10 Building class 2015 (if floor area is 100m²). One

could say that Danish buildings have higher energy efficiency than those of China, since overall energy consumption of buildings includes factors others than SH.

The high energy-efficiency of Danish building stock is the result of a consistent effort over many years, relying on strict requirements and standards, an experience that could be an inspiration to China. For China, enhancing energy efficiency could be an effective way to ease the pressure of energy supply security, reduce CO₂ emissions, mitigate the pollution issue, improve the thermal comfort level of building, and so on. There is a significant series of advantages (Richerzhagen et al., 2008).

Table 8. Building energy efficiency codes in China combined with the 3-step approach

	Year and design standard	q_c :Standard coal ¹ consumption (kg/m ²)	Energy saving ratio	q_H :Building heat consumption index (w/m ²)	η_1 :Efficiency of distribution network	η_2 :Efficiency of boiler
Datum	1980 Year	25.2	100%	27.4	0.8	0.5
Step 1	1986: JGJ26-86	17.64	30%	22.4	0.85	0.55
Step 2	1995: JGJ26-95	12.4	50%	20.6	0.9	0.68
Step 3	2010: JGJ26-2010	8.28	65%	14.5	0.92	0.7

Table 9. The overview of comparison DH systems used in China and Denmark

Items	Denmark	China	Potentials for China
DH season	Whole year	Winter Only	
DH system	SH and DHW integrated.	DH is mainly for SH.	DHW generation from DH has great potential to expand the market share.
Heat generation	Efficient and flexible heat production system, optimizing the combination of heat generation technologies and mix of fuels. Boilers (biomass, fossil fuel). Heat pump/electric heat boilers. Solar heat. Biomass CHP & geothermal DH plants, Gas CHP. Waste incineration heat/CHP. Surplus heat from industry.	Coal is dominate DH fuel. Large-scale, high-capacity CHP plants are encouraged mostly. Fossil fuel CHP. Fossil fuel heat-only boilers.	Renewable energy, waste energy, clean energy technologies.
Distribution network	Development tendency is LTDH, from 70/40°C ~55/25°C. Reduced heat loss of distribution pipeline based on multiple techniques: directly buried, pre-insulated steel pipe, optimized geometry of service pipes, applied low DH supply, and high temperature differential operation.	High DH supply temperature (130/70°C). Large dimension of distribution pipes due to high heat density. Small temperature difference, hydraulic imbalance and the lack of intelligent control comprise the efficient of DH system.	Improve the efficiency of DH system by achieving the overall hydraulic balance.
DH network control	Building level substation or flat station for each apartment. Single family house and multi-storey buildings are typical.	Large substation for a group of buildings. High-rise and multi-storey buildings are typical.	Building level sub-station, or even flat station concept
End users	Adjustable indoor temperature due to regulation devices at end of internal building heating system. Heat bill is based on actual consumed energy. Government regulates building energy consumption and supervises implementation.	Non-adjustable indoor temperature is min.18°C legally. Heat bill is fixed and charged by floor heating areas. Building efficiency can be improved through reduced consumption of heat.	Retrofit for heat metering and temperature-adjustable heating systems.

¹ China typically converts all its energy statistics into "metric tons of standard coal equivalent" (tce), a unit that bears little relation to the heating value of coals actually in use in China. One tce equal 29.31 GJ (low heat) equivalent to 31.52 GJ/tce (high heat).

3. Results

Table 9 gives an overview of comparison of DH systems used in China and Denmark, also states the potentials of the Chinese DH system.

4. Discussion

Energy efficiency permeates the main aspects of the Danish DH system. The fundamental idea of DH, “utilizing local energy otherwise wasted,” has been well fulfilled. The idea of heat production is to carry out a wide range of CHP technologies, define according to the corresponding scale, in accordance with local conditions—larger for major cities and smaller for suburban areas. Meanwhile, a diverse range of DH fuels are available, especially renewables, such as biomass, geothermal, and solar energy. Moreover, waste energy is also a well-utilized resource within Denmark’s DH system. This utilizes low quality energy in the DH sector, thus reducing the consumption of primary energy. In addition, all kinds of heat storage facilities can adjust the heat supplied from storage systems or heat production units, depending on the price of electricity in different periods, ensuring the economical operation of the DH system. As such, Danish DH systems establish an efficient and flexible heat production system by optimizing the combination of heat generation technologies and a mix of fuels.

As for the distribution network, innovative methods have been explored and utilized, these technologies not only reduce the heat loss of the distribution network, also keep DH competitive in low-heat-density areas. In addition, sophisticated control systems have been implemented, wherein a powerful programmable controller is usually set, with weather compensation and segmentation control. Control valves, working together with sensors, ensure the extract differential pressure in individual branch that the DH system operates under hydraulic balance. Customer substations are even closer to heat users to gain better network control. Additionally, the installation of heat meters and regulation devices at the ends of the heating system enable a heat metering and billing mechanism based on actual consumption. This motivates the heat user to consider means for saving energy. Wide ranging, energy-saving measures and mandatory building energy requirements have improved the energy efficiency of Danish buildings. These facts, together, will accelerate the transition process of Danish DH from 3rd to 4th generation and, as a result, DH will contribute towards realizing the ambitious energy targets.

China has a substantial DH market with large heating areas and high linear heat density. It is full of potential and possibilities. Environmental issues will force China to adjust its energy consumption structure, with less fossil fuel and more sustainable energy as a safer model. Surplus heat from industrial processes presents a valuable resource, which is expected to be utilized properly by combining appropriate

technologies. In addition, the reduction of heat loss and the improvement of hydraulic issues can also greatly enhance the efficiency of DH networks. Applying building-level substations rather than large-scale ones, will allow DH systems to be more flexible and efficient. Heat reform opens the door for establishing wise heat metering and billing mechanisms, and will encourage the heat consumers to consciously save energy. Other focuses of the heat reform are to improve the thermal properties of building envelopes and to upgrade heating systems; these create a platform for applying advanced technologies. One could say that China is in a transition stage of upgrading DH systems and can benefit from the successful experience of other countries. In fact, collaboration and idea exchanges in the DH field between China and Denmark have already started. This does not mean, however, that China should directly copy the experience of other countries. Rather, with sensitivity to national conditions and in compliance with relevant regulations, China can selectively absorb, adopt, and implement best practices in the context of its own heating reforms.

5. Conclusion and Policy Implications

This paper has analyzed the current situation of the DH industry in these two countries. Based on the comparison of the main elements of DH systems used in China and Denmark, it is clear that China can take inspiration from the Danish DH system development and selectively adopt the relevant technologies, based on the real situation.

One experience from Denmark is to establish smart heat production in DH systems by combining different heat generation technologies and a mixture of fuels, as well as the utilization of thermal storage to make the system flexible.

The fundamental idea of DH in Scandinavian countries, “using local energy otherwise wasted,” should be propagated in China’s DH field. For China, the existing valuable resource could be surplus heat from industrial processes, which is readily available around high-density urban areas, where the DH pipeline infrastructure is available, since DH has developed in these areas for some years.

Improvement of the efficiency of DH networks by enhancing automatic control level into hydraulic balance and achieving higher building energy efficiency would be shortcuts for China’s DH system to reach energy-saving and emission-reduction targets.

For China, supply security, pollution, and GHG emissions could be the most important current challenges. Meanwhile, efficiency improvement and modernizing DH with clean energy technologies have the maximum synergy between energy supply security and air pollution abatement. These challenges could also represent other opportunities. Updating DH systems in a sustainable way definitely benefits China in terms of long-term development.

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This PhD thesis is based on four scientific papers that describe challenges related to space heating (SH) and domestic hot water (DHW) systems used in China, and provides suggestions for solutions. The results indicate that SH systems can achieve hydraulic balance when control devices are applied at apartment level; consequently, energy consumption and emissions can be reduced, comfort level can be improved. Use of flat station to produce DHW is technical feasible. The thesis concludes that Chinese district heating systems can be improved when the appropriate control measures are applied.

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