SEPTEMBER 2016
EUDP SECRETARIAT

RESULTS AND EXPERIENCE FROM THE PROJECT

EUDP 2013-II: "ENERGY EFFICIENT COMFORT IN OLDER APARTMENT BLOCKS"

FINAL REPORT

Byg rapport: R-373
ISBN: 9788778774675

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CONTENT

1 Introduction

This report is the final report for the EUDP supported project EUDP 13-II: “Energy Efficient Comfort in older apartment blocks” (J.no. 64013-0574). The project period ran from August 2013-July 2016 with a total budget of 3,055,893 DKK.

The project partners are:

› DTU Byg
› Dresden Technical University
› Rønby.dk
› Ekolab
› E&P service
› Kingspan
› Introflex
› Airmaster

The project group has used COWI A/S as external consultancy for help with the administrative work. The project is a follow up on the previous supported EUDP project: “1:1 demonstration af koncepter til renovering af ældre etageboliger til lavenergiklasse 1” also known as the Ryesgade 30 project. Experience from Ryesgade 30 suggests that for internal insulation and ventilation there are challenges and opportunities. Therefore, the project focuses on these topics. The aim was to find test-apartments and apply both internal insulation and decentralised ventilation systems in order to analyse the consequences and operation.

There are 600,000 apartment blocks built before 1960, and most of these are without insulation and modern ventilation. Renovation of these happens in various ways, either for the whole building or apartment by apartment, often associated with the replacement of tenant/owner, and usually without taking sufficient account of energy conservation and indoor climate. This project works with both the energy conservation and indoor climate aspects, and support that the focus on these are intensified. The project aim was to develop mature solutions for the energy and indoor climate optimization of buildings with facades worth preserving, so that both comfort and energy consumption are brought to a standard that is close to the new buildings. The aim was not to analyse the energy consumption but to investigate specific solutions and the use of them in order to ensure that the solutions are robust for future applications where energy renovations takes place and energy consumptions are minimized and indoor comfort are optimized.

The project team includes Dresden University, who is a leader in insulating materials in Germany, and works with the same topic of optimizing energy and indoor climate without getting structural problems in old heritage buildings. Dresden University has developed a hygrothermal simulation program (Delphin) that has been used for analyses of moisture and temperature conditions in the building constructions when applying insulating materials.
Furthermore the project has involved a wide group of suppliers with solutions that fulfil the requirements for renovation, energy conservation and indoor air quality. This includes two insulation companies (Kingspan and IntroFlex) and two ventilation companies (Airmaster and Nilan). Unfortunately Nilan had to leave the project because it was not possible to find any test apartments for their decentralized ventilation units. As in the Ryesgade project also contractors (E&P service) was involved to ensure that more parts of the value chain was represented.

The test buildings were found through different channels:
Arup & Hvidt, who administrates 1800 apartments in Copenhagen, provided

› two test-apartments in Meinungsgade where internal insulation was applied (Kingspan) and decentralized ventilation (Airmaster) on apartment level in the same two apartments where the insulation was applied.

Through the “Klimakarré” at Østerbro in Copenhagen Municipality contact was established to different apartment owners and

› two test-apartments in Kildevældsgade was found where internal insulation was applied. Unfortunately, one of the occupants in one of the apartments got ill so we were only able to apply internal insulation (Kingapan) in one test apartment.

› two test apartments in Thomas Laubs gade was found where internal insulation was applied in one of them (IQ-therm), but due to economical restriction in the project it was not possible to apply internal insulation in the other. However, the other apartment is still projected to be a test apartment for a new internal insulation system developed by Isover, but will not be within this project period.

Futhermore

› one test building in Haderslev was found where internal insulation was applied (IQ-therm).

On top of the mentioned test apartments a follow up on temperature and relative humidity measurements established in previous projects when installing internal insulation has been included in this final report. The measurements include Ryesgade 30, Copenhagen (EUDP supported) and Mønsgade 16, Aarhus (Fornyelsesfond supported).

As the project evolved focus was turned a lot towards the use of internal insulation since the project group still see some challenges in some exposed buildings. In order to try to cope with this challenge a new insulation system was developed in parallel with this EUDP project. All expenses for the product development have been paid from Isover and DTU Byg, and this part is as such not a part of the EUDP project. However, the project group still find it beneficial to report the findings so far in this report.

This final report is carried out in collaboration between:

- Maria Harrestrup, DTU Byg
- Tessa Kvist Hansen, DTU byg
- Rune Haferbier, Ekolab
- Jørgen Lange, Ekolab
- Leif Rønby Pedersen, rönby.dk
- Rasmus Karkov, E&P-service

The project group does not take any responsibility for further use of the project results and tools. Furthermore the project group takes reservation on any potential errors.

2 Summery

The project is a follow up on the previous supported EUDP project: “1:1 demonstration af koncepter til renovering af ældre etageboliger til lavenergiklasse 1” also known as the Ryesgade 30 project. The aim of the project was to involve different marked players for internal insulation and decentralized ventilation and install and document the performance in order to contribute to the market penetration of the energy saving and improved comfort solutions when energy renovating old multi-storey buildings without compromising with the architectural values of the buildings. The project is a continuation of the results and challenges found in Ryesgade 30. Measurements were carried out to document the performance of both internal insulation and decentralized ventilation in order to get more knowledge of how the two technologies work. The aim was to find test-apartments and apply both internal insulation and decentralised ventilation systems in order to analyse the consequences and operation during realistic conditions.

The test buildings were found through different channels:

Arup & Hvidt, who administrates 1800 apartments in Copenhagen, provided

- two test-apartments in Meinungsgade where internal insulation was applied (Kingspan) and decentralized ventilation (Airmaster) on apartment level in the same two apartments where the insulation was applied.

Through the “Klimakarré” at Østerbro in Copenhagen Municipality contact was established to different apartment owners and

- two test-apartments in Kildevældsgade was found where internal insulation was applied. Unfortunately, one of the occupants in one of the apartments got ill so we were only able to apply internal insulation (Kingspan) in one test apartment.

- two test apartments in Thomas Laubs gade was found and internal insulation was applied in one of them (IQ-therm), but due to economical restriction in the project it was not possible to apply internal insulation in the other. However, the other apartment is still projected to be a test apartment for a new internal insulation system developed by Isover, but will not be within this project period since it is new and extra work added to this project.

Futhermore

- one test building in Haderslev was found where internal insulation was applied (IQ-therm).

On top of the mentioned test apartments a follow up on temperature and relative humidity measurements established in previous projects when installing internal insulation has been included in this final report. The measurements include Ryesgade 30, Copenhagen (EUDP supported) and Mønsgade 16, Aarhus (Fornyelsesfond supported).

The results from the internal insulation are the following:
Generally the tendency of declining relative humidity is seen for both walls and beam ends in Mønsgade and Kildevældsgade, and for walls in Meinungsgade and Thomas Laubs Gade. This indicates the initial relative humidity being caused by built-in moisture that needs to dry out. Seasonal variations are also seen in most measurements, indicating somewhat influence of external conditions. In both cases of IQ-Therm, the built-in moisture appears to dry slower, despite the capillary activity. The thinner layer in Thomas Laubs Gade seems to be working intentionally, as a decline is observed. The 80 mm IQ-Therm installed in Ny Allegade possibly takes even more than 13 months for drying the built-in moisture, or it is simply too much insulation in this case. One year of measurement is too short time to draw final conclusions, but the measurement will continue after the end of this project.
From the measurements in Ryesgade 30 it is seen that the humidity levels are good and no risk of mould growth seems to be present.

Meinungsgade is the only apartment with Kingspan internal insulation where the humidity levels are above the critical levels. This could be explained by different reasons. The building is built before 1890 and the façade is in worse conditions compared to the other buildings. Furthermore, according to the building law from 1889 [1] buildings constructed after 1890 have generally higher qualities compared to buildings constructed before. Low façade quality, uneven internal surfaces that are badly rendered and different conditions might result in the fact that there can be a higher risk of applying internal insulation. One solution to this is to renovate the façade (internally and externally) when applying internal insulation to ensure intact facades. There is no measurements of the relative humidity levels before applying internal insulation. For future projects it is recommended to carry out some measurements before applying internal insulation so that the effect of the internal insulation can be registered correctly. There is a chance that the humidity levels already were in the risk zone before applying the insulation. One more safe solution could be to apply less insulation (in this case 60mm insulation boards were applied).
Initially the plan was to create a gap in the insulation above and below the beam construction, but due to technical challenges it was only created above the floor construction. If the gap was also created below it might have led to higher temperatures and lower relative humidities. However, the Delphin simulations shows that even with a gap below the temperatures at the beam ends do not increase significantly and they follow the weather profiles. Therefore the creation of the gap in the insulation seems not to have the expected effect and could be disregarded for future project. However, there is still a need to ensure completely safe and robust internal insulation solutions. From this project it is still uncertain when and in which situations (wall-thickness, wind-driven-rain exposure, insulation thickness etc.) internal insulation can be applied without any moisture risks. There is a need to understand different external factors and how they affect the moisture levels in the wall. Especially the effect of the wind-driven-rain has a large influence on the moisture levels and should be topic for future research.

The results from the installation of decentralized ventilation are the following:
It is difficult to draw any precise conclusions on the 3-way valve/damper used on the 3rd floor for the exhaust hood, but on the market there is a demand for effective, good and economical friendly solutions and the effective exhaust hood on the 4th floor will probably be in favor in most cases. The consultancy group involved in this project is in the process of renovating 35 apartments and 7 new penthouse apartments where the solution with the effective exhaust hood has been chosen.

In order to try to evaluate the exhaust hoods effectiveness from an indoor climate perspective the differences between the exhaust and the supply air was analyzed. When the difference is large the effectiveness is highest. But there is a large variation depending on the user patterns. The measurements are performed when the outdoor temperature is far below the indoor temperature, which result in high relative humidities in the supply air. This could look as a wrong control strategy to take in air with a higher relative humidity compared to the indoor values, but the absolute humidity in the outdoor air is less than the absolute humidity in the indoor air. The Airmaster unit is calculating the absolute humidity and will only ventilate when the outdoor values are lower than the indoor values.

On the 4th floor the measurements shows a larger deviation on the requested flow from the ventilation unit compared to the 3rd floor. It is not possible to evaluate if it is due to a more stable operation with the solution with the 3-valve damper.

It is difficult to evaluate which system performs the best. Both systems seem to be working as intended and the occupants are happy with the systems. The effective exhaust hood provides more efficient exhaust when cooking and is a more elegant solution, but also a more expensive solution.

New data extracted from Airmaster´s system (beyond the detailed measuring period) shows that the heat recovery surprisingly is running parts of the summer (The ventilation has a variable by-pass function). The heat recovery happens to ensure a minimum supply temperature (i.e. 18°C) to avoid draft. In other case-studies the system was installed with a “summer-operation” function to shut down the supply in order to save electricity. If the measurements show that the amount of hours below 18°C is too many the occupants can experience draft. In old badly insulated apartments it can also result in increased heating consumption if the radiators start to operate due to too low heating contribution from the heat recovery. In those cases it is better to operate the system with a heat recovery. This result in the fact that the optimal way to operate the system depends on the heating balance in the apartment. And thereby the energy savings applied in the specific renovation project (insulation/new windows etc.).

It is seen that there is too high CO2 values in the bedroom during night time, which is a rather known developing theme. One solution to this could be to have valve between the bedroom and the living room in order to let some of the polluted air from the bedroom enter the living room.

The experience from this project is that it the installation process is a difficult task when many people from the value chain are involved. One conclusion is that instead of having many different people involved is it better to have a turnkey contract so that things happens smoother and no breakdown in communications which leads to mistakes and chaos will occur.

In order to ensure that the system is operating as intended it is very important that the installation happens correctly and that the system is adjusted corrected to the specific apartment. Continuous commissioning is an important aspect of ensuring an effective and correct operation.

An analysis of operational time and volume flow rate was performed and concluded that it was not relevant to decrease duct dimensions in regards to normal practice. A reduction in diameter from 125mm to 100mm would have a small economic benefit and ease the process of installing ducts plus give the opportunity to raise the suspended ceiling etc. However, it will result in an increased energy consumption of approximately 50%.

3 New and continuous research and work derived from the project

The aim of the project was to involve different marked players for internal insulation and decentralized ventilation and install and document the performance in order to contribute to the market penetration of the energy saving and improved comfort solutions when energy renovating old multi-storey buildings without compromising with the architectural values of the buildings. The project is a continuation of the results and challenges found in Ryesgade 30. Measurements were carried out to document the performance of both internal insulation and decentralized ventilation in order to get more knowledge of how the two technologies work.

The conclusions from the internal insulation measurements and analyzes is that more research and knowledge is needed to draw final conclusions on when, how and where to install internal insulation successfully without risk of moisture problems. The simulation models derived from this project was validated at a first stage and will be further developed and used in a PhD project at DTU Byg “Hygrothermal performance of internal insulation in historic buildings” and in the European supported project RIBuild.

Furhermore the development of a new internal insulation system has started based on the results and conclusion from this project. It is evident that very robust solutions are being developed that can be used for the cases where other (more traditional) solutions cannot be used due to too high humidity levels, too high amount of wind-driven-rain on the façade etc. This new solution is described in Annex 1, which is an exam project carried out at DTU Byg and continuous research will be carried out.

Further research that has been established as an outcome/continuation of this project is measurement on wind-driven-rain on the façade of two of the test buildings. These investigations will be continued in the same PhD project at DTU Byg as described above. The measurements on wind-driven-rain are only a first step to understand the amount and influence of wind-driven-rain when applying internal insulation. It is a crucial parameter that has proven to affect the moisture levels significantly depending on the amount striking the façade, and it is evident that more research is established within this topic in order to widely implement internal insulation solutions on the market. The wind-driven-rain measurements are explained below in section 3.1.

As a further step of applying internal insulation in the market and based on the experience of Ryesgade 30 and the results from this project 35 apartment in Ryesgade 25 is in the process of being energy renovated and internal insulation is applied. Some of the same players as is part of this project is behind the refurbishment in Ryesgade 25. In order to understand what happens when applying the internal insulation the Technological Institute is performing:

› Measurements on air tightness before and after the renovation (Blowerdoor + tracergas tests)

› Measurements of relative humidity and temperature in 7 apartments after the internal insulation have been applied.

Furthermore decentralized ventilation with the effective exhaust hood is installed in 35 old and 7 new penthouse apartments.

3.1 Wind-driven-rain measurements

When applying internal insulation wind-driven-rain on the façade plays a significant role. Thin surfaces with high amount of wind-driven-rain can lead to moisture problems when applying internal insulation. However, we still don't know much about how much rain strikes the façade. Therefore as a continuation of this project wind-driven-rain measurements will be carried out on two of the case-buildings: Meinungsgade and Haderslev. The equipment has already been installed and measurements will be carried out from the summer 2016 and forwards. However, no measurement will be included in this report since the time frame was too short.

A short description of the method and equipment is seen below:

WDR Gauge

The WDR gauge for the experiment was based on existing types, experience and comparative tests. It was based on the gauges manufactured at K.U. Leuven's Laboratory for Building Physics, with some alterations according to recommendations found in the literature. The area of the collection plate is 300x300mm, with a 10mm raised rim around all edges. The raised rim catch splashing water to some extent [2], and prevented collection of water from outside the collection area [3,4]. The plate is constructed in acrylic glass (PMMA), which has shown better performance and fewer errors due to water adhesion/evaporation in comparison with teflon (PTFE) [5]. As the amount of adhesion water has proved to be smallest in ordinary sheet glass [3], which is hydrophilic, a hydrophilic coating was applied to the PMMA surfaces of the collection area. The WDR is monitored by a HOBO Rain Gauge (Metric) Data logger, which is a closed tipping bucket rain gauge that minimises the evaporation losses from the reservoir. The data logger is fixed to the collection plate, and the water drains directly into the HOBO, as illustrated in Figure 1. The HOBO has a diameter of approximately Ø15cm, which means that the collector plate is extended slightly from the wall surface.

The WDR gauge on Meinungsgade is mounted on the south-west orientated façade, at the 4th floor height. This faces a large cemetery, so no buildings or obstructions in the direct vicinity should influence the WDR measurements. On Ny Allégade the WDR gauge is located on the west orientated façade at 1st floor height. This facade is facing the street. The distance to the closest neighbour in this direction is approximately 20m and there are no large trees or other obstructions in the immediate vicinity.

The WDR loads on the walls will be measured with the above mentioned rain gauge.

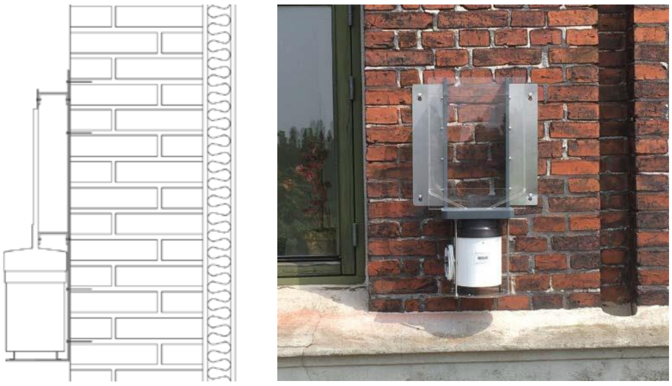


Figure 1: Wall-mounted WDR gauge with HOBO logger.

4 Dissemination and communication

4.1 Articles and reports

- Master thesis project at DTU Byg (2015), Investigation of Insulation Solution in Heritage Buildings, Maria Amparo Prieto Roca.

- Master thesis project at DTU Byg (2016), Internal facade insulation with active moisture control, Kjersti Fosso.

- Energi- og indeklimaoptimering af ældre etageejendom. rönby.dk og Ekolab. HVAC magasinet 09 2015

- Scientific article submitted to Building and Environment August 2016: Internal insulation system for heritage multi-storey masonry brick buildings using an air gap with dehumidified air to avoid mould growth, Anton White Orbaek, Maria Harrestrup, Svend Svendsen.

4.2 Presentations, talks and workshops

- Presentation of Ryesgade 30 og 25, Arup&Hvidt og rönby.dk
  - 09.07.14 for Dutch delegation
  - 19.08.15 for DTU´s and KDAK's 7PHN-konference
  - 30.09.15 for a SBI-group of international researcher and phd-students
- Poster presentation IDA kulturnat Oct. 2015, DTU og rönby.dk

- Gate 21 Seminar 27.10.15, Presentation of Ryesgade 30 og 25, rönby.dk

- Presentation of energy and indoor climate optimisation of Ryesgade 25 and 30 at a SBI/ReBuild seminar 21.01.16, rönby.dk

- Experience disseminated at ByggeCentrum courses and different conferences, Ekolab.

- Start-up workshop with all project partners, 18th of March, 2014

- Midway workshop with all project partners and invited relevant organizations and industry. 12th of December 2014

5 Internal insulation

The main purpose of this part of the project has been to get more experience of how internal insulation works in old preservation-worthy buildings, mostly with regards to the moisture performance of the wall and beam construction when internal insulation is applied. This has been done by carrying out measurements in test apartments in order to get more data and based on those develop an understanding of when and how internal insulation can be applied safely.

The measurements have been used to validate simulation models in the hygrothermal simulation software, Delphin, developed by Dresden Technical University. When the models are validated they can be used to simulate different scenarios and based on that guidelines could be developed in future projects. In order to develop guidelines to the full extent more measuring data is needed, and is not within the scope of this report.

5.1 Case studies

The project includes measurements from 4 case studies with internal insulation on multistory, masonry buildings built prior to 1960. Furthermore, follow-up measurements performed on two cases from two previous projects will be presented. All cases have been internally insulated with PUR foam in the form of either Kingspan K17 with 1=0.02 W/mK or iQ-Therm with 1=0.031 W/mK. The main difference between the two, being that iQ-Therm is capillary active, and no vapour barrier is applied, whereas Kingspan has an integrated vapour barrier. The material and construction for each case will be specified.

The case studies from this project include; Meinungsgade, Kildevældsgade, Ny Allegade and Thomas Laubs Gade. An additional case study has been included as a supplement to measurements; Mønsgade (project: Procesværktøjer til 360 grader indeklimarigtig energirenovering afældre etagebyggeri, Markedsmodningsfonden).
In all cases, sensors measuring temperature and relative humidity were placed behind the insulation, and at the beam ends (no beam end measurements in Thomas Laubs Gade) to gather data concerning the hygrothermal conditions at these areas of risk. The sensors behind the insulation were placed in either existing joints, or in a purposely-designed notch. The sensors in the beam ends were either drilled through the beam, or placed next to the beam, in the wall. In all cases, the sensors were sealed in place with sealing foam or the like. Sensor placements are shown in Figure 2.
In all cases, measurements were made pr. 1 minute, and in the expressed results, hourly averages will be presented.

Figure 2: Sensors placed (from left to right) in existing joint, purposely-designed notch, and drilled to beam end.

5.1.1 Meinungsgade

Meinungsgade 1, Copenhagen, is a residential building from 1877, seen in Figure 3, with wooden beams embedded in the walls. The bricks are exposed towards S, SW and SE and measurements are carried out towards S and SW. During renovation in the winter of 2014, wall of the 4th and 5th floor was insulated with 60 mm Kingspan K17 (20 mm for infill walls). Furthermore a 20 cm air gap was left above the floor, for creation of an intentional thermal bridge. The vapour barrier installed can be seen in the sectional view in Figure 3 as the blue line. The sensor placements and construction are also seen in Figure 3. Sensor 1 represents indoor conditions, sensors 2, 4 and 6 are placed at the interface between the existing wall and the interior insulation, and sensors 3, 5 and 7 have been placed at the beam ends between the two insulated apartments.

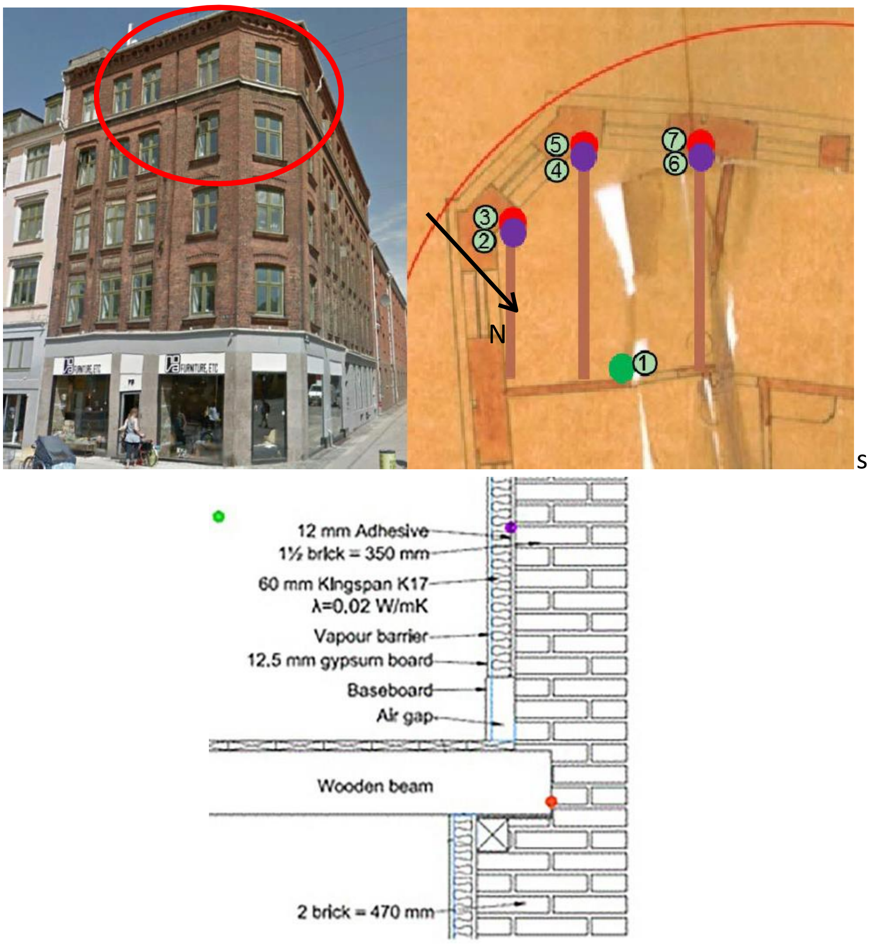


Figure 3: Meinungsgade and indication of wall placement (left), sensor placement on floor plan (middle) and construction with sensor placement (right)

5.1.2 Kildeværldsgade

Kildeværldsgade 69, Copenhagen, seen in Figure 4, is a residential building from 1905, with embedded wooden beams, and a rendered façade. In March 2015 internal insulation, 25mm Kingspan K17 (20 mm for infill walls), and a vapour barrier was installed on the northern façade on the 3rd floor. A 20 cm air gap was left above the beam in order to achieve higher temperatures at the beam end. The sensor placements and the structure are seen in Figure 4. Sensor 7 represents interior conditions, while sensors 2, 4 and 6 represent conditions at the interface between insulation and the existing wall, and sensors 1, 3 and 5 represent conditions at the beam ends. Only the upper apartment was insulated, hence higher temperature in the beam ends are expected compared to if both upper and lower apartment was insulated.

Figure 4: Kildevældsgade and indication of wall placement (left), sensor placement on floor plan (middle) and construction with sensor placement (right)

5.1.3 Ny Allegade

Ny Allegade 10, Haderslev, is a two-story residential building in Haderslev, from 1932 (Figure 5). The building has embedded wooden beams, and an exposed masonry surface. During renovation in the spring of 2015, 80 mm IQ-Therm (30 mm at infill walls) was applied to the west and south façades of the upper floor. The sensor placements and construction is seen in Figure 5. Sensor 1 represents interior conditions, whereas sensors 4, 6 and 7 represent conditions at the interface between the insulation and the existing wall on the west and south side respectively. Sensors 2, 3 and 5 represent conditions at the beam ends embedded in the west orientated façade.

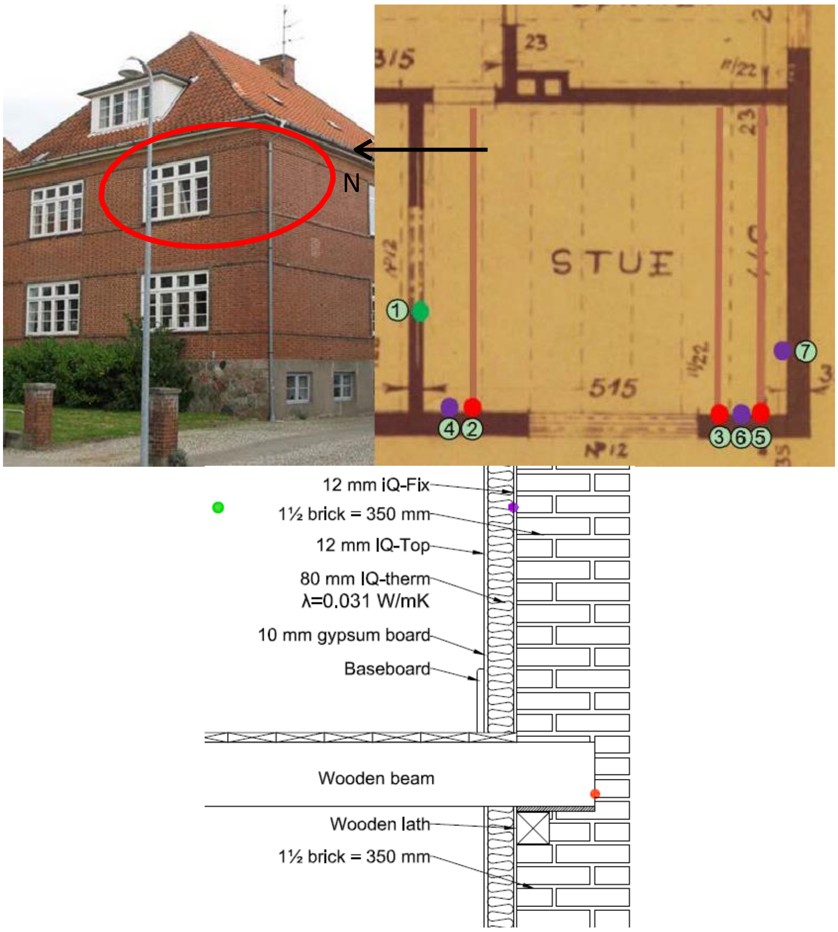


Figure 5: Ny Allegade and indication of wall placement (left), sensor placement on floor plan (middle) and construction with sensor placement (right)

5.1.4 Thomas Laubs Gade

Thomas Laubsgade 5, Copenhagen, is yet another multi story residential building, originating in 1899. The façade consists of exposed brick, as seen in Figure 6. The eastern façade of the 3rd floor apartment has been insulated with 30 mm IQ-Therm during the fall of 2015. The infill wall is insulated with 50 mm calcium silicate boards (SLP CS 50). Sensor locations and the construction with internal insulation are seen in Figure 6. Sensor 4 represents interior conditions, sensor 3 is located in the infill wall, between the internal insulation and the existing façade, and sensor 1 is located above sensor 2 behind the IQ-Therm.

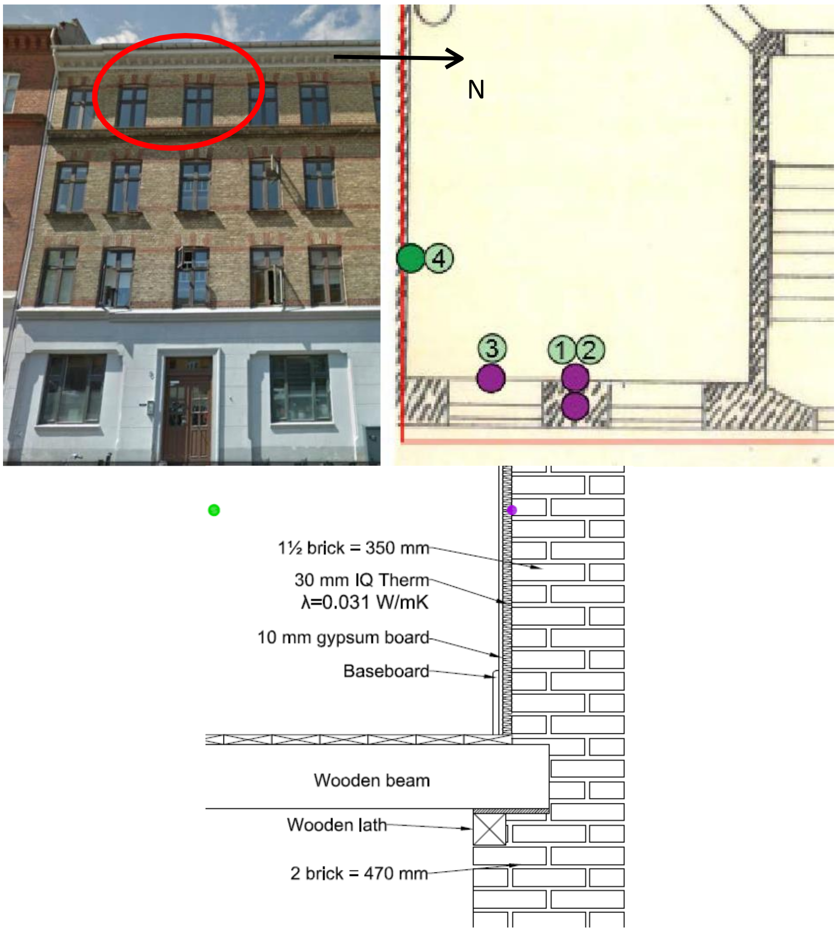


Figure 6: Thomas Laubs Gade and indication of wall placement (left), sensor placement on floor plan (middle) and construction with sensor placement (right)

5.1.5 Mønsgade

Mønsgade 16, Aarhus, is a residential building from 1910. As seen in Figure 7 the façade appears to be rendered. In the fall of 2014 the southwest wall of the 1st floor was insulated with 50 mm Kingspan K17 (30 mm for infill walls), with a vapour barrier included. The construction, as seen in Figure 7 illustrates, that a 20 cm air gap has been maintained at both sides of the beam.

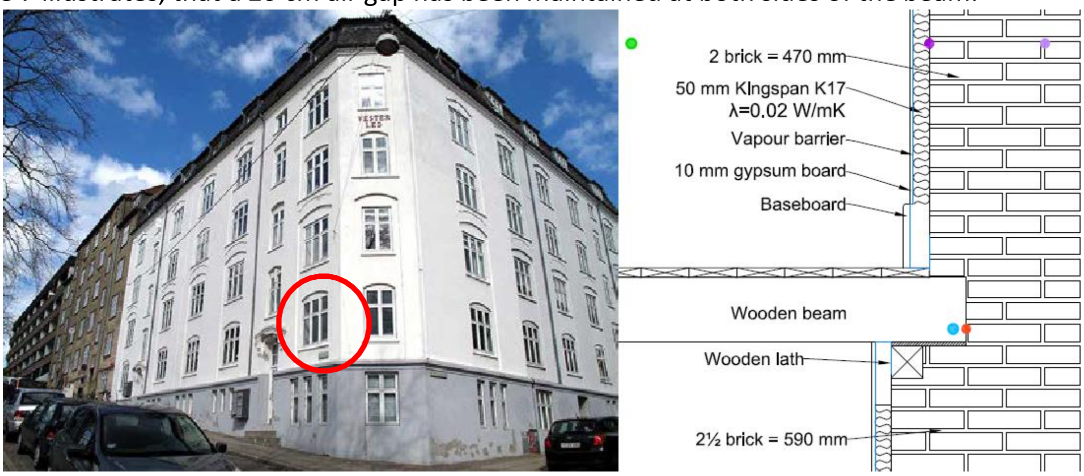


Figure 7: Mønsgade and indication of wall placement (left) and construction with sensor placement (right)

The sensor placements are given in Figure 8; sensor 8 represents interior conditions and sensor 9 has been drilled into the façade and is located closer to the external side. Sensors 1, 2, 6 and 7 represent beam ends, whereas sensors 3, 4 and 5 are placed behind the insulation at various heights, indicated in Figure 8.

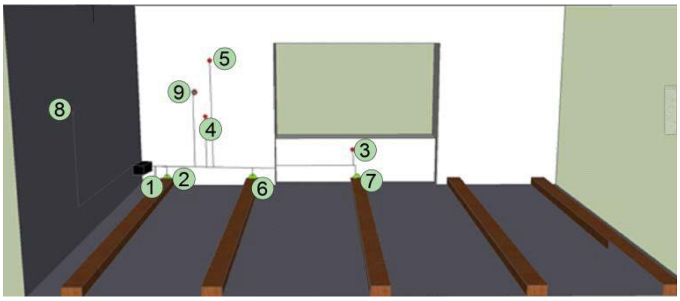


Figure 8: Mønsgade sensor placement on wall

5.1.6 Ryesgade 30 – follow up

From the previous EUDP project: "1:1 demonstration af koncepter til renovering af ældre etagebygninger til lavenergiklasse 1", measurements were carried out in Ryesgade on the 4th and the 5th floor in the corner apartments with orientation as seen in Figure 9. Also from Figure 9 the measuring points in both apartments can be seen. As seen the insulation is stopped 200mm above the floor construction in order to create a thermal bridge so that the beam ends have higher temperatures and thereby lower relative humidities. More details about the building can be found in the final report of the EUDP project: "1:1 demonstration af koncepter til renovering af ældre etagebygninger til lavenergiklasse 1".

Figure 9: Measuring points from Ryesgade 30.

5.2 Measurement results

Measurement results presented in this section represent hourly averages of measurements made until the end of July 2016. For the case in Mønsgade, only 8 months of data is available (October 2014-May 2015). From Ryesgade 30 the measuring period starts in May 2013 until July 2016.

5.2.1 Critical limits

According to Viitanen et al. [6], there is no risk of mould growth that can create smell and health problems on a wooden surface when the RH is less than 75%. This is in agreement with a guideline for avoiding mould growth on wooden surfaces in the Danish buildings developed by the Danish Building Research Institute [7]. They state that there is a risk of mould growth when RH > 75%. Another guideline [8] from Denmark directed at the building industry states that if the RH is above approximately 70%, mould growth can take place. This is in agreement with a study [9] that states that the lowest RH where mould growth can happen is at 70%. This however, is only at a temperature of 30°C. Other relevant literature

[10-13] states that when the RH < 75-80% there is no risk of mould growth on building materials at room temperature (about 20°C). Viitanen [14] states that if the RH > 80% for several weeks/months, there is a risk of mould growth in pine and sapwood when the temperature is between 5 and 50°C. Between 0 and 5°C, the mould growth is slow and only expected when RH > 90%.

The simple way of evaluating if there is any risk of mould growth is therefore to avoid that the relative humidity is higher than 75%, which has been chosen when commenting on the measurements. A more detailed approach for evaluating the risk of mould growth is carried out later on in the report under the section *5.3 Mould Index*.

5.2.2 Meinungsgade – Kingspan with vapour barrier

Figure 10 displays the decline in relative humidity of the wall sensor 2 and 4, from approximately April to October, as can be expected for the warmer period, as the masonry dries outwardly due to the vapour barrier. In the summer period, the humidity conditions in the wall resemble interior conditions. In general the measurements at these locations are regarded acceptable, as they only exceed 80% for a short period, fluctuates seasonally between 40-80%, and the drying is evident.

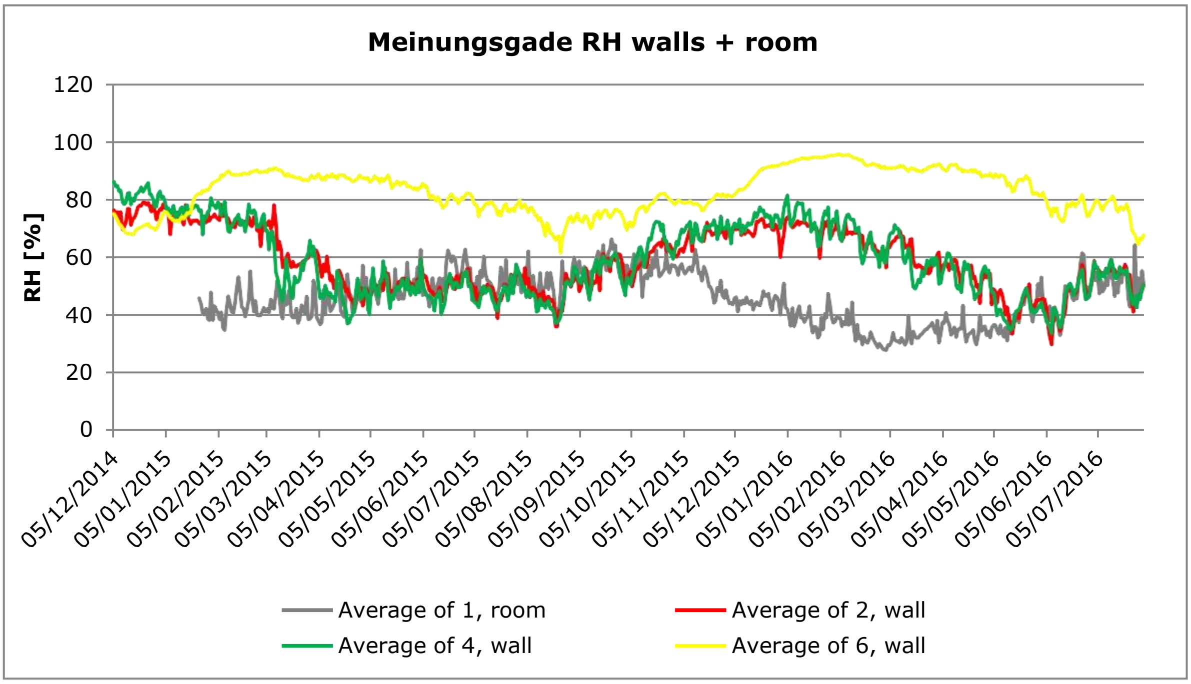


Figure 10: Relative humidity measurements in Meinungsgade, at interface between internal insulation and existing wall, as well as room conditions

Wall sensor 6 however, shows high measured relative humidity for the majority of the period, yet still yields some decline during summer. At the location of sensor 6, the thickness of the wall is slightly decreased, due to an indentation in the wall, for a previous installation of downspout, seen in Figure 11. Hence the external conditions, such as wind driven rain, may have a larger influence on these conditions contrary to the other two sensors. Furthermore sensor 2 and 4 are placed at walls facing south whereas sensor 6 is placed on a wall facing southwest. Sensor 2 and 4 could therefore be exposed to more sun and less wind-driven-rain as the main wind direction in denmark is west and southwest [15]. The south facing wall might therefore get less wet and dry out faster.

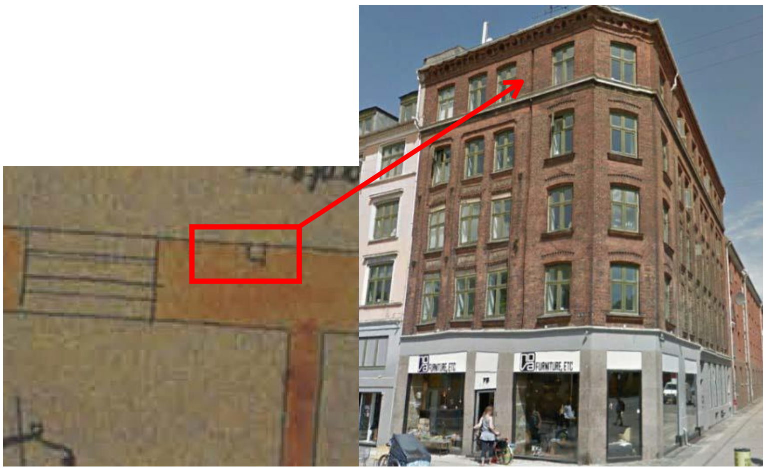


Figure 11: Indent in wall by sensor 6

The temperature measurements, as seen in Figure 12, show very similar conditions for all measurement locations. During summer, the temperature conditions in the wall resemble interior temperature conditions.

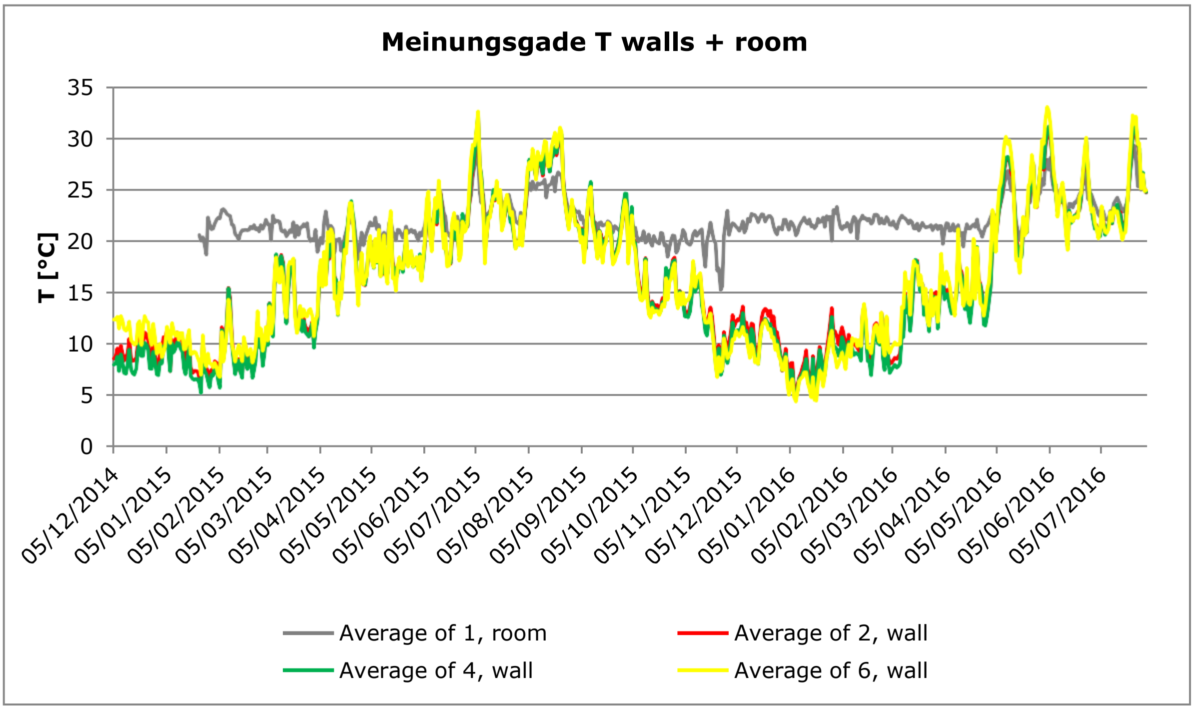


Figure 12: Temperature measurements from Meinungsgade, at interface between internal insulation and existing wall, as well as room conditions

Figure 13 displays very high relative humidities measured in the beam ends, approximately 70-80 % during the course of measurements. As the beams are embedded in the wall, the external wall is thinner at the location of beam ends, leaving them more exposed to external conditions, such as penetrating wind driven rain, as in the case of sensor 6.

Furthermore, the beam ends seem unaffected by the implementation of the intentional thermal bridges, and the temperature in beam ends, Figure 14, is generally slightly lower than at the interface, however the same seasonal tendencies are seen.

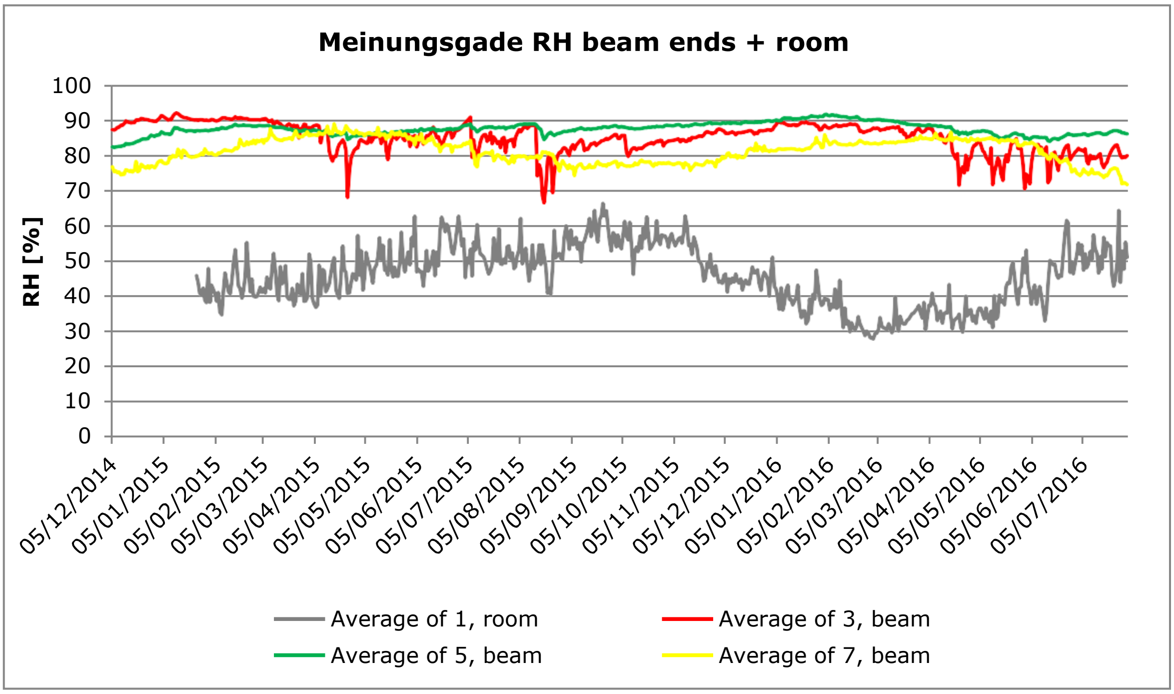


Figure 13: Relative humidity measurements in Meinungsgade, at beam ends, as well as room conditions

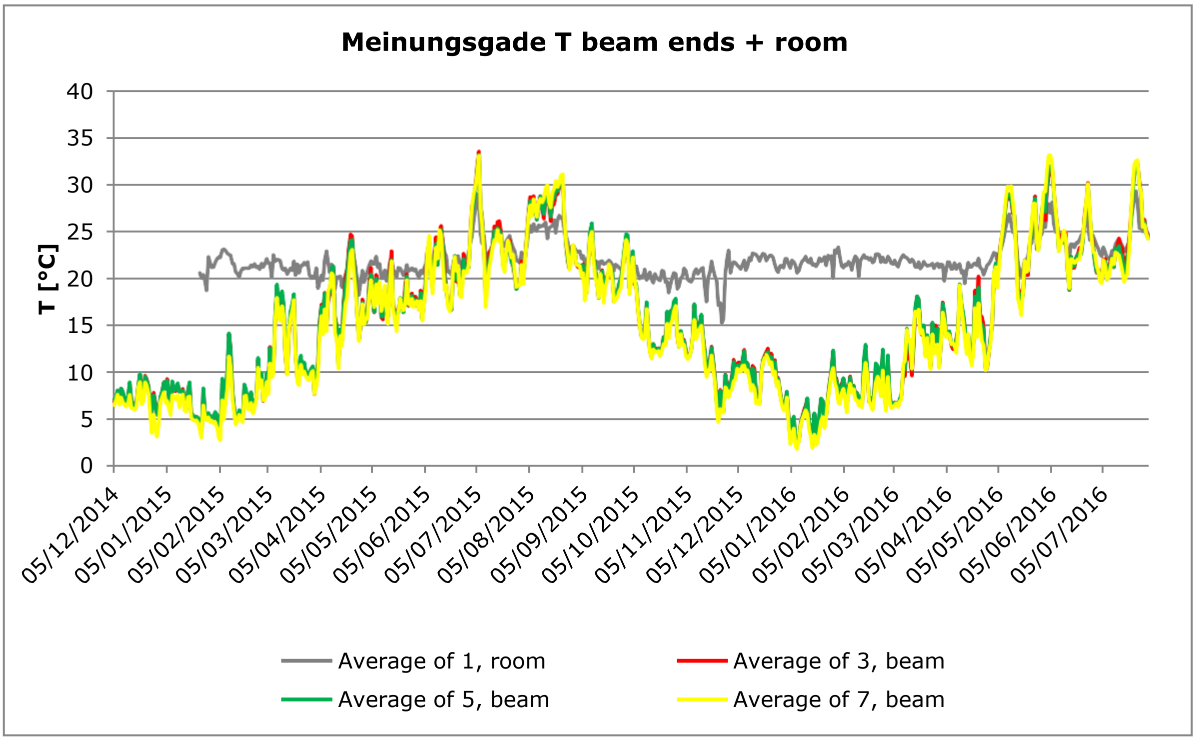


Figure 14: Temperature measurements from Meinungsgade, beam ends, as well as room conditions

5.2.3 Kildeværdsgade – Kingspan with vapour barrier

The relative humidity measurements depicted in Figure 16, show a decline in humidity conditions 4-5 months post insulation. The initially high relative humidity is likely built-in moisture, from applying the insulation boards with glue mortar or the like. After the decline, the relative humidity at the wall interface is 50-80 %, which is acceptable. The wall is north orientated and hence no sun strikes the façade. It is therefore expected that the wall will take longer time to dry out. The relative humidity measured by sensor 6 has a faster initial decline, and generally lower relative humidity. In Figure 17 it is seen, that sensor 6 shows a slightly higher temperature than the other measuring locations, likely influencing the relative humidity at this location. In the vicinity of sensor 6, hot water pipes are installed, as seen in Figure 15, which can be cause of the obtained results here.

Figure 15: Hot water pipes (red arrow) in the vicinity of sensor 6 location (green arrow)

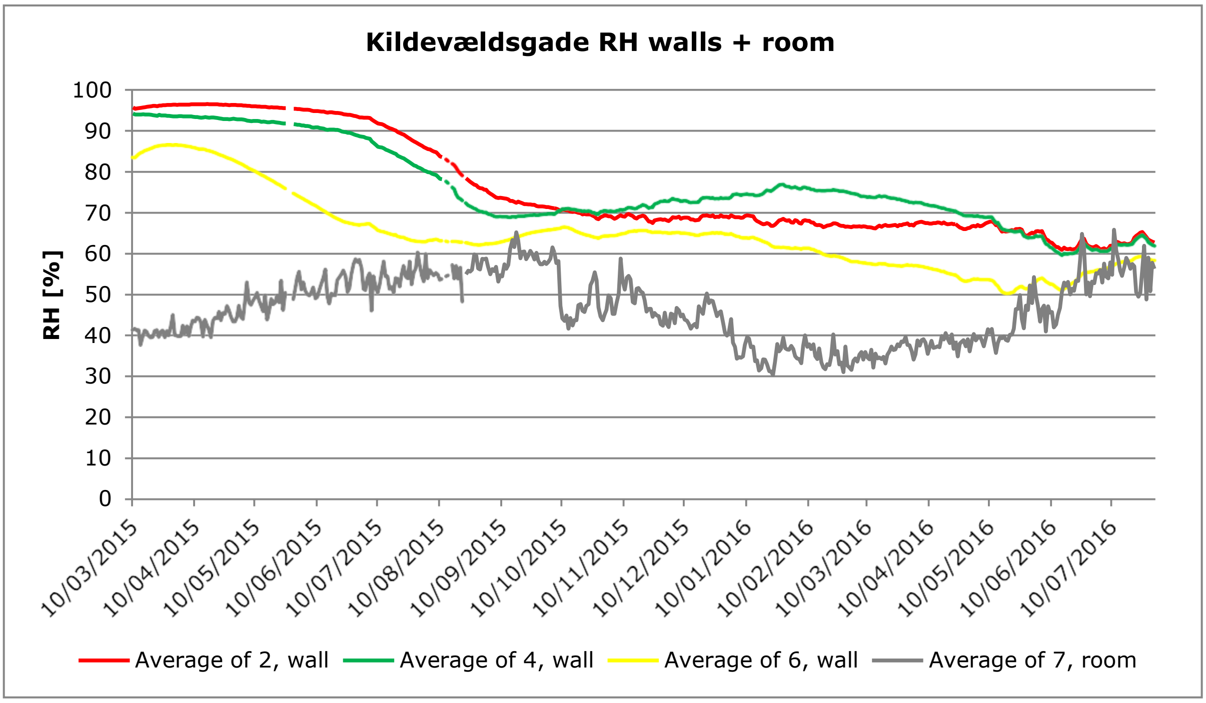


Figure 16: Relative humidity measurements in Kildevældsgade, at interface between internal insulation and existing wall, as well as room conditions

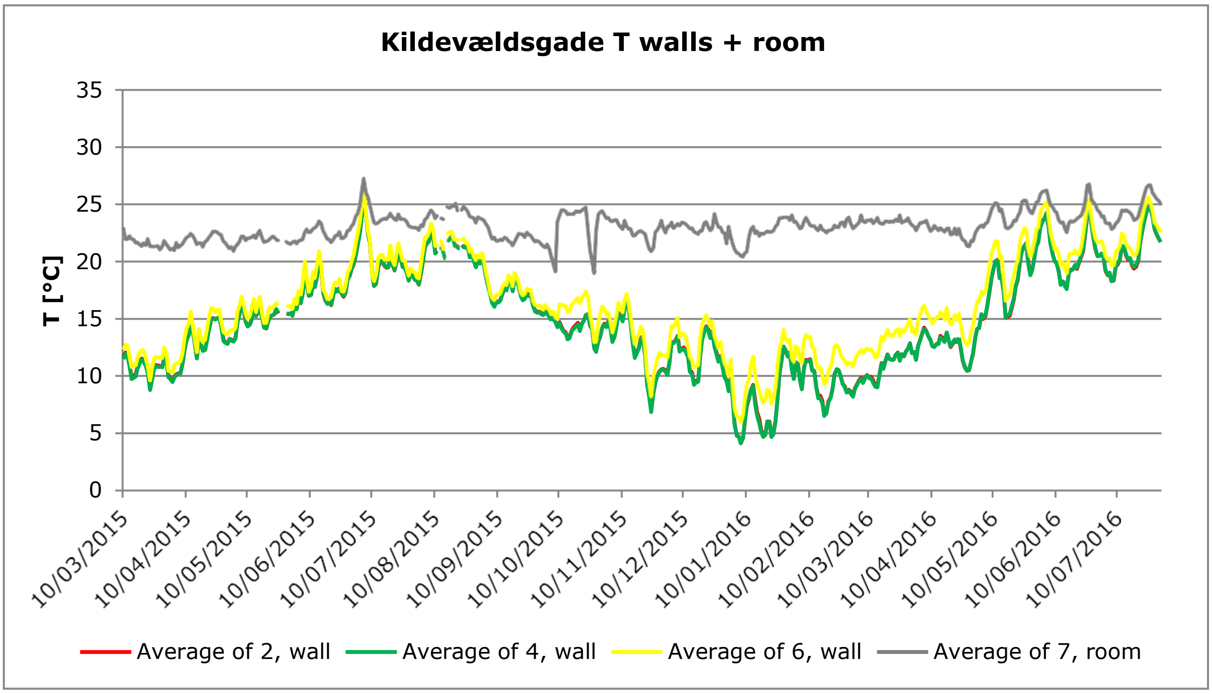


Figure 17: Temperature measurements from Kildevældsgade, at interface between internal insulation and existing wall, as well as room conditions

The relative humidity measured in beam ends at Kildevældsgade, seen in Figure 18, appear to be at acceptable levels during the measuring period from March 2015 - April 2016. The values generally vary seasonally between 50-80% - only sensor 1 exceeds 80 % slightly for short periods during winter. It is seen, that sensor 5 has the lowest relative humidity, and highest temperature, Figure 19, which again could be assumed to be caused by the hot water pipes. In this case, the temperatures in the beam appear to be slightly higher when compared to the wall-insulation interface. Despite the lower story not being insulated, the air gap installed may have the desired effect in this case.

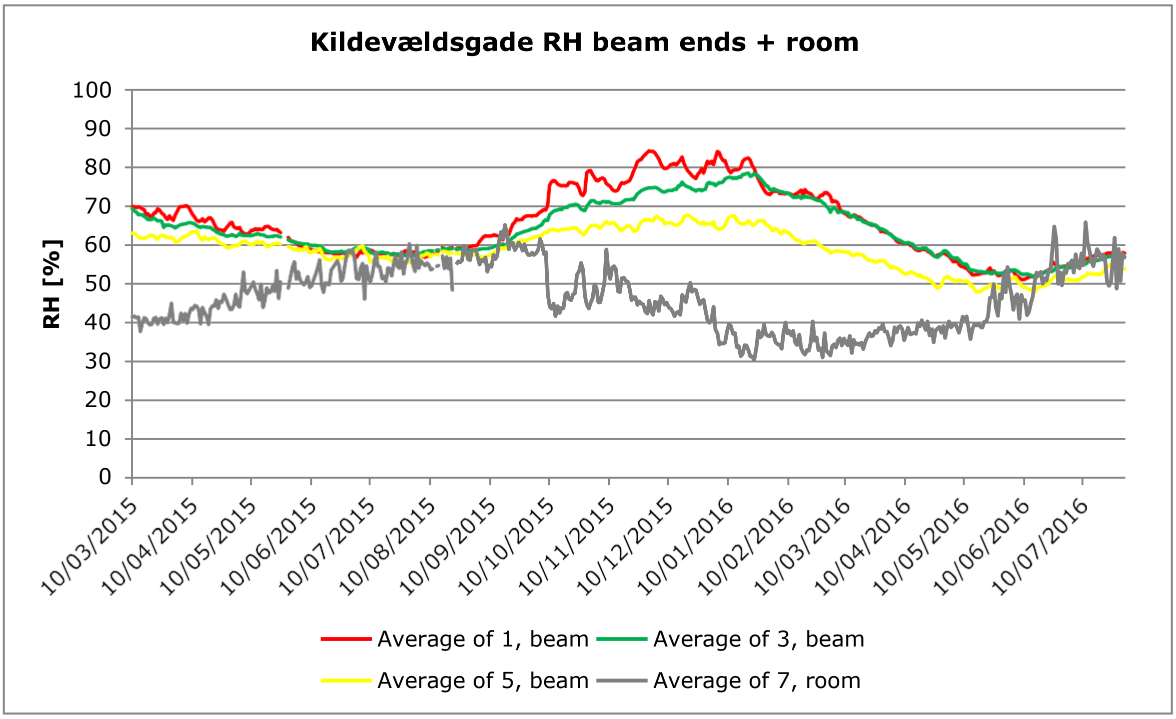


Figure 18: Relative humidity measurements in Kildevældsgade, at beam ends, as well as room conditions

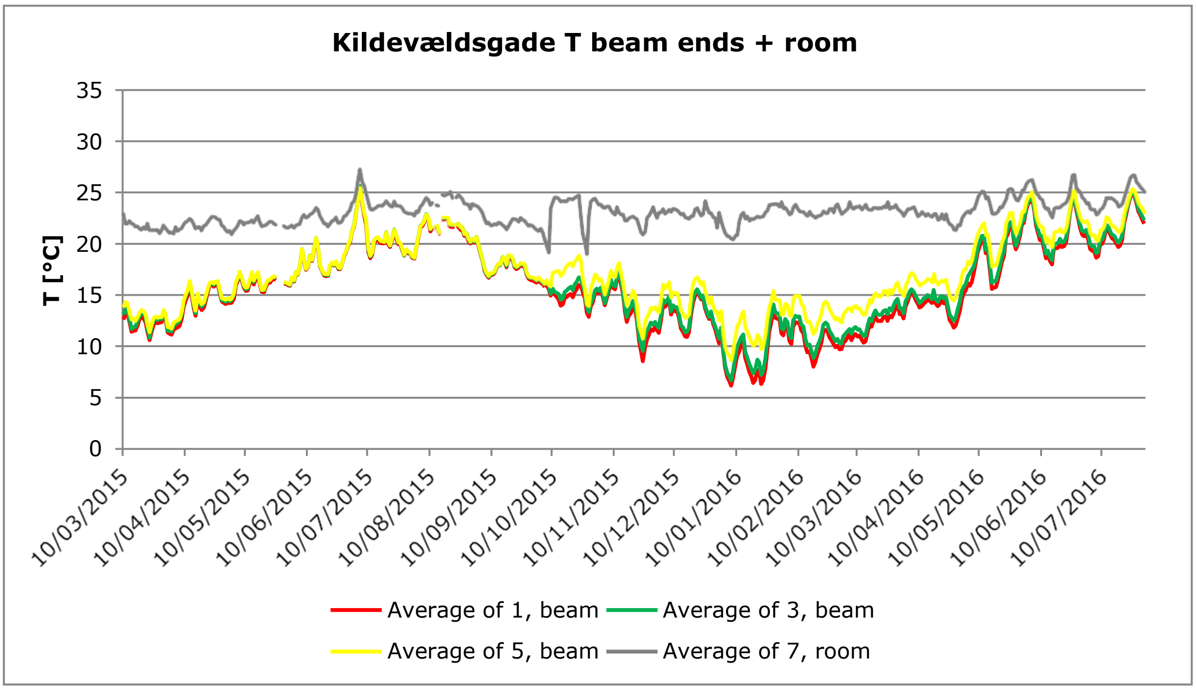


Figure 19: Temperature measurements from Kildevældsgade, at beam ends, as well as room conditions

5.2.4 Ny Allegade – iQ-Therm without vapour barrier

The relative humidities measured at the interface between the existing walls and insulation, Figure 20, are nearly 100 % for the entire measurement period. It is known, that the mortar used for installation of the insulation plates takes time to dry, however, there is currently, after 13 months of measuring, no indication of reduced relative humidity. However, according to a German study [16] it is seen that the relative humidity should start decreasing after 1 year and after 5 years the relative humidity is registered to have decreased until 80 % relative humdity. The measured values are not acceptable at the moment after one year of measurements, but it is too early to carry out any conclusions on the humidity levels. However, it can be discussed if it is a problem that the relative humidity stays above 80% for 5 years. No difference between sensors 4 and 6 (west) and 7 (south) are observed. Temperature measurements, Figure 21, show seasonal variation, summer conditions resembling interior conditions.

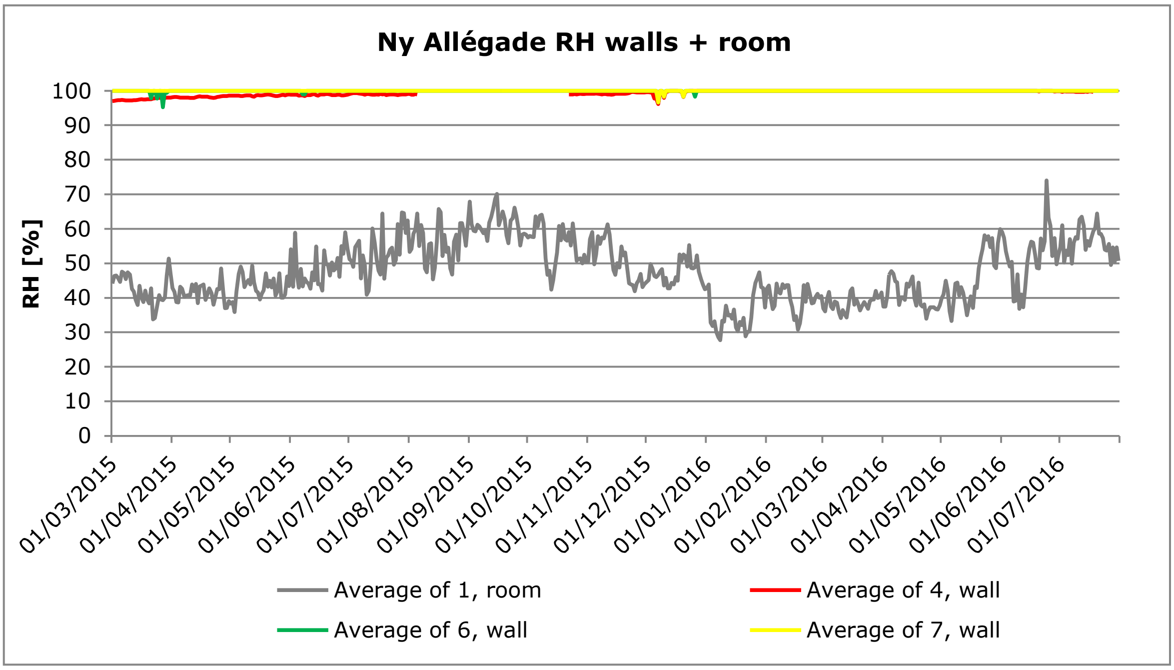


Figure 20: Relative humidity measurements in Ny Allegade, at interface between internal insulation and existing wall, as well as room conditions

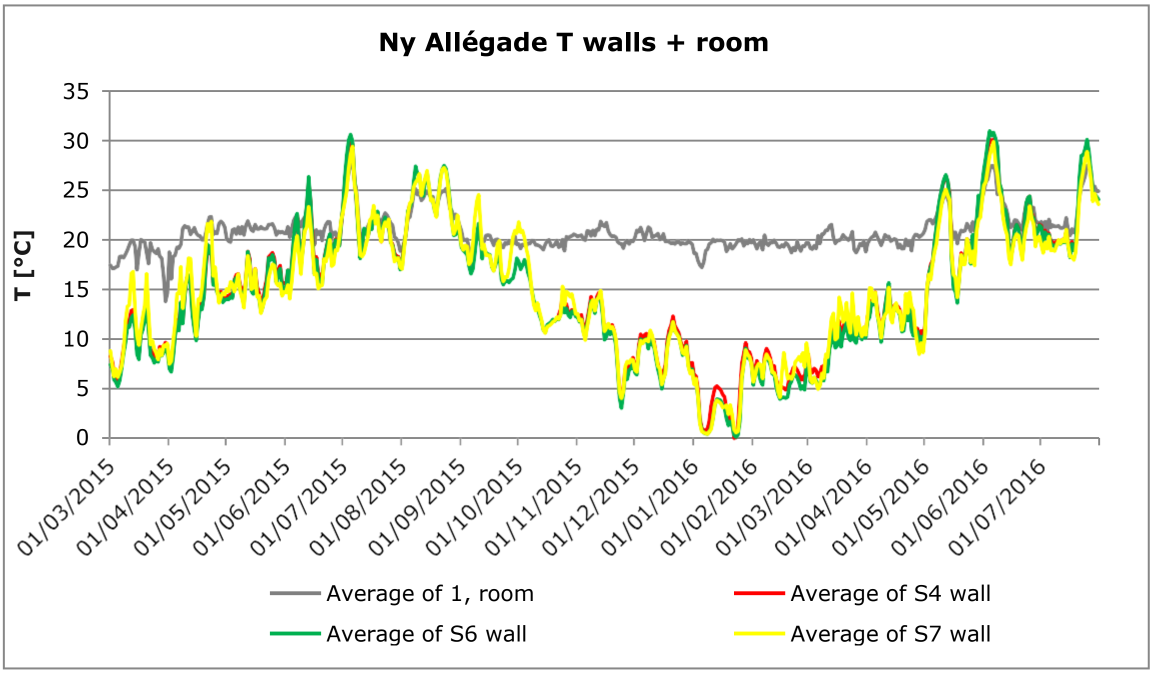


Figure 21: Temperature measurements from Ny Allegade, at interface between internal insulation and existing wall, as well as room conditions.

Relative humidities measured in beam ends, Figure 22, also show high values (above 90%) for sensors 3 and 5. Sensor 5 shows slightly higher relative humidity than sensor 2. Sensor 5 is located closer to the corner of the building, and is therefore more subjected to wind driven rain, which is a possible explanation to these discrepancies (however small). Sensor 2 measures a relative humidity of 70-80 % during the course, and also a higher temperature, as seen in Figure 23. These results are possibly caused by a wrong installation, where the sensor simply has not been drilled all the way to the beam end, and been placed incorrectly. In this case, the measurements may be affected by the indoor temperature and therefore not representative for the beam end, and should be discarded. In general, the measurements performed at Ny Allegade do not show satisfactory results at the present. A combination of insufficient capillary activeness and the omitted vapour barrier, may be cause of possible condensation, hence the high relative humidities.

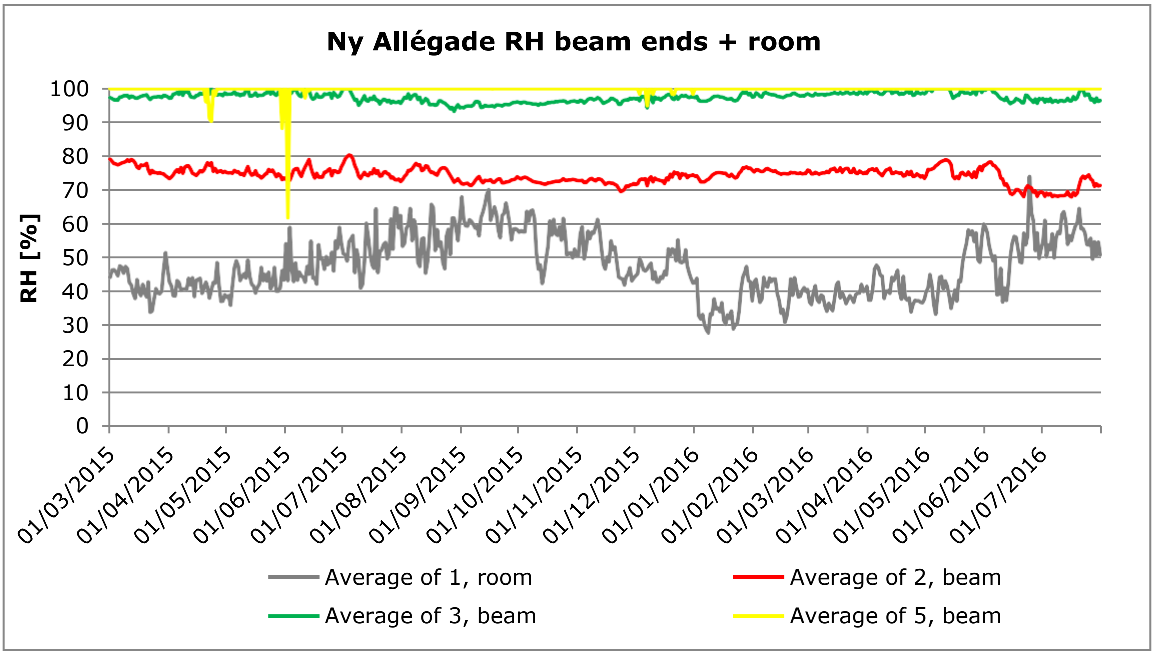


Figure 22: Relative humidity measurements in Kildevældsgade, at beam ends, as well as room conditions

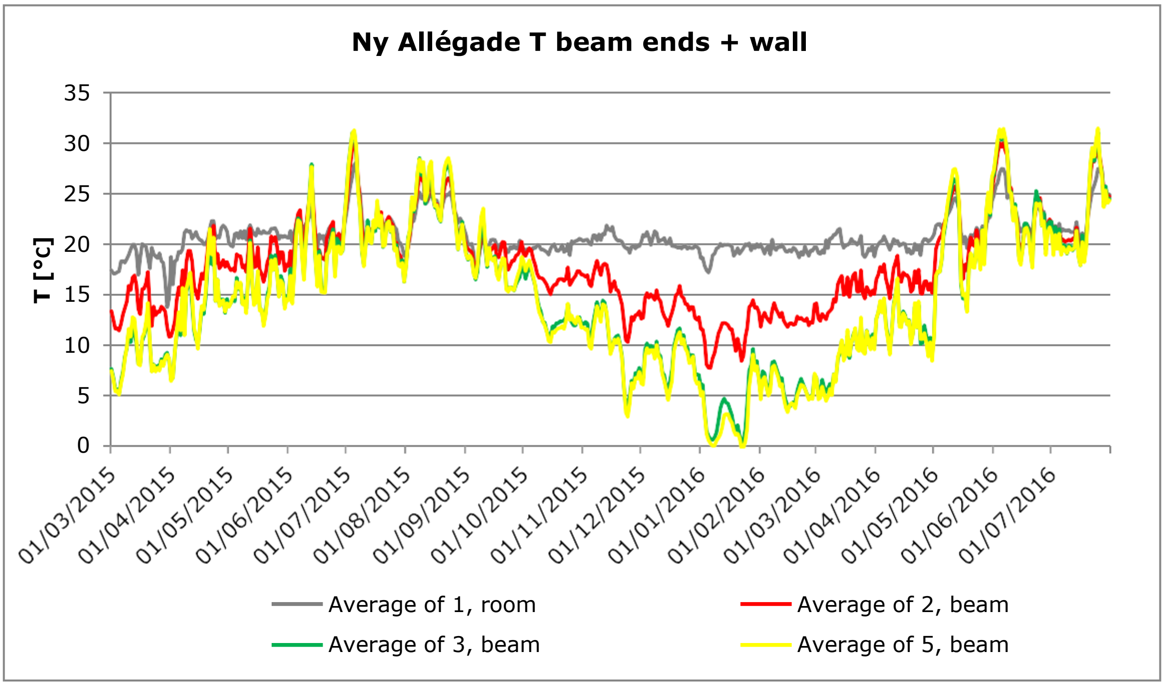


Figure 23: Temperature measurements from Kildevældsgade, at beam ends, as well as room conditions

5.2.5 Thomas Laubs Gade - iQ-Therm without vapour barrier

The renovation in Thomas Laubs Gade came relatively late in regards to measurements, and only approximately 6 months of measurements are currently registered. The conditions at the wall-insulation interface show very high relative humidities (Figure 24), though with a slow, continuous decline. The initially high values for relative humidity are assumed to be built-in moisture. Sensor 3, placed under the window, exhibits the highest relative humidity, but also the lowest temperature, see Figure 25, as the infill wall is thinner the exterior conditions influence the temperature.

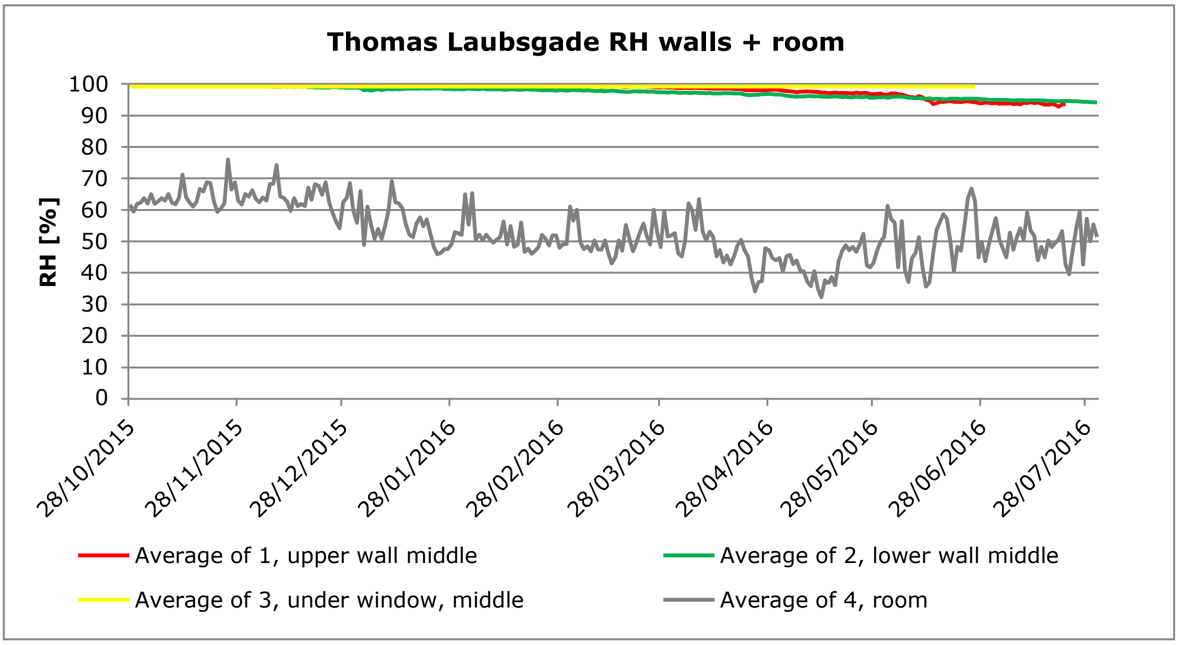


Figure 24: Relative humidity measurements in Thomas Laubs Gade, at interface between internal insulation and existing wall, as well as room conditions

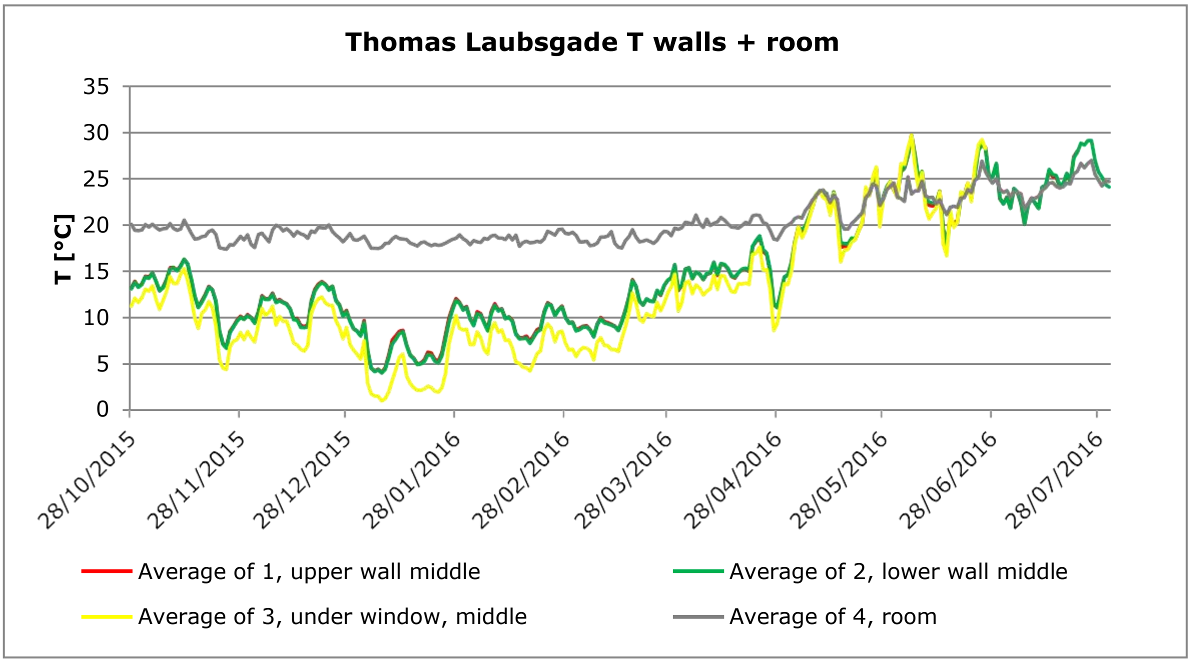


Figure 25: Temperature measurements from Thomas Laubs Gade, at interface between internal insulation and existing wall, as well as room conditions

5.2.6 Mønsgade – Kingspan with Vapour barrier

The relative humidities measured in the wall construction at Mønsgade, Figure 26, become relatively stable with values of 60-70 % - larger fluctuations occur during winter (barely exceeds 80%). The conditions in the sensor drilled into the façade, expectedly shows higher relative humidities. The conditions appear to be acceptable; however, measurements have only been performed for 8 months. The façade is rendered, which could have a positive effect and less wind-driven-rain is absorbed by the façade.

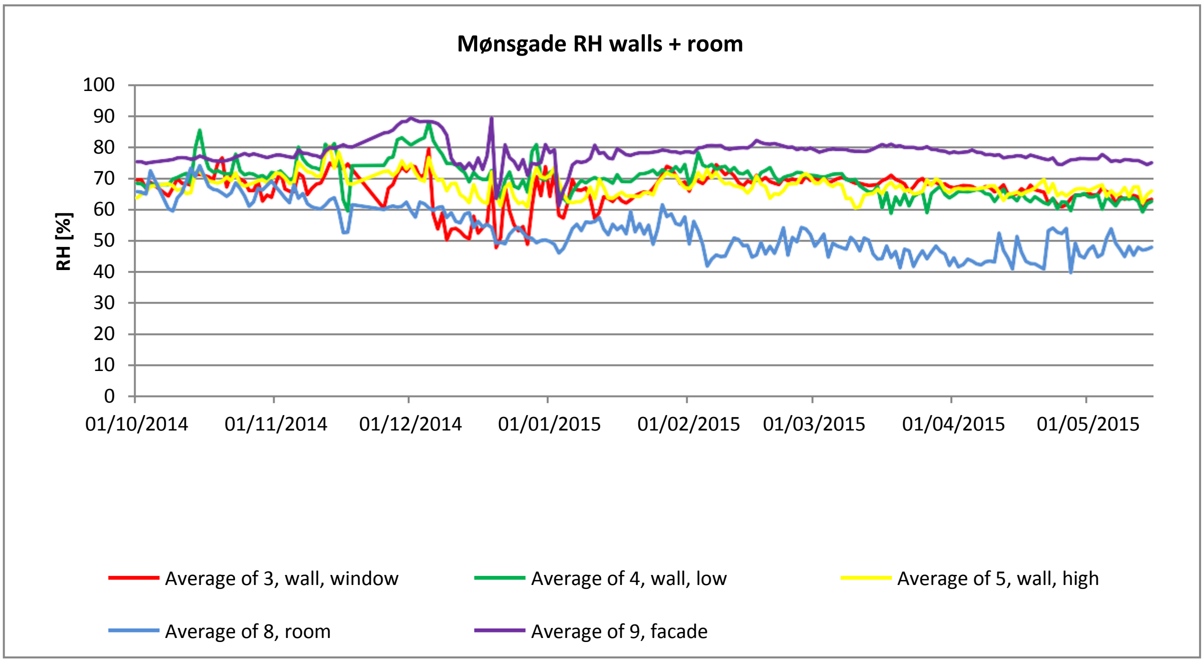


Figure 26: Relative humidity measurements in Mønsgade, at interface between internal insulation and existing wall, in the façade towards external conditions and room conditions

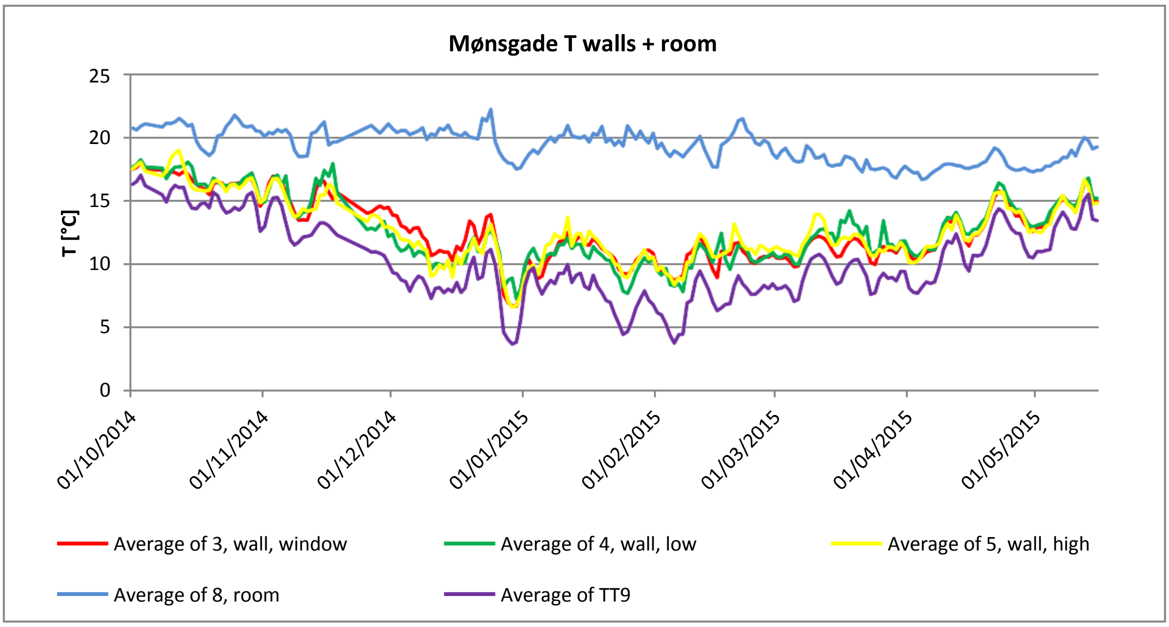


Figure 27: Temperature measurements from Mønsgade, at interface between internal insulation and existing wall, in the façade towards external conditions and room conditions

Figure 28 depicts relative humidity in the beam ends at Mønsgade. As in the wall construction, fluctuations are seen during winter, but generally the relative humidity is 60-80%, and appears to be declining for sensors 1, 2 and 6. The lowest relative humidity is found in the middle beam, and the highest relative humidity is found in the beam under the window, sensor 7, where the external wall is thinner.

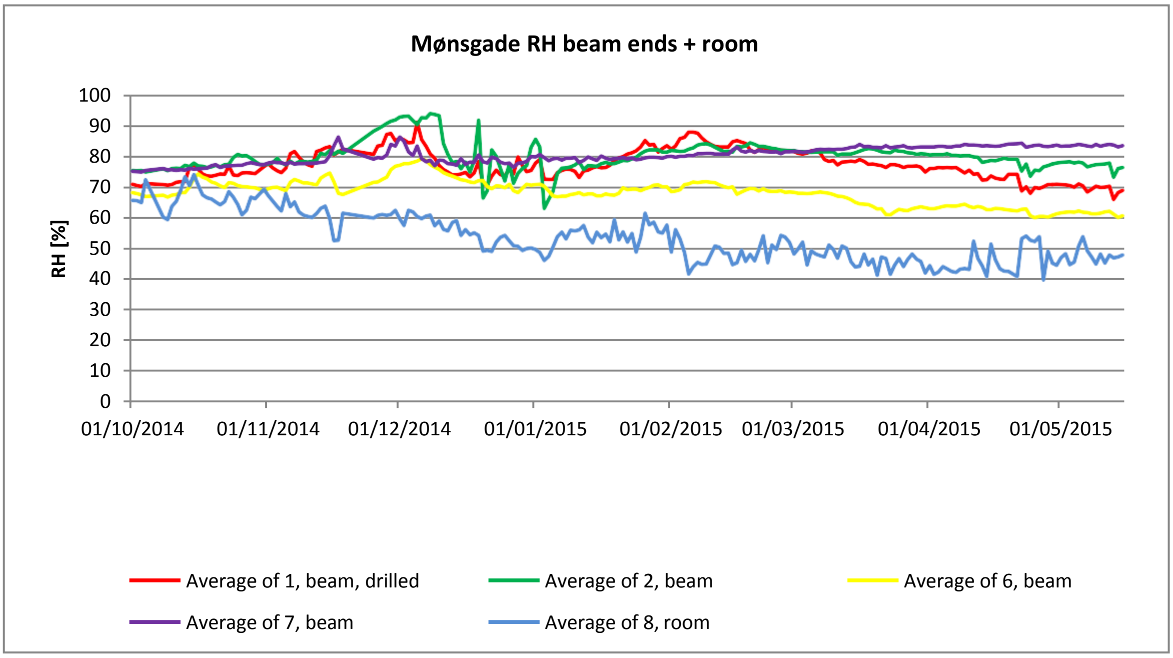


Figure 28: Relative humidity measurements in Mønsgade, at beam ends, as well as room conditions

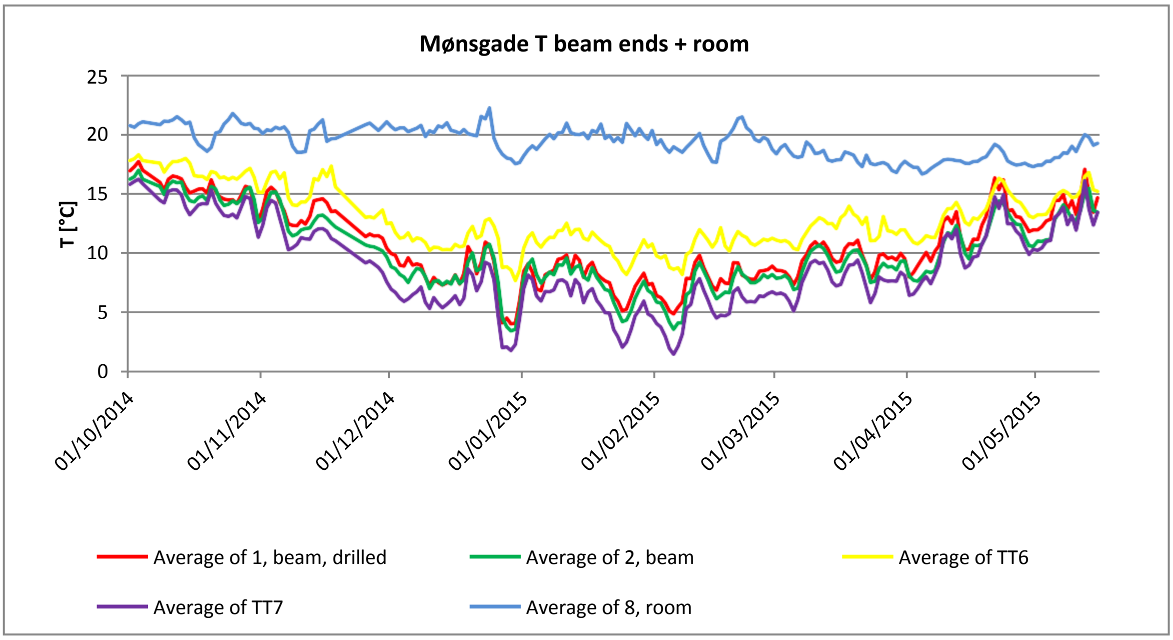


Figure 29: Temperature measurements from Mønsgade, at beam ends, as well as room conditions

5.2.7 Ryesgade 30 – follow up

Figure 30 and 31 show the temperature and relative humidity measurements on the 4th floor and figure 32 and 33 show the temperature and relative humidity measurements on the 5th floor.

As shown in Figure 31 and 33, the relative humidity is less than 75% at all times (for both the 4th and the 5th floor) except for point 3 on the 5th floor, which has RH>75% during the first months, probably due to built-in moisture. Point 3 on the 5th floor has generally higher relative humidity and a lower temperature than the other points, since the façade is facing directly west and exposed to less sun. From the measurements it seems that there is no risk of mould growth and other moisture problems.

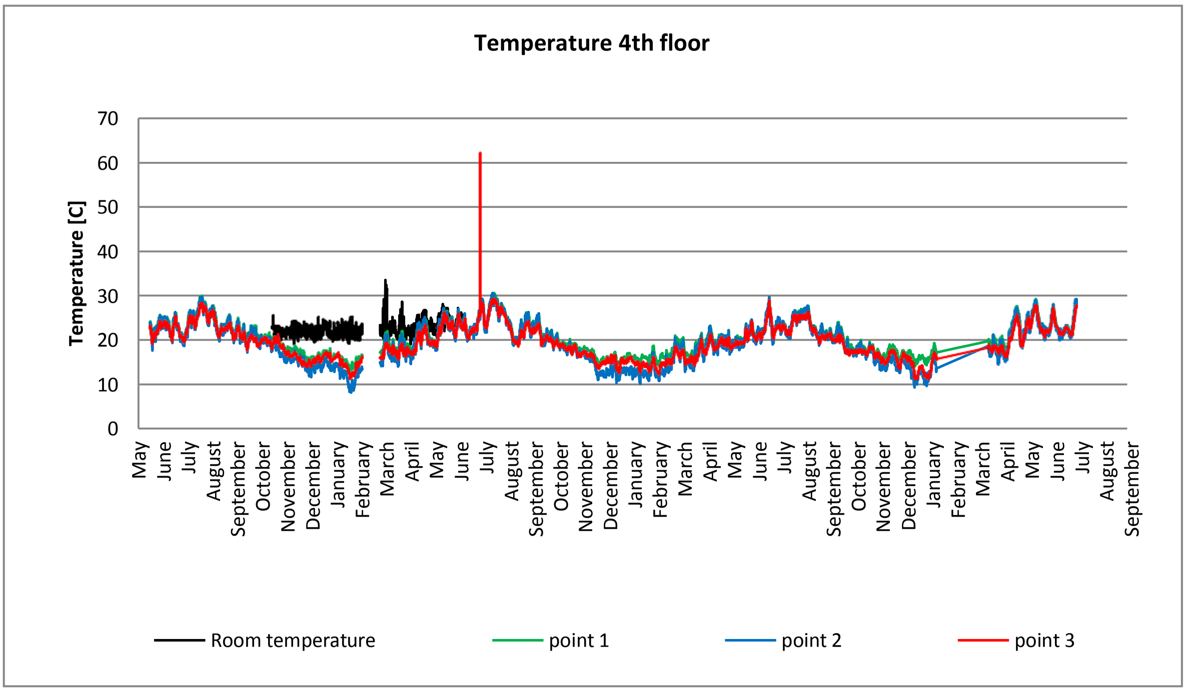


Figure 30: Temperature measurements on the 4th floor from Ryesgade 30 at beam ends.

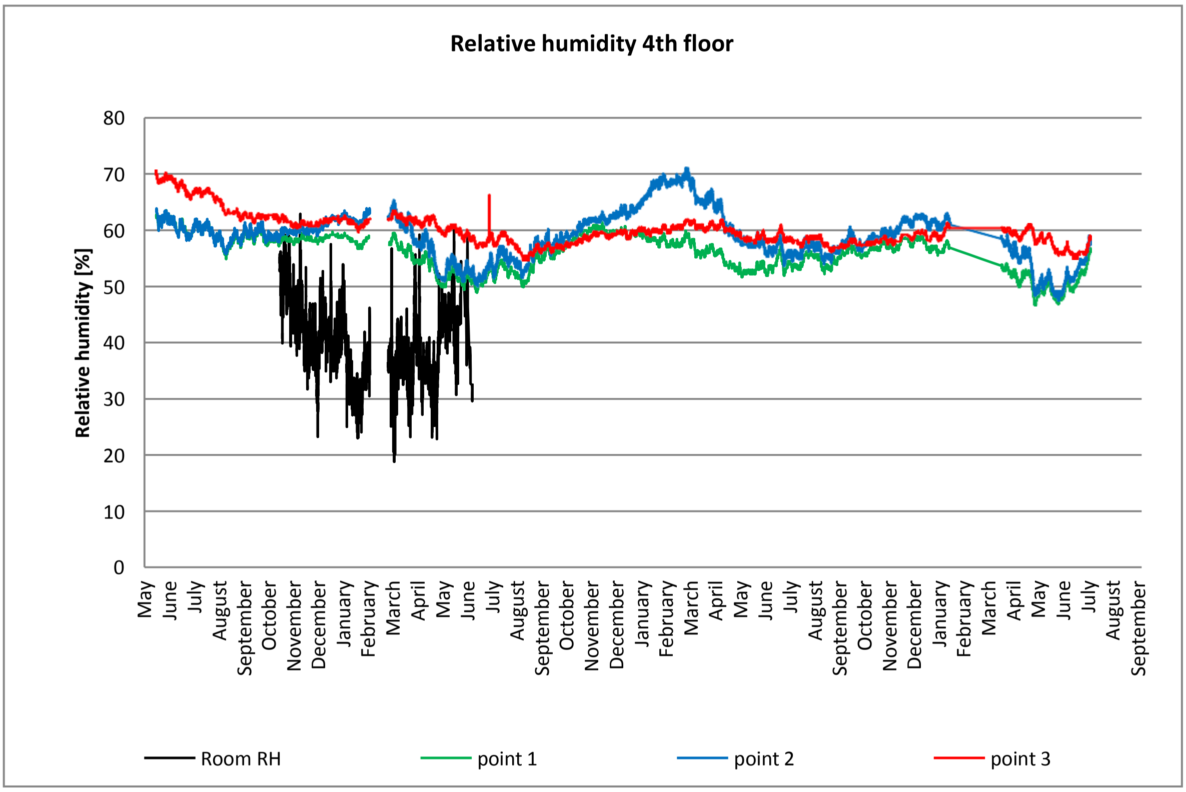


Figure 311: Relative humidity measurements on the 4th floor from Ryesgade 30 at beam ends.

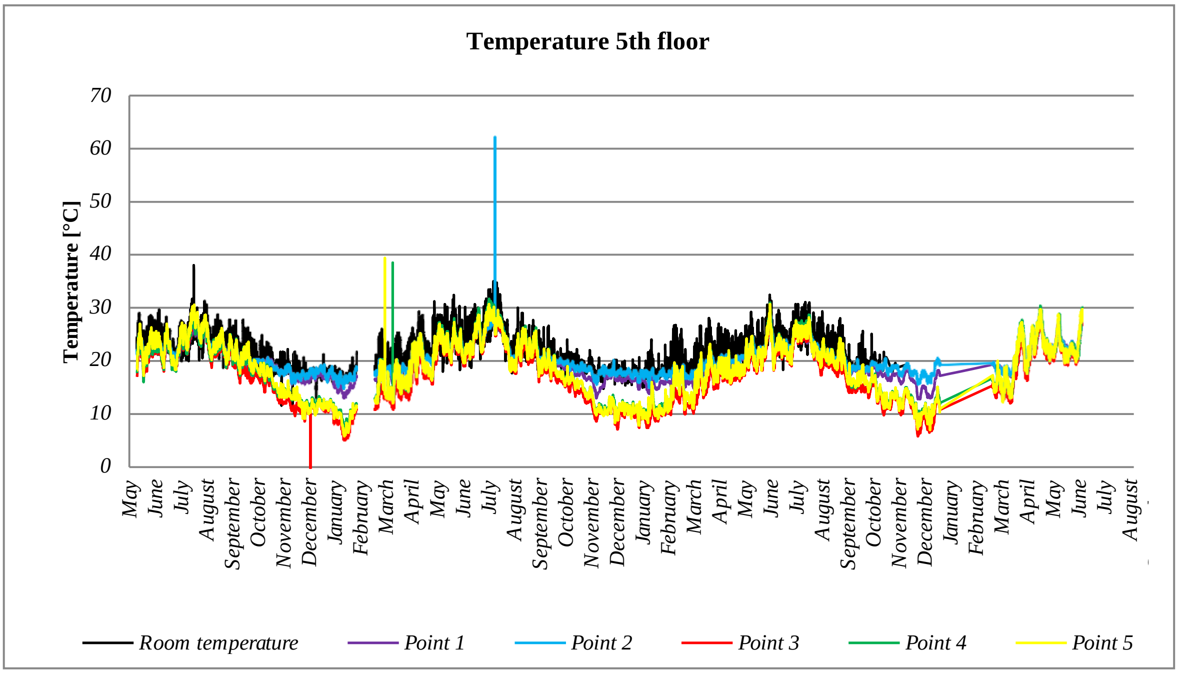


Figure 32: Temperature measurements on the 5th floor from Ryesgade 30 at beam ends.

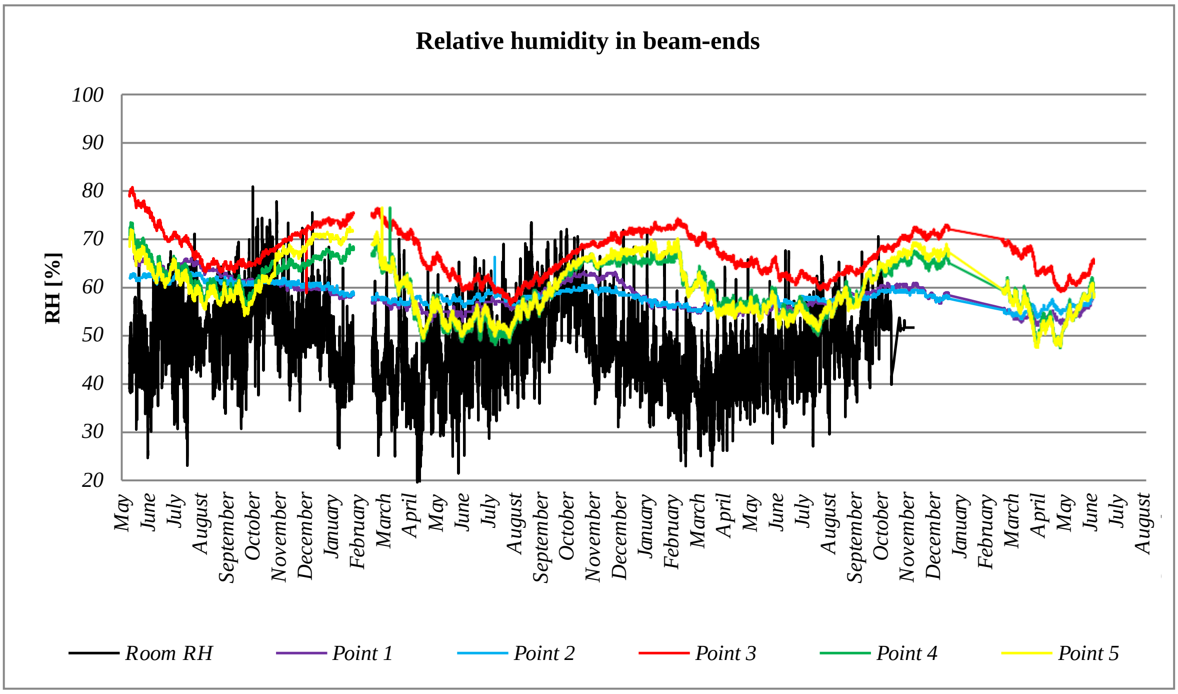


Figure 33: Relative humidity measurements on the 5th floor from Ryesgade 30 at beam ends.

5.3 Mould index

For assessment of mould risks in the monitored cases, the improved mould model [17] (based on the VTT mould growth model [18]) has been implemented for determination of mould growth index. The improved mathematical model takes various materials and sensitivity classes into consideration.

Favorable mould growth conditions are generally dependent on temperature and relative humidity conditions, as well as exposure time. The model is initially developed for prediction of mould growth on (wooden) surfaces [17], why the predicted risks of mould growth should be taken with precaution. However, the assessment of the risk for mould growth can be used to compare performance of different solutions. The mould growth index describes the growth rate of mould by a number ranging from 0-6. The description of the mould growth index range is found in Table 1 If the mould growth index is below 1, there is no mould growth.

Table 1: Description of mould growth index classifications [19]

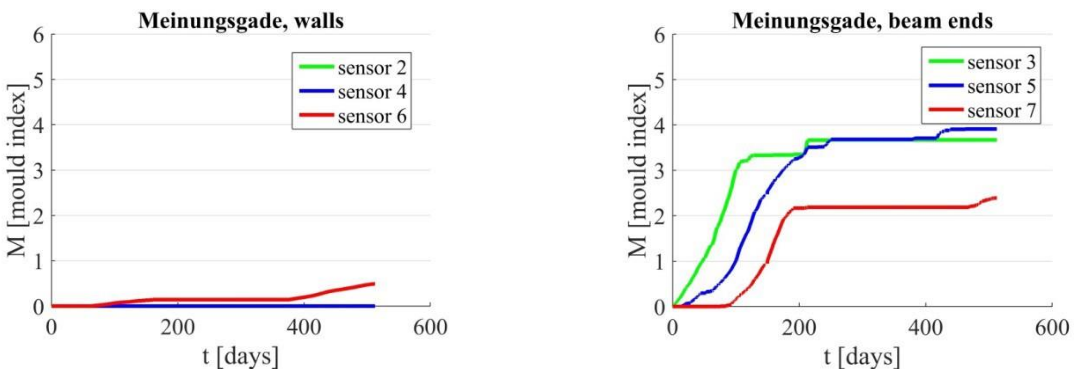
Index	**Growth rate**	**Description**
0	No growth	Spore not activated
1	Small amounts of mould on surface (microscope)	Initial stages of local growth
2	<10% coverage of mould on surface (microscope)	Several local mould growth colonies
3	10-30% coverage mould on surface (visual)	New spores produced
4	30-70% coverage mould on surface (visual)	Moderate growth
5	>70% coverage mould on surface (visual)	Plenty of growth
6	Very heavy and tight growth	Heavy growth, coverage around 100%

The mould model is applied to measured results, by means of a MATLAB R2015a script. The wooden beam ends are considered to be "very sensitive" (untreated wood, includes lots of nutrients for biological growth), and the interface between the existing wall and internal insulation is considered "medium resistant" (Cement or plastic based materials, mineral fibres). Parameters for the applied sensitivity classes are given below in Table 2. RH_{min} indicates the level of relative humidity that is considered to be the lowest to allow mould growth for a long exposure time. A, B and C are coefficients dependent on the material sensitivity class. The factor k_1 represents the intensity of growth. Furthermore, a coefficient of decline in mould intensity of 0.5 (moderate decline) during unfavorable conditions has been assumed as a qualified attempt to produce results on the safe side.

Table 2: parameters given for the applied sensitivity classes

Sensitivity class	**RH_{min}**	**A**	**B**	**C**	**k_1 M<1**	**k_1 M≥1**
Very sensitive	80%	1	7	2	1	2
Medium resistant	85%	0	5	1.5	0.072	0.097

Results from the mould growth models, are seen in Figure 34 below.



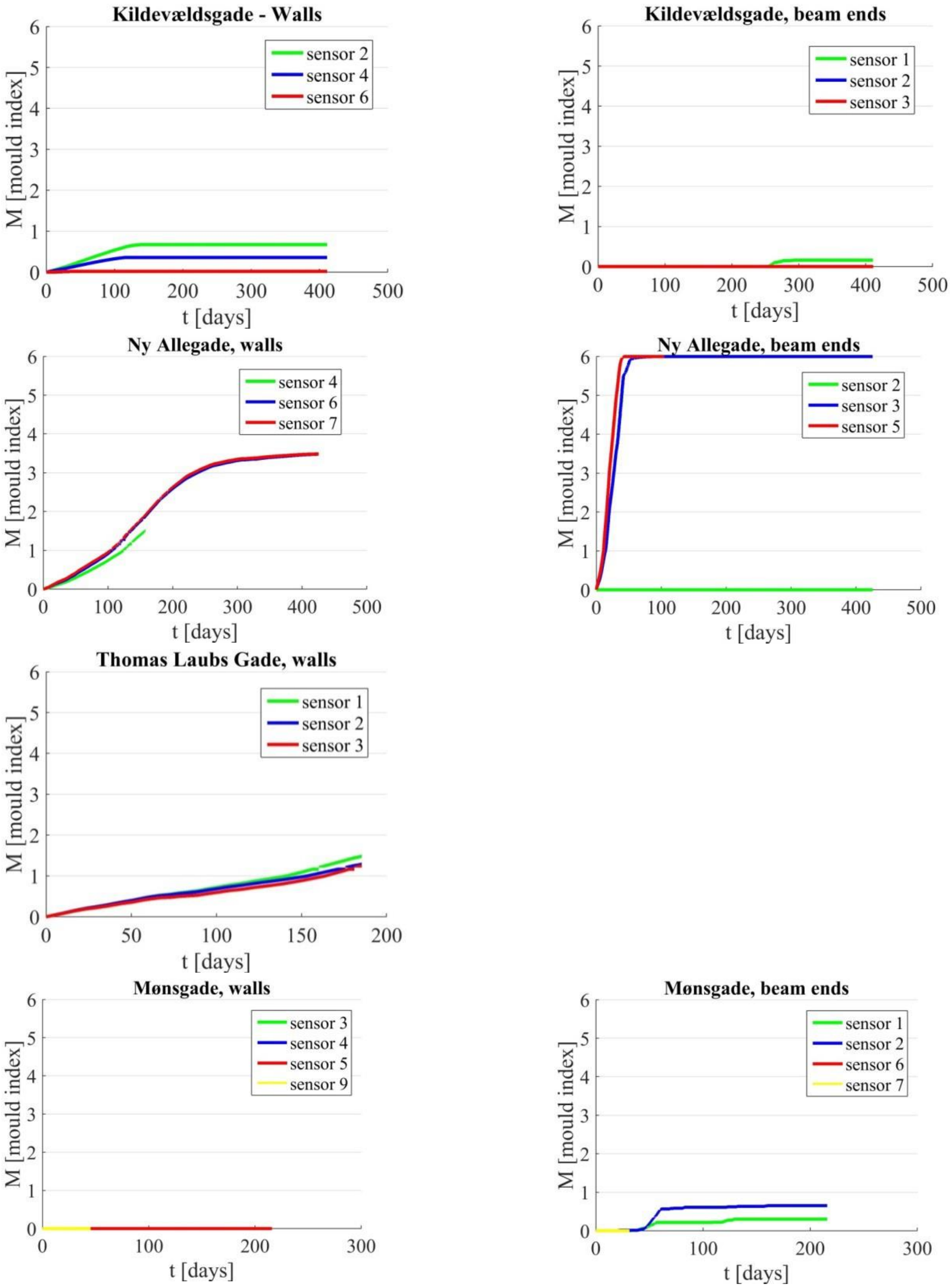


Figure 34: Mould growth index for all cases presented in the project.

As seen in Figure 34, there is a large difference in mould growth index between the various cases, and even between interface and beam ends within single cases. In Kildevældsgade and Mønsgade the mould growth index at no time exceeds 1, and the constructions are considered "safe" in regards to mould growth. Both these cases have rendered façades, and are insulated with Kingspan K17 (25 and 50 mm respectively) and have installed vapour barriers and air gaps around the beams. It is also seen in the measured results that the relative humidity in walls and beam ends for these two cases, is hardly above 80% (Figure 16, Figure 18, Figure 26, Figure 28).

It is also seen in Figure 34, that Thomas Laubs Gade has a slowly increasing mould growth index. However, the measurements have, at this point, not been carried for more than 6 months, and the relative humidity appears to be decreasing, see Figure 24.
Meinungsgade appears to have acceptable mould index behind the internal insulation. However the beam ends seem to be disposed to risky mould conditions. This is despite the fact that a 20 cm air gap was left around the beam, as an intentional thermal bridge for increased temperature in beam ends. The measurements show that the relative humidity in the beam ends lies relatively constant between 80-90% in the measuring period, and only a slight decline is apparent during the summer. As the building is from 1877, the façade can be assumed to be somewhat weathered. The façade is only 1½ brick thick, and the embedded beam end is possibly 1 brick thickness (or less) from the external surface. In addition, the case is very exposed to wind driven rain, as it is located on the 4th floor and in south west direction. For these reasons, it is probable that driving rain is an influential factor to the high relative humidities measured in these beam ends.
In the section 2. Measurement Results, it is clearly seen that the relative humidity in both beam ends and at existing wall-internal insulation interface in Ny Allégade are high for the entire measurement period. This is also reflected in the calculated mould growth risk, as seen in Figure 34. The case has 80mm capillary active IQ-Therm insulation, no vapour barrier and no air gap around the beams. It seems that the applied insulation has thus far, not had sufficient capillary active capabilities for drying out the glue mortar during the first year. The high humidities in the beam-ends, are likely linked to the decreased temperature and drying potential. Only measurements from sensor 2, in the beam towards the middle of the façade, has OK conditions in regards to the predicted mould growth, but as mentioned this sensor is likely placed faulty, and results disregarded.
As previously mentioned, the model was developed for superficial mould growth on (wooden) surfaces. The results are therefore estimates of the risk of mould growth. It is unknown how the limited access of air behind fully bonded insulation plates, or in beam end, influences the risk of mould growth.

5.4 Delphin modeling

There are various uncertainties involved in hygrothermal modeling; nevertheless they are valuable tools for prediction and analysis. This project has produced a wide range of valuable in-situ measurements, which can be used for further work and analyses by using them to validate simulation models. These models can then create fast theoretical indications of future and long term hygrothermal conditions when applying internal insulation. In this project the validation of Delphin model has started as an extra supplement to the measurements and documentation created within the scope of this project. The validation of a hygrothermal model is a time consuming process, and the work with validation and measurements performed will continue, and prospectively bring valuable information and contribution to the research area of internal insulation in historical buildings. The work with the in situ measurements and validation of models will continue as important work for the European Union funded Horizon 2020 project, RIBuild (Robust Internal Thermal Insulation of Historic Buildings).

Uncertainties in regards to the hygrothermal models include unknown material parameters for historic brick, mortar and wood, assumptions of various exchange coefficients, unknown conditions/materials around beam ends, unknown initial conditions of moisture content in the masonry, the amount of wind-driven-rain on the facades, and the general condition of the exterior surface. The validation process is therefore also a sort of parameter analysis. In this report, the preliminary work with the validation process will be described.
The hygrothermal simulation program Delphin 5.8.3 has been used for modelling two of the cases; Meinungsgade and Ny Allegade. The models are made for areas of risk, namely beam ends and the interface between the existing wall and internal insulation, in the internally insulated cases of

Meinungsgade and Ny Allegade, 60mm Kingspan and 80mm IQ-Therm respectively (described in section 5.1.1 and 5.14). As the conditions in these locations have been monitored for more than a year, this data can be used for validations. The model constructions and output locations are seen in Figures 35-38. However a mistake has occurred in the application of the internal insulation in Meinungsgade. Initially the plan was to create an airgap above and below the floor construction but in practice an airgap was only created above the floor construction. However, the Delphin simulations are performed with an airgap above and below, which creates a small difference between measurement and calculated results.

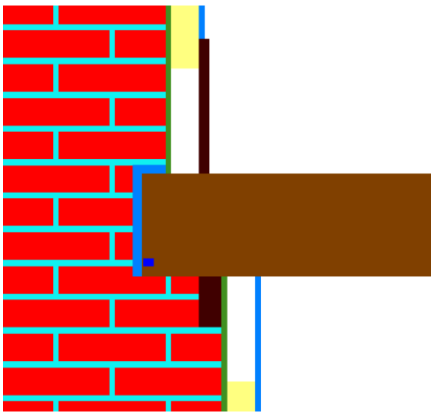


Figure 35: Meinungsgade, beam end model

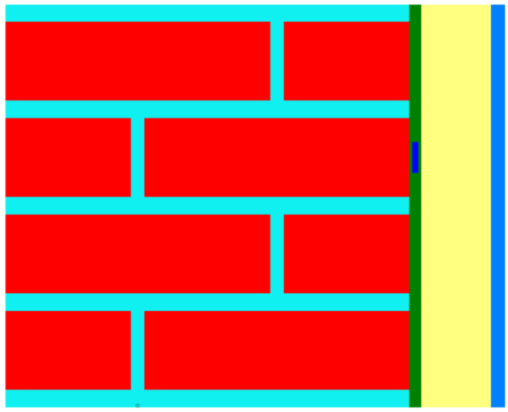


Figure 36: Meinungsgade, wall-insulation interface model

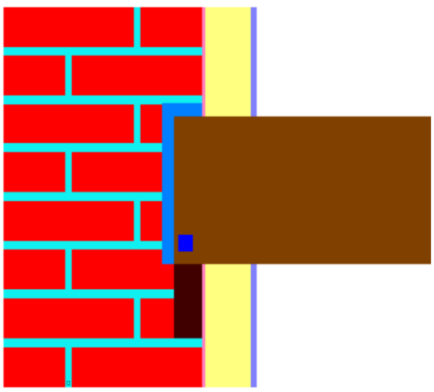


Figure 37: Ny Allegade, beam end model

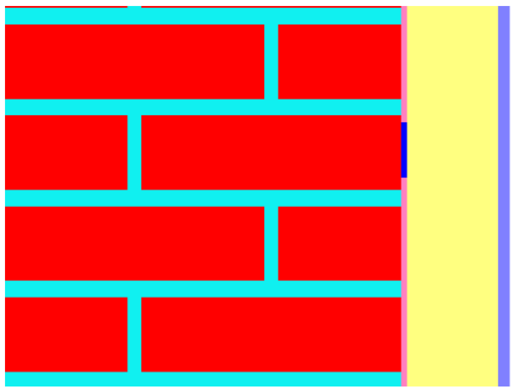


Figure 38: Ny Allegade, wall-insulation interface model

Materials were selected from the Delphin database, and provided in Table 3.

Table 3: Materials used in hygrothermal models

Both cases	**Ny Allegade**	**Meinungsgade**
Brick Joens	iQ-Fix	Glue mortar (For Mineral Insulation Boards)
Lime Cement mortar	iQ-Therm	Kingspan K17*
Spruce SW Longitudinal (baseboard and lath)	iQ-Top	Gypsum board
Spruce SW Radial (beam)		

*Kingspan K17 was created from Polystyrene Board - Extruded, altered with manufacturers data for specific heat capacity, thermal conductivity and water vapour diffusion resistance factor.

Local weather data has been collected, for the measurement periods, from the Danish Meteorological Institute (www.dmi.dk) for the modelling of boundary conditions externally. In Table 4 the periods of collected data as well as gathered climate conditions are seen. As seen in the table, models from Meinungsgade initiate in April 2015, and Ny Allegade initiates in March 2015. For validation, measured data from the same period is used.

Table 4: Local weather data for simulations

Weather data	**Case**	**Period**
Copenhagen	Meinungsgade 1	01.04.2015 – 31.03.2016
Haderslev	Ny Allegade 10	01.03.2015 – 29.02.2016
Climate conditions		**Utilized in boundary condition:**
Temperature	°C	Heat conduction, vapour diffusion, rain
Relative humidity	%	Vapour diffusion, rain
Rain on horisontal plane	$l/(m^2h)$	Rain
Wind velocity	m/s	Rain
Wind direction	°	Rain
Direct sun radiation (derived from global)	W/m^2	Short wave radiation
Diffuse sun radiation (derived from global)	W/m^2	Short wave radiation
Atmospheric counter radiation (derived from temperature, relative humidity and cloud cover)	W/m^2	Long wave radiation

The weather data is treated cyclic, and the simulations run for 5 years in order to achieve realistic initial conditions. However, it must be noted, that treating one year's weather data cyclic, is not representative of any actual period. The interior conditions are set to measured values of temperature and relative humidity for the individual cases. In Meinungsgade all the sensors (both beam ends and wall-insulation interface) are placed in southwest direction, as in the models. In Ny Allegade, the beam ends and two wall-insulation interface sensors face west, whereas one sensor in wall-insulation interface faces south, which is represented in the models.
In the following, the results from the hygrothermal simulations this far will be presented. Note that there is room for improving the models, which is an ongoing process that is currently underway. The investigation will continue within a different framework. For validation of models, and for the results presented, the 5th year of simulation is used (unless otherwise noted), as the initial conditions are uncertain. After 4 years of simulation, the conditions will have settled at more realistic values.

Figure 39 illustrates 5 years (1825 days) of simulation in the beam end in Meinungsgade. The initial condition for relative humidity in the beam end was increased from 80% - 92% in an attempt to achieve a representative 5th year. It is seen in the figure that the relative humidity in the beam end is increasing year by year, but the increase of initial relative humidity in the beam end, has very little effect on the 5th simulation year. The simulations were therefore completed with initial relative humidity of 80 %. The models for wall-insulation interface showed representative data after a few years of simulation.

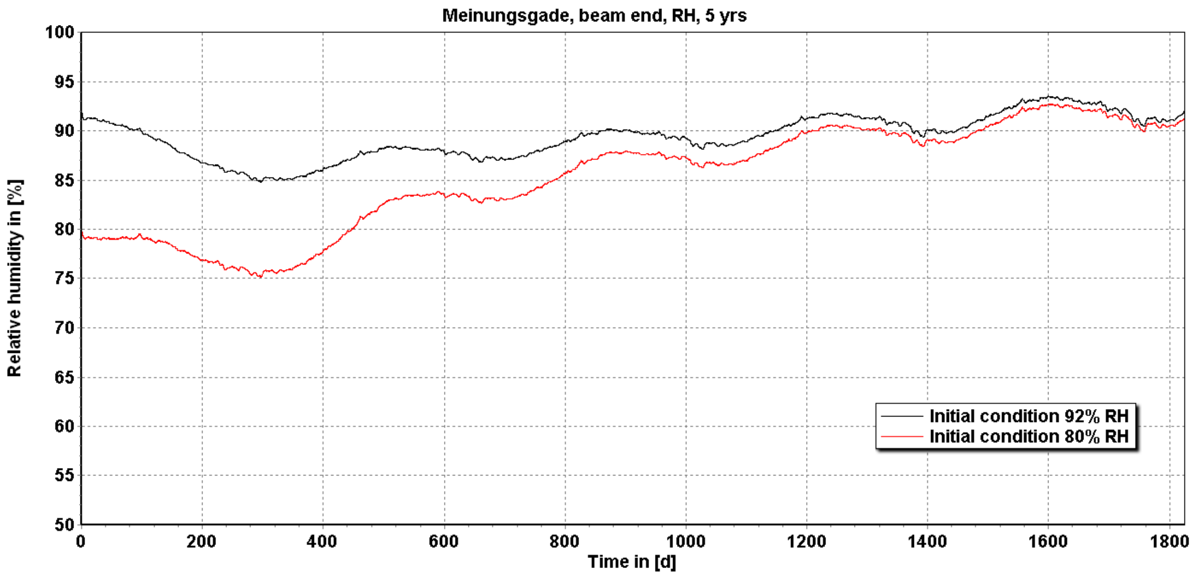


Figure 39: Relative humidity in beam end of Meinungsgade, 5 years simulation

For the initial period of the validation process, the wind-driven rain (WDR) factors have been altered. The WDR factor expresses how much rain that strikes the façade. This can be expressed by rain intensity vectors, which make up the catch ratio or the rain exposure coefficient (WDR factor) [20,21]:

$$CR(t) = \frac{Rdr\ (t)}{Rh(t)}$$

Where

CR(t) = Catch ratio (WDR-factor)

Rdr(t) = Driven rain intensity (integrated over all raindrop diameters)

Rh(t) = Unobstructed horizontal rainfall intensity (integrated over all raindrop diameters)

The WDR factor has a large influence on the relative humidity found in the walls and beam ends, as illustrated in Figure 40 for a case of wall-insulation interface. The same tendency is apparent in beam ends. The WDR factor is in many cases unknown and therefore a wild-card in hygrothermal modelling, however it can be essential for the results achieved.

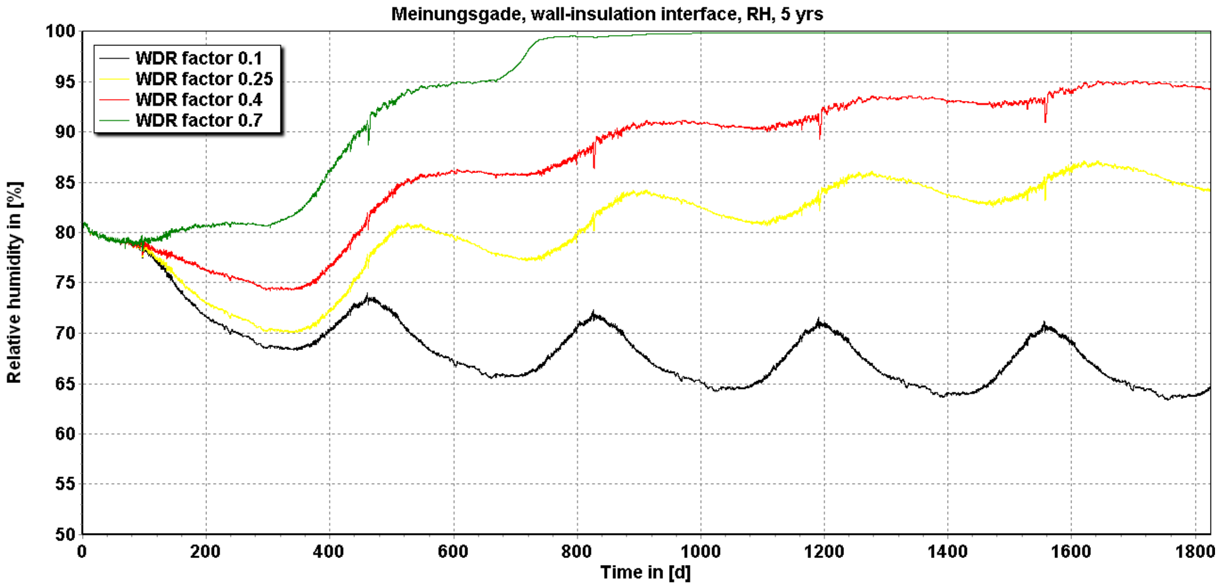


Figure 40: Impact of WDR factor on relative humidity in wall-insulation interface, Meinungsgade

Figure 41 shows temperature measurements from the sensors in the beam ends at Meinungsgade as well as the simulated data for the case. The same tendencies are apparent, and it's clear that the WDR factors in simulations do not affect the temperature. It is seen, that the simulations in general have slightly lower temperature values despite the fact that an airgap is create both above and below the floor construction in the model whereas it is only created above in reality (measurements). This confirms that leaving out the insulation seems not to have the expected effect. The differences between the measurements and the calculated results are due to uncertainties in the Delphin program and in the measurement equipment. Larger discrepancies are seen in measurement peaks, which can be caused by the unknown conditions in the beam ends. In the current models, the beam ends are surrounded by 20mm air, but in reality it could be mortar/dirt/etc. with a higher thermal conductivity that which could affect the temperature in the beam ends. Also, the absorption coefficient for short wave radiation is set to 0.6, corresponding to a medium gray wall. This could be increased due to the darker red brick surface, and would likely contribute to producing a better fit.

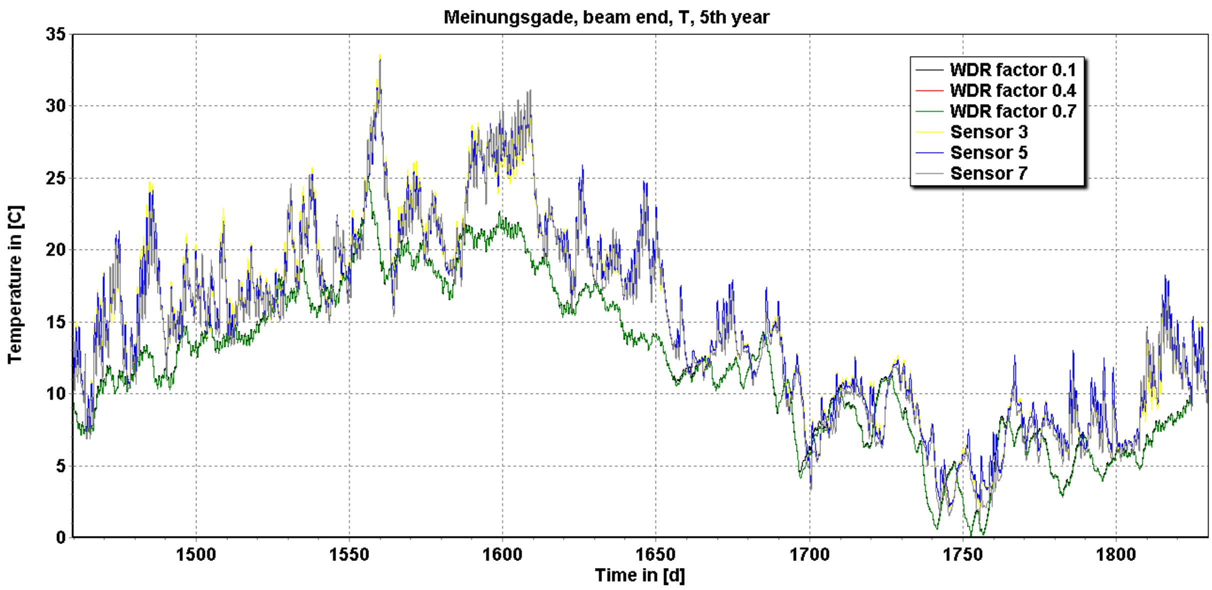


Figure 41: Temperature measurements and simulation results for beam end in Meinungsgade

The simulated and measured relative humidities in the Meinungsgade beam end are seen in Figure 42. As shown in Figure 42, the WDR factor has a large influence on simulated results. It is seen, that WDR factor 0.4 is very similar to measurements in sensor 5 from April until approximately October (day 1675). At this point, the measured relative humidity in sensor 5 increases, and resembles a WDR factor of 0.7 for January-February. Large fluctuations are seen in measurements from sensor 3 and 7; however, WDR factor 0.4 seems the best fit in an overall assessment. The unknown material characteristics of the existing wall, e.g. water uptake coefficient of brick and mortar, also have an impact on the simulated results for relative humidity. Alterations in these parameters may yield better fits, but ultimately material characterization of prospective cases would be preferred.

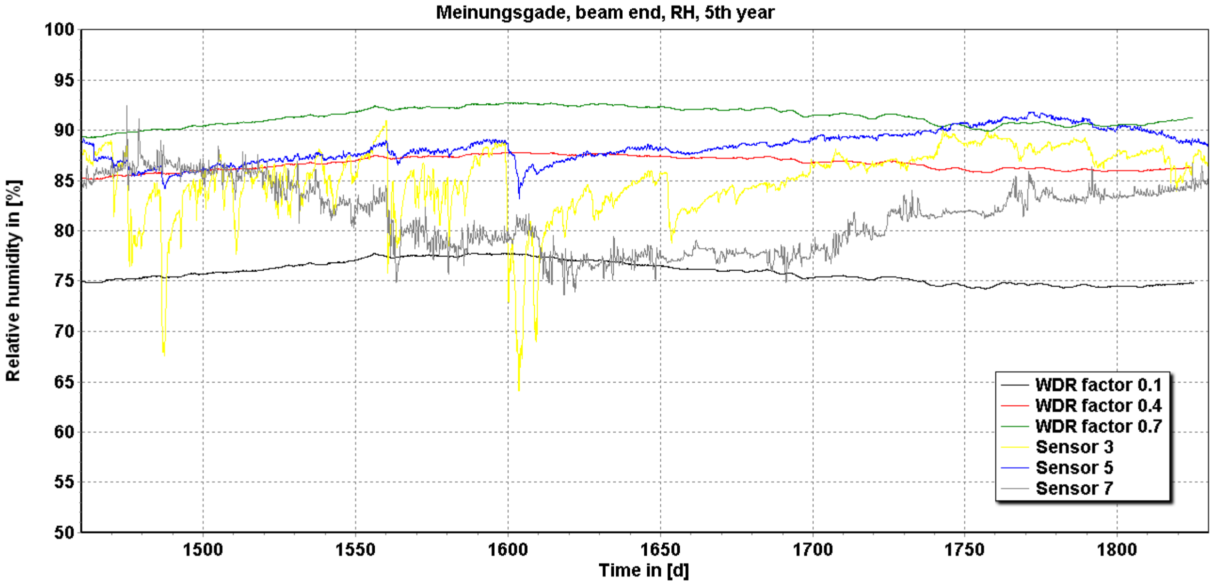


Figure 42: Relative humidity measurements and simulation results for beam end in Meinungsgade

Temperature measurements and simulation results for the wall-insulation interface are depicted in Figure 43. Again it is apparent, that WDR factor doesn't influence the temperature conditions. It is apparent, that temperature measurements and simulation results are coinciding until the middle of August (day 1600). The simulation results hereafter show lower values than the measured for the fall/winter/spring period. This could be partly explained by the absorption coefficient described previously, but perhaps also an inaccurate thermal conductivity of the insulation material could explain the results.

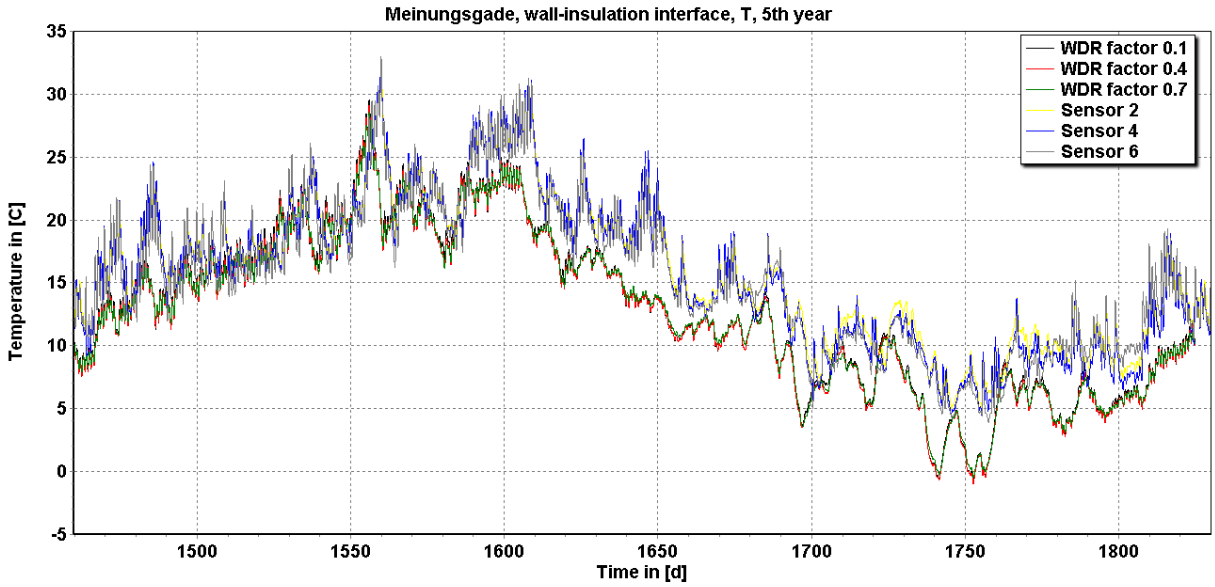


Figure 43: Temperature measurements and simulation results for wall-insulation interface in Meinungsgade

The relative humidities measured and simulated, are shown in Figure 44. The seasonal fluctuations are barely apparent in simulation results. Only a slight variation is seen with WDR factor 0.1. The measurements have large fluctuations showing significant decrease in relative humidity during warmer periods. The WDR factor of 0.4 does not seem representative of the measurements, despite being the best fit in the beam end (Figure 42), why the combination of altered WDR factor and other factors is needed to create a better fit, as the models must exhibit the same parameters and coefficients. Possible alterations include material parameters, surface absorption coefficient, and various exchange coefficients.

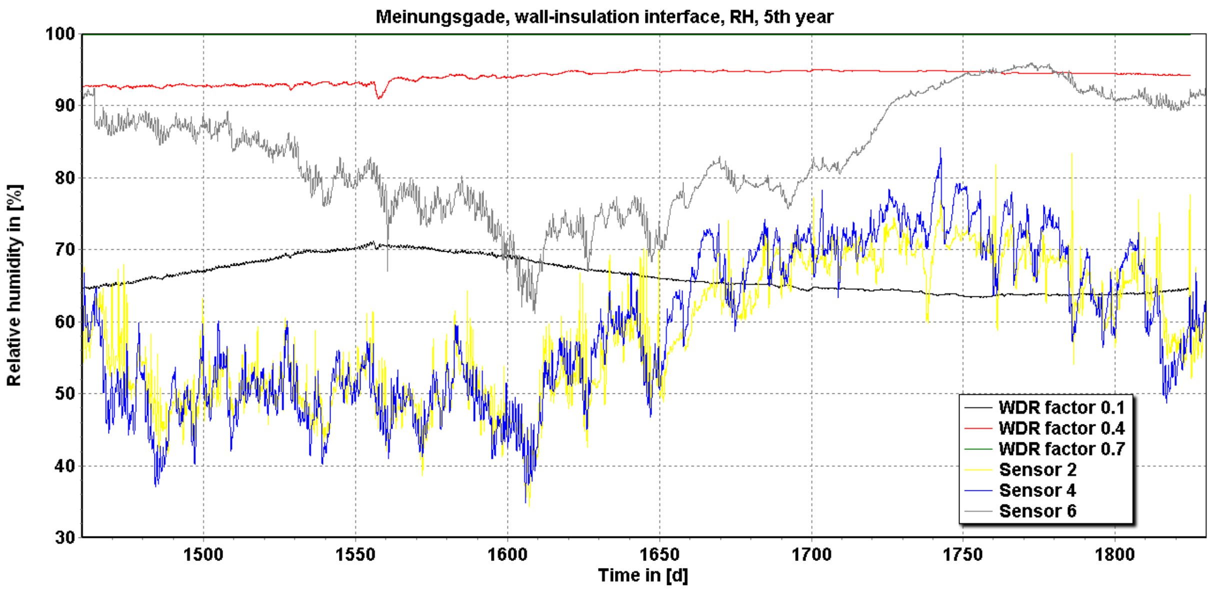


Figure 44: Relative humidity measurements and simulation results for wall-insulation interface in Meinungsgade

Figure 45 shows the temperature measurements and simulation results achieved for the beam end in Ny Allegade. As seen, the temperature in sensor 2 lies higher than both simulation results and the other measurements in the cold period (October-April) – likely due to hot water pipes in the vicinity of this sensor. The other two sensors measure lower values than the simulated during winter, indicating that perhaps the thermal conductivity of iQ-Therm is in fact lower than provided in the

Delphin database, or as mentioned, the conditions surrounding the beam ends. In the summer period, the results coincide very well.

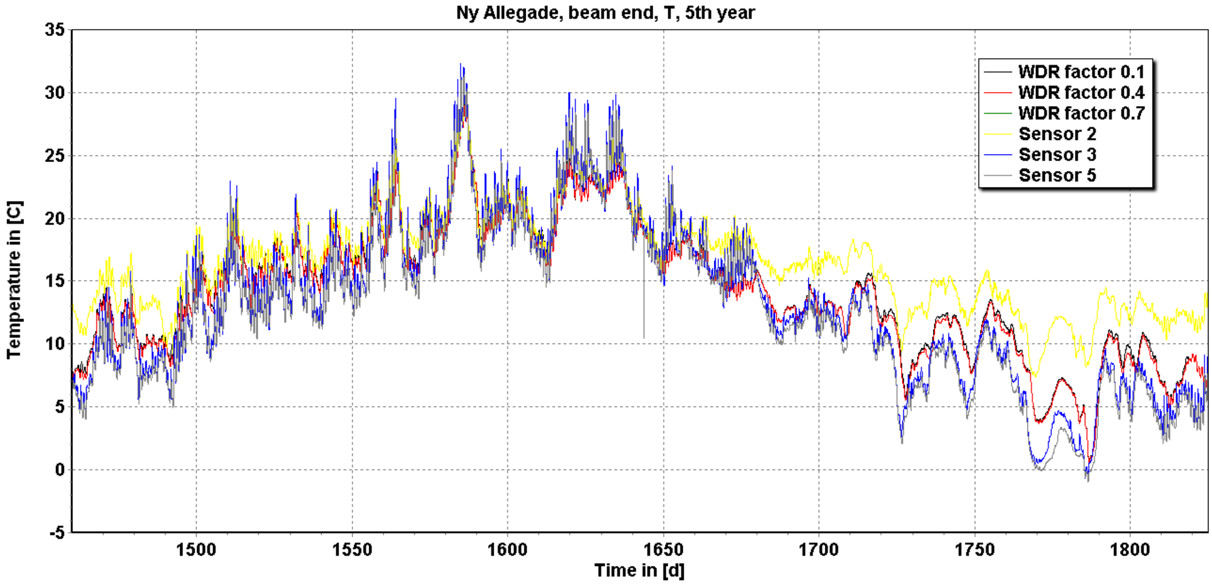


Figure 45: Temperature measurements and simulation results for beam end in Ny Allegade

The relative humidity in the beam ends depicted in Figure 46, suggest very high relative humidity in sensors 3 and 5 (not heated by hot water pipe), which is likely to coincide with simulation results for WDR factor 0.7. Unfortunately this simulation is currently only half way done, but the tendency does show an increase in relative humidity, and likely to end in the 95-100% range (see Figure 46), which would coincide with the measured results.

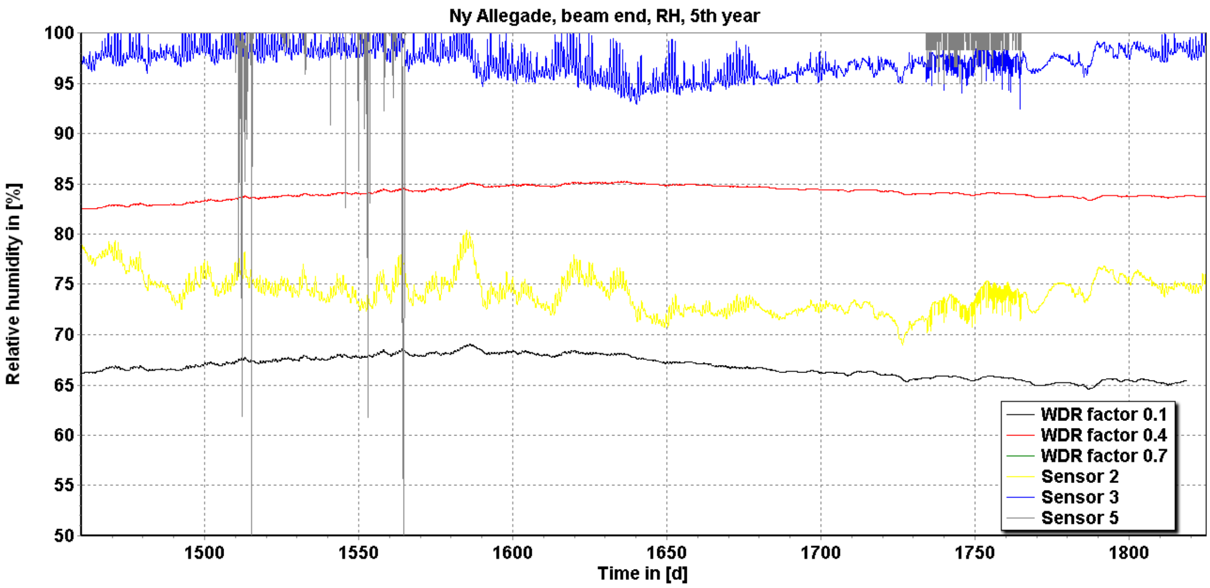


Figure 46: Relative humidity measurements and simulation results for beam end in Ny Allegade

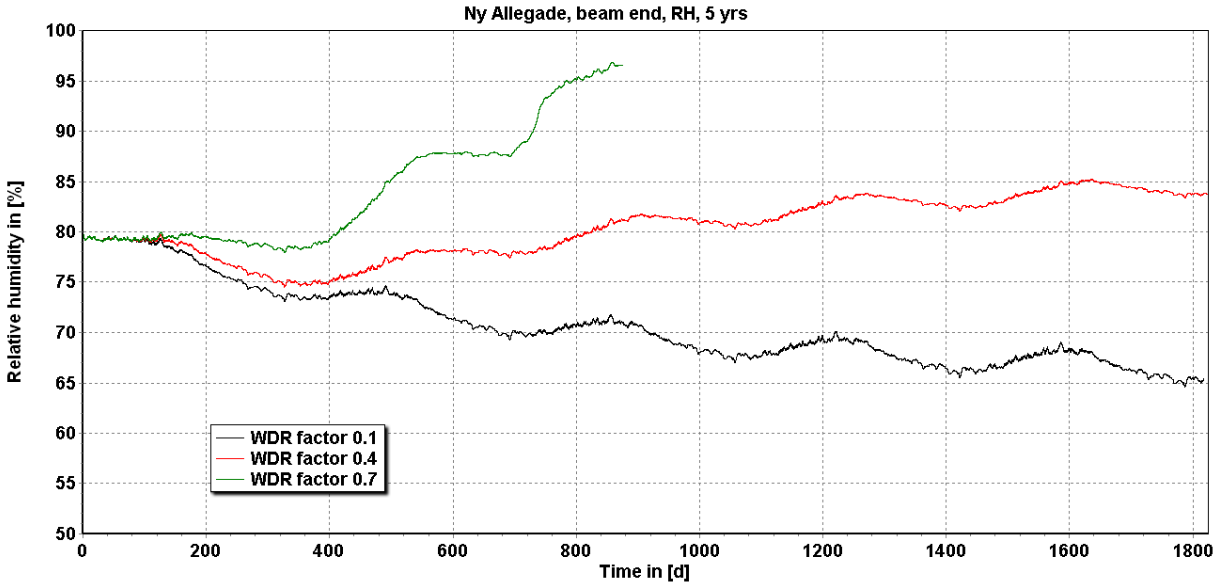


Figure 47: Simulated relative humidity in the beam end at Ny Allegade, various WDR factors

The simulated temperatures on the southern façade of Ny Allegade (Figure 48) coincide well with measured data, despite peaks, which again could possibly be explained by the surface absorption coefficient for short wave radiation.

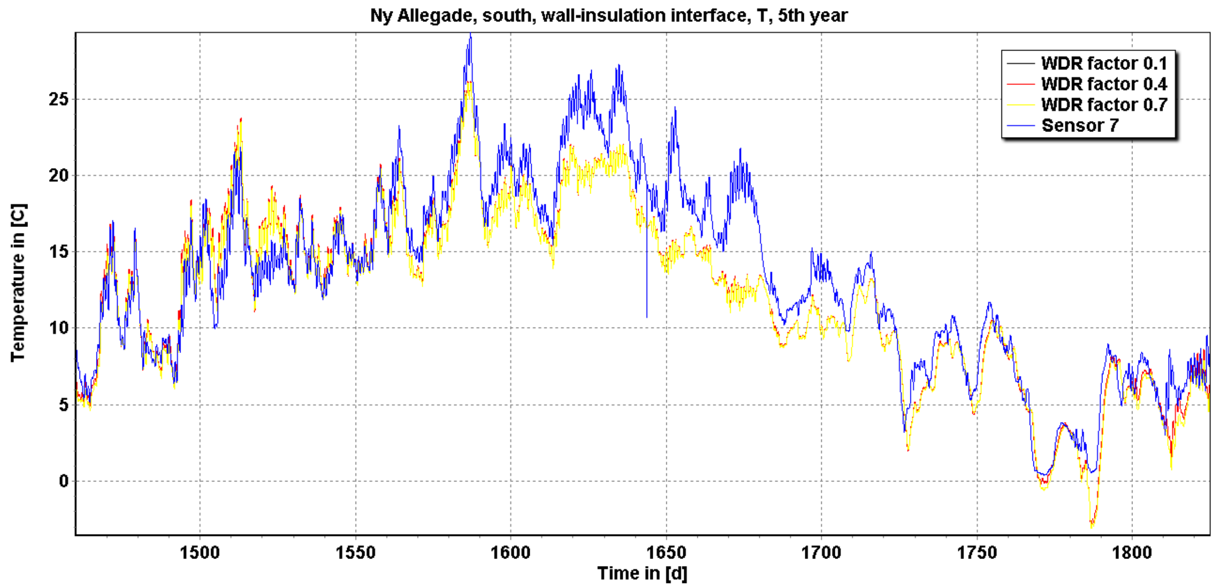


Figure 48: Temperature measurements and simulation results for south wall-insulation interface in Ny Allegade

The relative humidity measured in the wall-insulation interface on the southern wall is 100% during the measurement course (Figure 49). The discrepancies seen in December (around day 1750) are assumed to be disturbances in the measuring equipment/signal. In order to achieve the high relative humidity measured here, it could be a solution to increase the initial condition of relative humidity, as the mortar in the interface is very wet when applied, and according to measurements has not been able to dry out during the measuring period.

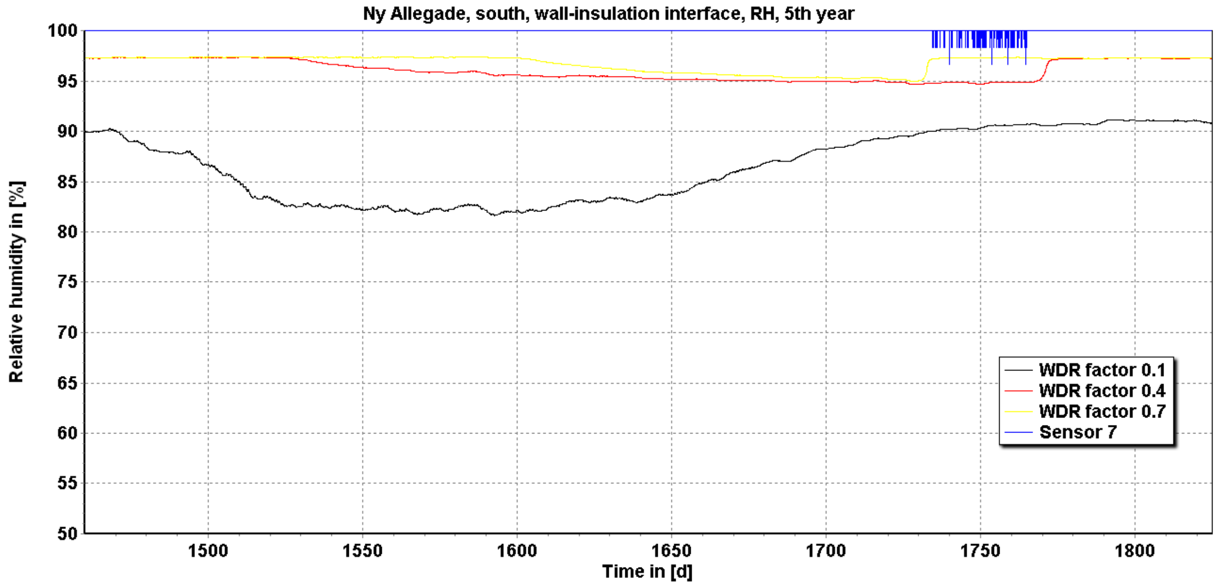


Figure 49: Relative humidity measurements and simulation results for south wall-insulation interface in Ny Allegade

On the western façade of Ny Allegade, the tendencies are very much the same as for the southern façade, as seen in Figure 50. The measurements from sensor 4 can be disregarded, as the hot water pipe is not taken into consideration in the Delphin model. In this case, the largest discrepancies are found in the peaks in June-September (day 1575-1675), and can likely be explained by the surface absorption coefficient.

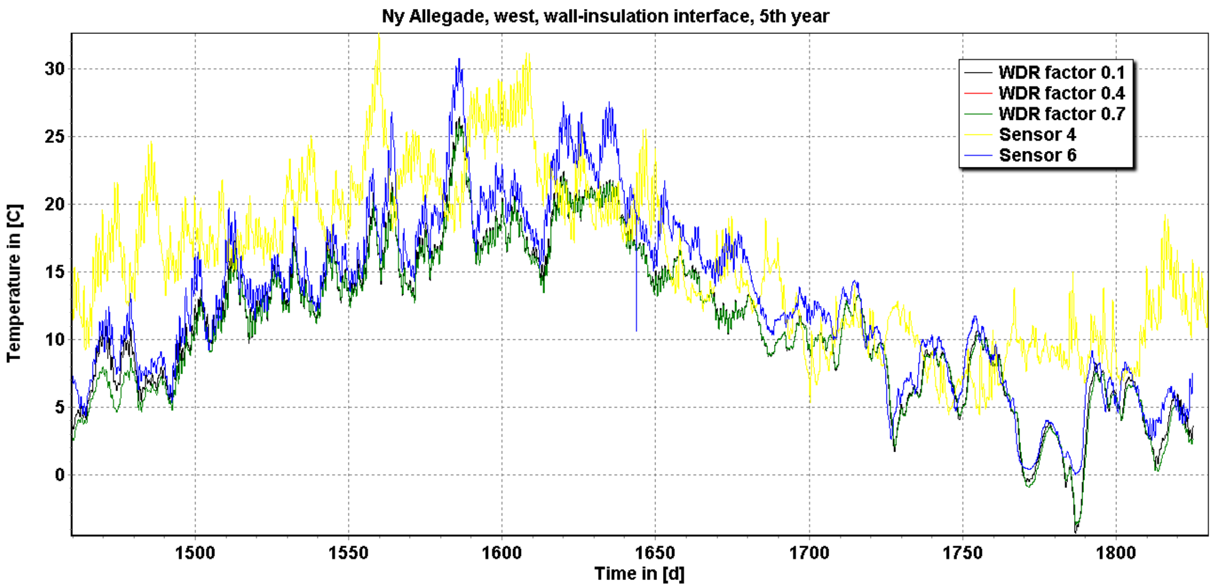


Figure 50: Temperature measurements and simulation results for west wall-insulation interface in Ny Allegade

The relative humidity measured and simulated on the western façade of Ny Allegade, can be seen in Figure 51. The results are very much alike the ones for the southern façade. The high relative humidity measured in the interface, could be possibly be constructed in the model by increasing the initial condition of relative humidity in the iQ-Fix layer.

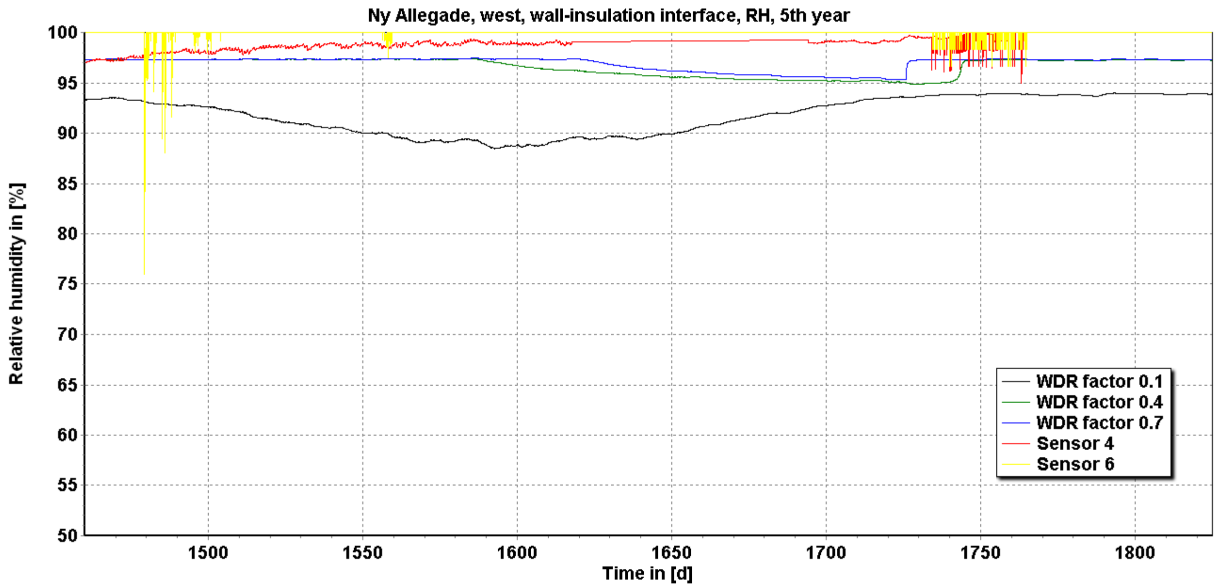


Figure 51: Relative humidity measurements and simulation results for west wall-insulation interface in Ny Allegade

Consequently, at this point no distinct conclusions can be drawn from the hygrothermal simulations performed, however the basis for future validation models has been founded. Prospectively, when the models are validated, the Danish Reference Year (DRY) for climate data can be added for future years, and the hygrothermal conditions in the cases for internal insulation can be predicted and analyzed. This will be valuable information for the research area, and especially also the RIBuild project, where the work with the models continues.

5.5 The practice of applying internal insulation

Applying internal insulation in small room apartments, which are only subject to the single operation of insulation, is a complicated process. It is complicated because of two main factors: 1. Adaption of insulation concept to the old building and 2. High user involvement.

5.5.1 Adaption of insulation

In most of the cases the project worked with the fully glued insulation material as shown in the picture below. In this case all organic material (such as wall paper) had to be cleaned of all walls, the stucco removed, wood plates in windows removed, panels removed, etc. This almost lead to a full refurbishment of the implicated rooms and the involvement of different professions such as carpenters, electricians, stucco workers, painters, plumbing and heating, etc. It would be a solution to establish a turnkey contract so that the coordination between different people in the chain would be smoother.

Since this project is a rather new concept lots of details had to be worked out in the field. The reconstruction of the vapour barrier was complicated and details as shown in pictures below regarding the airgap above the floor and detail regarding the window wooden plates, needed some extra focus.

The deformation of the walls was another obstacle to be solved in Meinungsgade. The standard prescription is the use of spot filling of plates and the use of 2 fitting screws. Because of heavy deformation there was a need to fully glue the plates and use 6-8 fitting screws to adapt the insulation correctly to the walls as shown in pictures below. However, this building was constructed earlier that 1890 where the building standard generally was lower [1]. This is less of an issue for building constructed after 1890.

Other unexpected barriers were working with the right plate insulation plate size. Stairways and rooms in old apartments are small and a standard plate is 120 cm x 260 cm and therefor impossible to get around stairways, through doors and around corners.

5.5.2 High user involvement

The refurbishment of an apartment demands a high user involvement since the planning has to be very precise to minimize the working time in the apartments. At the same time the apartments has to be left in the same condition as they were before the operation. This calls for a harmonization of expectations and a time schedule that do not slip – even though the project calls for custom made solution doing the process. Therefor communication is a vital part of the projects to keep a high satisfaction after the end of projects.

5.5.3 The future in working with internal insulation from a practical point of view

To solve the process regarding the adaptation of the concept to old building, the scope of the project has to be large and involve other parts of the apartment building such as kitchen and bathrooms. In this way it becomes a total refurbishment of the building, the residents are rehoused and the process will be much smoother. In this way an economy of scale will be possible and the timeline for total cost of ownership will dramatically improve. However, if the internal insulation should be widespread it would be an obvious possibility to apply the insulation when occupants move away or if they are on holiday for instance. Other possibilities would be to rehouse the occupants at a hotel for a small period while the work is carried out in the apartment.

Other matters such as prefabrication of the isolation plates to minimize adaptation work in the field, will highly streamline the process but will require precise pre-registration and probably 3D modelling.

5.6 Conclusions on internal insulation

Generally the tendency of declining relative humidity is seen for both walls and beam ends in Mønsgade and Kildevældsgade, and for walls in Meinungsgade and Thomas Laubs Gade. This indicates the initial relative humidity being caused by built-in moisture that needs to dry out. Seasonal variations are also seen in most measurements, indicating somewhat influence of external conditions. In both cases of IQ-Therm, the built-in moisture appears to dry slower, despite the capillary activity. The thinner layer in Thomas Laubs Gade seems to be working intentionally, as a decline is observed. The 80 mm IQ-Therm installed in Ny Allegade possibly takes even more than 13 months for drying the built-in moisture, or it is simply too much insulation in this case. One year of measurement is too short time to draw final conclusions, but the measurement will continue after the end of this project.
From the measurements in Ryesgade 30 it is seen that the humidity levels are good and no risk of mould growth seems to be present.

Meinungsgade is the only apartment with Kingspan internal insulation where the humidity levels are above the critical levels. This could be explained by different reasons. The building is built before 1890 and the façade is in worse conditions compared to the other buildings. Furthermore, according to the building law from 1889 [1] buildings constructed after 1890 have generally higher qualities compared to buildings constructed before. Low façade quality, uneven internal surfaces that are badly rendered and different conditions might result in the fact that there can be a higher risk of applying internal insulation. One solution to this is to renovate the façade (internally and externally) when applying internal insulation to ensure intact facades. There is no measurements of the relative humidity levels before applying internal insulation. For future projects it is recommended to carry out some measurements before applying internal insulation so that the effect of the internal insulation can be registered correctly. There is a chance that the humidity levels already were in the risk zone before applying the insulation.

Initially the plan was to create a gap in the insulation above and below the beam construction, but due to technical challenges it was only created above the floor construction. If the gap was also created below it might have led to higher temperatures and lower relative humidities. However, the Delphin simulations shows that even with a gap below the temperatures at the beam ends does not increase significantly and they follow the weather profiles. Therefore the creation of the gap in the insulation seems not to have the expected effect and could be disregarded for future project. However, there is still a need to ensure completely safe and robust internal insulation solutions. From this project it is still uncertain when and in which situations (wall-thickness, wind-driven-rain exposure, insulation thickness etc.) internal insulation can be applied without any moisture risks. There is a need to understand different external factors and how they affect the moisture levels in the wall. Especially the effect of the wind-driven-rain has a large influence on the moisture levels.

6 Decentralized ventilation

The other part of the project was to install decentralized ventilation on apartment level and carry out measurements to understand how the system is operating in order to ensure that it is working. The conclusions from the previous EUDP project on Ryesgade 30 were that the operation of ventilation showed challenges. Therefore one of the aims in this project was to install a unit in a test apartment, carry out measurements and ensure a good operation of it so that a good indoor climate was provided. Focus was given to different designs of the system with regards to the exhaust hood. Using test apartments gives the opportunity to understand how the occupant experiences the decentralized ventilation during installation and operation. Furthermore installing decentralized ventilation in test apartments provides real conditions and all practical challenges when installing the system appears.

6.1 Description of test apartments

The apartment chosen for installing the decentralised ventilation was the same two apartments as where internal insulation was installed in Meinungsgade, on the 3rd and 4th floor. Two Airmaster units were placed in the entrance of both apartments below a lowered ceiling. The intake and exhaust was placed on the façade towards the backyard.

According to the Danish Building Regulation 2015 dwellings needs to have an exhaust on 20 l/s from bathrooms, 15 l/s from kitchens and in case there is a separate toilet an exhaust of 10 l/s is required. Furthermore the entire dwelling needs to have a ventilation rate corresponding to 0.3 $l/s/m^2$. The specific fan power (SFP) for constant and variable controlled ventilation cannot exceed 1000 $W/(m^3/s)$, the heat recovery has to be minimum 80% and the noise from the system cannot exceed 30 dB(A) in living rooms.

The Airmaster units are demand controlled based on humidity and is working with a step-function that can increase/decrease the air flow rate to the demanded rate. A detailed description of the different steps can be seen in Annex 2.

Focus was given to optimizing the design of the systems based on energy efficiency and noise from the system together with cost optimization. The system design is based on previous designs in test apartments in Ryesgade 25 and 30 and Mønsgade 16. Both systems are described below.

An analyzis of operational time and volume flow rate was performed and concluded that it was not relevant to decrease duct dimensions in regards to normal practice. A reduction in diameter from

125mm to 100mm would have a small economic benefit and ease the process of installing ducts plus give the opportunity to raise the suspended ceiling etc. However, it will result in an increased energy consumption of approximately 50%. A detailed description is given in Annex 3

6.1.1 Description of the ventilation system on the 3rd floor

On the 3rd floor a CV200 unit was installed. The system is demand controlled based on humidity but can be overruled by the occupant at the control panel placed in the entrance. The total air flow rate is dimensioned based on 126/198 m^3/h. When the air flow is boosted due to the exhaust hood in the kitchen or the exhaust in the bathroom the air flow rate increases to 144 m^3/h and 54 m^3/h respectively.

The system is designed with a 3-way damper that secures maximum air flow from the exhaust hood by optional forced operation and maximum air flow from the bathroom at any other time interval. Traditional Lindab KIR supply valves and KSU exhaust valves are used.

As seen from Figure 52 there is an air inlet to the bedroom and to the living room. It was decided not to supply air to the small room in connection to the bedroom. It is possible to connect that room later on if wanted. The exhaust takes place from the shower and kitchen. A silencer is placed on each room inlet pipe and on the exhaust between shower and kitchen exhaust. The pipes have a diameter of 160mm. The system was installed with a 3-way damper to be able to move the exhaust air better in the apartment. Furthermore the system is a closing damper and a heating plate. More details can be seen in Annex 2 and Annex 4.

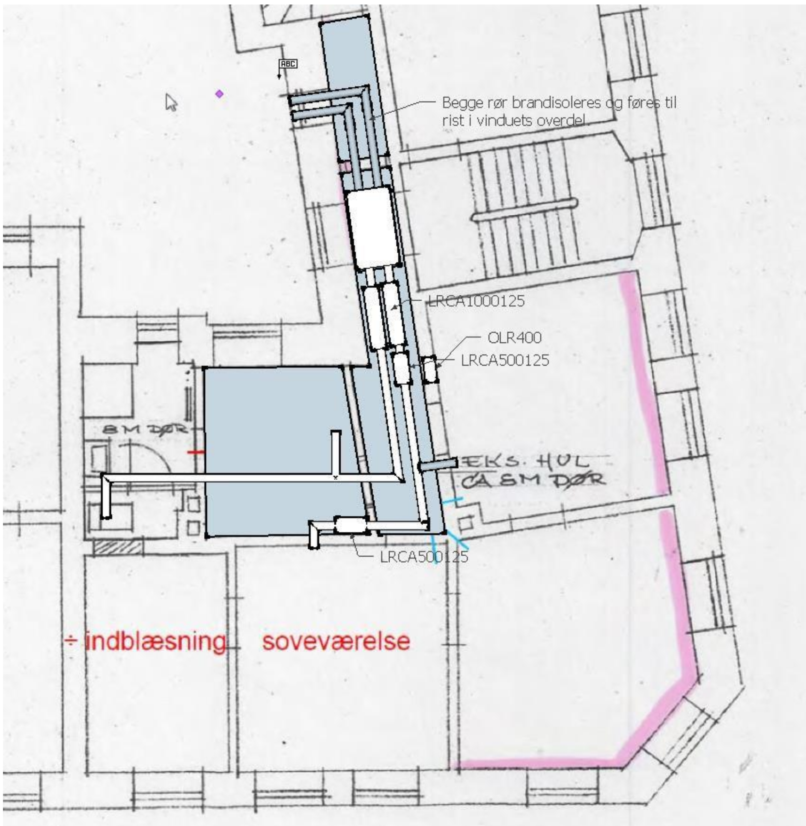


Figure 52: Ventilation system at the 3rd floor

6.1.2 Description of the unit on the 4th floor

The system on the 4th floor is similar to the system on the 3rd floor. However, no 3-way damper, closing damper or heating plate was installed.

A newly developed and more efficient exhaust hood (Thermix Airgrip) was installed, which requires 40% less air to obtain similar efficiency as the 3-ways system. The exhaust hood activates a boost-function through a cable connection from the exhaust hood to the ventilation unit. I this apartment demand controlled ventilation based on humidity in the bathroom was installed with a Neotherm Hygro exhaust valve. For the supply Lindab AIRY is used.

As seen from Figure 53 there is an air inlet to the bedroom, two inlets to the living room and one inlet to the children room. The exhaust happens from the shower and kitchen. A silencer is placed on each room inlet pipe and on the exhaust between shower and kitchen exhaust. The pipes have a diameter of 160mm. More details can be seen in Annex 4 and detailed drawings can be seen in Annex 5.

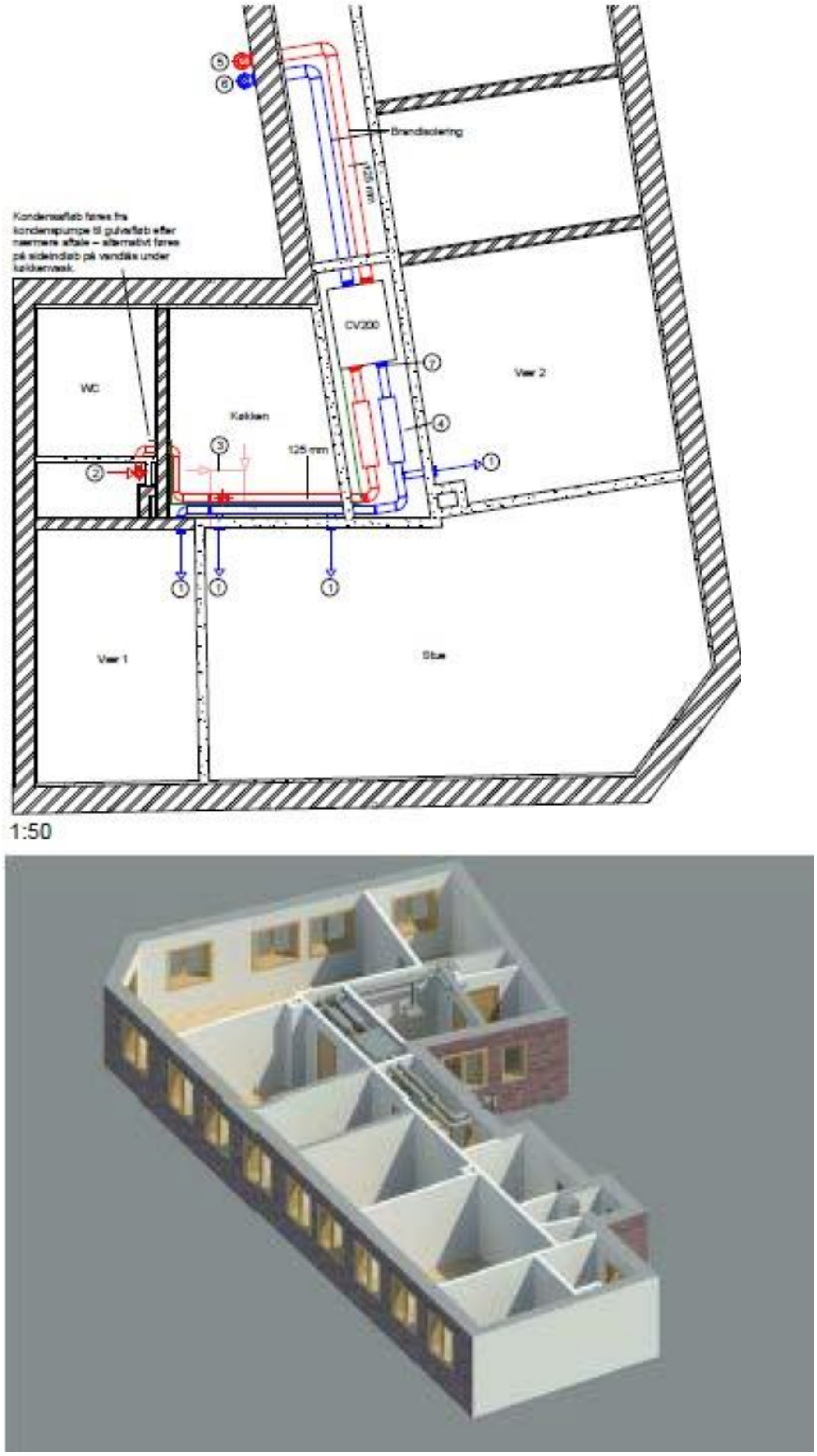


Figure 53 Ventilation system at the 4th floor

6.2 Measurements and analysis

Measurements were carried out for approximately a month (18th of March to 21st of April 2016) in the two apartments. Sensors in the Airmaster units measured the 4 temperatures; inlet and exhaust on the cold and warm side, the relative humidity from the room exhaust, and the requested flow. Simultaneously HOBO loggers and IC-meters were placed in the apartments in order to compare the measured values in the Airmaster unit and in the rooms. The arrangement was that HOBO loggers was placed can be seen in the Table 5 below. As seen the IC-meters was placed in the kitchen, living room and bedroom on the 4th floor during the first period and then moved to the 3rd floor during the second period replacing the HOBO loggers. This was done in order to get CO_2 measurements from both apartments.

Table 5: Sensor placement for measurements

	18.03.2016-06.04.2016	06.04.2016-21.04.2016
3rd floor		
Living room	HOBO logger	IC-meter
Bedroom	HOBO logger	IC-meter
Kitchen	HOBO logger	IC-meter
Extra room	HOBO logger	HOBO logger
4th floor		
Living room	IC-meter	HOBO logger
Bedroom	IC-meter	HOBO logger
Kitchen	IC-meter	HOBO logger
Children´s room	HOBO logger	HOBO logger

6.2.1 Measurements from the 3rd floor

Figure 54 shows the temperature measurements in each room (room sensors) together with the requested ventilation flow for the entire period. Figure 55 shows the relative humidity measurements in each room (room sensors plus the Airmaster exhaust RH) together with the requested ventilation flow for the entire period.

As seen from the figures the temperatures and relative humidity generally seems to have good levels. The temperatures are fluctuating around 20°C and the relative humidity varies between 30-60%. The requested airflow varies between 50%-100% operation determined mainly on the relative humidity. Figure 56 and 57 shows the same measurements zoomed in during 2 days from the 10th-11th of April.

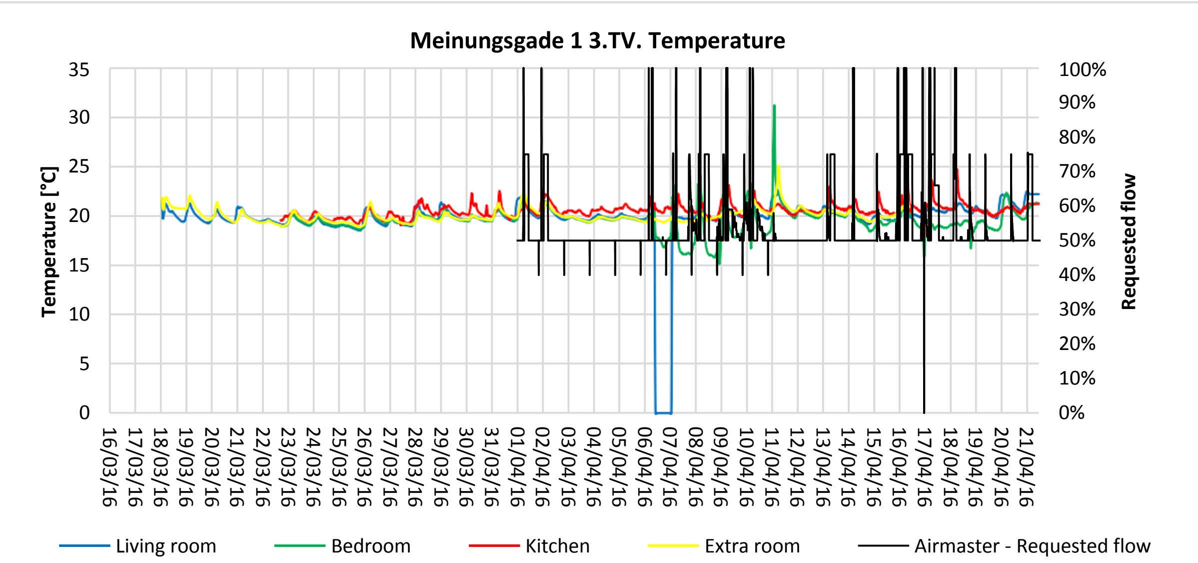


Figure 54: Temperature measurements for the entire period.

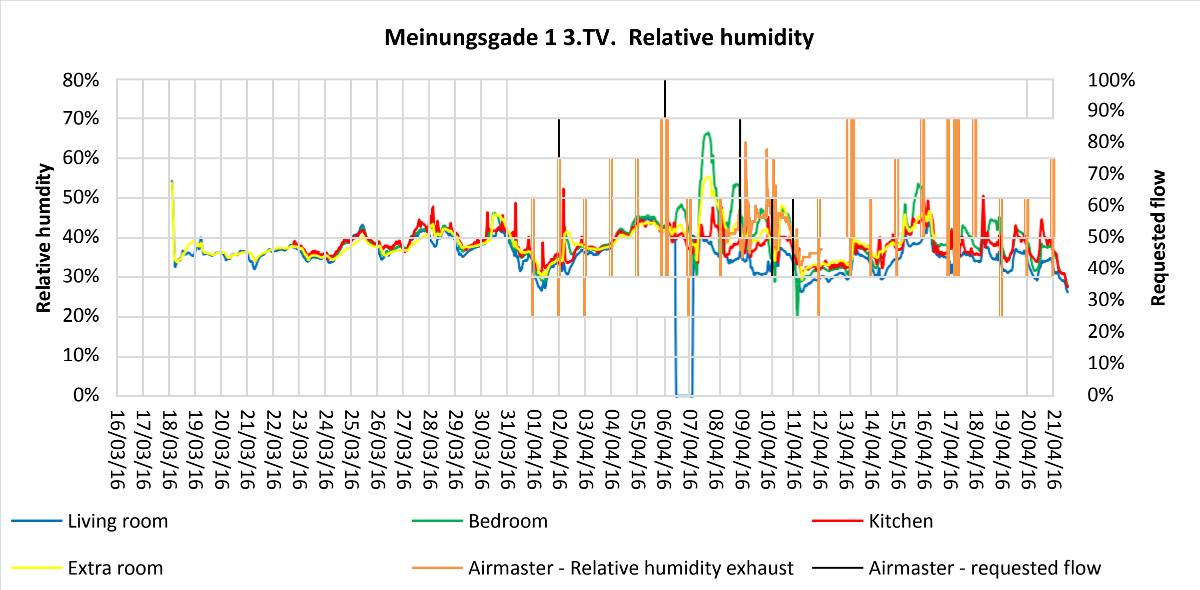


Figure 55: Relative humidity measurements for the entire period.

The 10th was a Sunday and the occupant was home the entire day/night except from 11:30-15:00. On the 11th the occupant left in the morning at 06:30 and was away the remaining day. As seen from Figure 56 the temperature in the bedroom is lower during the night time and increases during day time. The bedroom and the extra room are connected and both are facing southwest, which implies that they get direct sun in the afternoon. The requested air flow is following the measured relative humidity in the Airmaster unit as can be seen in Figure 57. The measured relative humidity in the unit is generally higher than the relative humidity measured in the rooms. This is probably due to an increase in relative humidity in the exhaust due to showers in the bathroom where there is no room measurements. The first peak happens in the morning where the occupant may take a shower, and the relative humidity measured in the unit slowly decreases over the next hours. Simultaneously the relative humidity increases in the kitchen shortly after, which could indicate that the occupant leaves the door open from the bathroom to the kitchen after the shower. In the afternoon the requested flow rate increases to 100% even though the measured relative humidity decreases. This peak could be explained by cooking and the increase of the kitchen exhaust hood. A small increase in relative humidity is furthermore seen in the kitchen followed by an increase in measured relative humidity in the Airmaster unit. As seen from Figure 56 the temperature in the bedroom decreases dramatically when the exhaust hood is activated and rises again when the exhaust hood is deactivated again. The de- and increase in temperature levels in the bedroom could also be caused by opening of windows in the bedroom. The following day when the occupant is away the temperature in the bedroom and extra room increases a lot. This could be explained by low operation of the ventilation system. Furthermore even though the sensors are placed so that no direct sun should be able to reach the sensors it could be that the bedroom sensor has been placed in such a way that sun might reach it and thereby monitor very high temperatures.

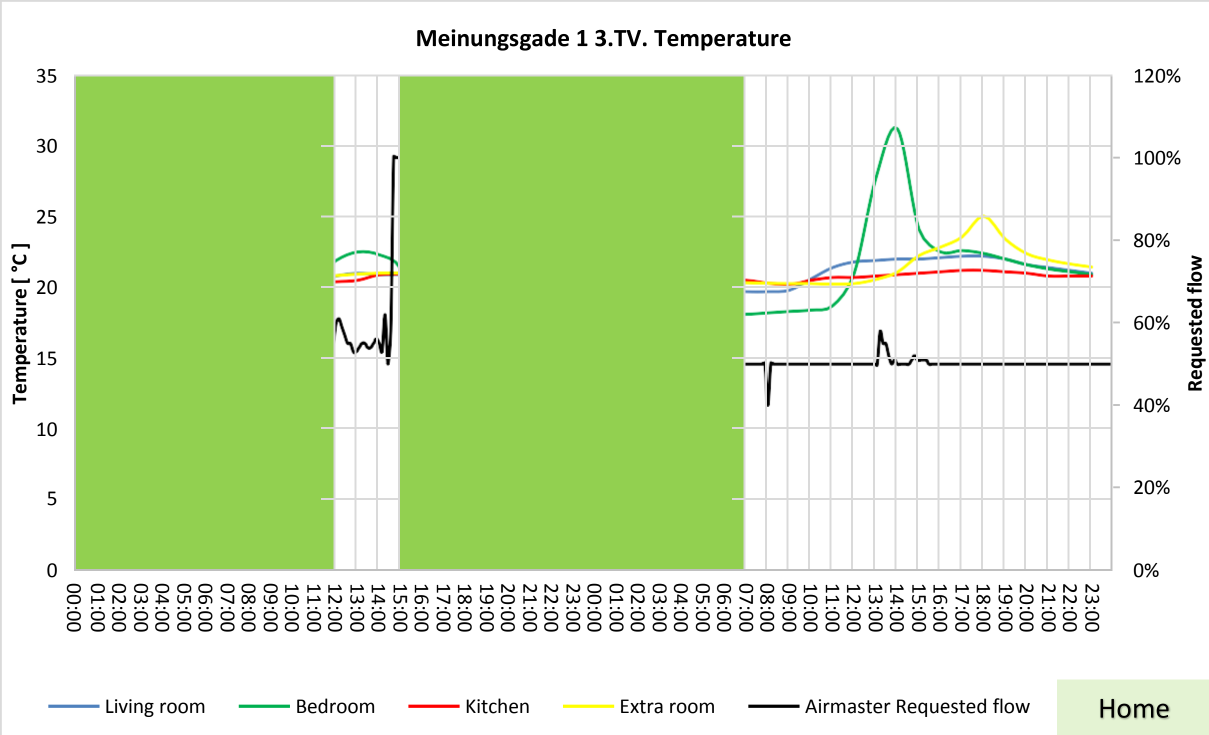


Figure 56: Temperature measurements from the 10th-11th of April.

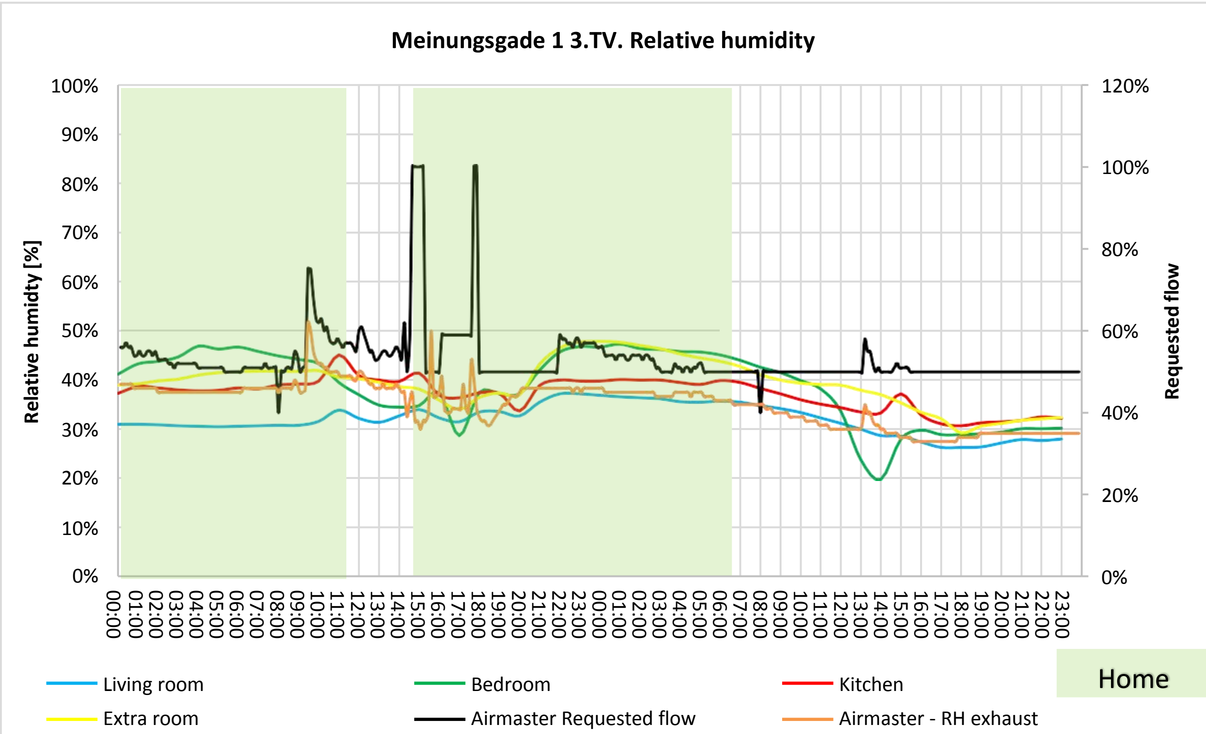


Figure 57: Relative humidity measurements from the 10th-11th of April.

From Figure 58 the CO2 measurements in each room can be seen. The CO2 measurements are measured by the IC-meters and the requested ventilation flow is measured by the Airmaster unit. Generally it is seen that the CO2 level increases in the bedroom up to 1400 ppm, which is unacceptable. It is seen that the ventilation flowrate is not increasing despite the high values since the unit is only controlled by humidity. As seen from the figure the occupant is away from the 11th-14th of April and the CO2 level falls to 400 ppm in all rooms. Figure 59 shows the measurements carried out Sunday the 10th of April where the occupant was away from 11:30-15:00. As seen the CO2 level in the bedroom reaches 1400 ppm during the night and the ventilation flowrate remains constant. Only in the morning the flow rate increases due to high humidity levels because of the shower. In the afternoon/evening the CO2 increases slightly in all rooms due to the fact that the occupant returns home. However, the CO2 levels are at acceptable levels. It is important that the ventilation system is not only controlled by the humidity but also the CO2 in the bedrooms in order to achieve acceptable level. This is not the case in this test apartment.

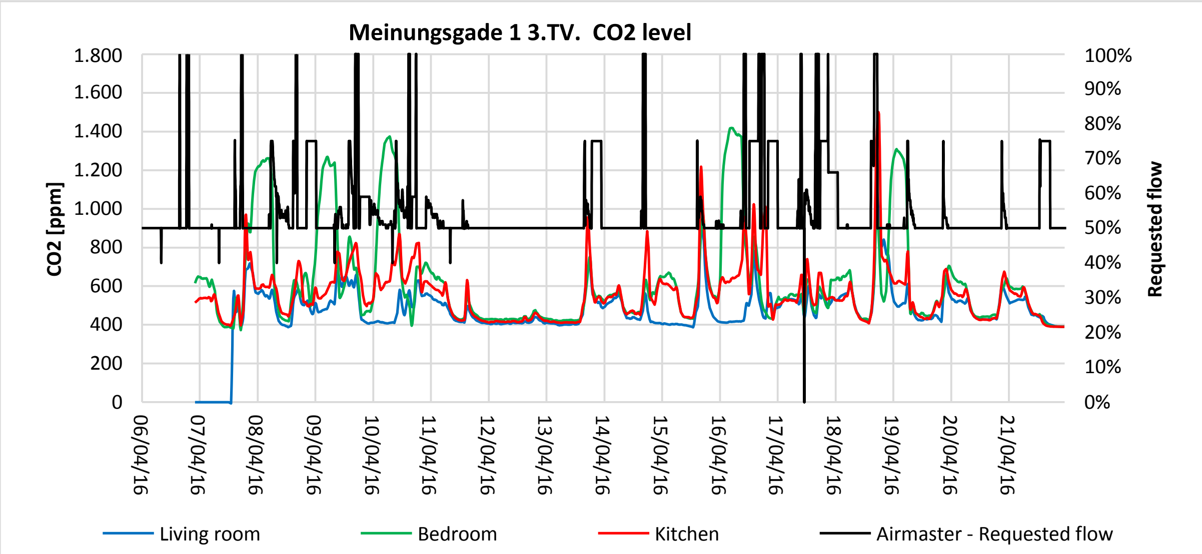


Figure 58: Measured CO2 levels from the 6th -21st of April.

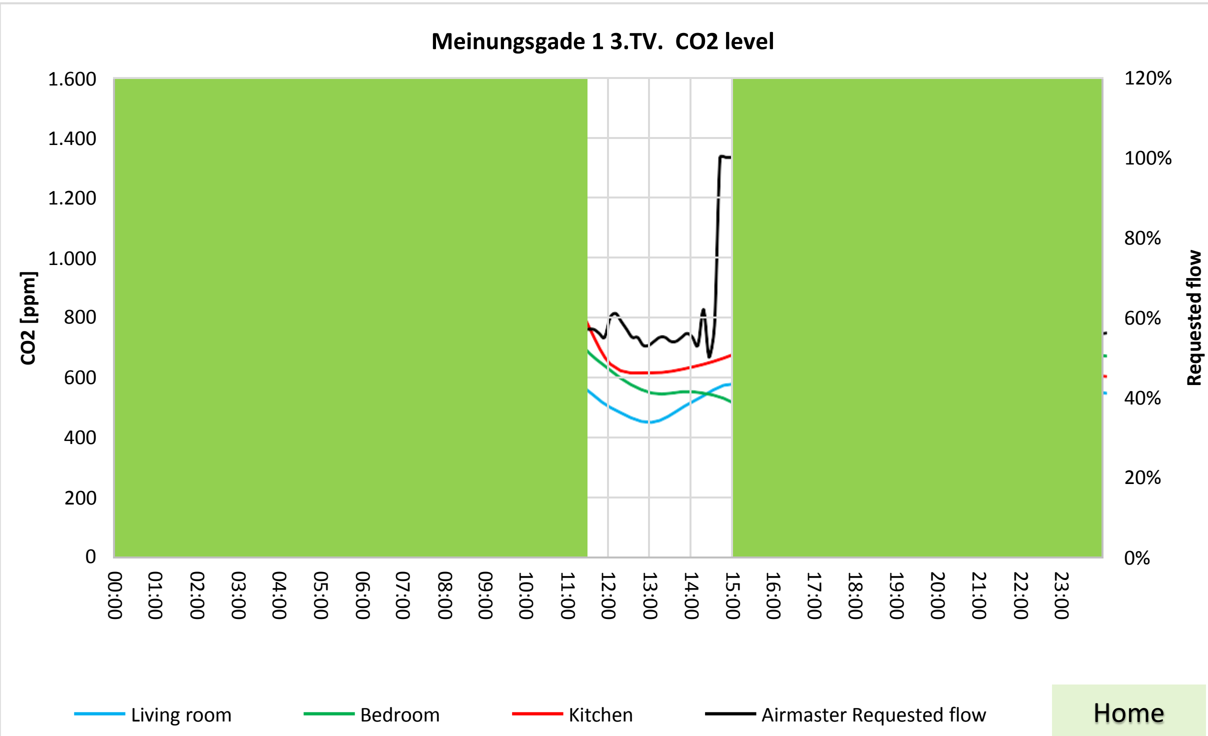


Figure 59: Measured CO2 levels from the 10th of April.

6.2.2 Measurements from the 4th floor

Figure 60 shows the temperature measurements in each room (room sensors) together with the requested ventilation flow for the entire period. Figure 61 shows the relative humidity measurements in each room (room sensors plus the Airmaster exhaust RH) together with the requested ventilation flow for the entire period.

As seen from the figures the temperatures and relative humidity generally seems to have good levels. The temperatures are fluctuating around 22°C and the relative humidity varies between 30-50%. The requested airflow varies between 50%-100% operation determined mainly on the relative humidity. The temperatures in the living room and children´s room are generally higher than the remaining rooms, mainly because these two rooms are facing south/southwest and are exposed to more direct sun radiation. Furthermore it is seen that the relative humidity generally is higher in the kitchen compared to the remaining rooms, due to cooking and the fact the kitchen is connected to the bathroom. As seen from Figure 61 the relative humidity measured in the unit is higher than the relative humidity measured in any other rooms at all times. This could indicate that the bathroom is not ventilated sufficiently and therefore holds high humidity levels. Figure 62 and 63 shows the same measurements zoomed in during 2 days from the 10th-11th of April.

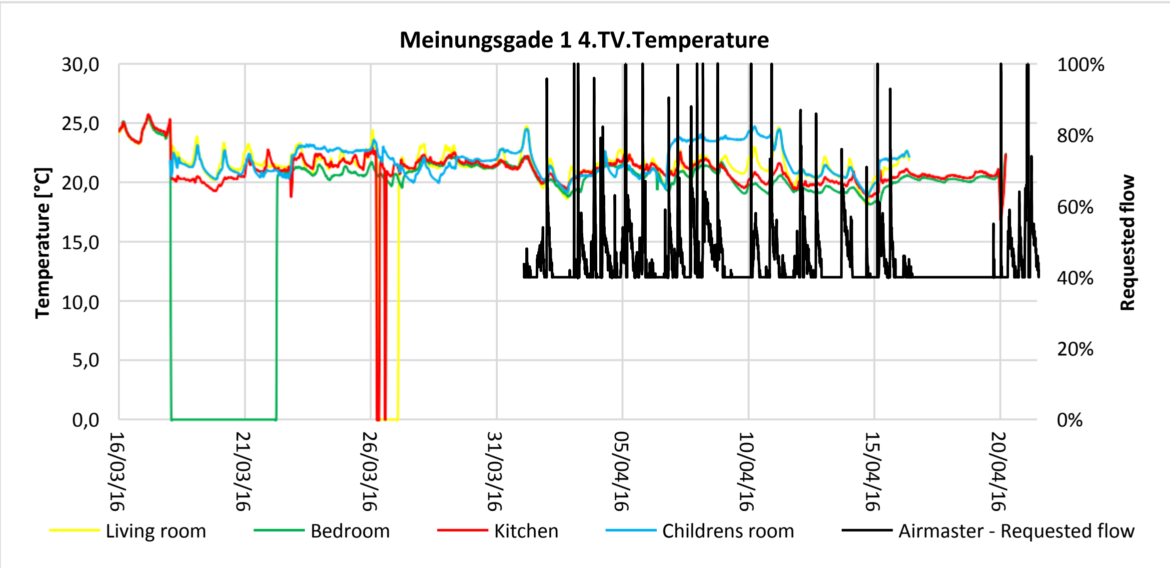


Figure 60: Temperature measurements for the entire period.

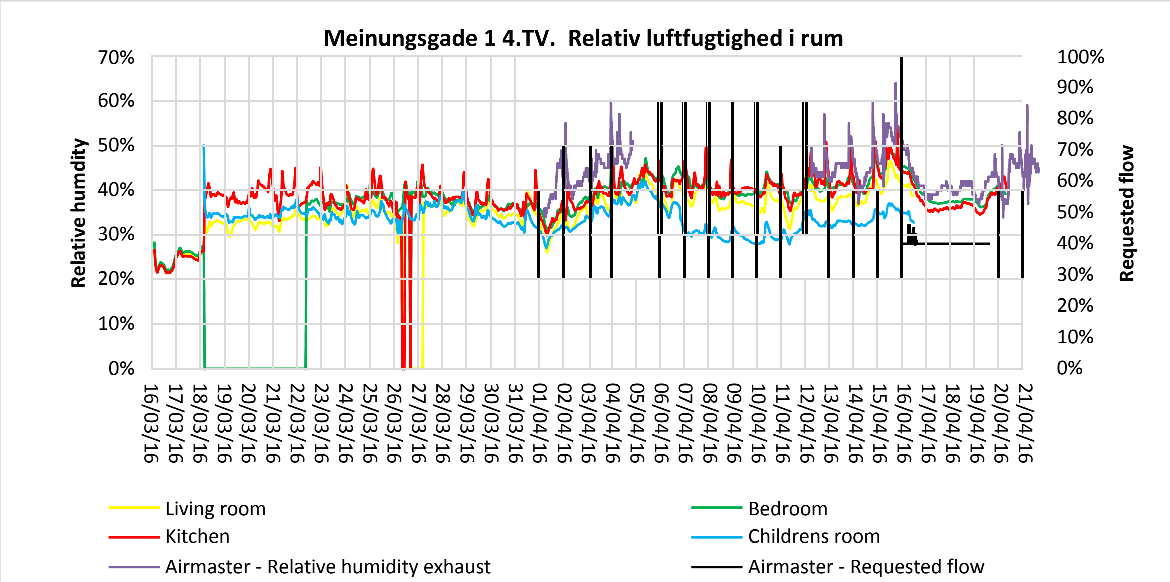


Figure 61: Relative humidity measurements for the entire period.

Figure 62 shows the temperatures from the 4th – 5th of April together with the requested airflow. Figure 63 shows the relative humidity measured in the rooms and the relative humidity measured in the unit together with the requested airflow. As seen from Figure 62 the temperatures stays at constant levels around 21-22°C, whereas the relative humidity fluctuates over the day. As seen from figure 63 the relative humidity peaks in the morning and in the afternoon and the requested flowrate increases during those periods. During the 5th it is seen that the requested airflow rate increases from around 50% to 100%, which can be caused by activating the exhaust hood or by manually increasing the flow rate at the control panel. It is seen that shortly after the increase the relative humidity drops significantly.

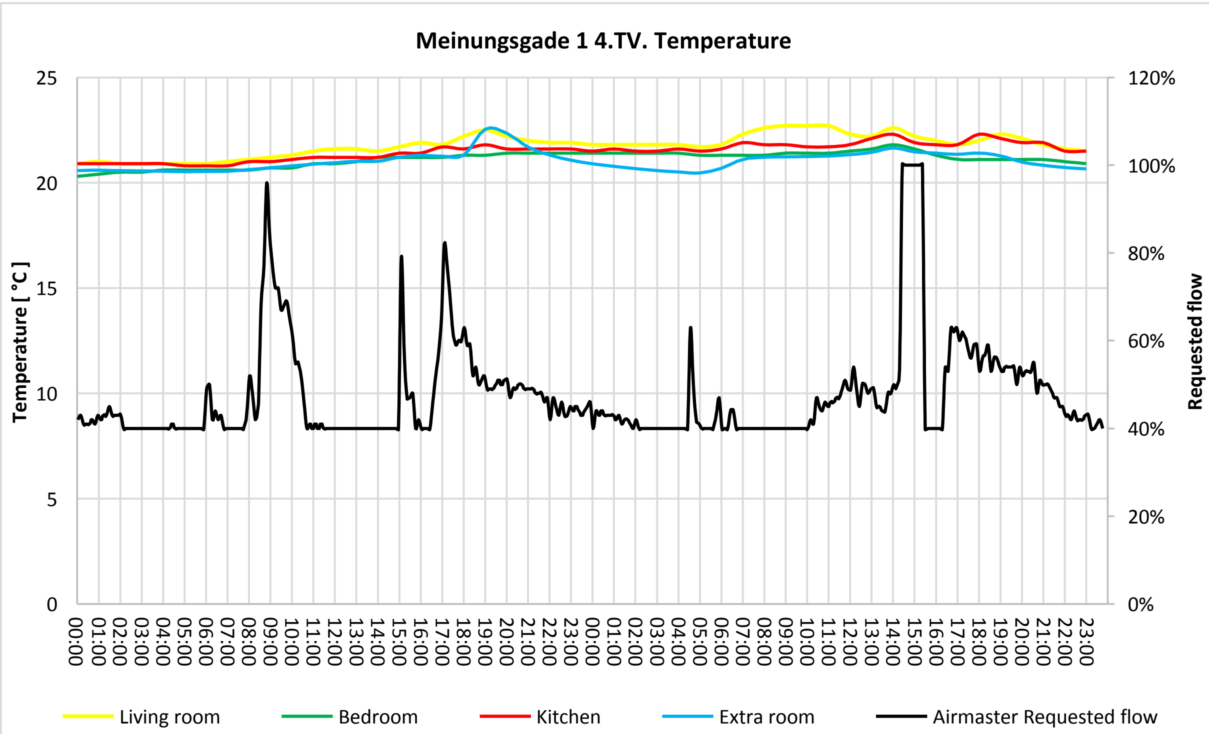


Figure 62: Temperature measurements from the 4th - 5th of April.

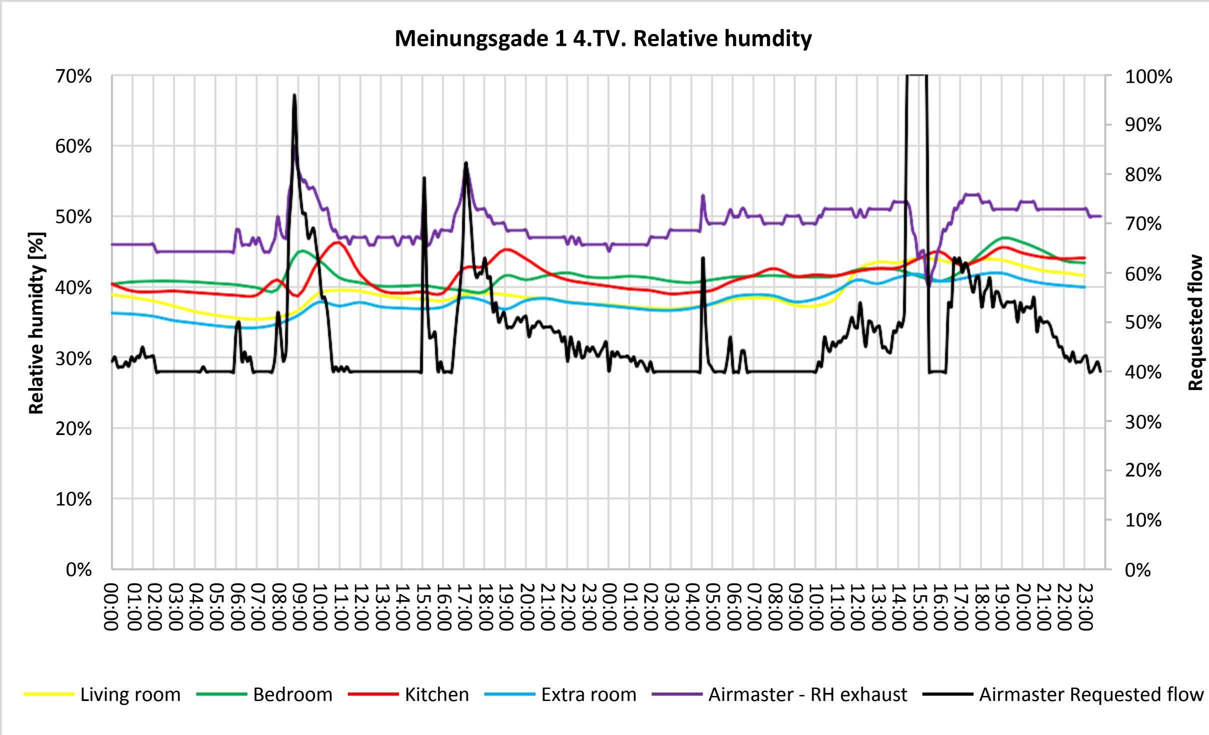


Figure 63: Relative humidity measurements from the 4th - 5th of April.

Figure 64 shows the CO2 levels for the entire period and Figure 65 shows the CO2 levels the 4th and the 5th of April. As seen from both figures the CO2 levels are at good and acceptable levels during the entire measuring period. They generally stay below 800ppm only with a few exceptions.

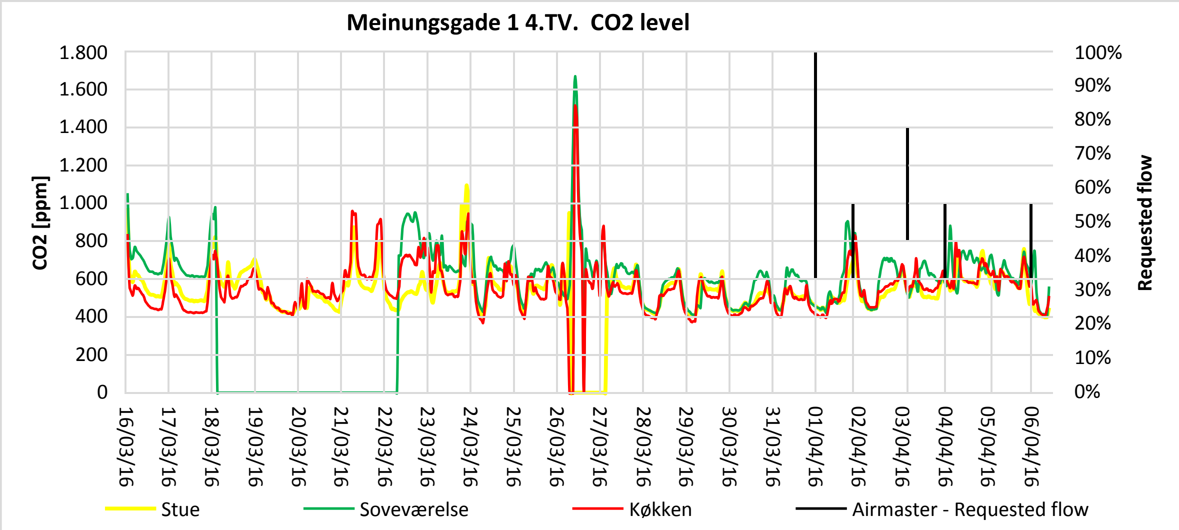


Figure 64: CO2 measurements for the entire period.

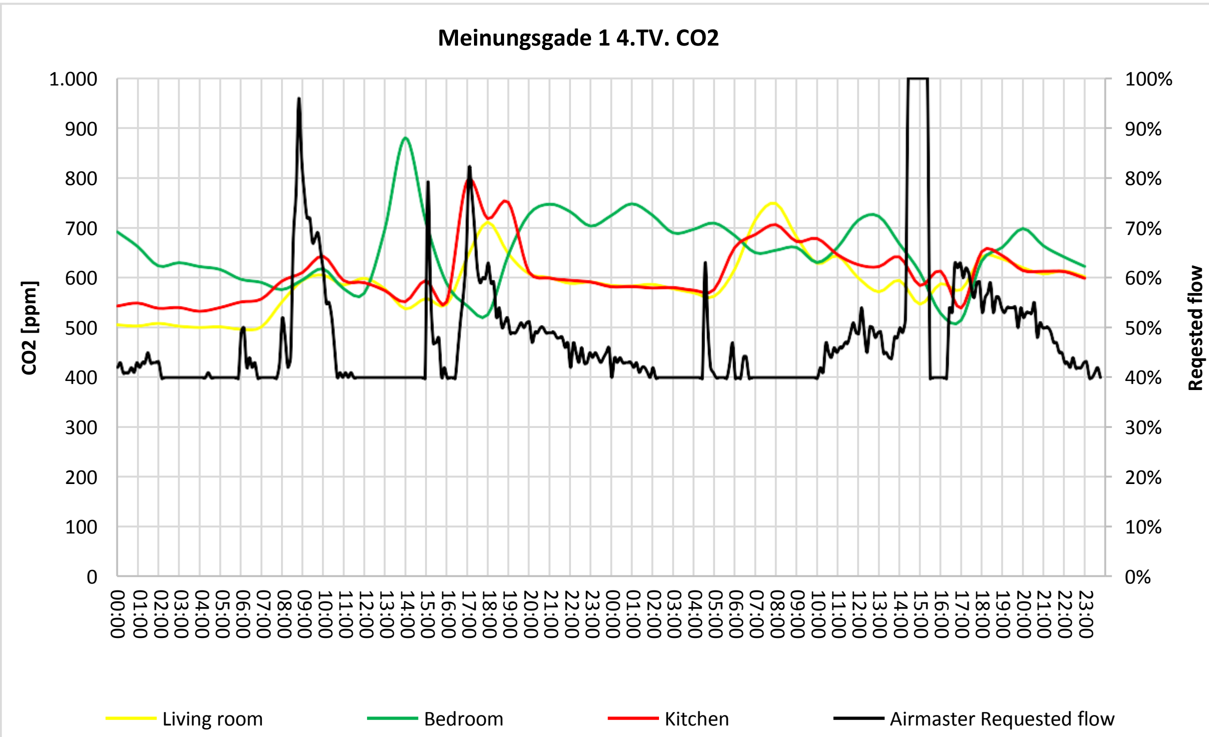


Figure 65: CO2 measurements for the the 4th and the 5th.

6.2.3 The actual heat recovery

The actual heat recovery of the ventilation systems have been calculated from measured temperatures in the Airmaster units. The actual heat recovery is calculated based on

$$\eta\eta = \frac{T_{rrrrrrrr} - T_{eeeehaaaaaaa}}{TT_{rrrrrrrr} - TT_{iiiiaaaaiiee}}$$

Figure 66 and 67 shows the calculated heat recovery efficiency for the ventilation systems on the 3rd and 4th floor respectively. The heat recovery on the 3rd floor has an average value of 85% with the highest values in the beginning of the measuring period and a slightly decreasing trend. The heat recovery on the 4th floor has an average value of 82% being rather constant over the measuring period. Both system fulfil the requirement of a minimum heat recovery efficiency of 80% according to the Danish Building Regulation 2015.

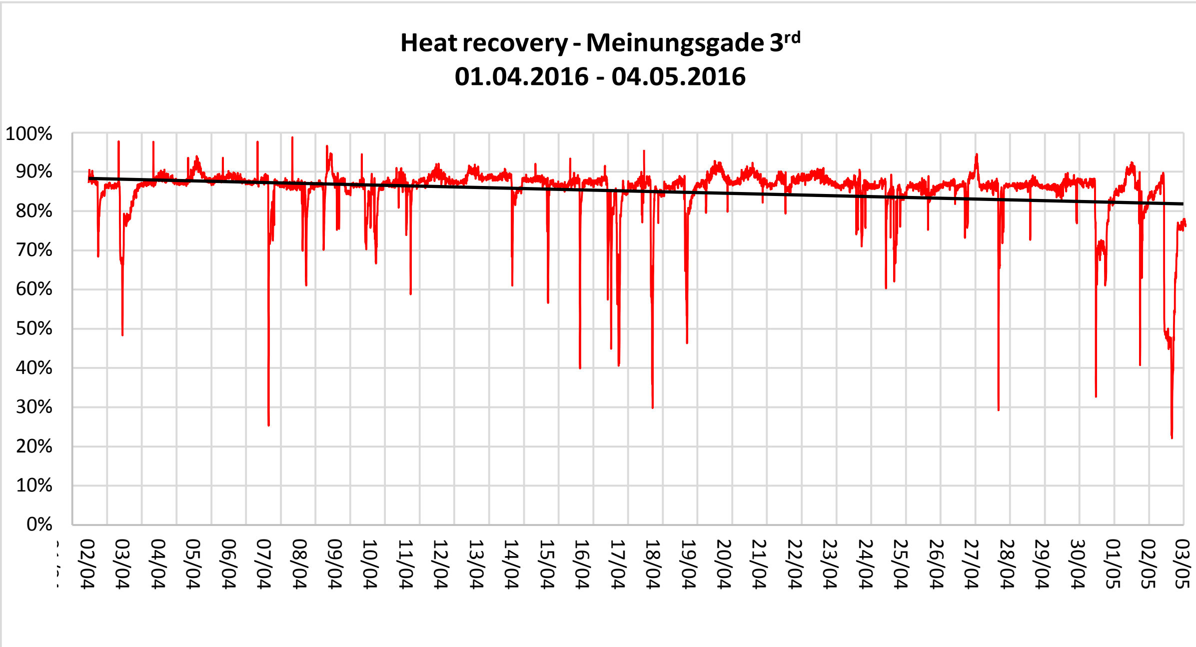


Figure 66: Calculated heat recovery based on the measurements for the unit at the 3rd floor

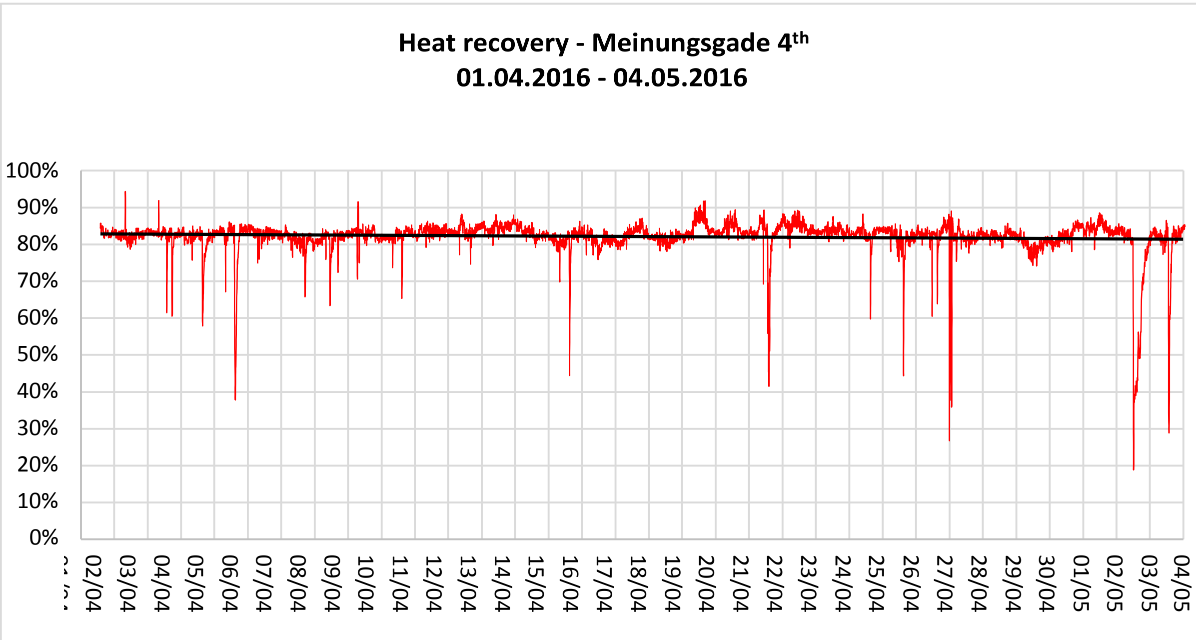


Figure 67: Calculated heat recovery based on the measurements for the unit at the 4th floor

New data extracted from Airmaster´s system (beyond the detailed measuring period) shows that the heat recovery surprisingly is running parts of the summer (The ventilation has a variable by-pass function) – see Figure 68. The heat recovery happens to ensure a minimum supply temperature (i.e. 18°C) to avoid draft. In other case-studies the system was installed with a "summer-operation" function to shut down the supply in order to save electricity. If the measurements show that the amount of hours below 18°C is too many the occupants can experience draft. In old badly insulated apartments it can also result in increased heating consumption if the radiators start to operate due to too low heating contribution from the heat recovery. In those cases it is better to operate the system with a heat recovery. This result in the fact that the optimal way to operate the system depends on the heating balance in the apartment. And thereby the energy savings applied in the specific renovation project (insulation/new windows etc.).

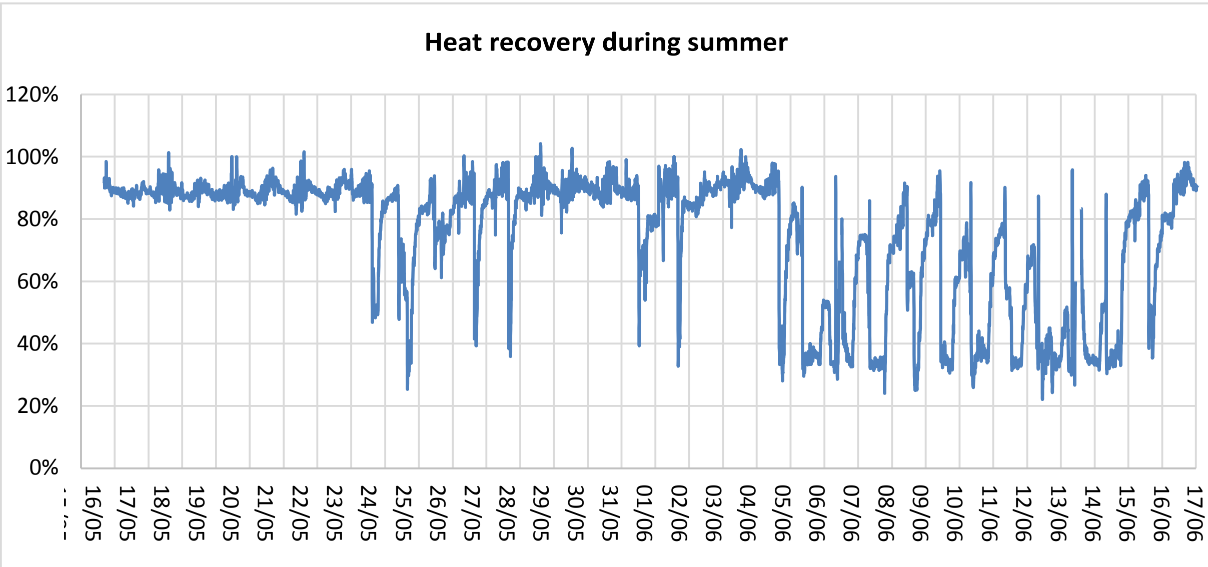


Figure 68: Calculated heat recovery based on the measurements for the unit at the 3rd floor during summer

6.2.4 Evaluation of exhaust hood performance

In order to try to evaluate the exhaust hoods effectiveness from an indoor climate perspective the difference between the exhaust and the supply air was analyzed (Figure 69 and 70). When the difference is large the effectiveness is highest. But there is a large variation depending on the user patterns. The measurements are performed when the outdoor temperature is far below the indoor temperature, which result in high relative humidities in the supply air. This could look as a wrong control strategy to take in air with a higher relative humidity compared to the indoor values, but the absolute humidity in the outdoor air is less than the absolute humidity in the indoor air. The Airmaster unit is calculating the absolute humidity and will only ventilate when the outdoor values are lower than the indoor values.

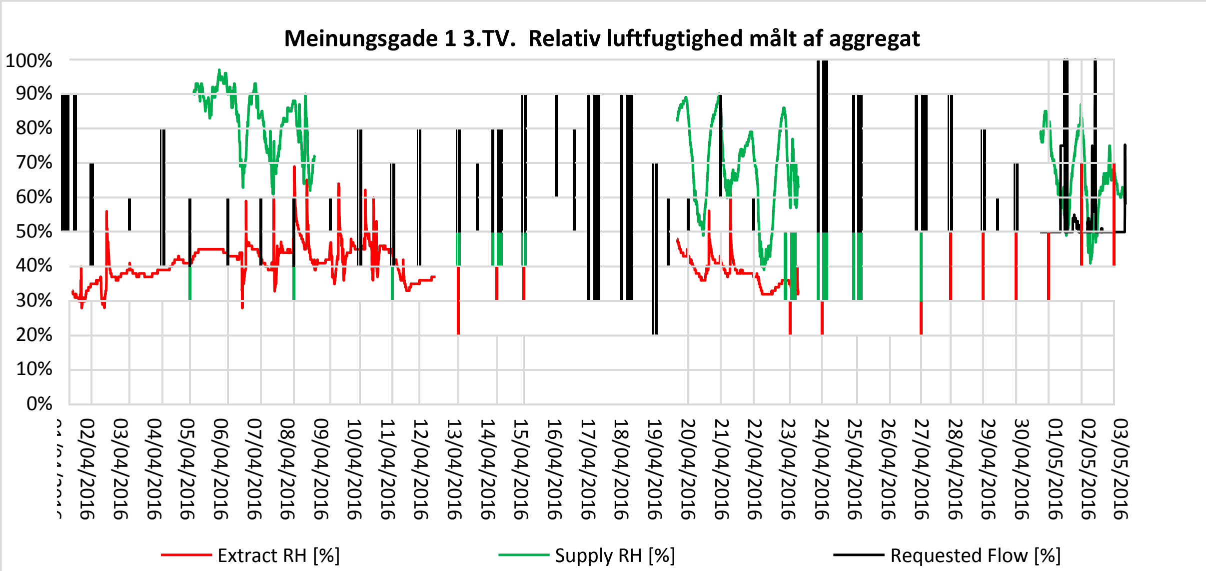


Figure 69: Calculated heat recovery based on the measurements for the unit at the 3rd floor

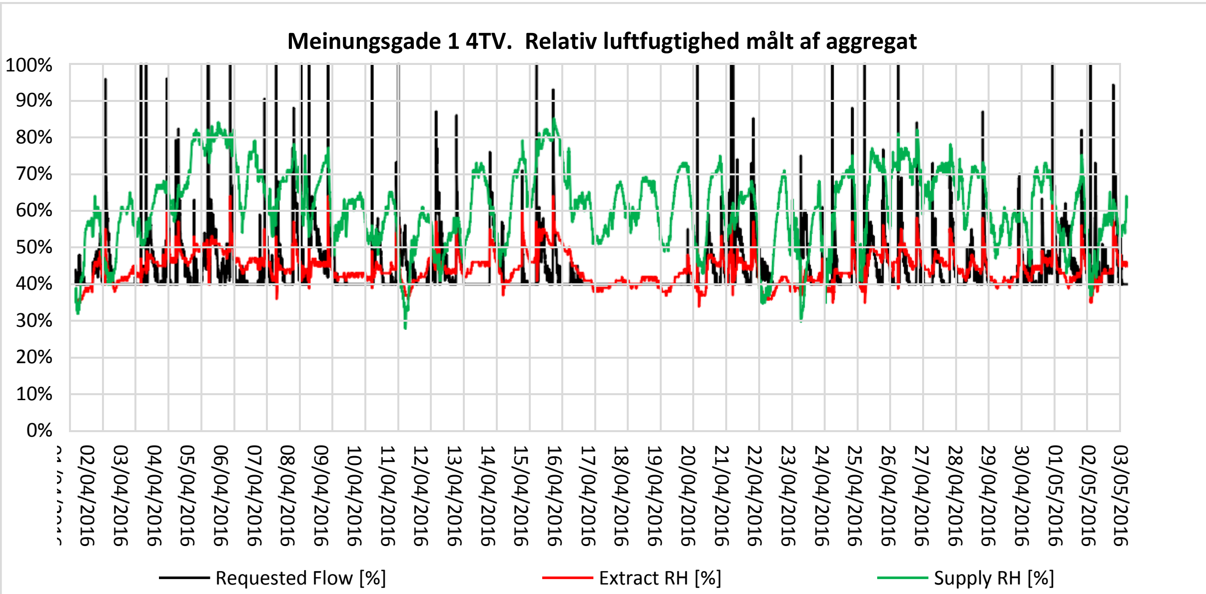


Figure 70: Calculated heat recovery based on the measurements for the unit at the 4th floor

6.3 The practice of installing decentralized ventilation units

The planning of the ventilation systems has been carried out in two different ways on the 3rd and the 4th floor in order to find optimal solutions. The planning of the system on the 3rd floor has happened through dialog and sketching with the contractor and the supplier, whereas the system on the 4th floor has been carried out creating 3D drawing with integrated pressure loss and noise calculations. The dialog between the supplier and the consultant has been very constructive and efficient. The installation of the ventilation system was performed by the entrepreneurs (ventilation, carpenter and electrician) hired from the operating organization of the building administrator.

Based on interview the occupant has given the following information on their experience with the process and product:

3rd floor:

- Very happy with the final product. The occupant feels that there is a significantly improved indoor climate. Especially during winter there is no condensation on windows. Also there are no problems with mould growth which has been a problem earlier on specific walls. The exhaust hood cannot exhaust everything during cooking but due to ventilation in the apartment it disappears fast afterwards.
- The filter has to be chance more often than expected.
- Not happy with the process of the installation. Many problems with coordination and communication. The workers left a lot of mess. The plan was that the system should be installed during the occupant's holiday but was time delayed with 2-3 weeks.
- Overall conclusion: Very happy with the final product but not with the process

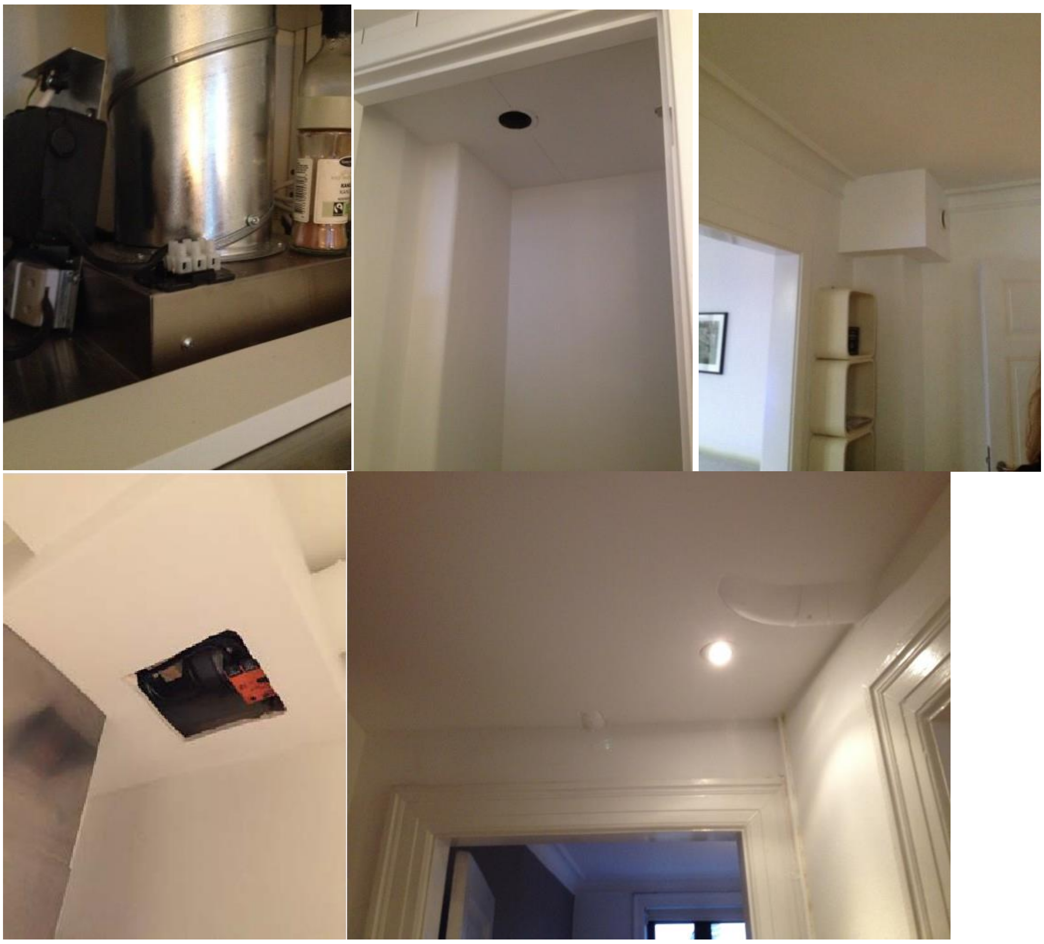
4th floor:

- Happy with the ventilation system. The occupant feels a better indoor climate. During the summer the air is cleaner and do not feel stuffy and closed.
- The exhaust hood works very well now. It took long time before the connection between the exhaust hood and the ventilation unit was established due to misunderstanding in communication between the different people involved in the installation process.
- Very bad installation process that was very chaotic and no coordination between the different installation people. The carpenter installed a ceiling below the unit, which makes it very difficult to access the unit. The occupant is now waiting for that to be chance so that access can be reestablished.
- Overall conclusion: Very happy with the final product but not with the process.

The experience with the entire process is therefore that:

- It is very relevant to understand the experience of the occupants of both the installation process and the operation of the ventilation system, since neither the consultants nor the administrators are present in the apartment through the process of installing the unit and after when the system is operating.
- There are many players in the value chain, which easily can lead to bad coordination and mistakes.
- Ad hoc solutions with duct and valve placements (see pictures below)
- One conclusion is that instead of having many different people involved is it better to have a turnkey contract so that things happens smoother so there is no breakdown in communications which leads to mistakes and chaos.
- The experience from the installation of the ceiling at the 4th floor shows that the carpenter had no understanding of the importance of accessing the unit.

As an outcome of the experiences gathered in this project decentralized ventilation will be established in 35 energy renovated apartments and in 7 newly constructed penthouse apartments in Ryesgade 25.



6.4 Conclusions on decentralized ventilation

It is difficult to draw any precise conclusions on the 3-way valve/damper used on the 3^{rd} floor for the exhaust hood, but on the market there is a demand for effective, good and economical friendly solutions and the effective exhaust hood on the 4^{th} floor will probably be in favor in most cases. The consultancy group involved in this project is in the process of renovating 35 apartments and 7 new penthouse apartments where the solution with the effective exhaust hood has been chosen.

In order to try to evaluate the exhaust hoods effectiveness from an indoor climate perspective the differences between the exhaust and the supply air was analyzed. When the difference is large the effectiveness is highest. But there is a large variation depending on the user patterns. The measurements are performed when the outdoor temperature is far below the indoor temperature, which result in high relative humidities in the supply air. This could look as a wrong control strategy to take in air with a higher relative humidity compared to the indoor values, but the absolute humidity in the outdoor air is less than the absolute humidity in the indoor air. The Airmaster unit is calculating the absolute humidity and will only ventilate when the outdoor values are lower than the indoor values.

On the 4^{th} floor the measurements shows a larger deviation on the requested flow from the ventilation unit compared to the 3^{rd} floor. It is not possible to evaluate if it is due to a more stable operation with the solution with the 3-valve damper.

It is difficult to evaluate which system performs the best. Both systems seem to be working as intended and the occupants are happy with the systems. The effective exhaust hood provides more efficient exhaust when cooking and is a more elegant solution, but also a more expensive solution.

New data extracted from Airmaster´s system (beyond the detailed measuring period) shows that the heat recovery surprisingly is running parts of the summer (The ventilation has a variable by-pass function). The heat recovery happens to ensure a minimum supply temperature (i.e. 18°C) to avoid draft. In other case-studies the system was installed with a “summer-operation” function to shut down the supply in order to save electricity. If the measurements show that the amount of hours below 18°C is too many the occupants can experience draft. In old badly insulated apartments it can also result in increased heating consumption if the radiators start to operate due to too low heating contribution from the heat recovery. In those cases it is better to operate the system with a heat recovery. This result in the fact that the optimal way to operate the system depends on the heating balance in the apartment. And thereby the energy savings applied in the specific renovation project (insulation/new windows etc.).

It is seen that there is too high CO2 values in the bedroom during night time, which is a rather known developing theme. One solution to this could be to have valve between the bedroom and the living room in order to let some of the polluted air from the bedroom enter the living room.

The experience from this project is that it the installation process is a difficult task when many people from the value chain are involved. One conclusion is that instead of having many different people involved is it better to have a turnkey contract so that things happens smoother so there is no breakdown in communications which leads to mistakes and chaos.

In order to ensure that the system is operating as intended it is very important that the installation happens correctly and that the system is adjusted corrected to the specific apartment. Continuous comminising is an important aspect of ensuring an effective and correct operation.

An analyzis of operational time and volume flow rate was performed and concluded that it was not relevant to decrease duct dimensions in regards to normal practice. A reduction in diameter from 125mm to 100mm would have a small economic benefit and ease the process of installing ducts plus give the opportunity to raise the suspended ceiling etc. However, it will result in an increased energy consumption of approximately 50%.

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Annex 1

Internal façade insulation with active moisture control

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Technical University of Denmark

Department of Civil Engineering

Master thesis

June 2016

DTU Byg
Institut for Byggeri og Anlæg

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Period:	*January 25th 2016 – June 25th 2016*
Project type:	*Master thesis*
Comments:	*This report is a part of the requirements to achieve a Master of Science in Architectural Engineering at Technical University of Denmark.* *The report represents 30 ECTS points*
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LEARNING OBJECTIVES

The content of the thesis is agreed with the programme supervisor. The thesis may contain a combination of experimental work, fieldwork, theoretical studies, synthesis, modelling and analysis. All these must include elements of literature studies and criticism. In addition, the thesis contains the following overarching learning objectives:

- *Can identify and reflect on technical scientific issues and understand the interaction between the various components that make up an issue*
- *can, on the basis of a clear academic profile, apply elements of current research at international level to develop ideas and solve problems*
- *masters technical scientific methodologies, theories and tools, and has the capacity take a holistic view of and delimit a complex, open issue, see it in a broader academic and societal perspective and, on this basis, propose a variety of possible actions*
- *can, via analysis and modelling, develop relevant models, systems and processes for solving technological problems*
- *can communicate and mediate research-based knowledge both orally and in writing*
- *is familiar with and can seek out leading international research within his/her specialist area.*
- *can work independently and reflect on own learning, academic development and specialisation*
- *masters technical problem-solving at a high level through project work, and has the capacity to work with and manage all phases of a project – including preparation of timetables, design, solution and documentation*

PREFACE

This thesis is written in association with the two-year Master of Science program in Architectural Engineering at Technical University of Denmark (DTU). In collaboration with Saint-Gobain ISOVER A/S, their new concept of internal insulation with active moisture control is investigated in this thesis. The whole thesis is carried out in cooperation with the two parts.

At a conference in Aarhus last year hosted by Cotes AS, I was lucky to be tipped off about the project Isover were developing in cooperation with DTU. In this regard I would first of all like to thank Thomas Rønnow Olesen and Rasmus Toftegaard for the good tip that later turned out to be the topic of my thesis.

I would also like to thank Kristian Koldtoft and Erling Jessen for the collaboration and pleasant meets at DTU and at the Isover factory in Vampdrup. A great thank you to Anton Ørbæk who has continuously helped out with practical headaches concerning pressure drop measurements, smoke machines and other concerns throughout the process. I would also like to thank all other staff at DTU byg for providing measuring tools, Tom Robert Sletta for the sponsoring of sensors to the project and Maria Harrestrup for help with Delphin software.

Also, I would like to thank my father, Odd Olav Fosso, for valuable guidance related to the physics of humidity and continuous feedback on my work. Moreover, I would like to thank family and friends for good advice and moral support throughout the process.

Furthermore I would like to especially thank my supervisor Svend Svendsen for weekly meetings with constructive feedback, great ideas, inspiration and motivation

---

Kjersti Fosso

Kongens Lyngby, June 24, 2016

ABSTRACT

The basis of this report is the pressing need for a moisture safe solution of internal insulation to historical brick walls with embedded wooden beam ends in cold climates with heavy wind driven rain. The purpose of this report has been to investigate whether the newly developed internal façade insulation concept "RetroWall" with active moisture control is suitable for *retrofitting of historical brick facades in regards to moisture. The active moisture control consists of a dehumidifier integrated in the wall and is removing moisture from a 25mm air gap between the brick surface and insulation.*

Methods of investigation include hygrothermal simulations conducted with Delphin software. The simulations are carried out with Danish climate data and with the extreme rain exposure coefficient of 0.5 which represent the worst case scenario. Additionally, airflow in critical sections are investigated and later measured in a mock-up test with a window section to examine the related challenges around windows. The results show that for north and west oriented walls the RetroWall is moisture safe only when dry air is also supplied around the beam ends. The results also indicate that the catch ratio of 0.5 most probably is too high when comparing with moisture content for reference cases. A large part of the investigation has also involved examination of the pressure drop in the system in order to obtain an even airflow throughout the wall and around the beam ends.

CONTENTS

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1 INTRODUCTION

1.1 Background

As buildings accounts for over 40% of the total energy consumption in Denmark today, the energy requirements has become stricter for both existing buildings and new building projects. A major challenge on the path towards reduced energy consumption in buildings is that a significantly large percentage of the buildings in 2050 will consist of buildings that already exist today [1]. As a result of today's energy requirements and the high heating demand in older buildings, and due to the poor indoor climate caused by cold internal surfaces the measure is to insulate exterior walls. Exterior insulation is not an option for many historical buildings because of preserved architectural facades, thus these require internal insulation. However, internal insulation comes hand in hand with the risk of moisture damage. The disturbed balance between temperature and moisture can lead to mould growth and in worst case damage the structural beams embedded in the historical brick walls. Bad retrofitting without cautions taken towards moisture can thus be financially damning and defeat the initial purpose of improving the building quality.

1.2 Aim

The purpose of this thesis is to investigate whether the concept RetroWall developed by Isover, Saint-Gobain, consisting of internal insulation with an integrated dehumidifier, is suitable for retrofitting of historical preserved buildings in the matter of moisture.

The investigation mainly examines the risk of mould growth and rot in the structural beam ends embedded in the brick wall, in addition to other critical locations such as sections around windows. Hygrothermal simulations will work as the main tool in the investigation, which will give a good indication to growth of any mould.

The main focus is directed towards the beam ends because of a pressing need for a solution in cold and wet climates with heavy wind driven rain, such as Denmark. Another notable risk is the potentially lack of dry air supply beneath the window section, which can give rise to local moisture damage. To avoid this, the capacity of the dehumidifier and the airflow must also be examined. Previous work and investigations have found solutions to reduce the risk of moisture damage when applying internal insulation, but there is still room for improvement *and better solutions to the moisture problems in cold climates that causes much trouble in retrofitting of historical buildings.*

Based on the results and findings of the investigation the aim is to find a well thought out moisture safe solution for the RetroWall. The solution should simultaneously be simple and foolproof in order to avoid imperfections.

1.3 Structure of report

The report consists of an introduction and recent research on the topic, relevant theory and background material, and a presentation of the concept investigated before it is divided into four parts of investigation:

- *Part 1 – Hygrothermal behaviour in a brick wall with and without insulation*
- *Part 2 – Airflow distribution*
- *Part 3 – The dehumidifier*
- *Part 4 – Optimization of the system*

The main focus and majority of the study is dedicated to part 1 and part 2 because these are investigating the requirements of the system, while part 3 and part 4 will consist of less investigation and more discussion and around the concept.

In part 1 consists of hygrothermal simulations performed in the software Delphin which works as a main tool to investigate the moisture development in historical brick walls.

Results, such as required moisture removal and detection of critical situations from part 1 are then used when investigating the airflow in part 2.

Moreover, the results from part 1 and part 3, such as required moisture removal and pressure drop in the airflow are used in part 3 when examining the capacity of the dehumidifier.

Part 4 examines all results from the previous parts and discusses the optimization potential of the concept.

Finally a conclusion with proposal for solution is presented based on the investigation.

2 STATE OF THE ART

This chapter will present some of the newest research within the field of internal insulation and moisture issues, in addition to new methods of energy efficient dehumidification.

2.1 Wall configurations and insulation

Several studies have investigated how different configurations of traditional internal insulation will affect the moisture content in critical sections of historical brick walls, such as thicknesses of insulation and uninsulated portions above and below the floor section.

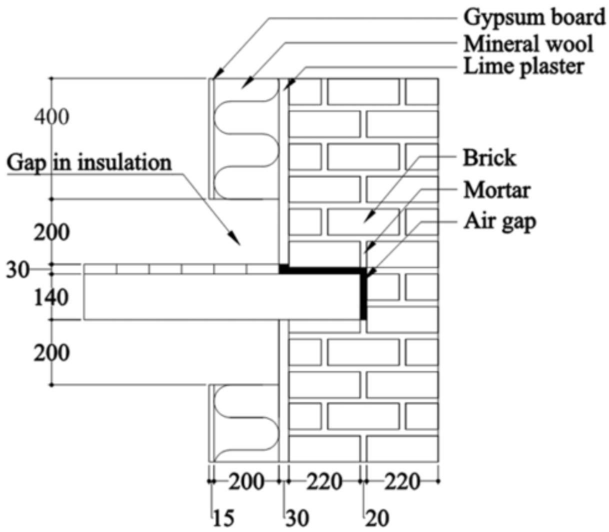


Figure 1: traditional insulation with 200 mm gap above and below floor section[2]

In the article "**Investigation of interior post-insulated masonry walls with wooden beam ends**" [2], Morelli and Svendsen are investigating whether the moist*ure problems can be solved by not insulating a portion of 200 mm above and below the floor division shown in Figure 1. It is pointed out that earlier studies related to the subject where the results have shown no moisture problems in the beam end, has no hygrothermal simulations with wind driven rain (WDR) as a parameter. In the study, hygrothermal simulations of the embedded beam end with 200mm insulation gap above the floor show that the moisture content and relative humidity at the beam end would be similar to an uninsulated wall with a climate data for Northern Germany. However it is concluded that the WDR has a major effect on the moisture content in and around the beam end, which furthermore leads to the conclusion that the retrofit should not be used in northern Europe before further studies with different climate conditions has been carried out. The study by Morelli and Svendsen, the hygrothermal* *simulations also show that moisture content (MC) at the beam end was close to unchanged in the cases of 100cm and 200cm of insulation gap. In more recent studies on the matter, is it discovered that the heat gain to the beam end from the insulation gap is not efficient enough to secure drying of the beam ends. Hence, it is therefore still necessary to develop another solution related to the wooden beam ends that will prevent any mould growth. In the article* "**Full-scale test of an old heritage multi-storey building undergoing energy retrofitting with focus on internal insulation and moisture**"[3], Harrestrup and Svendsen are *investigating the hypothesis stating that* "it *is possible to carry out moisture safe energy renovations in the old existing multi-storey buildings with heritage value and still save 50% of* the building's energy consumptions by the use of existing technologies". The insulation *in the test-apartment was stopped 200 mm above the floor section to increase the heat flow through the wall. Both numerical simulations of temperature and real testing measurements of the RH and temperature of the beam end were performed. Based on approximately a year of measurements in the test apartment it was concluded that no risk of mould would occur in the beam ends, however it is pointed out that the winter temperatures during the test year were relatively high which would decrease the risk of mould growth.*

In a follow-up study "**Internal insulation applied in heritage multi-storey buildings with wooden beam ends embedded in solid masonry brick facades**"[4], Harr*estrup and Svendsen are comparing the results from the measurements of the test-apartment [3]with hygrothermal simulations of three different insulation strategies including a 200 mm insulation gap above and beneath the floor section. Based on findings it is concluded that this solution is moisture-safe only when the rain exposure coefficient is less or below 0.1 with a wall orientation towards west. Therefore, further investigation is needed for north-oriented walls and with higher rain exposure coefficients.*

Another important matter is the thickness of the internal insulation, which can increase the thermal resistance thus decrease the heat loss though the façade. Simultaneously, internal insulation will reduce the floor space. When increasing the thickness of the insulation, the temperatures will decrease.

2.2 Non-conventional materials

Another approach to moisture problems of internal insulation is to apply non-conventional insulation technologies, such as vapour diffusive permeable insulation, capillary active insulation materials or vacuum insulated panels among others.

In the article "**Long-term measurements and simulations of five internal insulation systems and their impact on wooden beam heads**" [5], Ruisinger investigates five different *vapour diffusion permeable insulation materials and their impact on moisture content at wooden beam ends embedded in masonry brick walls, installed in an apartment located in Graz, Austria.*

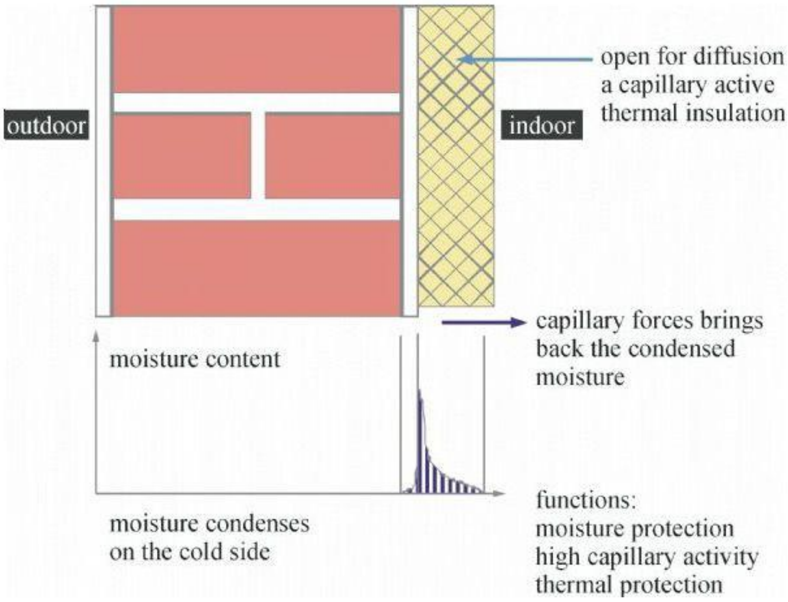


Figure 2: Capillary active insulation [6]

Vapour diffusion permeable materials, such as i.e. reed or wood fibre insulation board, will allow drying to the interior. The measurements show that the internal insulation has little influence on the wooden beam end. However, it is pointed out that this might be due to lack of driving rain load and very porous bricks which will increase the drying potential to the exterior. Also such vapour diffusive materials will be riskier in colder climate as mean temperature of the masonry interior surface will be low and risk of condensation of interior air on this surface will increase. In the article "**Retrofit with interior insulation on solid masonry walls in cool temperate climates – An evaluation of the influence of interior insulation materials on moisture conditions in the building envelope**" [7], Bjarløv et *al. are testing several models using different capillary active insulation materials, such as calcium silicate boards and rigid PUR-foam panels, in hygrothermal simulations for cool* *climates. A capillary active system can capture the condensed moisture and move it towards the interior as shown in Figure 2. The conclusion of the findings is that capillary active internal insulation without additional impregnated masonry façade is not suitable in climates with heavy rainfall such as Denmark due to the accumulation of moisture behind the insulation. In the article* **"Interior insulation for wall retrofit – A probabilistic analysis of energy savings and hygrothermal risks"** *Vereecken et al. [8] are comparing the hygrothermal performances of two capillary active systems with two standard systems of internal insulation during the heating season. The two tested capillary active insulation systems were calcium silicate and secondly a smart vapour retarder, while the standard insulations systems were extruded polystyrene (XPS) and the other mineral wool with traditional vapour barrier. Based on the results the article concludes that a capillary system might be a favourable choice to prevent any frost damage, or when wooden beam ends are embedded in the masonry. However, it is emphasized that the output is always the result of the input, and this input should be realistic. The climate data used in the study is from Bremenhaven and München (Germany), thus when dealing with other climates and other boundary conditions these results should be* used with caution. In the article "**Interior insulation retrofit (…) using vacuum insulation panels: hygrothermal numerical simulations and laboratory investigation**" [9] Johansson et *al. are applying vacuum insulated panels on the interior to test hygrothermal performance of a brick wall with wooden beam ends with both numerical simulations and laboratory testing applying cool and wet climate data from Sweden and Norway. The tests showed that the relative humidity in the wall increased significantly when exposed to wind driven rain, which also influences the RH at the colder beam ends. It also showed that the properties of the bricks would have a large effect on the moisture content in the wall.*

2.3 Dehumidification

A few modern dehumidification methods are developed based on the need for improvement of indoor environment and to reduce energy in a sustainable future, as conventional systems require much energy.

In the article "**Membrane processes for heating, ventilation, and air conditioning**" [10] *Woods are reviewing literature on the use of membranes in HVAC, including dehumidification. Several alternatives to conventional cooling and dehumidification which can save a lot of energy in the future have been developed by researchers. This advanced* *method of dehumidification consists of artificial hydrophilic membranes having the ability to selectively attract vapour from the air without removing much air. The membranes are high permeable with high selectivity meaning they can transfer up 100,000 molecules of water for every molecule of nitrogen, visualized in Figure 3a.*

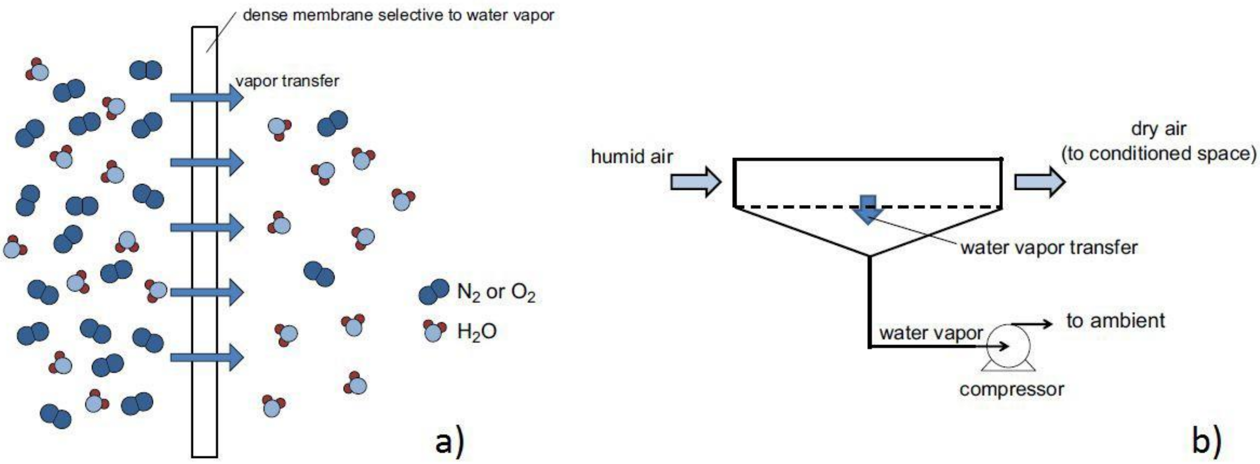


Figure 3: function of dehumidification membranes: a) Membrane-fluid interface for dense membrane [10] b) Schematic of membrane vacuum drying [10].

When the purpose is to remove humid air and to add dry air, the recommended method is "vacuum membrane dehumidification", Figure 3b. This is a method where a compressor *creates a pressure gradient used to move the vapour. The water vapour absorbs into the membrane and then diffuses through to the other side of the membrane. The vapour then desorbs from the membrane because of the lower pressure.*

Theoretically this system could be a good solution to the dehumidification of a 25mm air gap in an internal retrofitting of a brick façade as small amounts of vapour has to be removed with the help of a small compressor. However, it is unknown whether such solutions are developed for commercial use. Also, compressors are noisy which could potentially be a problem if it was integrated in the wall. Getting rid of the liquid water would also be necessary which would require either the tenants to manually empty it periodically, or potentially a drain through the wall. However, this method could be used in such way of installing small porous plastic pipes with small spacing which could directly dehumidify the airgap without requiring circulating airstream. A separate vacuum pump in the basement could then be connected to all floors.

Another method of membrane dehumidification is called “liquid desiccant dehumidification", *which has the same function as the vacuum membrane, but does however not include pressure gradients from a compressor. Instead the vapour from the air is absorbed into the desiccant. A regeneration process heats the desiccant which makes the vapour evaporate into a separate airstream, displayed in Figure 4. The liquid desiccant is typically liquid in the form of strong salt concentrations, such as lithium chloride or calcium chloride which has a strong affinity to water due to its close to zero vapour pressure.*

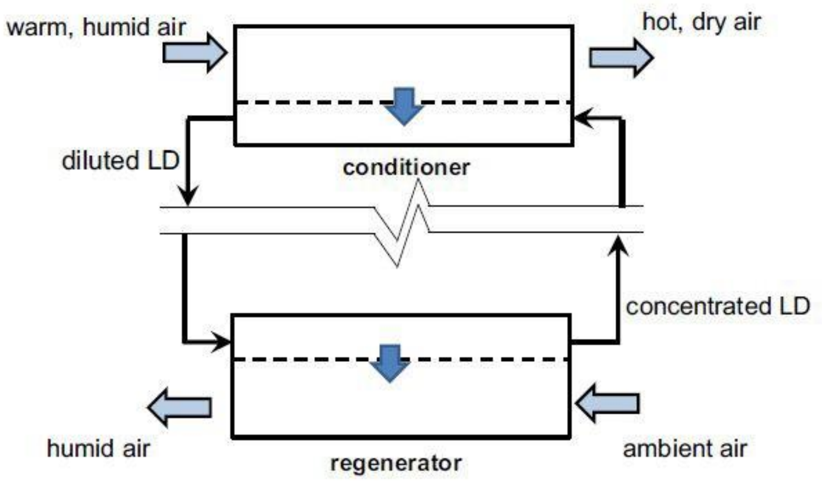


Figure 4: Schematic of liquid desiccant dehumidification[10]

The dehumidifier from Cotes which will be integrated in the RetroWall is a desiccant dehumidifier with a honey comb structured silica gel rotor as the desiccant. Silica gel has a strong affinity to water molecules and will thus adsorb vapour from passing air. The dehumidifier is divided into two separated air flows of process air and regeneration air. The process air flow removes moisture from air by passing the humid airflow through the silica gel rotor. The water molecules adsorps to the large area of silica gel, and dry processed air comes out on the other side. The regeneration air flow releases the water molecules from the desiccant rotor. Room air is heated by a heating coil, and passes through a quarter of the rotor to release the water molecules gained from the process air. The regeneration air will then return as humid air.

Compared to the vacuum membrane dehumidification where the product is liquid water, the latter solution is more practical as the humid air do not require being removed the same way as liquid.

3 THEORY RELATED TO INTERIOR INSULATION AND MOISTURE IN HISTORICAL BUILDINGS

This chapter contains theory related to the application of internal insulation in historical buildings and its effect on moisture. In addition, some facts about the construction history and typical construction methods of building apartments in the late 1800's to the early 1920's is *presented to provide a better overview of the situation.*

3.1 Historical buildings and construction method

According to SBi 2010:56 [11] the registrations in BBR (Danish Construction and housing register) shows that the typical building period from 1850 to 1930 was a period of intense residential development, where apartment buildings accounted for about 30% of the total building area in Denmark in this period, displayed in Figure 5. Most of the today's preserved *building area was also built during this period; hence these are the target buildings for the RetroWall system in this thesis. The fact that the preserved building area only count for a very small part of the total building area does not mean the potential is as small. Many building owners wish to preserve the facades even though it is not officially protected. Also, an external insulation project demand greater planning due to the new façade design, wh*ich isn't *an issue with internal insulation.*

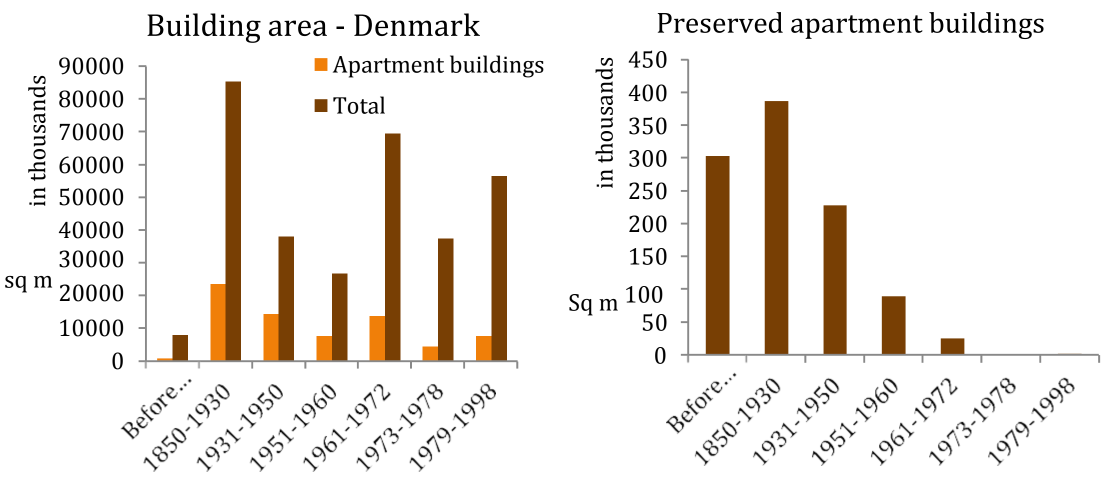


Figure 5: Building trend the last century (left) and preserved building area (right)

Based on the SBI report 124 about Copenhagen apartment buildings from 1850 to 1900 [12] some information is gathered to get an overview of the typical building trend from the 1850's.

The apartment buildings were built more or less in the same manner from 1850 until ca 1930, i.e. solid brick walls with wooden floor beams constructed into the brickwork, and almost exclusively made of brick by brick and lime mortar. A typical way to construct these apartment buildings was that the massive brick walls would decrease in thickness at every second floor hence the lower levels have thicker walls than the upper levels. With the Building Act of 1856 the thickness of the outer wall was determined based on number of floors. The top floor should have outer walls of 1 ½ stone thickness, and in the two subsequent levels with walls of 2 and 2 ½ stone thickness respectively, and thereafter ½ stone thicker for every floor. The dimension of ideal stone thickness was 230x115x55 mm.

The parapet walls beneath the windows were built 1 stone thick on all levels. Floor beams were not bricked into the wall beneath the windows, but resting on a perpendicular beam mounted to the adjacent beams as displayed in Figure 6. Timber beams from south Sweden that was less moisture absorbent than Danish spruce were typically used as floor beams between apartments.

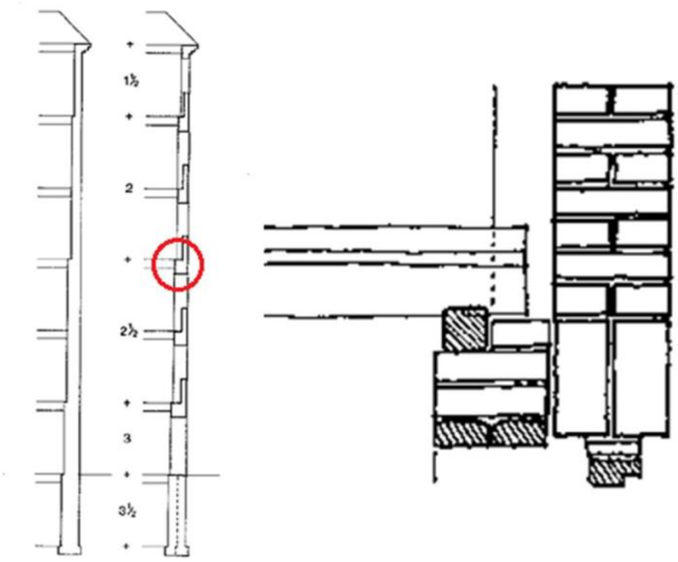


Figure 6: Vertical and horizontal sections of wall and floor construction [12]

To avoid that the beam end to come in contact with moisture in the brick wall, the beam was typically placed with an air cavity around it. According to the SBI report [12], a testing of the bearing capacity of wooden beams extracted from historical buildings in Copenhagen showed that despite of cracks, they still plentifully met the capacity of modern requirements for construction timber. Additionally they were all free from any substantial mould or moisture damage.

3.2 Effects of internal insulation

Internal insulation will certainly protect the preserved historical facades, and also improve the building envelope, but it requires a well thought out fit inside to avoid structural damage due to moisture.

A common issue with internal façade insulation is that the initial external wall will lose its natural heat gain from the inside, which therefore results in lower temperatures within the brick wall. This causes slower drying after driving rain and will therefore give rise to rot development in floor construction that is bricked into the wall. Moisture issues will also evolve below and around windows and around wall joints.

The major problem with internal insulation is the colder masonry wall, hence a slower drying process after driving rain resulting in longer periods of moist walls. The bearing wooden floor beams are mounted into the brick wall as shown in Figure 7. The slower drying of the porous wall materials will expose the wooden beams to higher levels of relative humidity over longer periods of time. This can result in rot and mould growth, thus damage the structural integrity.

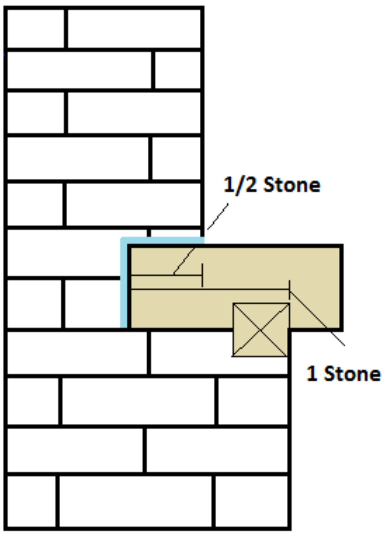


Figure 7: Wooden beam support

Original external walls without internal insulation gain heat from the inside resulting in faster drying after driving rain. The temperature in the wall has an approximately linear distribution. When applying internal insulation, the temperature of the original wall will decrease resulting in slower drying and colder internal surfaces. Condensation on the brick surface will occur as a result of warm humid air leaking through any imperfections in the vapour barrier, in addition to accumulation of driven rain and capillary suction in the porous brick wall. A vapour barrier will to a certain point solve the problems related to condensation and mould *growth on cold layers from interior air; however, the vapour barrier will stop the diffusion and drying of the wall to the interior. This will result in longer periods with moist walls and will therefore increase the risk of rot and mould growth of the bearing structure and on intermediate layers between the insulation and the original brick wall.*

3.2.1 Common problems of internal insulation related to moisture

Typical appearing problems when applying conventional internal insulation are mould growth in the intermediate layer between the insulation and cool brick surface, mould growth around window sections due to the lower temperatures close to the window, around beam ends and the at T-wall intersections. The critical locations for mould growth after internal insulation is applied are displayed and listed in Figure 8 and in Table 1.

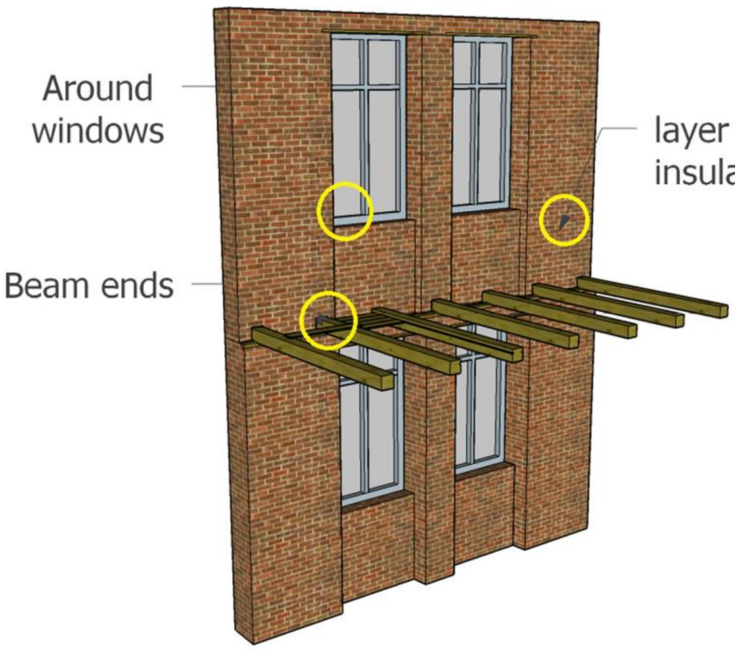


Figure 8: Critical locations of mould growth in apartment buildings (SketchUp)

Table 1: Critical locations for mould growth when applying conventional insulation

Beam ends	*Rotting and decay of structural integrity*
Around windows	*Colder surfaces cause warm interior air to condensate resulting in mould and rot.*
Cold interior brick surface	*Imperfections in vapour barriers will cause warm indoor air to condensate on the colder brick surface.*
T-wall	*Thermal bridges where exterior walls and separation walls meet can also cause risk to mould growth is the temperature is critical.*

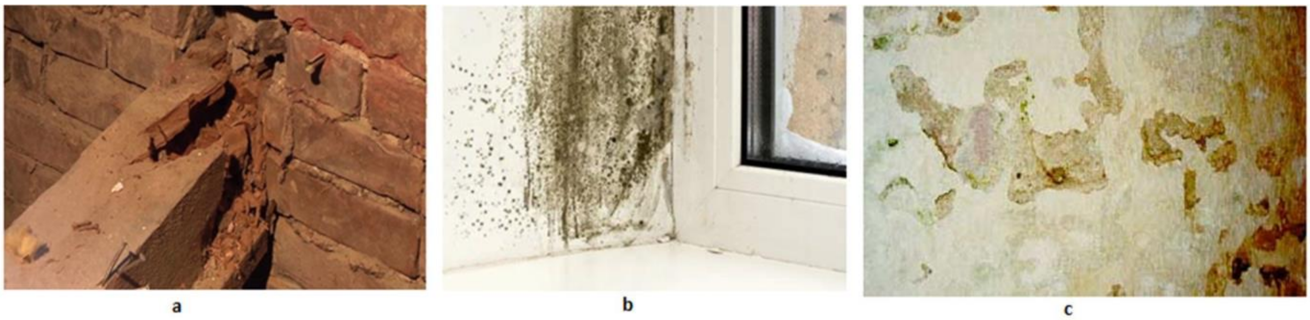


Figure 9: a) decayed beam end, b) mould around window, and c) mould on cold surface

3.2.2 Thermal Bridges

Thermal bridges contribute to increased heat loss in buildings. They typically appear where the floor construction and inner walls meet the exterior façade. When upgrading a building with internal insulation, these thermal bridges get more significant which can result in moisture problems and habitable discomfort. Heat flow through the thermal bridges is displayed in Figure 10.

These thermal bridged are inevitable when insulation is added on the interior; however measures can be taken to decrease the significance of the thermal drop which can cause moisture problems. Measures such as insulation configurations can prevent the temperature to reach the critical dew point, and is describes closer in the next chapter, 3.2.3 about temperature differences.

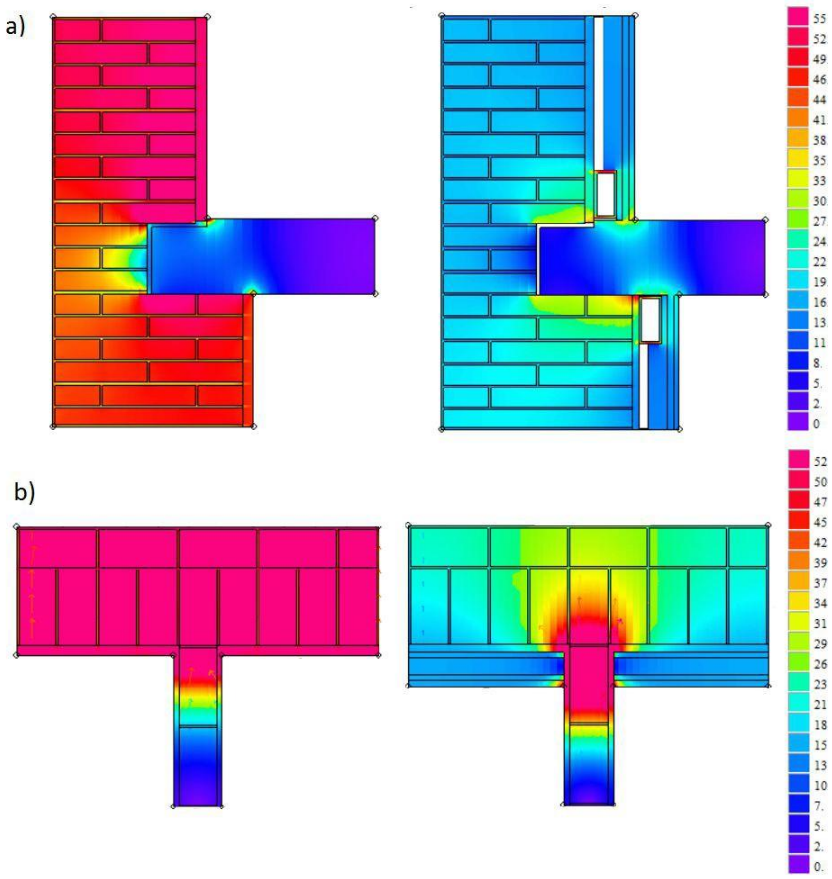


Figure 10: Heat flow (W/m²) through uninsulated and insulated facade. a) Floor construction, b) Separation walls intersecting with the façade (HEAT2)

3.2.3 Temperature difference

A brick walls temperature profile changes when applying internal insulation. An original wall will have a linear temperature profile, while an internal insulated wall will have a large temperature drop due to the thermal resistance of the insulation.

Figure 11 show the temperature distribution for an original wall with and without insulation. The original wall gain heat from the interior, which will prevent sudden cold surface leading to condensation. When applying internal insulation the temperature in the wall will decrease. This can lead to condensation when the interior warm air comes in contact with the cold wall behind the wooden beam. Even though there is a vapour barrier installed on the warm side of the wall, taking into consideration that carpenters will not always secure a 100% moisture tight barrier, there will always be some leakage of warm humid air onto the cold brick wall causing condensation in this layer.

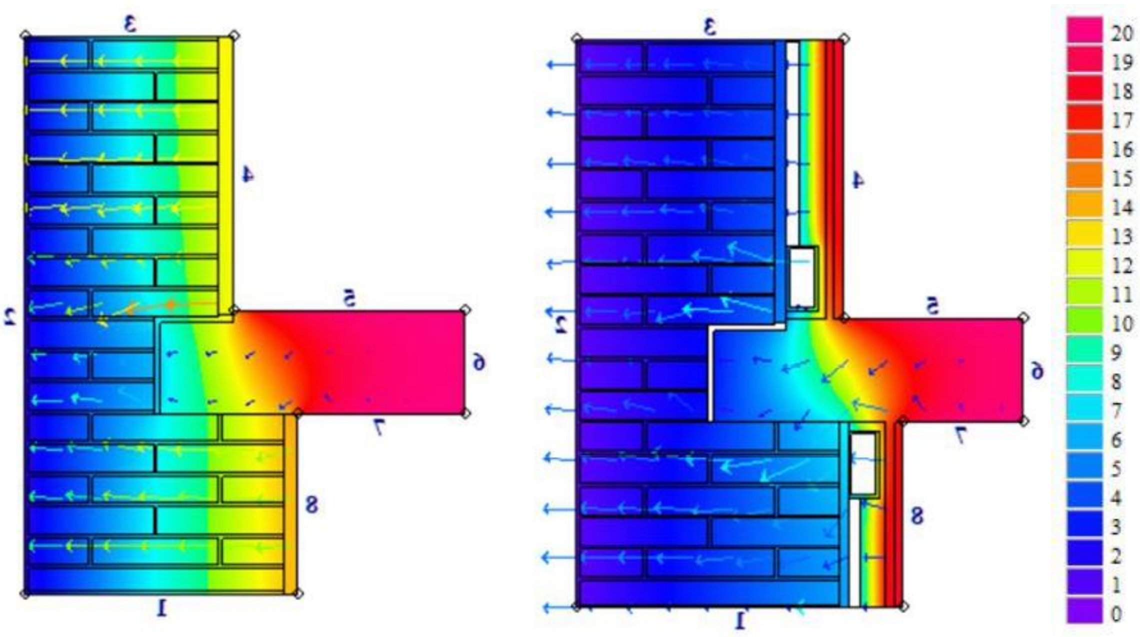


Figure 11: Temperature distribution in original wall and insulated wall, when 0°C outside and 20°C inside (HEAT2)

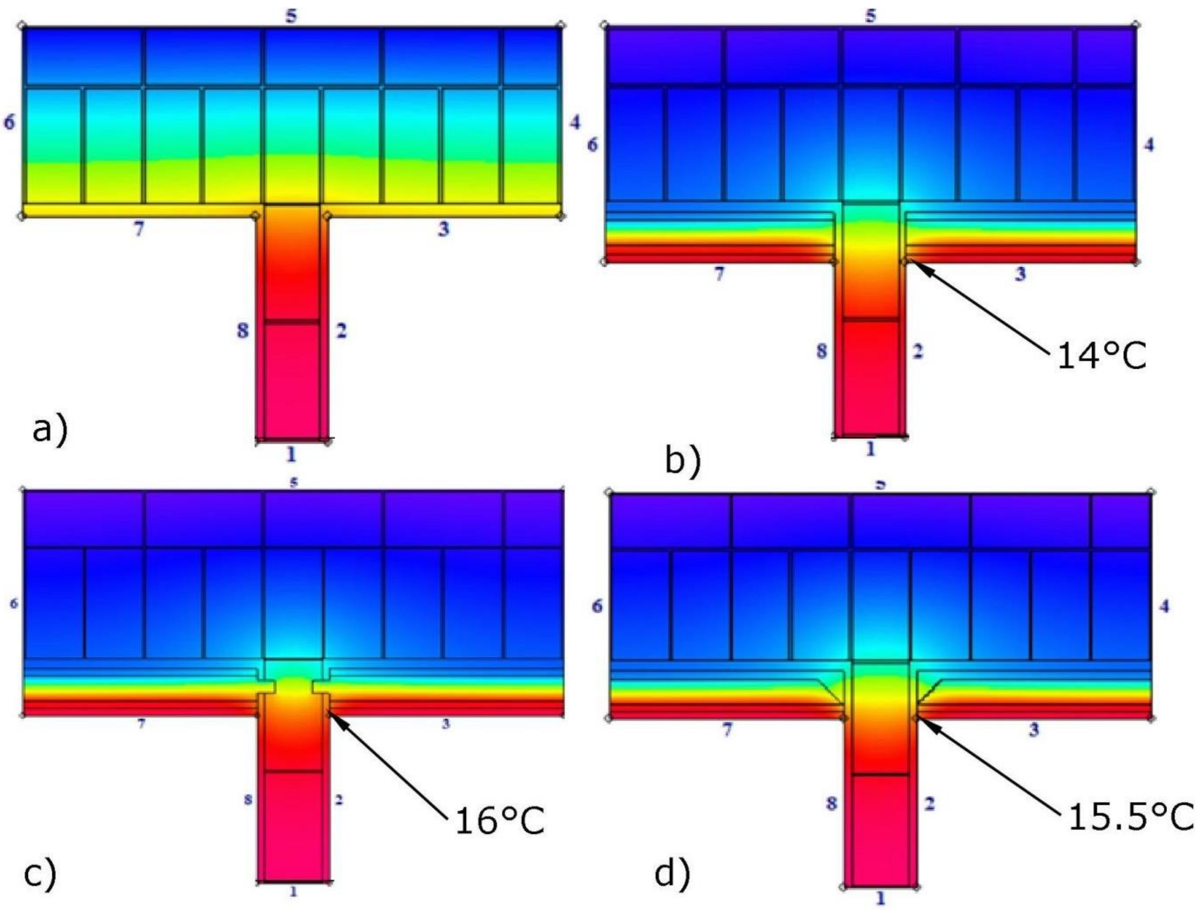


Figure 12: Temperature of T-wall, a) without insulation, b) with insulation, c) with insulation and 30mm drilled columns in masonry filled with insulation d) 45° diagonal insulation (HEAT2)

The T-walls separating apartments will also create a thermal bridge, and result in a cold spot where the insulation and wall intersect. When it is 0°C outside and 20°C inside, the temperature in the corner is 14°C. This is most likely above dew-point as interior relative humidity is around 50-60%. However, it is preferred to avoid cold corners like this to avoid the uncomfortable thermal bridges. Figure 12 shows the temperature around the wall intersection without (a) and with insulation (b). A simple way to reduce the thermal bridge can be to drill columns in the masonry and fill them with insulation (c). This increases the corner temperature with 2 degrees. This however, requires the efficient wall section area to be less than the actual wall area if these are bearing walls. According to Professor Søren Peter Bjarløv, the bearing of the separation walls are individual for each apartment building, thus this would be too time consuming in compared to other easy solutions, such as installing the insulation with 45° diagonal cut at the corners. This solution will increase the temperature with 1.5°C, which is above dew point.

3.2.4 Wetting and drying of the historical brick wall

A brick façade will easily absorb not only vapour from the air but also driving rain by capillary suction because of its porous characteristics and often lack of surface treatment.

First of all, it is important to understand that moisture and vapour will move in the direction of lower vapour pressures, hence it will always seek equilibrium. When insulating a wall with vapour barrier on the inside, the moisture can no longer be diffused to the interior. This will lead to a slower drying of the wall because all the moisture will have to diffuse to the exterior. Because of the colder wall surface, the vapour pressure difference between interior and the exterior will become very little, which will result in accumulation of moisture and thus longer periods of moist walls.

An original historical wall will absorb moisture and vapour, but because of the higher temperature within the wall, and because the lack of insulation and vapour barrier the moisture in the wall will diffuse to both the interior and the exterior depending on the variation of internal and external vapour pressure.

A rough estimation and some assumptions are used to show how internal insulation will affect the critical levels of relative humidity inside the wall visualized in Figure 13. A brick wall exposed to wind driven rain will absorb moisture and the capillary suction will make water accumulate into the brick wall; hence the relative humidity within the wall will increase and result in a waterfront. The waterfront is where the transition between over hygroscopic water *content with free water and hygroscopic water content in balance with the relative humidity. When the wall is diffusion open on both sides the drying capacity is much larger compared to an insulated wall.*

Due to the decrease in temperature in an insulated wall, the accumulation will increase and thus move the waterfront closer to the beam end. As the internal surface of the brick wall will become colder due to insulation, the vapour pressure also decreases, hence the driving force of diffusion is decreased. The result is longer periods of critical levels of relative humidity close to the beam end. Any vapour diffusion to the interior could ultimately end up condensing in the intermediate layer behind the insulation and run down the wall to the embedded wooden beam.

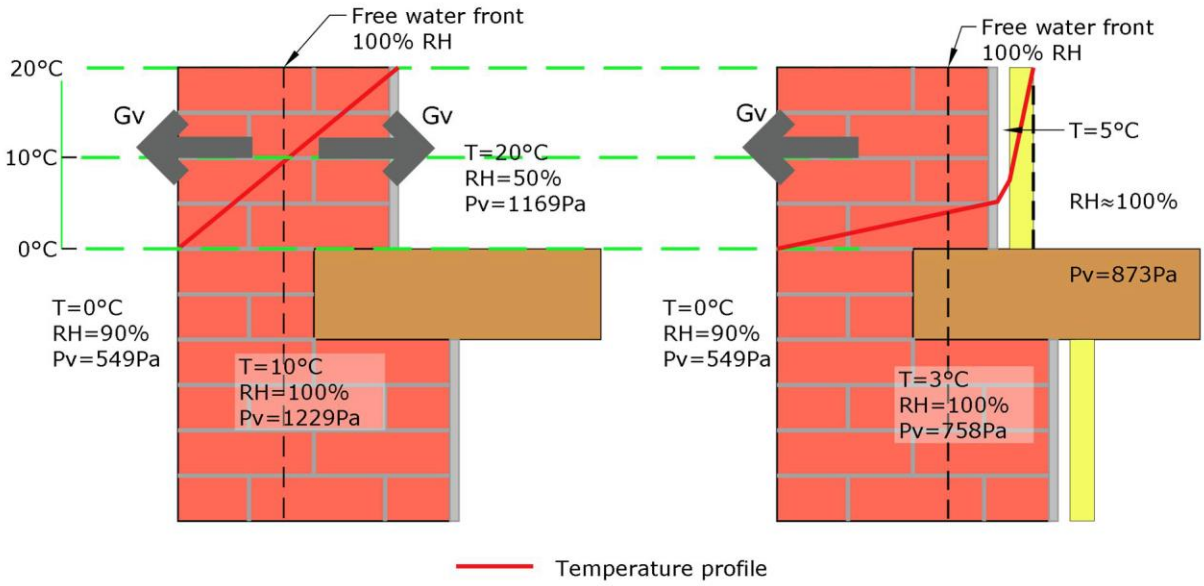


Figure 13: Accumulation and diffusion in a brick wall without insulation (left) and with conventional insulation (right) (Layout)

The moisture in a brick wall is way more complex than the presented estimate as the wall will be exposed to different weather conditions throughout the year. During winter the climate is cold and wet with few hours of sun exposure, thus the porous brick wall will absorb and store more water and less will be dried out to the outside by the heat from the sun. During the summer however, the temperature rises in addition to many more hours of sun exposure which will give temperature rise to the wall surface and longer periods of diffusion and drying to the exterior. Data of a monthly average climate are collected from the announcement no. 281 of 1995 by the laboratory of thermal insulation, DTU [13], and are presented in Figure 14.

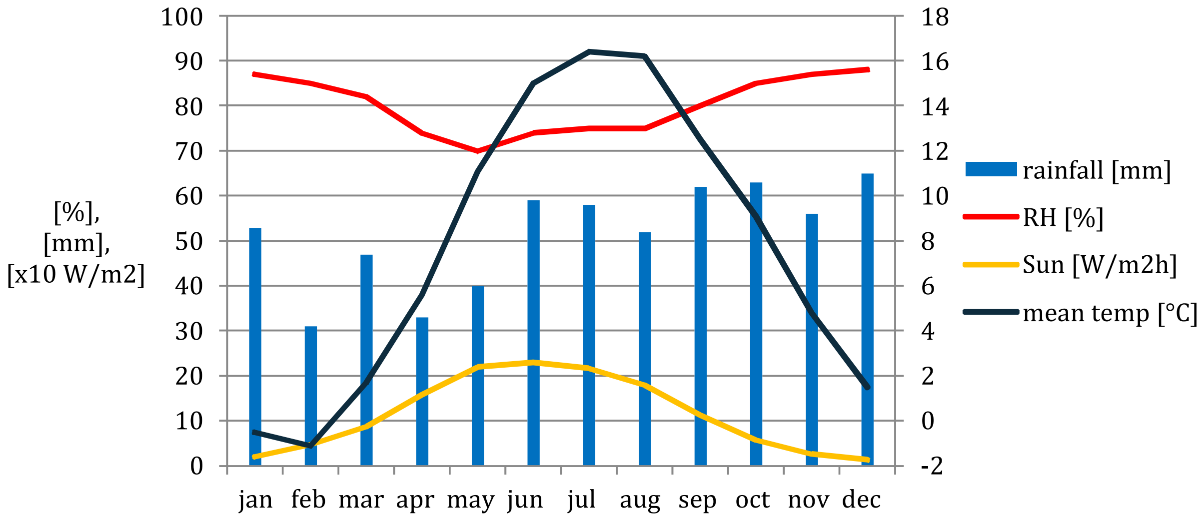


Figure 14: measured weather data 1975-1989

In order to get an understanding of how much solar radiation can affect the diffusion to the exterior some assumptions are made to make an estimated calculation of diffusion. Based on the data of the solar radiation, the temperature of the exterior surface and the interconnecting moisture diffusion to the exterior assuming that after a rain shower the exterior surface has a 100% RH, and that all solar radiation strikes the facade is presented in the Figure 15.

As expected, more moisture will evaporate to the exterior during summer when the façade temperature is higher and when the relative humidity is lower.

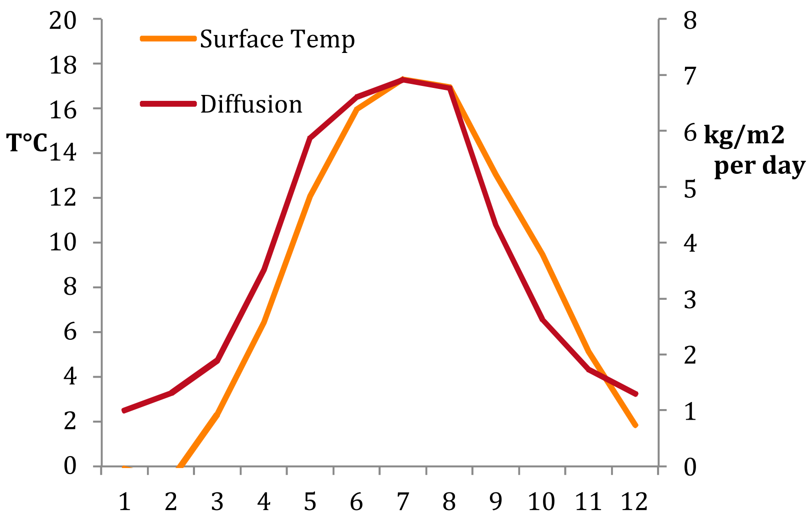


Figure 15: Annual relationship between external surface temperature and diffusion

In conjunction with the calculated amount of evaporated moisture in figure 15, some assumptions are made to provide this rough estimate of relationship between the amount of *sun exposure and surface evaporation. A crucial assumption resulting in the large amount of diffusion is the constant relative humidity of 100% on the surface of the façade. The wall is also assumed to orient towards the south, and global radiation is used as solar radiation, assuming all solar radiation hits the wall. These assumptions are not close to realistic; however the graph shows how surface temperature affects the diffusion to a great extent.*

Average surface temperature of a brick wall is calculated using the heat balance in Figure 16 and equations below (Appendix A).

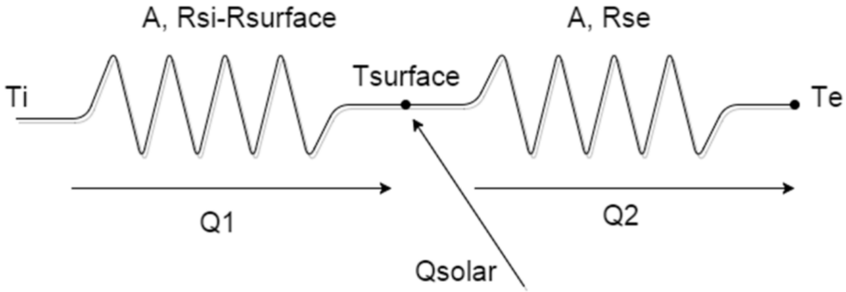


Figure 16: heat balance through a wall exposed to solar radiation

$$Q1 + Qsolar = Q2 \qquad \text{Eq. 1}$$

$$* \frac{T_i - T_{surface}}{R_{si\text{-}surface}} + Q_{solar} = * \frac{T_{surface} - T_e}{R_{se}} \qquad \text{Eq. 2}$$

$$T_{surface} = \frac{T_i \frac{A}{R_{si\text{-}surface}} + T_e \frac{A}{R_{se}} + Q_{solar}}{\frac{A}{R_{se}} + \frac{A}{R_{si\text{-}surface}}} \qquad \text{Eq. 3}$$

$$Diffusion = \frac{p_{v,surface} - p_{v,e}}{Z_{surface}} \qquad \text{Eq. 4}$$

Based on this investigation where the surface temperature seems to have a great influence on the drying to the exterior, it is expected to see much less drying of a north oriented wall in the hygrothermal investigations, due to lack of sun exposure.

3.3 The Mollier diagram

The Mollier diagram is a graphical representation of the relationship between the heat content and water content of air, and was first published by Richard Mollier of Dresden in 1923. It is a very useful tool in calculations related to humidity [14].

As an example the Mollier diagram can be used to easily find the dew-point temperature of air with specific temperature and relative humidity. As shown in Figure 17, warm interior air at a temperature of 20°C and 60% relative humidity has a dew-point temperature of 12°C. This means if the warm interior air hits a surface with a temperature of 12°C or below, it will condensate. This is because warm air contains much more water vapour than cold air, as the saturated vapour pressure depends on the temperature.

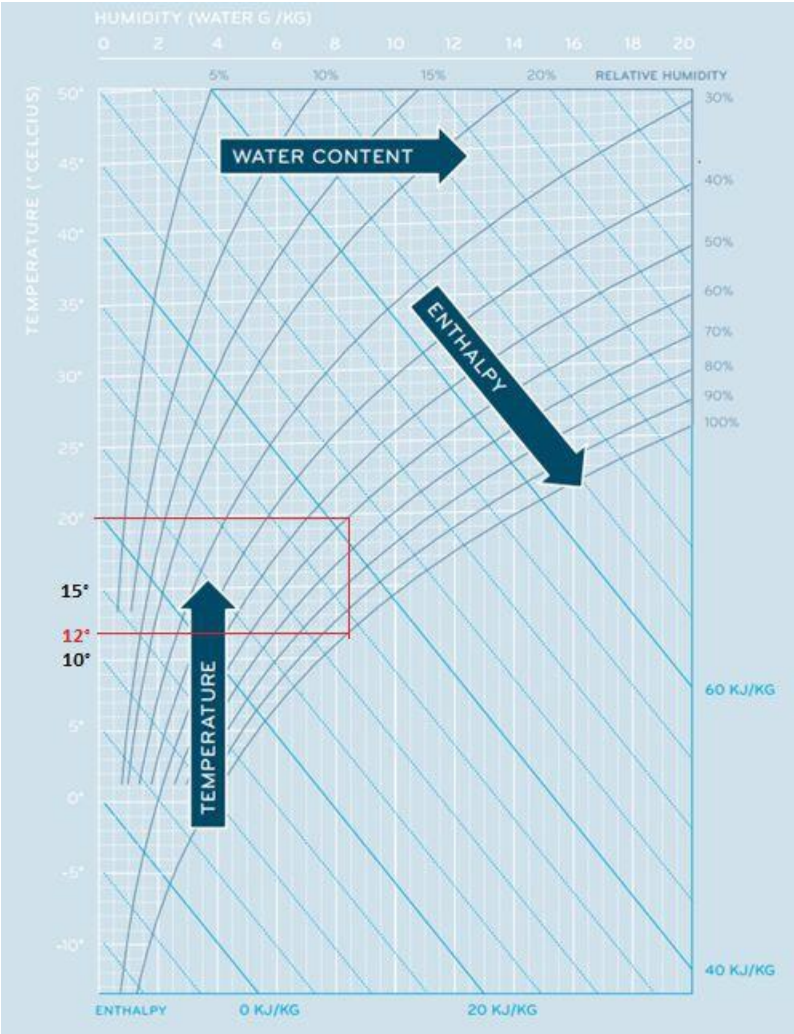


Figure 17: Mollier diagram [14]

3.4 Mould growth and harmful organisms

Wood, ceramic brick and other hygroscopic materials absorbs moisture from the air. A combination of certain temperature, humidity and material affect the growth of mould over a certain period of time. A rule of thumb is that when relative humidity and temperature exceed 70% and 5°C respectively, the risk of mould growth increases significantly. This can cause damage to the structure and can also develop into a health hazard for residents. Moreover, excessive moisture and mould growth comes hand in hand with the risk of harmful organisms that feed on wood. There are different types of such tortious insects, but what they have in common is attacking the wood and its structural integrity. Moreover, the punctuated wood can be more susceptible to water and thus mould growth [15].

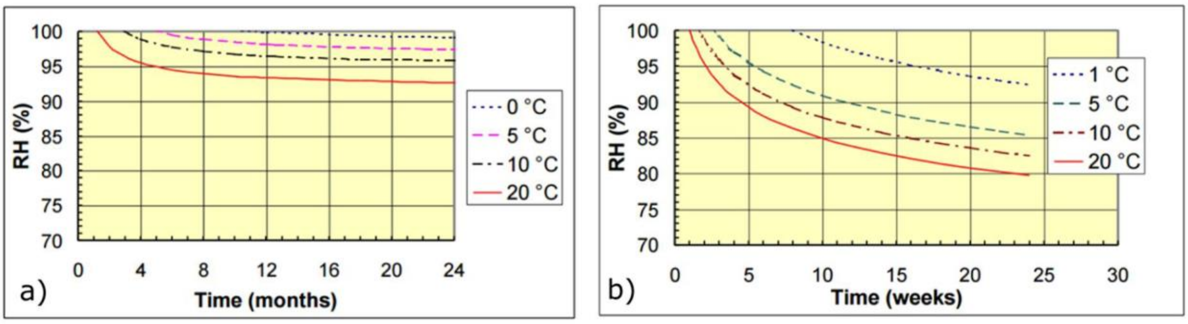


Figure 18: a) Critical conditions for decay development in pine sap wood. Constant conditions, b) critical conditions for mould growth in pine sap wood. Constant conditions [16]

Figure 18 show the critical conditions for decay development and mould growth in pine sap wood. Both pine sap wood and spruce were typically used in the historical floor constructions, depending on the decision of the current contractor[12]. However, the conditions may apply to spruce on the safe side as pine sap wood has a greater tendency to mould attacks than other construction materials [17]. According to the literature [16] and [18] a relative humidity below 70% is the safe long term limit for mould growth in building materials.

For timber, spruce and pine sap the moisture content should be below 20% to avoid mould growth [19] and below 25% to avoid decay [20]. Many factors apply when determining the risk of mould growth, such as material properties and specific periods exposed to critical combination of temperature and ambient RH. It is therefore best to be on the safe side and aim for lowest possible humidity levels when developing moisture safe solutions for retrofittings of old heritage apartment buildings.

4 ISOVER RETROWALL – THE CONCEPT

The RetroWall of internal façade insulation with active moisture control is investigated in this thesis. The concept is developed by Isover, Saint-Gobain in the light of the pressing need for a moisture safe solution to retrofitting of historical preserved apartment buildings.

4.1 The concept

The RetroWall consists of an insulating wall with a dehumidified air gap between the insulation and the brick wall. The idea is that a small dehumidifier developed by Cotes AS will remove the required amount of moisture that is causing problems for internal insulated brick walls. The dehumidifier which will be integrated in the wall will supply dry air into the air gap of around 50% relative humidity, which will prevent the chances of any mould growth.

Figure 19: Isover RetroWall, left) showing all layers and right) the ducting

The concept is displayed in Figure 19, with all the layers and the ducting system. Perforated steel profiles work as partitions for the 25 mm air gap between the brick wall and the insulation. The idea is that dry air will enter at the top of the wall through a rectangular duct with small perforations along the bottom side. This duct will in a way act like a pressure *chamber to get an equal air distribution along the wall. Furthermore, the same rectangular duct on the bottom of the wall will draw the humid air out of the wall and into the dehumidifier. When drying of the beam ends are necessary, two hoses are connected to the supply duct and drawn down and along the wall over the beams. A section of the wall including all layers is displayed in Figure 20.*

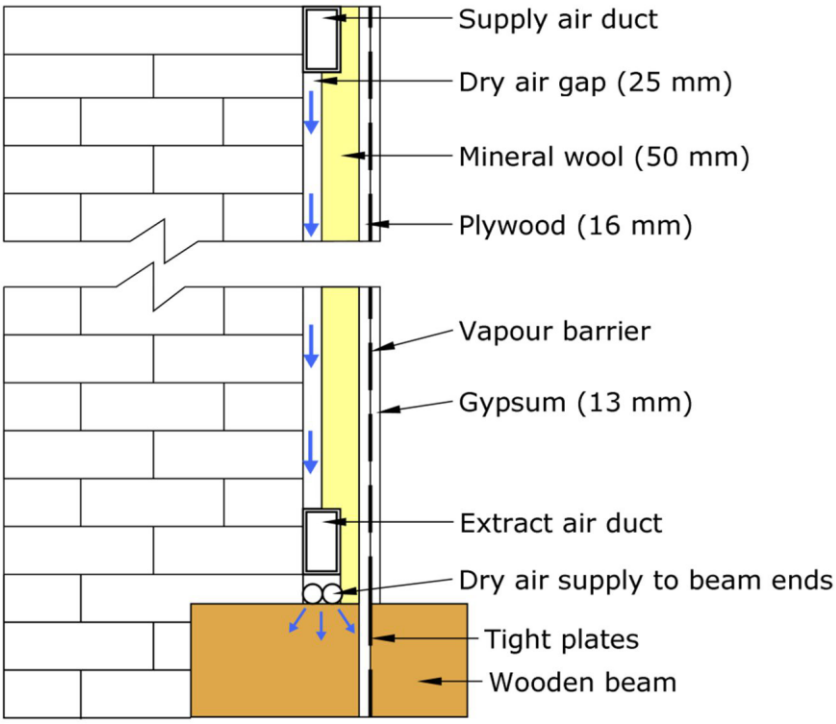


Figure 20: Section of the RetroWall with details (Layout)

The initial concept is essentially developed for a set of apartments that have a certain space above the windows due to the ducting system with dry air supply above the windows. According to the SBI report [12] most floor construction in buildings were built with a 30 cm distance from the top of the window, hence the system is believed to be fit for most cases.

4.2 Challenges

The concept has a few challenges related to dry air distribution around windows and whether drying of the wall will be enough to keep the embedded wooden beam ends moisture safe.

1. *Airflow around window*
2. *Airflow beneath window*
3. *Moisture related effect of the system on the wooden floor construction*
4. *Temperature and moisture effect around the separating t-walls*

The chances of stagnant air beneath the window can cause local moisture damage. Also the lower temperature around the window sills can give favourable conditions for mould growth if dry air is not supplied here. Additionally, the system may solve the moisture problems behind the insulation and around the windows, but the beam ends might still be in danger of moisture damage due to the lowered temperature and resulting moisture accumulation within the wall. An important notice is however that the condensation that occurs on the brick surface when conventional insulation is applied will be completely removed when the wall is dehumidified. Hence, any running water will not have an impact on the wooden beam ends.

4.3 Cotes dehumidifier

The crafty dehumidifier displayed in Figure 21 developed by Cotes AS is customized for the RetroWall. It is 35 cm tall, 13 cm wide and 10 cm thick and is small enough to be integrated into the RetroWall. As mentioned earlier in chapter 2.3 this dehumidifier is a desiccant dehumidifier. The desiccant is a honeycomb structured rotor made of silica gel, and have two separated air streams of process air and regeneration air. The humid process air is drawn from the airgap and through the silica gel rotor. The silica gel attracts water molecules from the humid air and dry air is then passed out into the airgap again. The regeneration air is drawn from the room and heated up by a heating coil. Warm air breaks up the chemical links between the silica gel and water molecules. The humid air is then drawn out into the room again.

It is simple in the way that any exhaust to the exterior is unnecessary due to the small amount of removed moisture; therefore the humid regeneration air flow is passed into the interior. Moreover, the dehumidifier will be installed in the wall in a way that makes it possible for the regeneration air to be drawn in and out of the room. The installation is still subtle with a paintable plate matching the wall visualized in Figure 22.

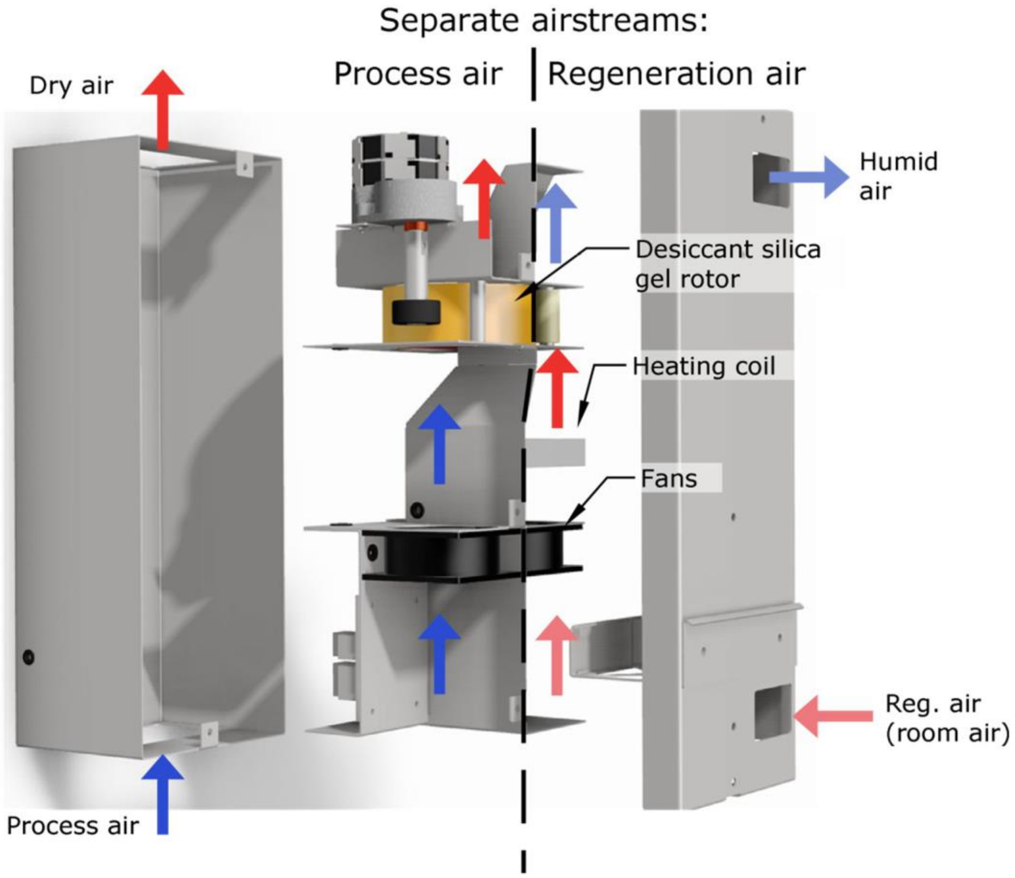


Figure 21: Model of Cotes C8 wall dehumidifier

Figure 22: Visualization of an integrated dehumidifier, designed for Isover by C. Lockenwitz, Industial designer MDD

5 *INVESTIGATION OF THE CONCEPT*

This chapter includes all investigation concerning the moisture challenges when applying the RetroWall in historical building apartments. This applies to investigation of necessary removal of moisture in the air gap, airflow throughout the wall and related pressure drops to get a balanced flow, comparison of hygrothermal behaviour in the brick wall of different situations, capacity of the dehumidifier and optimization of the whole system.

Part 1 Examination of moisture development using Delphin simulation tool

The first part of the investigation is dealing with the hygrothermal behaviour within a brick wall where the main tool is the simulation software Delphin. The main objective of this part is to identify critical situations, thus being able to detect situations that require further prevention related to moisture. Additionally, the simulation results are used to determine the required amount of moisture that has to be removed in order to keep the relative humidity at levels to obtain a dry air gap.

Part 2 Airflow

The second part of the study focuses on the airflows in the 25mm air cavity, with a strong emphasis on the window section, as this is one of the main challenges associated with the RetroWall. An investigation of the pressure drop in the system is also conducted to find a best solution in context of the setup of the system and balanced air flow to all sections.

Part 3 The dehumidifier

The third part deals with the dehumidifier which will remove the necessary amount of moisture in the airgap to obtain an upgrade free from mould growth. The crafty dehumidifier is customized by Cotes AS, and will be integrated in the wall. The investigation includes its capacity, and a discussion around operation time, whether it is necessary for the dehumidifier to run at all hours.

Part 4 Optimization of the system

The last part of the investigation consists of analysing and optimization of the system based on the three previous parts.

5.1 Part 1 – Examination of moisture development using Delphin simulation tool

Delphin software is a simulation tool used to perform 1D and 2D hygrothermal simulations. In this particular project, Delphin is used to simulate and investigate the hygrothermal behaviour of the historical brick wall over 10 year periods before and after RetroWall is applied. This is done in order to find the required removal of moisture to obtain a dry environment in the air gap, and also to examine whether the system will secure a moisture safe solution for the embedded wooden floor beams.

5.1.1 Inputs in Delphin

In this study it is desired to find a moisture safe solution fit for walls of any orientations. In Denmark the most frequent wind direction is south-west [21], thus the wind driven rain (WDR) will have the most effect on the walls facing towards south-west. However the walls facing south will also have more sun exposure which will affect the temperature and drying potential of the wall. A wall facing north will not be as prone to WDR, but will in contrast have much less sun exposure and will thus not obtain the same temperature gain as the south facing walls. All the different boundary conditions will affect the moisture content in the wall, including orientation. Therefore simulations of facades facing both south, north, west and southwest is completed in this study. The used parameters are defaults developed by Delphin which is based on Standards in building physics. These values, some listed in Table 2 are changed depending on the different situations, for example such as the heat conduction coefficient for interior and exterior.

Material properties listen in Table 3 are chosen based on propertied used in previous studies [2] where Delphin simulations tool is also used to simulate the hygrothermal behaviour in historical brick walls with embedded beam end.

Table 2: Inputs in Delphin - Climate and coefficients

Rain exposure coefficient - Catch ratio (CR)	*0.5**
Orientation	*West, North, South, Southwest*
Climate	*Denmark, Copenhagen (DMI- DRY files)*
Exchange coefficient for heat flow	*Interior: 8 W/m2K* *Exterior: 25 W/m2K*
Exchange coefficient for vapour diffusion	*Interior: 2E-8 kg/m2 s Pa* *Exterior: 1.5E-7 kg/m2 s Pa*
No surface treatment or coating	*Sd = 0 m*
Emission coefficient of building surface	*0.9*
Ground reflection coefficient	*0.2*

**The chosen catch ratio of 0.5, also called the rain exposure coefficient, represent the extreme event that 50% of the horizontal rain intensity will strike the exposed wall, which is considered to be the worst case scenario of wind driven rain. According to M. Harrestrup [22], the catch ratio in urban areas will usually be around 0.1, but as there are uncertainties around the theory concerning this coefficient due to variance in surroundings, a 0.5 CR is used in the simulations in this study.*

Table 3: Material properties used in the hygrothermal simulations

Material	Density ρ [kg/m3]	Thermal conductivity λ [W/mK]	Open porosity θp [m3/m3]	Water absorption coefficient Aw [kg/m2s0.5]	Water-vapour diffusion resistance factor μ [-]	Moisture permeability δ [kg/msPa]
Wood beam	520	0.13	0.69	0.58	236	8.0E-13
Brick	1790	0.87	0.36	0.227	14	1.36E-11
Lime cement mortar	1570	0.70	0.41	0.176	11	1.73E-11
Lime plaster	1800	0.82	0.30	0.127	12	1.58E-11
Air gap	1.3	0.14	-	-	0.4	4.75E-10
Mineral wool	195	0.035	0.92	-	1	1.9E-10
Plywood	595	0.13	0.9	0.002	165	1.15E-12
Gypsum	850	0.2	0.65	0.277	10	1.9E-11

5.1.2 Simulations

To compare different hygrothermal behaviour in historical brick walls before and after retrofitting, several models have been simulated in Delphin, all in 2D. To investigate the hygrothermal impact of internal insulation, five models have been created and simulated in Delphin, all listed in Table 4. The simulation outputs make it possible to compare the moisture conditions for the different situations, and will work as an important tool to find solutions for the RetroWall depending on different situations, such as orientation.

The first three models are simulated with orientations towards North, South, West and Southwest while the last models with embedded beam end is only simulated towards north and west. All models are exposed to the highest rain exposure coefficient of 0.5 which is the worst case scenario. The accuracy of this coefficient is discussed later in chapter 5.1.4. Furthermore, all walls have the wall thickness of 1,5 brick (360mm) which represent the thinnest wall dimension on the top floor of a historical apartment building.

Table 4: List of models simulated in Delphin simulation tool

Model	Description	Purpose
M1	*Original brick wall without insulation*	*Will work as a reference case to compare with other situations*
M2	*Brick wall with conventional insulation*	*Initially simulated to extract temperature data for 25mm airgap used as boundary conditions in model M3.*
M3	*The concept – Retrowall with active moisture control (without embedded wooden beam)*	*Temperature data from simulation M2 is used as boundary condition to investigate the hygrothermal effect of moisture control*
M4	*Brick with embedded beam end – vertical cut.*	*Used to investigate the moisture content in the beam end for the different situations*
M5	*Brick wall with embedded beam end – horizontal cut*	*As models are simulated in 2D, a horizontal cut is compared with M4 and will represent a more realistic 3D situation*

M1

The first model (Figure 23) simulated is an original brick wall with no internal insulation. The results from these simulations will work as a reference case and as indicators for desired results for a retrofitted wall. The aim is not to create a dryer environment than the initial conditions, but to obtain the same conditions. However if this is the case, it is considered a bonus. The internal boundary conditions are constant, with a temperature of 20°C and RH of 55% which will represent indoor conditions in an apartment.

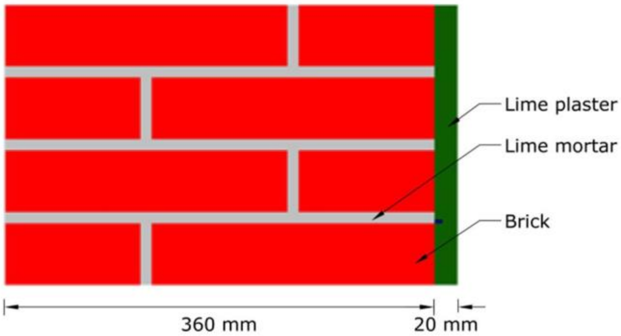


Figure 23: Simulation model M1 – Original brick wall

M2

The second model (Figure 24) simulated is primarily conducted to extract temperature data files for the 25mm air gap between the brick wall and the insulation, which are used as boundary conditions in simulation M3 representing the RetroWall with moisture control. The layers represent the correct insulation used in the RetroWall. Moreover, the results will show how conventional internal insulation will affect the moisture behaviour in a brick wall.

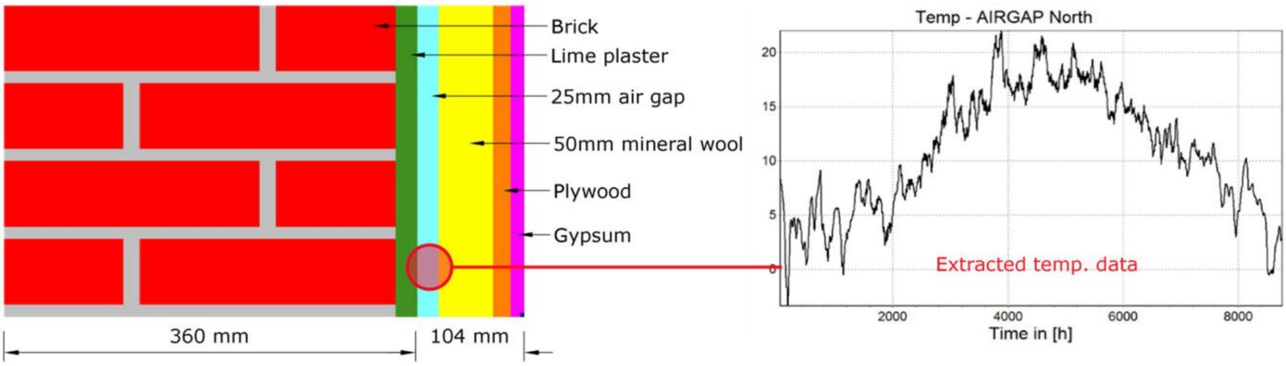


Figure 24: Simulation model M2 – Conventional insulation

M3

The simulated model representing the Retrowall with moisture control consists of an original historical brick wall with special boundary conditions displayed in Figure 25. To replicate the hygrothermal behaviour in the brick wall once the RetroWall is applied, the combination of dry air and cold temperatures will work as the internal boundary condition. Thus, the temperature files extracted from simulation M2 will represent the boundary temperature. The other boundary condition of internal relative humidity is set to a constant value of 50%.

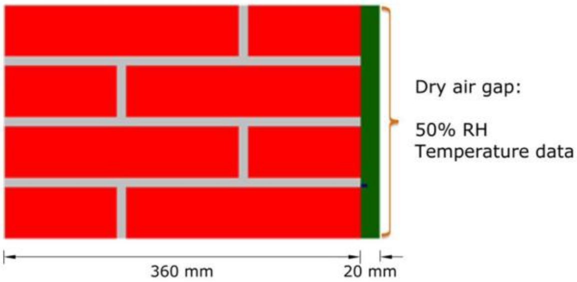


Figure 25: Simulation model M3 – Moisture control

M4 and M5

The simulations of a wall with an embedded wooden beam end will show its effect on the moisture content at the beam end. The other models are focusing on the moisture 10 cm into the brick wall to investigate the waterfront and to get a picture of how humid the beam end probably is considering it is embedded about 10 cm into the brick wall. The moisture content (MC) at the beam end is the focus of the simulations of model M4 and M5. Moreover, only north and west oriented walls were investigated as the previous simulations of south and southwest walls appears to be less critical with moisture control along the wall compared to the reference original wall. Boundary conditions are displayed in Figure 26.

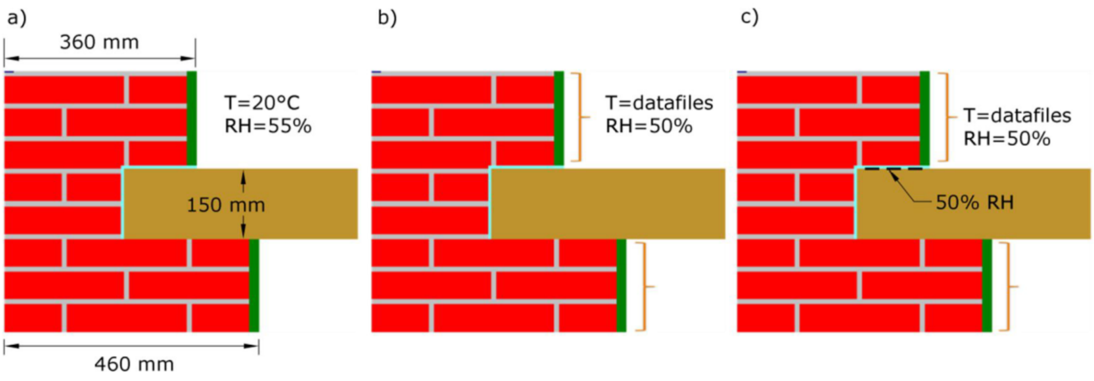


Figure 26: Simulation model M4 – Vertical cut, a) Reference case, b) Moisture control along wall only, c) Moisture control at beam ends and wall

The simulations are done in 2D, meaning that the software think that the beam is continuous, which it isn’t in *reality. To get a better picture of the situation, a horizontal cut of the section is also simulated (Figure 27). The results from both simulations will work as more realistic indicators, to the safer side.*

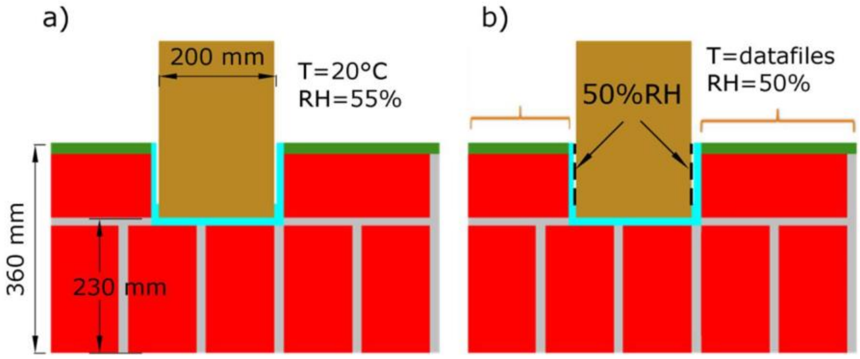


Figure 27: Simulation model M5 – Horizontal cut, a) Reference case, b) Moisture control along wall and beam ends

The models are firstly simulated with the original conditions with no insulation to compare with the second situation representing the RetroWall with moisture control along the wall, and along the beam end.

5.1.3 Hygrothermal results

Outputs from the hygrothermal simulations are used to compare the different configurations and orientations related to moisture close to the beam end. Additionally the results will determine which cases are the most and least critical in regards to moisture, which also decides whether further actions are necessary to avoid any moisture issues. Moreover, the outputs from Delphin will be used to figure out the amount of water vapour that has to be removed in order to obtain an air flow of 50% relative humidity.

5.1.3.1 Relative humidity and moisture content at beam end

It is preferred to keep the relative humidity (RH) below 70% to avoid any mould growth on the surface of the beam end. Additionally, the moisture content (MC) in the beam end should not exceed 20% water (kg/kg) which is the limit before mould growth can occur, mentioned earlier in chapter 3.4. The results of RH for simulations M1, M2 and M3 are extracted from Delphin and compared. Furthermore, the MC results of simulations M4 and M5 are extracted and examined.

As expected the RH at the beam end is more critical when a brick wall is oriented towards north. Figure 28 shows the extreme accumulating trend of a conventional insulated wall, for all orientations except towards south. The accumulation has a less extreme trend in the brick wall when there is moisture control along the wall, but is still critical for west and north orientation. The south and southwest orientations show that the moisture dries out over a yearly cycle when the wall is dehumidified at 50% RH.

The south and southwest walls are considered to be moisture safe when moisture control is added along wall due to the fact that the RH 10 cm into the brick wall appears to be lower than the reference case of the original situation. Based on the results in Figure 28, the north and west oriented walls are considered critical and therefore need further investigation. Simulations of the models M4 and M5 are therefore only conducted for north and west orientations to investigate the moisture content at the beam ends.

The measure taken to improve the moisture situation for the beam ends towards north and west is to apply dry air with 50% relative humidity over and on the sides of the beam ends. This is feasible in practice do to the intended gap left around the beams when it was built to prevent that the beam came in close contact with wet bricks.

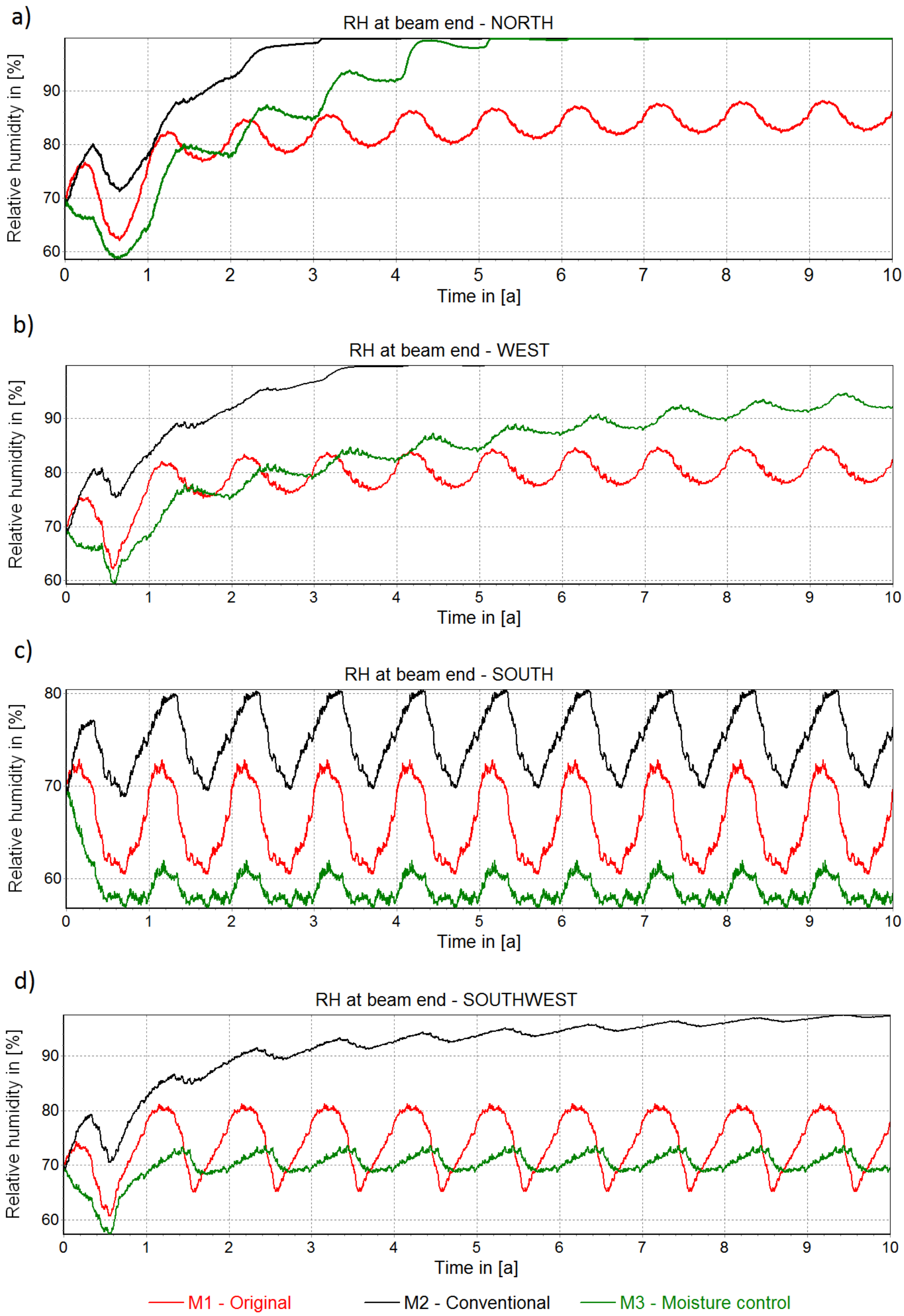


Figure 28: Simulation M1, M2 and M3: Relative humidity 10 cm into brick wall for the original brick wall, with conventional insulation and with moisture control 50%RH for orientations a) North, b) West, c) South and d) Southwest

By investigating the moisture content (MC) at the beam ends, it is possible to determine if applied dry air will prevent moisture damage. The MC is measure at the very end of the beam ends, displayed in Figure 29. The MC in the beam end extracted from the simulations M4 and M5 towards north and west is displayed in Figure 30.

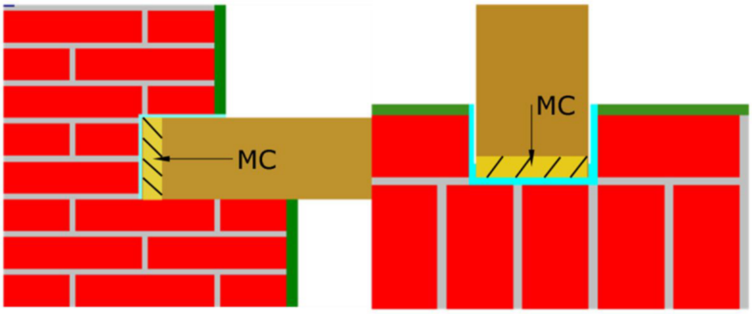


Figure 29: Location at beam where MC is investigated, M4 (left) and M5 (right)

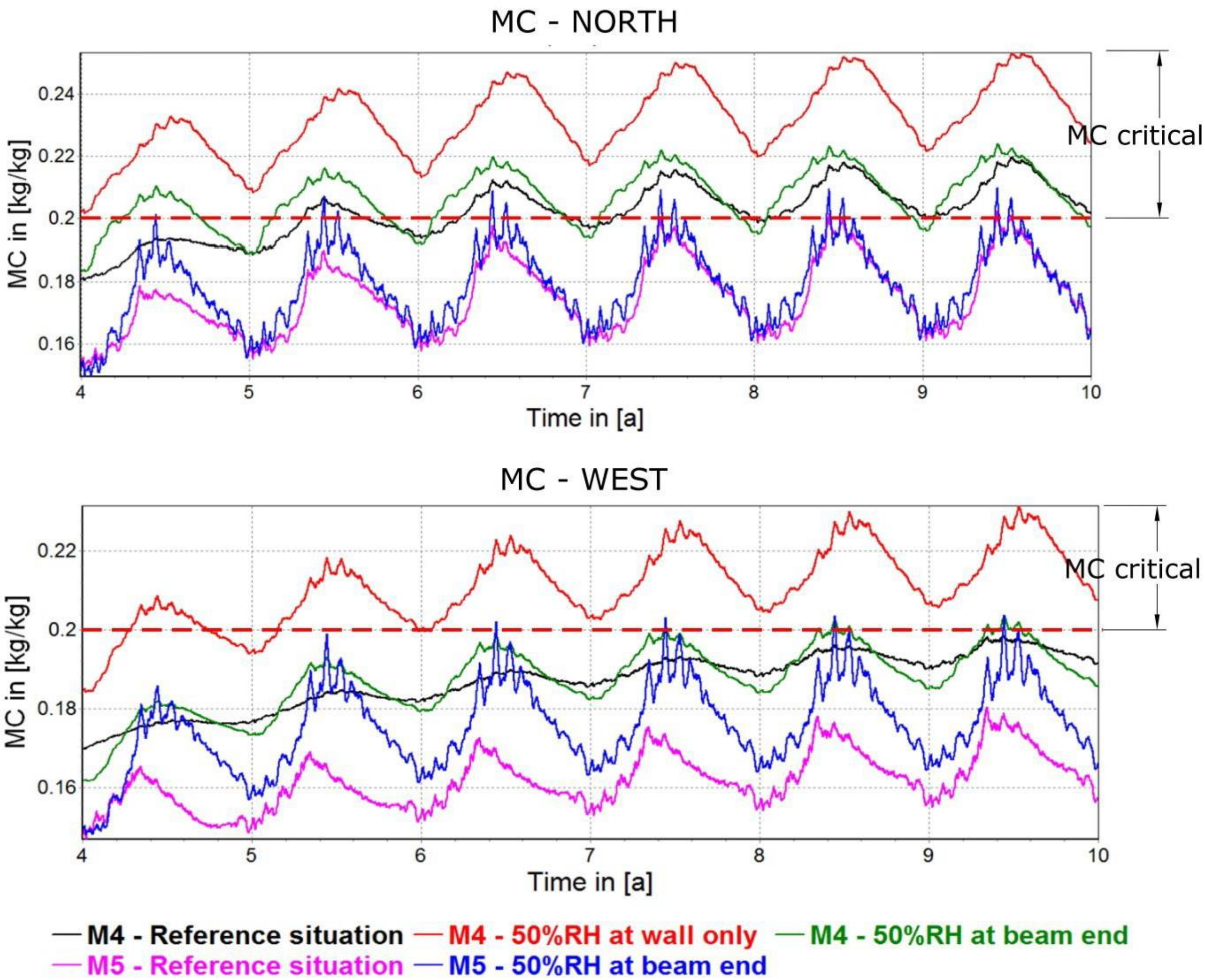


Figure 30: MC at beam end, from simulation M4 and M5 towards north and west

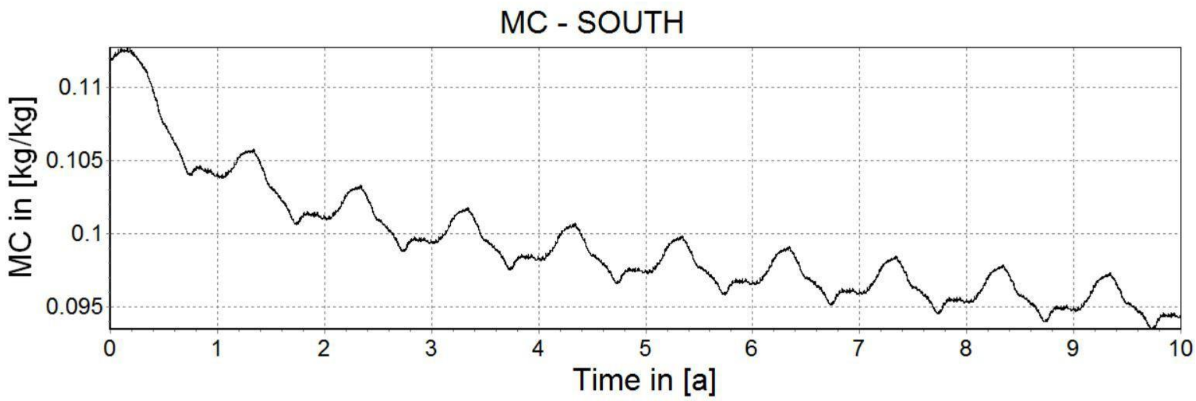


Figure 31: MC at beam end for south oriented beam end, with no dry air supplied around beam ends.

Figure 30 show that the vertical cut M4 simulations towards north all show a critical MC above 20%, which is not very realistic considering the reference case. If the MC values for the reference case towards north are realistic, then the beam end would be full of mould and all storeys would be close to decay or already be lying in the basement. Again it is therefore unlikely that the rain coefficient (CR) is 0.5. Figure 31 show the anticipated low levels of moisture content in south oriented beam ends when dry air is only applied along the wall.

Moreover, the MC peaks during summer in contrast to RH which peaks during winter. This is correct in practice, due to the equilibrium moisture content (EMC) in timber (Figure 32) which means that timber reacts on its surrounding air humidity. Therefore it will release moisture to the dry interior air during winter. And during summer the moisture content in the air is much larger compared to during the winter, which then reflects in the moisture content in the timber.

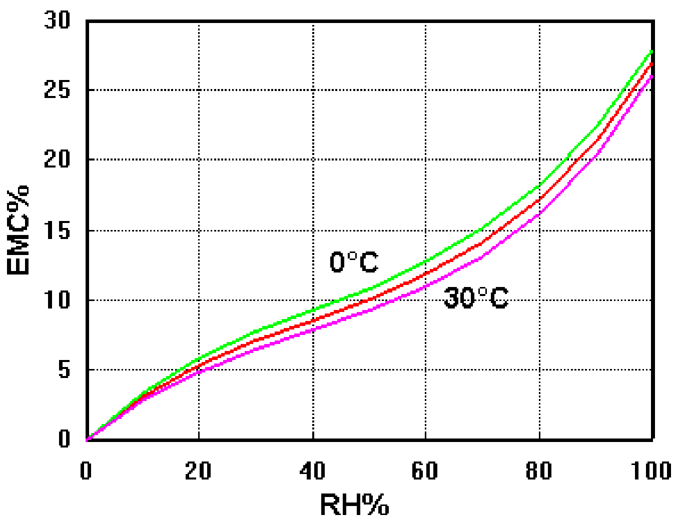


Figure 32: Equilibrium moisture content in timber (EMC)

Most importantly, the results show that when dry air is supplied above and around the beam end, the MC decrease to below 20% compared to the case when dry air is only applied on the wall. It will also obtain around the same MC as for the reference case. Due to the fact that both the horizontal and vertical cuts are simulated in 2D, a combination of the two situations in a 3D model would most likely be significantly less humid than what is displayed in Figure 30.

5.1.3.2 Waterfront

The outputs from Delphin show a critical trend for both the north and west oriented walls in regards to high levels of relative humidity and accumulation of moisture. Brick walls with orientations towards south and southwest appear to dry out throughout the yearly cycle, and are considered less critical. The RH field and locations of relating waterfronts of M1, M2 and M3 oriented towards north and west is displayed in Figure 33. The accumulation is extreme for the brick wall with conventional insulation giving a waterfront all the way into the inner brick surface. When boundary conditions representing the RetroWall are applied the waterfront is closer to the interior compared to the reference case, but is still about 10cm from the inner brick surface. The accumulation depends on temperatures and the possibility of drying to the interior and exterior. The closer the waterfront is to the interior, the more vapour diffusion to the interior.

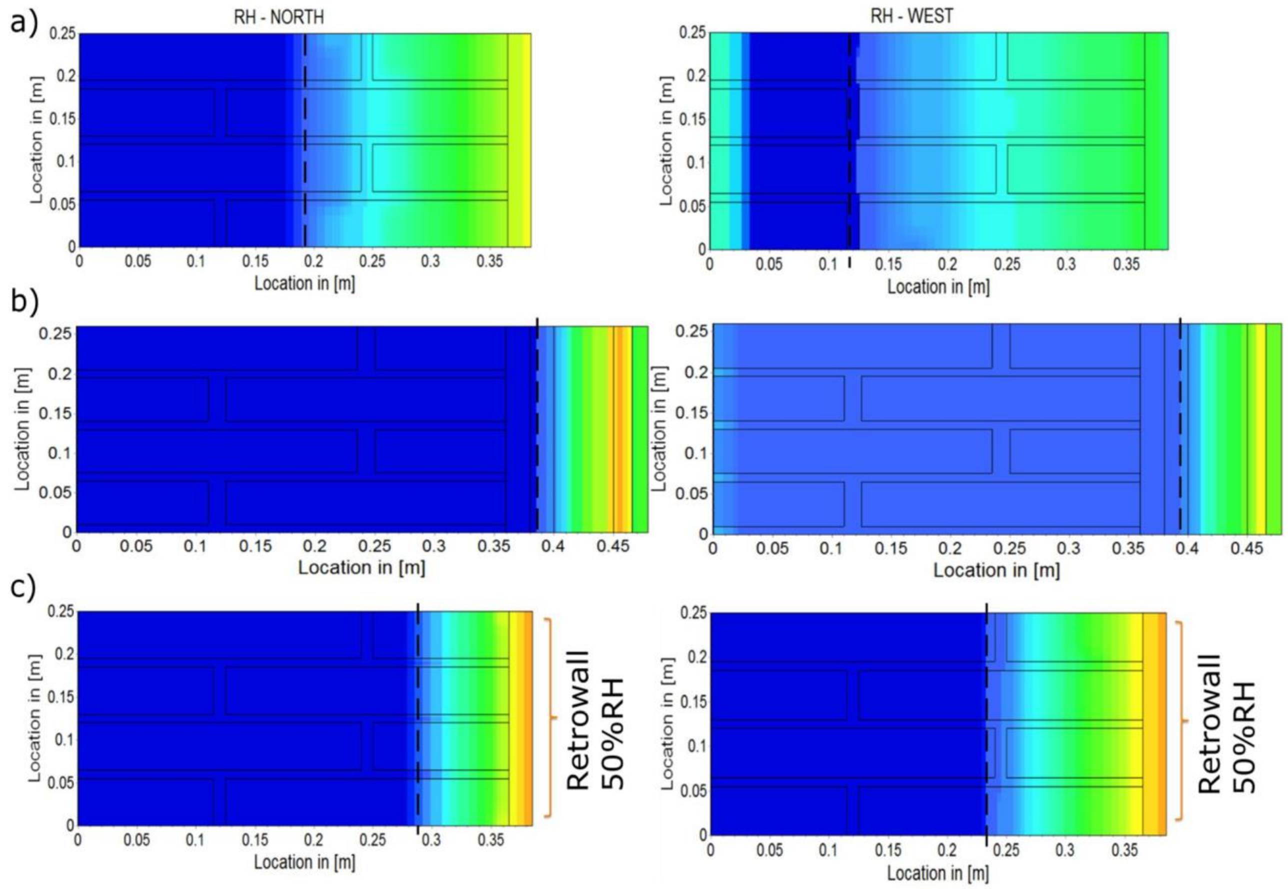


Figure 33: RH field with displayed waterfront (stippled line) of north and west oriented facades; a) original wall, b) conventional insulation and c) with moisture control

5.1.3.3 Mould growth at beam end

Depending on the relative humidity and the relating temperatures, the VVT mould model carries out the mould index 10 cm into the wall for model M1, M2 and M3 displayed in Figure 34. The model is used to estimate the mould growth in different exposure conditions, where the index 0 indicates no mould, and index 6 indicates a very heavy and tight mould growth with around 100% coverage. It is desired to obtain dry enough conditions in order to keep the mould index below 1, which indicates insignificant small and microscopic amounts of mould growth on the surfaces [20].

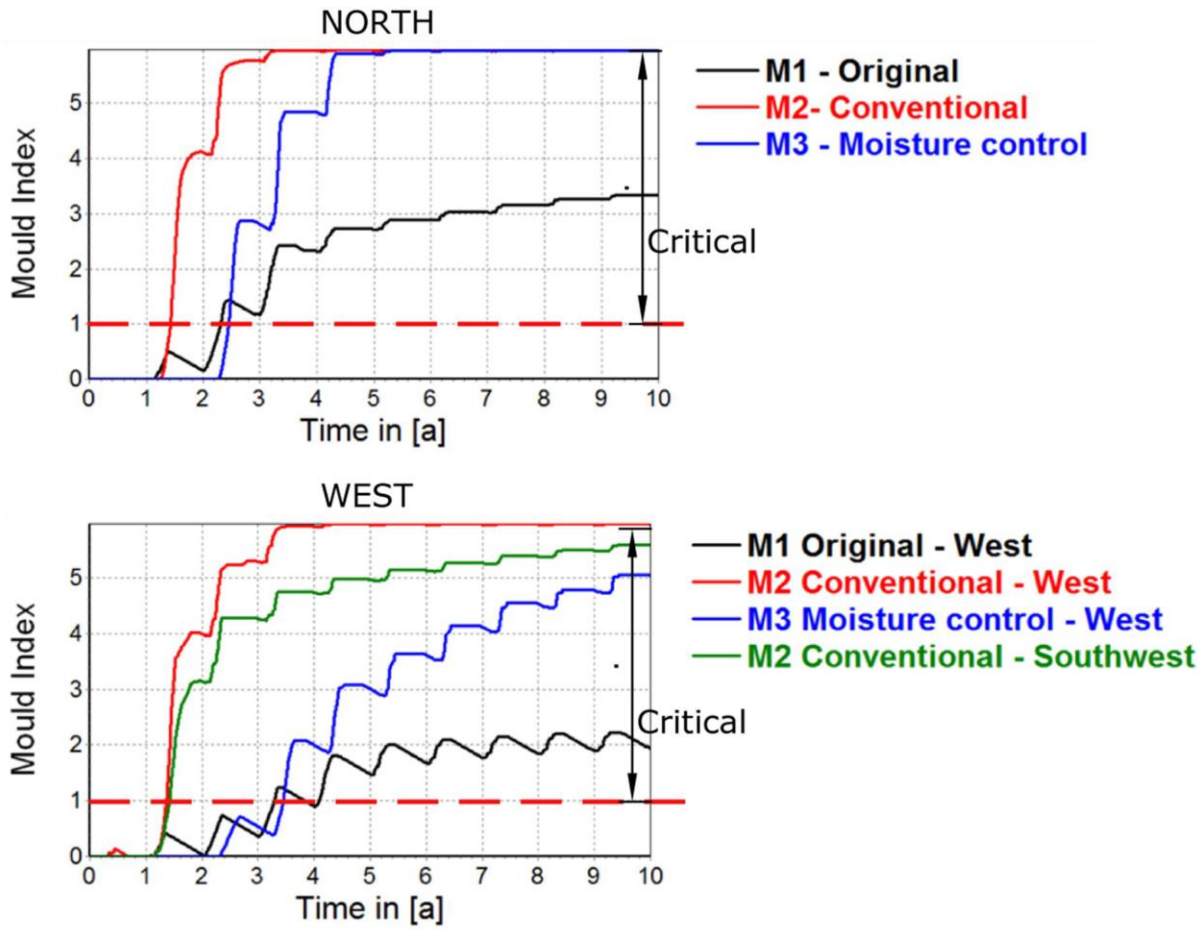


Figure 34: Mould index 10 cm into the wall, for all critical orientations (Delphin)

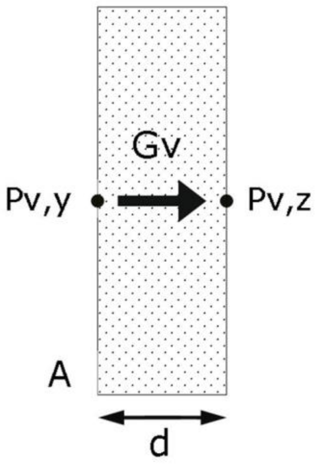
The mould index displayed applies to very sensitive pine sapwood with almost no decline in mould growth. The south and southwest oriented walls not included all have mould index close to zero, and is therefore not included in the mould model graph. The north and west orientation have high mould index for all models including the measure of moisture control. However, the original wall towards north and west also show a relatively high mould index which is questionable when considering that the testing of historical wooden beam ends in the SBI report showed that the extracted historical wooden beams were free from substantial mould growth, mentioned earlier in chapter 3.1.

5.1.3.4 Required moisture removal

To keep an air flow of 50% relative humidity in the air cavity, the vapour diffusion into the air gap determines how much removal of moisture is necessary. According to previous studies at DTU, an airflow of 1.2m3/m2h is efficient and should be attained from the dehumidifier. The necessity of this particular airflow will be evaluated later in the report. The vapour diffusion will increase the humidity in the air flow, and will end up more humid at the bottom *of the wall. It is therefore important to investigate whether the vapour diffusion will cause the relative humidity to increase to critical levels, such as above 70% at the bottom of the wall.*

Estimation of required moisture removal using Fick's Law of diffusion

Manually, the vapour diffusion into the air gap can easily be calculated according to Fick's *law of diffusion, Eq. 5. This method will however only give a seasonal estimate of the vapour diffusion based on a few seasonal situations.*



$$G_v = \delta \frac{pv_y - pv_z}{d}, \quad [\frac{kg}{s}]$$ Eq. 5

The estimated vapour diffusion during winter and summer for a north oriented wall has waterfronts at 10 cm into the wall, which is evident from Delphin simulations. During summer the conditions at the waterfront is 20°C with a 100%RH, while the air gap has a temperature of 20°C and a RH of 50%. During the winter the waterfront will have the temperature down to 0°C and 100% RH, while the air gap will have a temperature of 3°C and a 50% RH, as displayed in Figure 35.

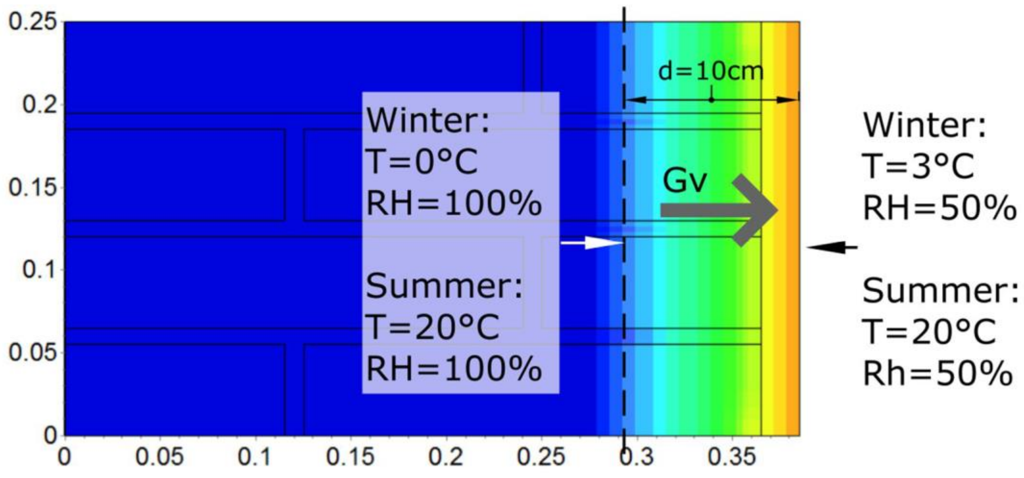


Figure 35: Vapour diffusion during winter and summer – an estimation

The resultant vapour diffusion will be higher during the summer due to the larger difference in vapour pressure, because warm air can contain more water vapour than cold air. The estimated seasonal vapour diffusion to the air gap is listed in Table 5.

Table 5: Vapour diffusion in a north oriented wall according to fick's law

Winter	*0.12 g/m2h*	*Added MC: 0.08 g/kg*
Summer	*0.53 g/m2h*	*Added MC: 0.37 g/kg*

Note: A more detailed explanation of calculated vapour diffusion can be found in Appendix.

Moisture removal based on Delphin simulations and the resulting vapour diffusion

In reality the vapour diffusion will constantly vary depending on the temperature, relative humidity in the air and in the brick wall, and the location of the waterfront. Therefore a comparison to the vapour diffusion flux from Delphin will be another indicator of the actual necessary moisture removal in the air gap.

To get the accurate vapour flux output from Delphin software, it is necessary to make an appropriate boundary condition with the correct temperatures for the air gap. By creating a model representing the RetroWall, annual temperature data for the 25mm air gap is extracted for all orientations.

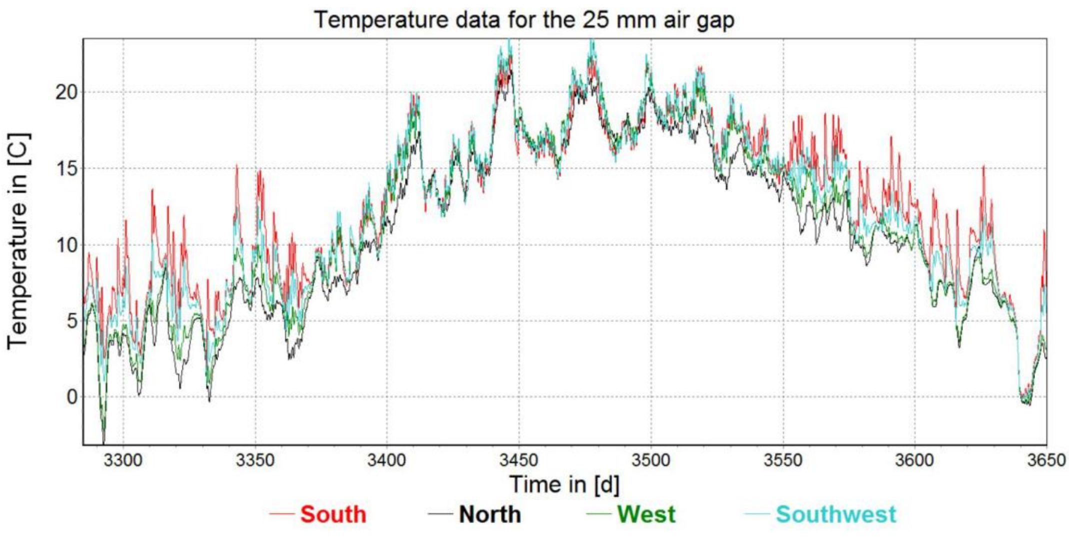


Figure 36: Temperature data for the air gap extracted from Delphin, simulation M2.

The extracted temperature data in Figure 36 show higher variance during winter, most probably because the low solar altitude opposed to summertime where the variance is less significant. An overview of external factors, such as external temperature and solar radiation and its effect on the temperature in the air gap during January and July is showed in Figure 37 *and Figure 38 respectively. As expected, the intervals of solar radiation result in temperature peaks for the south and southwest oriented walls during winter. While the temperatures in the north and west oriented walls seem to fluctuate along with the external temperature. As it turns out, these factors causes the large temperature differences of up to 8°C in the air gaps between the north and south walls. During summer the temperature is in average higher and the solar radiation lasts for longer period during the day. The fact that the sun is standing taller during the day must be the explanation of why the south facing airgap is not significantly warmer than the west and south facing facades.*

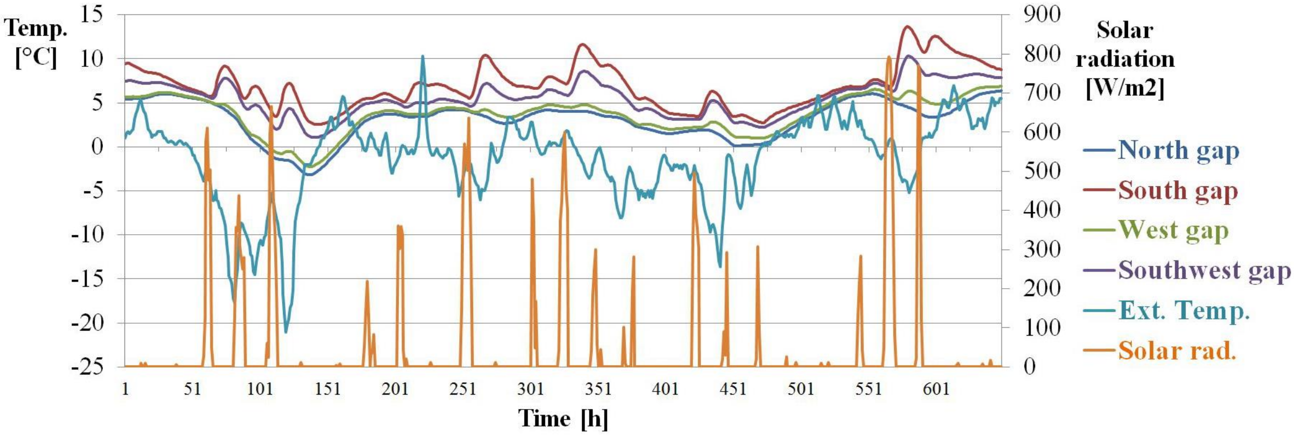


Figure 37: Relationship between external temperature, solar radiation and temperatures in the interior air gap during January (Excel)

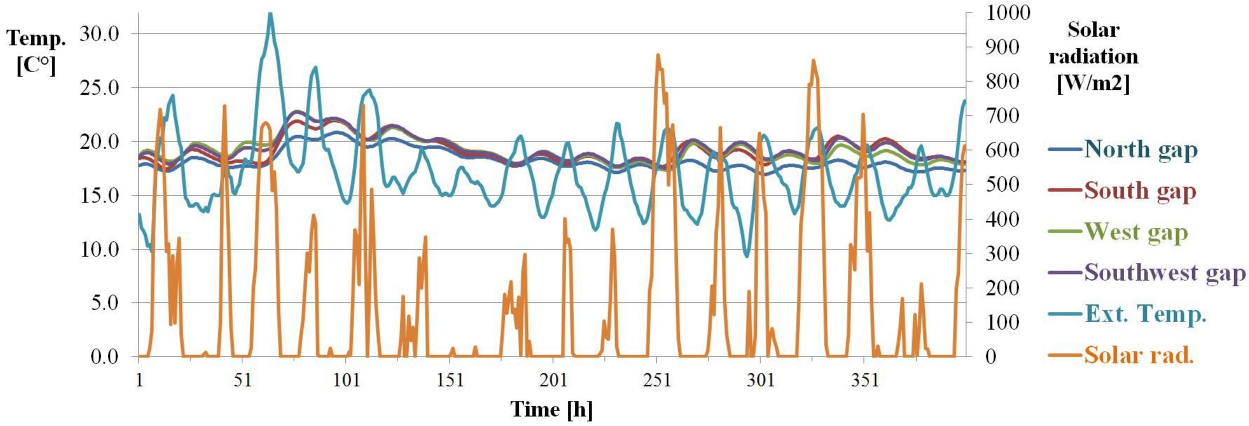


Figure 38: Relationship between external temperature, solar radiation and temperature in the air gap during July (Excel)

After retrieving the temperature data from simulation M2, a model of the original brick wall is used to simulate the effect of the dehumidified air gap. The temperature data in addition to a constant relative humidity of 50% act as boundary condition for the interior brick wall. As the *dehumidified process air is heated by the chemistry of the process which will result in a warmer air flow, the extracted temperature data is considered to be on the safe side.*

From simulation M3 representing the RetroWall with a dry air gap of 50%RH, data of vapour diffusion into the air gap is extracted and used to investigate the required removal of moisture.

To get the amount of added moisture to the airflow of 1.2 m³/m²h, the vapour diffusion in g/m²h is divided by the airflow multiplied by the density of air, 1.2 kg/m³, Eq. 6 . This additional moisture content (MC) is used to find the increase in relative humidity of the initial 50% dry air.

$$MC = \frac{G_v}{V^{\cdot} * p_{air}} = \frac{G_v}{1.2 * 1.2}, \quad [\frac{g_{water}}{kg_{air}}] \qquad \text{Eq. 6}$$

When comparing the total amount of interior diffusion for all orientations, north is the outcome with highest total vapour diffusion, with the related values displayed in Table 6. The other orientations have more hours of diffusion to the exterior which is not unexpected as the sun will hit these walls more frequently.

Table 6: Vapour diffusion and required removal of vapour for north, west, southwest and south

	Season	Hours of interior diffusion [h]	Avg. diffusion [g/m2h]	Total diffusion [g/m2]	Avg. increase in RH [%]	Excessive MC [g/kg]
North	Winter	1695	0.22	491	3.2	0.15
	Spring	1730	0.41	770	3.7	0.28
	Summer	1950	0.58	1190	2.8	0.40
	Autumn	1850	0.38	707	2.4	0.26
Annually		7220 (82%)	0.36	3150	3	0.3
West	Winter	1530	0.18	400	2.7	0.13
	Spring	1550	0.34	566	3.3	0.24
	Summer	1710	0.47	887	2.2	0.33
	Autumn	1630	0.31	533	2.0	0.21
Annually		6410 (73%)	0.35	2387	2.5	0.24
South	Winter	890	0.14	327	4	0.10
	Spring	1090	0.27	317	3.3	0.19
	Summer	1000	0.24	314	1.1	0.17
	Autumn	960	0.31	324	1.6	0.21
Annually		3930 (45%)	0.27	1282	2.5	0.19
Southwest	Winter	1120	0.15	340	3	0.10
	Spring	1290	0.29	400	3.2	0.20
	Summer	1340	0.32	525	1.5	0.22
	Autumn	1200	0.26	350	1.7	0.18
Annually		4953 (56%)	0.29	1612	2.3	0.20

The 10th year of simulation data of average vapour diffusion per hour into the interior air gap is extracted from the Delphin simulation M3 with boundary conditions of temperature data and 50% RH moisture control.

Displayed in Table 6 are the average and total vapour diffusion, and the average and maximum increase in relative humidity for all four orientations. The average increase in relative humidity represent the hours where there is vapour diffusion to the interior. Due to the fact that diffusion also happens to the exterior, vapour diffusion to the interior does not always occur, especially for the south oriented walls where the sun boosts drying to the exterior.

For north oriented walls interior vapour diffusion will occur 82% of all hours annually, with the total sum of about 3 kg/m². As anticipated, it is also evident that a larger amount of water vapour diffuses to the air gap during the summer opposed to the winter season. The data also show that the average increase in relative humidity when moisture enters the air gap will be around 2-3%, which will not increase the risk of mould growth when initial relative humidity is 50%. Airflow of 1.2m³/m²h is therefore considered efficient.

The simulation data compared to the estimation from Fick's law show the same seasonal trend *of more vapour diffusion during summer, which is expected as warm air contains more moisture than cool air. This is a result of greater forces due to the larger difference in vapour pressures inside the brick wall and in the air gap.*

Peak diffusion of over 1 g/m²h will occur periodically, but will not happen over longer periods that will cause any risk of mould growth. As an example, the peak diffusion is displayed in Figure 39 below and represents a week during summer. It shows that the peaks only last for a few hours before decreasing again.

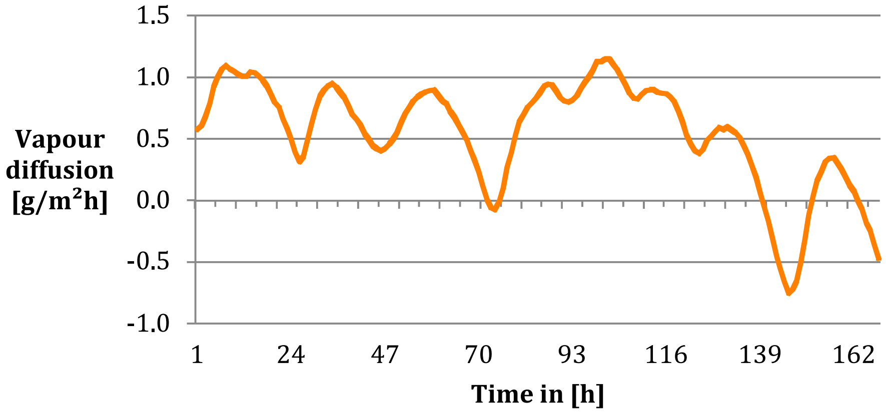


Figure 39: Vapour diffusion into the air gap a week during summer

5.1.4 Discussion of simulation results and accuracy of the catch ratio

The hygrothermal investigation show that the north and west facades are the most critical in terms of moisture. Dry air flow applied on the wall will still results in accumulation close to the beam end, which suggest that additional measures are necessary for the north and west orientations, such as dehumidification around beam ends. Moreover it is safe to say that conventional insulation is expectedly not a good solution for internal insulation in any orientations.

It is important to remember the fact that a testing of extracted beams in historical apartment building in Copenhagen showed little to no mould attacks and that their bearing capacity met the modern requirements of construction timber in 1983 [12].

One particular issue that frequently repeats itself throughout this investigation is the uncertainty around the high rain exposure coefficient (CR), which often give unrealistic results considering the reference situation. It is very unlikely that the wooden beams in existing historical building contain much more moisture content than 20%, as this indicate mould growth and risk of decay. One can therefore argue that the CR of 0.5 is too high based on the findings. In an article [23] which further supports this argument, Abaku et al. finds that the CR appears to be critical when the wind velocity is above 8 m/s displayed in Figure 40

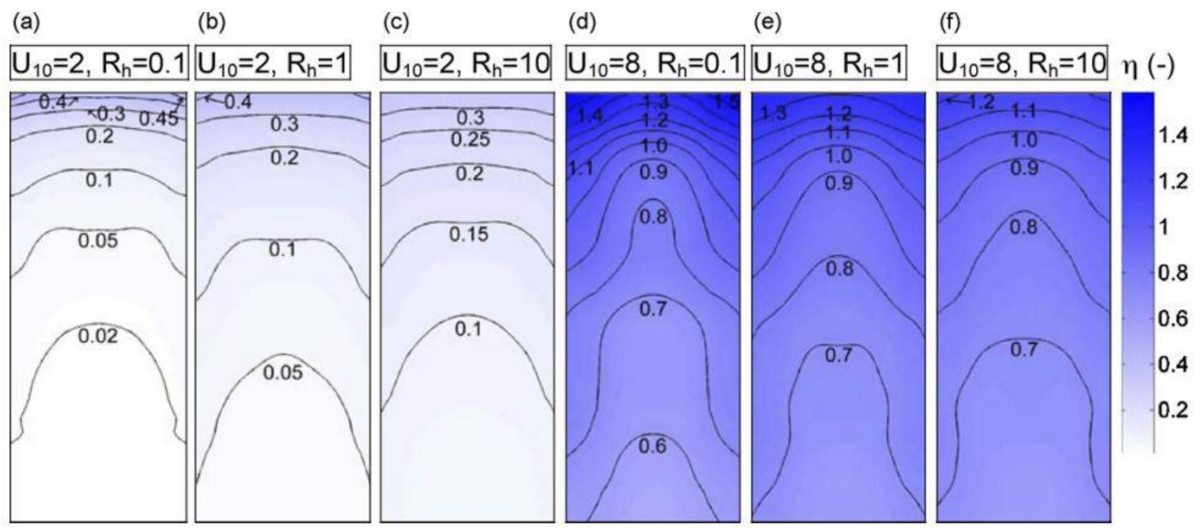


Figure 40: Catch ratio distribution on a façade (4x10m) U=wind velocity (m/s), R=rain intensity (mm/h) [23].

According to a DMI report [24], The mean wind velocity in Denmark is 5.8 m/s and 4.5 for the 20x20km grid around Copenhagen. However the wind velocity depends on terrain category and height of the building in addition to other surroundings [25],hence it is usually lower in suburban areas.

Also in an article [26] Blocken and Carmeliet finds by numerical simulations that when wind speed is above 20 m/s and the rain intensity is above 10 mm/h, the CR is above 0.5. According to DMI report [27], measurements of rainfall from 1874-2010 show that the average number of days with rainfall more than 10mm is 25 days. Thus the mean daily rainfall is below 10mm per day. Furthermore, the maximum rainfall per day is in average between 80-100 mm, which occurs 25 days per year.

Hence, the mean rainfall and number of days with maximum rainfall of 100mm supports the theory that CR is probably below 0.5 most of the time. A CR of 0.5 or above will only occur periodically and not constantly. And when it occurs, it will have the largest impact on the top corners of the buildings. In the hygrothermal simulation a constant CR of 0.5 is used, which is most probably not the realistic case, and is therefore most probably giving unrealistic results. Despite of this, further measures around the beam ends is still considered necessary for the north and west oriented walls due to the accumulating trend when dry air is only applied along the wall. This measure consists of supplying dry air around the beam ends, and is described in more details in the next chapter.

5.1.5 Preliminary conclusion of part 1

- *North and west oriented walls require dry air supply around beam ends to reduce the moisture content to below 20% in order to avoid mould growth.*
- *South and southwest oriented walls are moisture safe with the initial concept of only moisture control along wall; hence the need for dry air supply around beams is unnecessary.*
- *The catch ratio of 0.5 is an extreme case and will only occur periodically, which is therefore giving unrealistic results from hygrothermal simulations*
- *Airflow of 1.2m^3/m^2h is more than efficient enough to remove the required amount of moisture with an increase of relative humidity along the wall with only about 2-3 %.*
- *Average diffusion into the airflow in the gap*
    - *Winter: 0.22 g/m^2h*
    - *Summer: 0.58 g/m^2h*
- *Average required drying of airflow in the gap*
    - *Winter: 0.15 g/kg*
    - *Summer: 0.40 g/kg*

5.2 Part 2 - Airflow

The airflow in the air cavity is investigated to ensure that all nooks and corners are supplied with enough dry air. The main challenge is around the window section because of the break of airflow, and because the risk of mould growth is higher due to lower temperatures around the windowsills. The investigation mainly consists of a mock-up test and proposals to obtain the airflow around the windows, and some theory to back up the issue of slow vapour diffusion in stagnant air. Moreover, pressure drop of a system where air is supplied along the wall and around the beam ends is calculated and measured. This is done to get desired airflows and to determine the required fan capacity. When the beam ends require further measures in the form of dry air supply, the system consist of additional hoses connected to the supply duct, displayed below in Figure 41. A mock-up test will be used to measure the flow and pressure drop of the wall with a window section, while the beam and hose system is measured separately and then compared.

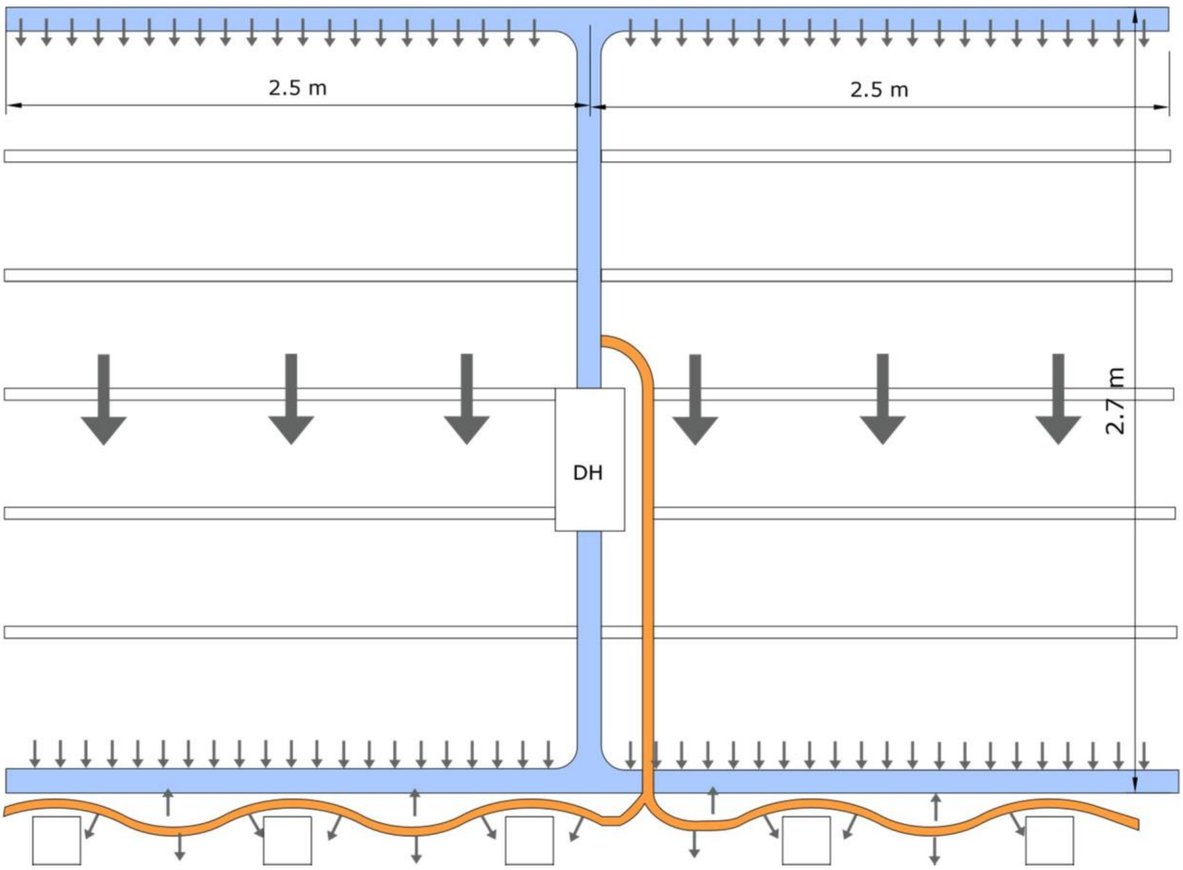


Figure 41: Distribution of air for a 5 meter long wall with additional dry air supply around beam ends.

5.2.1 Mock-up test of a wall with a window section

*The mock-up test is made to observe the airflow throughout the wall and to detect any critical locations where the airflow is absent or critically low. The section beneath the window is especially prone to less airflow compared to the rest of the wall. Fi*ck's law of diffusion state *that molecules diffuse from high concentration to lower concentration until equilibrium is reached. Hence, a higher vapour pressures will even out towards lower vapour pressures. The question is whether it will equilibrate fast enough compared to the amount of moisture entering the airgap from the brick wall.*

Figure 42: Mock-up test constructed by Isover

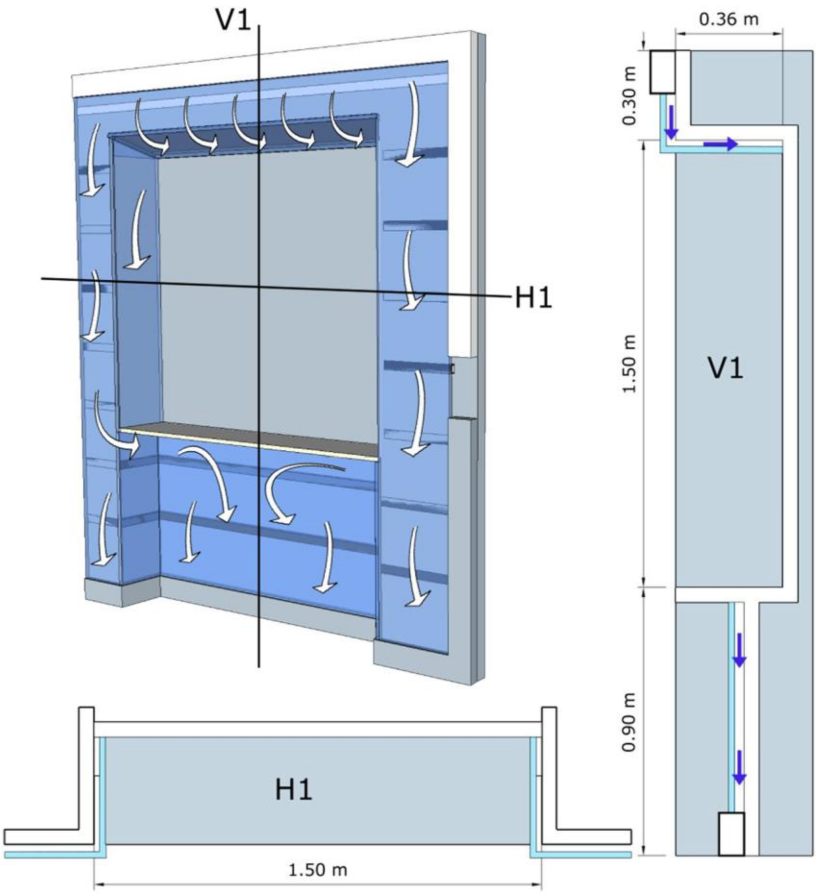


Figure 43: Model of mock-up test for airflows (SketchUp)

In order to get an understanding of what could possibly happen underneath the window section in a retrofitted wall where the chances of getting a section of stagnant air is critical, an examination of diffusion in still air is carried out.

For instance, underneath the window section the conditions of 5°C and 100% RH is assumed to figure out the amount of diffusion to the surrounding environment of 50% RH.

Fick's law of vapour diffusion, G_v *[kg/s] in air depends on the diffusion area, A* [m^2], *the* vapour permeability in air, δ [kg/msPa], the differences in vapour pressure, pv [Pa] and the *distance of diffusion from one location to the other, d [m].*

With a temperature of 5°C the assumed vapour permeability in air is 1.795E-10 kg/msPa, and the air gap of 25mm gives an area of 0.0225 m^2. *Using the temperature- and RH-dependent vapour pressures beneath the window and the surrounding dry air next to the window in addition to the distance from the critical point to the secured dry locations, the diffusion, Gv* [kg/s] can be calculated according to Fick's law

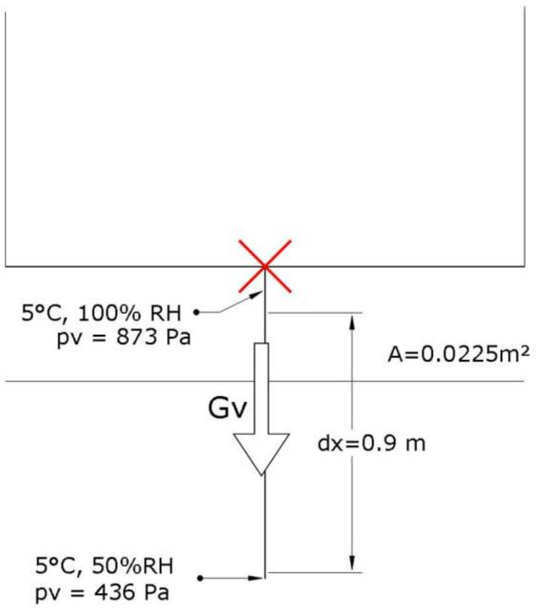


Figure 44: visualization of vapour diffusion beneath window (Layout)

$$G_v = A\delta * \frac{p_v - (p_v + dp_v)}{d} \qquad \text{Eq. 7}$$

$$G_v = 0.025 * 1.8E^{-IO} * \frac{873 - 436}{0.9} = 0.18\, g/day$$

From Eq. 7, vapour diffusion in still air is calculated to be 0.18 g/day. From the investigation in part 5.1 the measured interior diffusion is in average 0.58 g/m²h during summer. Even though the area just beneath the window is less than one square meter the natural vapour diffusion in still air is not enough to remove the moisture beneath the window.

Due to the fact that vapour diffusion in still air is little compared to the actual moisture diffusion to the interior, a mock-up test has been developed and then constructed by Isover to test the actual air flow around and beneath the window, and also to compare the actual pressure drop in the wall with the calculated pressure drop.

When the air flow is 1.2m³/m²h this gives a velocity of 0.036m/s down a 2.7m tall wall, and the excessive moisture content in the air at this airflow will increase the relative humidity in the air by approximately 3%, calculated in chapter 5.1. The less air flow, thus air velocity, the more increase in relative humidity beneath the window. It is therefore desired to have an air velocity that will obtain a relative humidity of less than 70%. This also applies to the airflow around the window.

The mock-up model displayed in Figure 42 is developed based on the structure of historical buildings and the widest allowable window section of 1.5m according to building regulations in the 1800's [12]. The wall *is 5.7 m² with a 1.5x1.5m window and built up of plates and Plexiglas with a 25mm air gap in between according to the model displayed with a few details in Figure 43. The airflow supplied at the top of the window will flow down and into the top windowsill. From there the air will flow to the sides of the window. In order to get some flow beneath the window, it is proposed to seal some of the perforated holes in the steel profiles, visualized in Figure 45. This will force some of the air to move towards the middle of the wall.*

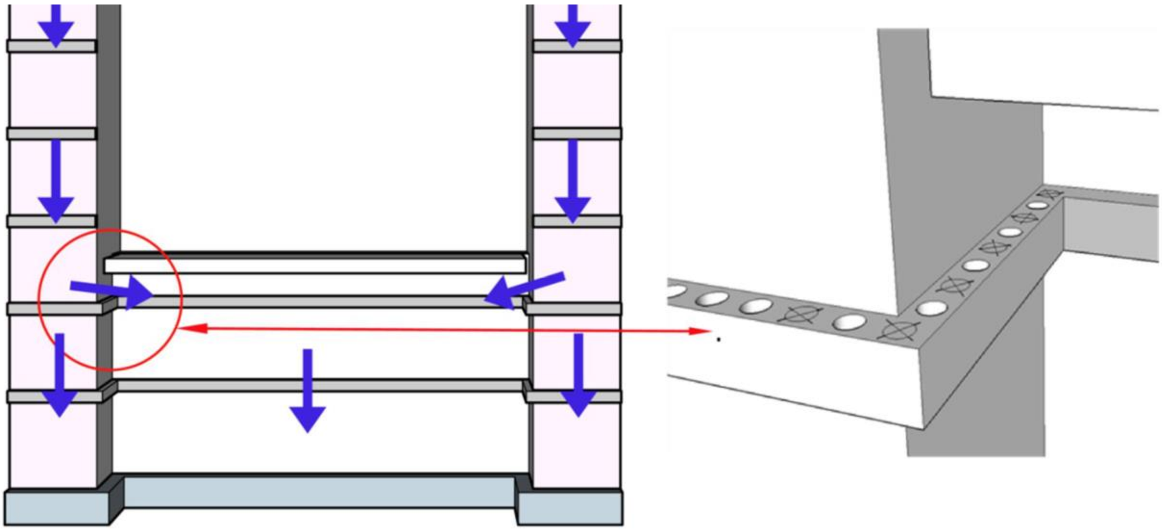


Figure 45: Detail of sealed perforations to force airflow beneath window (Layout)

Necessary air flow and air velocity beneath window

Based on the findings of diffusion to the interior in chapter 5.1.3.4, the minimum required air flow and air velocity can be calculated. The calculation is carried out to determine the necessary air flow to keep the relative humidity below 70% during summer and winter. During summer the average vapour diffusion into the air gap is 0.58 g/m²h, and temperature is in average 20°C for the north wall. In the winter season the average vapour diffusion is 0.22 g/m²h and the temperature is around 4°C.

Table 7 presents the average and maximum vapour diffusion to the air gap and the moisture content in air when the relative humidity is 70% and 50%.

Table 7: Seasonal diffusion and resulting MC values

	Summer/winter	
Avg. vapour diffusion, [G_v]	*0.58/0.22*	*g/m²h*
Temperature	*20/4*	*°C*
Maximum MC (70%RH), [MC_{max}]	*10/3.5*	*g/kg*
MC (50%RH), [$MC_{50\%}$]	*7.3/2.5*	*g/kg*
Saturated MC	*14/5*	*g/kg*
Wall height,[h_{wall}]	*2.7*	*m*
Area of 1 m air gap [$_a$]	*0.025*	*m²*

The minimum required airflow is calculated by using the saturated moisture content (MC) to find the maximum MC for air at 70% RH and then compared with the Mollier diagram. The MC for the initial dry air of 50% RH determines how much moisture needs to be removed. It is then possible to find the necessary airflow and velocity by following equations, Eq. 8, Eq. 9 and Eq. 10. When the temperature is 20°C, the moisture content in the air can be 10g/kg to keep the RH at 70%. Necessary airflow is listed in Table 8.

$$MC = \frac{G_v}{\dot{V} * p_{air}} + MC_{50\%} \qquad \text{Eq. 8}$$

$$V_{min} = \frac{G_v}{(MC_{max} - MC_{50\%}) * p_{air}} \qquad \text{Eq. 9}$$

$$v = \frac{V_{min} * h_{wall}}{3600 * \ _a} \qquad \text{Eq. 10}$$

Table 8: Minimum required airflow and air velocity to keep RH below 70%

	Summer	**Winter**
Min. airflow, $\dot{V}_{min}$[m³/m²h]	*0.2*	*0.2*
Min. Velocity, v [m/s]	*0.006*	*0.006*

When calculating with average vapour diffusion into the airgap the minimum required airflow during summer and winter is both calculated to be 0.2m³/m²h to keep the relative humidity below 70% beneath the window. It is desired to measure a higher airflow due to the fact that sometimes the diffusion is higher than average. The necessary airflow is very little, and can possible be achieved with sealed steel profiles that will force the airflow to move beneath the window. Moreover, the duct at the bottom of the wall will draw the air at the same rate of 1.2m³/m²h, which will also affect the velocity in the air beneath the window.

Test method and measurements of mock-up model

The testing of the airflow is done using smoke tests to observe how the air actually moves in the airgap. An anemometer is also used to measure the air velocity. Furthermore, the pressure drop in the wall is measured using a micromanometer. As the mock-up test has an area of 5.7 m^2 the desired flow rate of 1.2m^3/m^2h gives a necessary total flowrate of 7m^3/h.

Figure 46: Mock-up test

The testing is divided into four parts:

1. *Smoke test*
2. *Measuring air velocity*
3. *Pressure drop in the wall*
4. *Pressure drop in hoses*

Method of testing and results are presented continuously and compared and discussed in the end of the chapter.

1. *Smoke test*

First of all, the airflow is adjusted to the necessary flow of 7m^3/h in conjunction with the supplied smoke. The smoke test makes it possible to observe how the airflow moves around and beneath the window and hence detect critical locations with little airflow. The smoke and fan configuration is displayed in Figure 47.

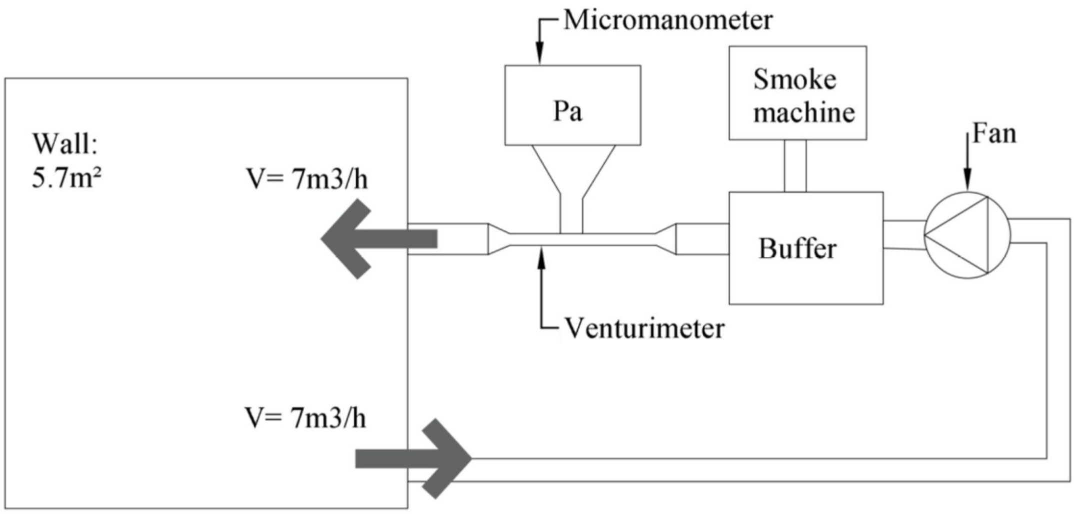


Figure 47: Closed loop smoke and fan configuration for Mock-up test (Layout)

When running smoke through the system we were able to see the movement of the air flow. As expected, the smoke did not access the area beneath the window, displayed in Figure 48. This is due to the fact that the air flows in the direction where there is less pressure loss. Another factor that also can affect the actual airflow is the force of gravity. The smoke in the air will have a slightly higher density than air because of the very small oil particles that makes the smoke. Just a little difference in density will cause the smoke to move downward and then distributes horizontally which occurred in the smoke tests.

Figure 48: Movement of air beneath window visualized with smoke test

A measure to increase the air movement beneath the window is to seal some of the perforations at the sides of the window where the airflow is higher. This will increase the dynamic pressure and force the air to move towards the middle of the window, displayed in Figure 49.

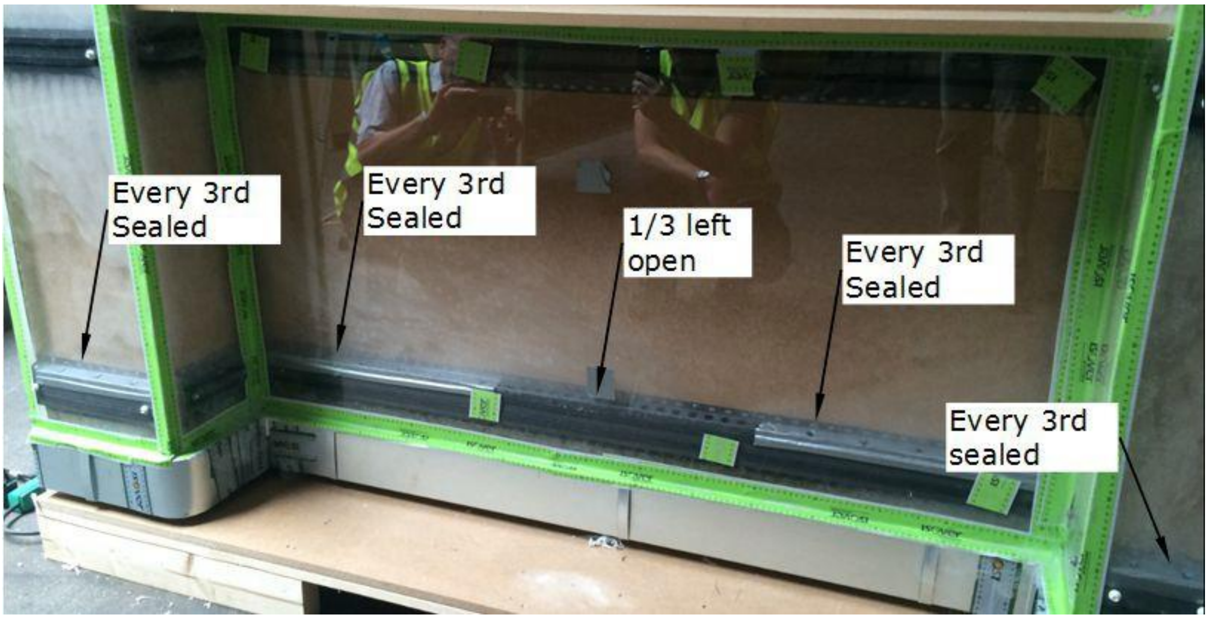


Figure 49: Sealed perforations to force air to flow beneath window

The sealing some of the perforations increased the air velocity beneath the window section compared to the initial situation and is documented by velocity measurements.

2. *Velocity measurements*

From the smoke test it is possible to determine critical locations of where the smoke has accessed slowly. As expected this was beneath the window. The very sensitive anemometer (Figure 51) is used to measure air velocity. However due to the very low velocities from an airflow of 7m³/h, the air flow was increased to 15m³/h in order to get any reading from the anemometer. Air velocity was measured at three locations (Figure 50) before and after perforations was sealed.

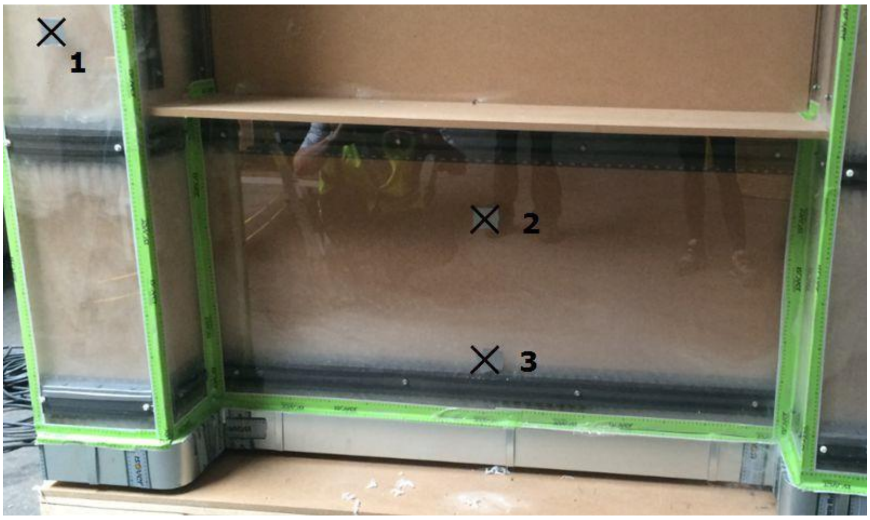


Figure 50: Locations of measured air velocities

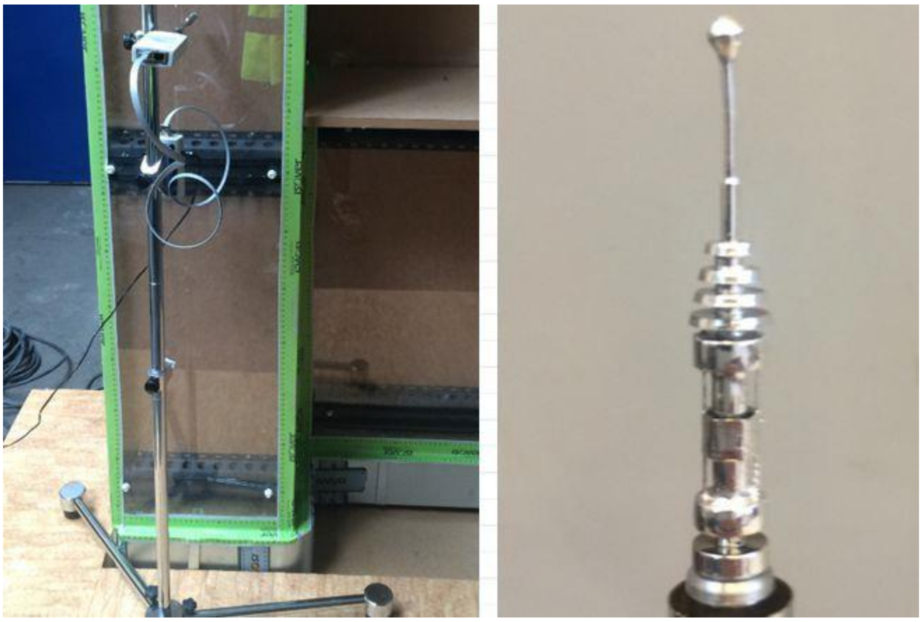


Figure 51: Set-up of the anemometer (left), sensor of the anemometer (right)

Table 9: Measured average air velocity in the air gap

	Average velocity* [m/s]	
Location	*Initial model*	*With sealed perforations*
1	*0.10*	*0.19*
2	*0.02 (20% of location 1)*	*0.08 (42% of loaction1)*
3	*0.10*	*0.20*

**Readings every 10 sec for 3 minutes*

The measurements listed in Table 9 show that when actions are taken with sealed perforations, the air velocity will increase beneath the window. The initial conditions gave 1/5 the velocity beneath the window compared to location 1. While the second conditions gave almost half of the velocity compared to location 1. Ultimately, small measures of forcing the airflow to move towards the middle will increase the airvelocity.

When the airflow is adjusted back to the required airflow of 1.2m³/m²h, it can be assumed that the velocity beneath the window is about 40% of the airflow on the side of the wall which has an air velocity of 0.036 m/s, giving a velocity beneath the window of 0.016 m/s.

3. *Pressure drop in wall.*

A micromanometer is used to measure the pressure drop in the system from the exhaust air duct to the bottom of the wall when the airflow is 7m³/h, displayed in Figure 52.

Figure 52: Pressure drop measurement of mock-up model

Table 10: Measured pressure drop in mock-up model

	Initial model	With sealed perforations
Measured pressure drop	*3.30 Pa*	*3.10 Pa*

The pressure drop was measured to be around 3-3,5 Pascal. The measurements also showed insignificant difference in pressure drop from the initial conditions compared to when perforations were sealed.

The pressure drop from the supply duct to the bottom of the wall is also the desired pressure drop for the hose system in order to obtain a balanced air flow

4. Pressure drop in hose

Last of all, the pressure drop in the perforated hose system around the beams is measured with a micromanometer. The affordable plastic flex hose (Figure 54) with 20mm inner diameter is tested to measure pressure drop. The area that should be covered when a wall is 5 meter long, and 20 cm high is 1m², thus the desired airflow is 1.2m³/h. As the hose system consists of two hoses, the airflow is 0.6 m³/h. Approximately 1 meter connected with a 2.5 meter perforated hose is measured in the test, and represent the marked loop in Figure 53.

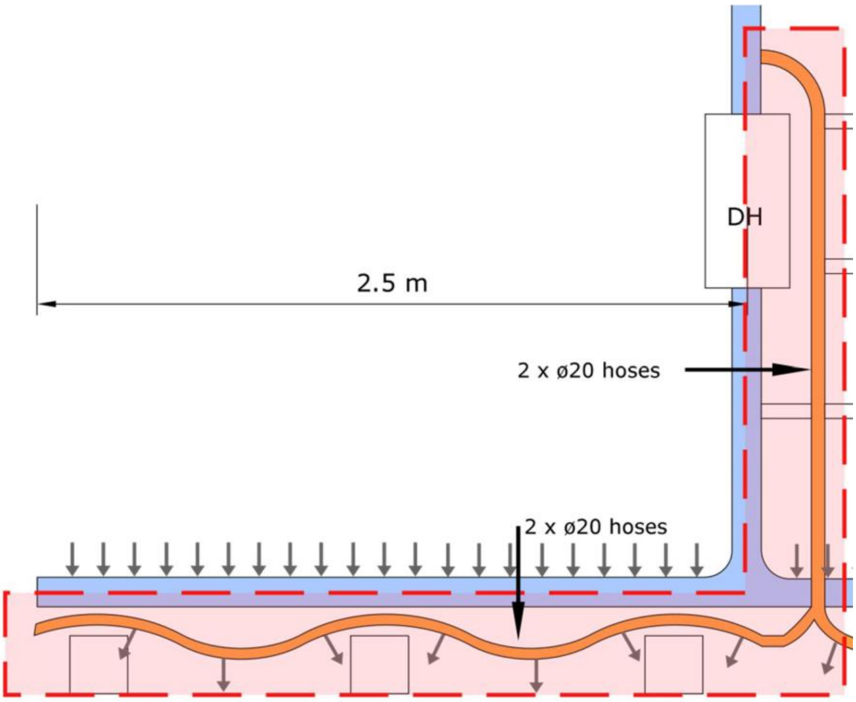


Figure 53: Measured hose system (Layout)

Figure 54: ø20mm (id) hoses, Left: PVC hose, Right: Flex hose (Bauhaus.dk)

A fan and a flow adjuster were used to get the desired air flow rate through the hoses. The desired pressure loss is the same as measured for the wall, namely 3.30 Pascal. First of all, the 2.5 meter hose was perforated with 9x3mm holes. The pressure was measured near the supply source. As the pressure loss was measured to be too large, more holes were added to decrease the total pressure loss to get the desired pressure loss. 20 holes was in the end close to the desired pressure loss.

Furthermore, to detect any friction loss along the hose with perforations, pressure loss was measured before perforations started, and then at the end of the hose. The friction loss appeared to be as much as 1.1 Pa which is a lot when it is actually desired to have an equal air flow along the perforations.

	Flex hose
Total pressure loss	*3.20 Pa**
Friction loss from start to end of perforated hose	*1.1 Pa*

** Average pressure loss out of 7 readings.*

5.2.2 Balanced pressure drop - calculations

A balanced pressure drop is calculated to compare with measurements from the mock up test. The calculations are also carried out to determine the dimensions of the measured hose system around beam ends. This is important to investigate in order to obtain the correct air flow behind the wall and around the beams, and thus secure that dry air will access everywhere. This is achieved when the pressure drop is equal in all flows. The duct system will in a sense act as pressure chambers to allow an equal flow throughout the wall. It is therefore also important that the dynamic pressure drop over the perforated holes is larger than the pressure loss due to friction in the ducts.

When calculating the pressure drop for the system, a 5 meter long and 2.7 meter high wall is assumed. Also, two options of installation are provided.

Two ways of installing the dehumidifier require different solutions to obtain a balanced flow:

1. *Dehumidifier installed at the end of the wall (Figure 55)*
2. *Dehumidifier installed in the centre (Figure 57)*

The first solution will result in higher pressure drop due to the longer distances in contrast with the centred system. In the figures, the blue section is the airflow in the airgap behind the insulation, while the orange is the airflow around the beam ends. As expected, the main pressure drop is in the ducting, but some minor losses also occur as friction losses and dynamic losses through the fittings supporting the insulation.

The ducting system consists of standard rectangular plastic ducts, which is perforated with small holes of 7mm every 50 mm of the duct. This pattern is based on Anton Ørebæk's *experiments, which will with very small deviation provide equal flow throughout the perforated duct.*

According to standards, the single loss factor of sharp edged holes is 2.8 [28]. This factor applies to a hole in a wall when the velocity is approximately equal to zero on both sides of the wall. According to the duct experiment with related pressure measurements, the single loss factor over the perforated holes is calculated to be 2.7 in average. Hence, this single loss factor of 2.7 is used in following calculations of perforations.

Apart from the dynamic loss from the perforations in the duct and in the supporting steel profiles, pressure drop due to friction and a few dynamic pressure drops due to duct bends will occur. In this examination of pressure drop the assumed airflow is 1.2m3/h per m2 of wall, which gives an airflow rate of 16m3/h for a 5 meter long and 2.7 meter high wall, which would most probably be the largest wall the system could be applied to because of the typical historical constructions.

Losses due to friction will occur basically everywhere and is calculated according to Eq. 11. However, as the ducts in a way work as pressure chambers the pressure loss goes to zero at the end of the duct, meaning that most of the friction low will occur at the vertical dust with no perforations.

$$\Delta pf = L * A * \frac{p * v^2}{D_h * 2}, [pa] \qquad \text{Eq. 11}$$

Dynamic losses will occur in fittings due to flow disturbances that change the airflow direction or flow path area and is calculated according to Eq. 12. This will happen over all fitting such as perforated holes in main ducts, duct bends, and at the steel fittings.

$$\Delta pd = (* \frac{p * v^2}{2}, [pa] \qquad \text{Eq. 12}$$

5.2.2.1 System 1

In this system the dehumidifier is installed at the end of a 5 meter long wall, as visualized in Figure 56.

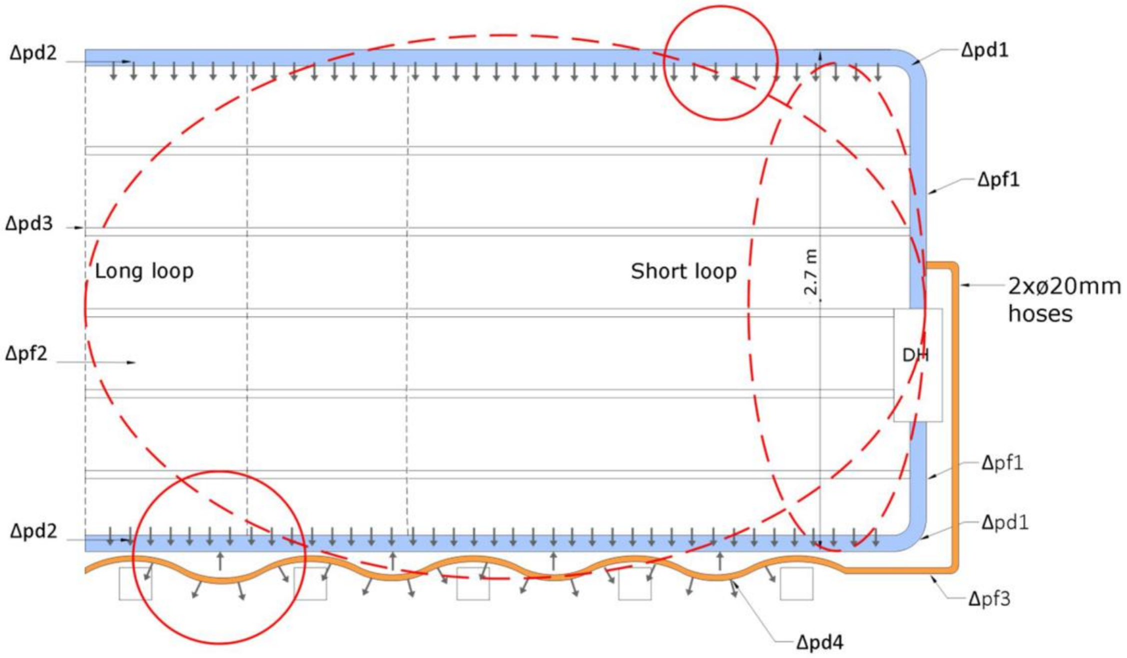


Figure 55: Ducting system 1 (Layout)

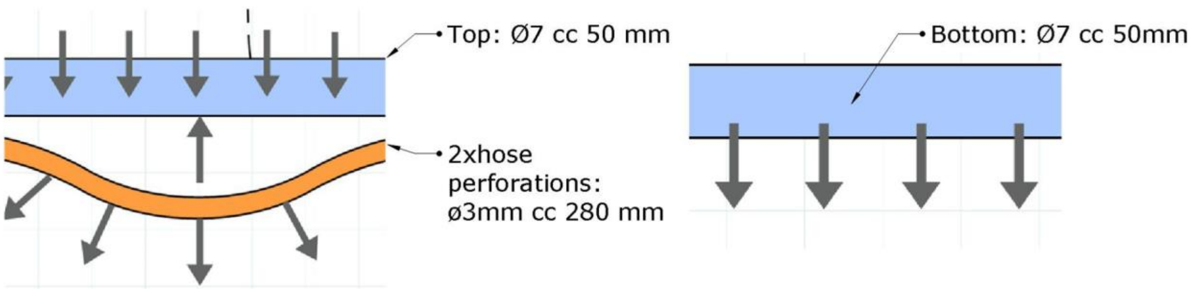


Figure 56: Ducting system 1 – details of perforations

Pressure losses provided in Table 11 represents the flow behind the wall.

Table 11: Pressure losses [Pa] in airflow behind wall – system 1

Pressure losses – behind wall [Pa]		**short loop**	**Long loop**
Friction loss in duct	2xΔpf1	*2.04*	*1.14*
Single loss over 90° bend	2xΔpd1	*0.40*	*0.40*
Friction loss from brick and mineral wool surfaces	Δpf2	*0.10*	*0.10*

Dynamic loss over 7mm holes	2x∆pd2	*4.32*	*4.32*
Dynamic loss steel profiles	10x∆pd3	*0.13*	*0.13*
Total pressure loss		*6.90*	*5.90*

In order to get a balanced pressure drop in the two sections, the dimensions and fittings for flow around the beams has to be modified to obtain the same pressure loss to secure the desired airflow rate. This depends on the dimensions of hoses, and number of perforated holes in the hoses. The pressure drop for the beam and hose system is listed in Table 12 below. Due to the fact that the measurements of the hoses showed a large friction losses along the hose, it is also expected to detect too much friction loss in the calculations.

Table 12: Pressure losses in air flow around beams – system 1

Pressure losses – around beams		**[Pa]**
Friction loss in hose (ø20 id)	∆pf3	*1.85*
Single loss hose (ø3cc130mm holes)	∆pd4	*0.69*
Dynamic loss bottom duct		*2.80*
Total pressure loss		*5.40*

By calculations with a single loss coefficient of 2.7 and the amount of perforations measured in the hose test, the friction loss is larger than the single loss over the holes will no longer give the desired pressure chamber effect in the hoses, hence the flow will not be equal throughout. A method to solve this issue is to minimize the friction loss by having more than two hoses, or larger hoses, and then decrease the perforations to get more single loss over the holes. On the other hand, when the pressure loss of the hose system is less than for the wall, this means that the airflow will increase which will therefore result in more dry air around the beam ends.

Table 13: Requirements of installation in system 1

Desired air flow rate (1.2m3/m2h)	*0.000333 m3/s*
hose	*4 x Ø20(ID) or 2 x Ø25*
Perforations in hoses	*Ø3mm cc 130 mm*

5.2.2.2 System 2

In the second system the dehumidifier is installed in the middle, visualized in Figure 57.

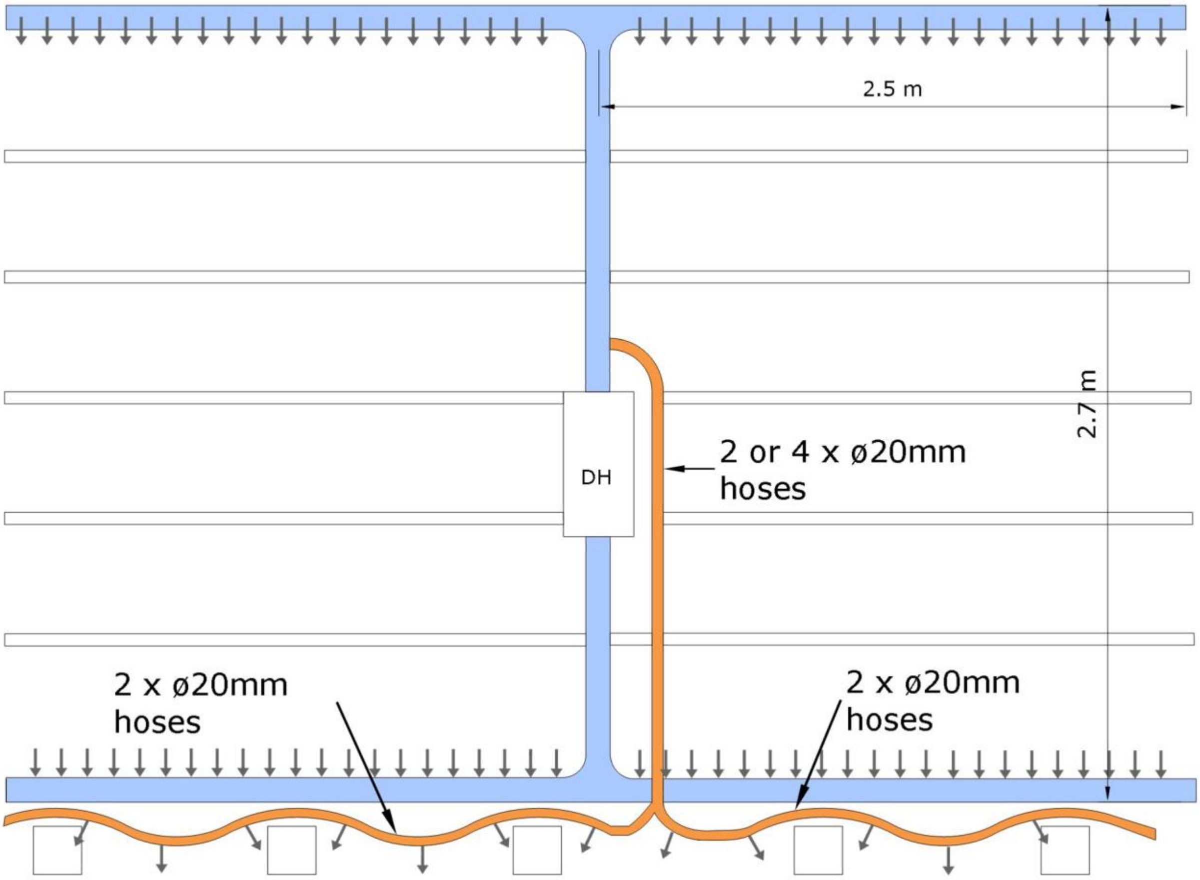


Figure 57: Ducting system 2

Due to the large friction loss in the hoses along the beams calculated for system 1, this system consists of more hoses to minimize the friction loss. Hence 4 hoses will be connected to the supply duct, and then two hoses are drawn along the beams at both sides. The pressure losses are listed in Table 14 below.

Table 14: Pressure drop for system 2

Pressure losses – behind wall		**[Pa]**
Friction loss in duct	2xΔpf1	*1.25*
Friction loss from brick and mineral wool surfaces	Δpf2	*0.10*
Dynamic loss 90° bends	2xΔpd1	*0.12*
Dynamic loss over 7mm holes	2xΔpd2	*4.32*

Dynamic loss steel profiles	10xΔpd3	*0.13*
Total pressure loss		*5.95*
Pressure losses – around beams		**[Pa]**
Friction loss in hose	Δpf3	*0.33*
Dynamic loss hose (ø3cc280mm holes)	Δpd4	*2.77*
Dynamic loss through bottom pipe		*2.80*
Total pressure loss		*5.90*

This system is better because it allows room for more hoses, hence a large decrease in friction loss.

The components used in the system are displayed below in Table 15, with dimensions and specific properties used in the calculations.

Table 15: Components with related data used in the system

Components	Description	Dimension/properties
	*Perforated steel profiles will be installed horizontally every 50 cm in the wall* *40% perforated*	*25x100 mm* *(=2.7*
	*Standard rectangular plastic ducts installed at top and bottom of the wall, perforated with ø7cc50 mm.*	*110x54 mm* *Roughness = 0.004* *(=2.7*
	*Air gap in between insulation and cement plaster will give some friction loss*	*Roughness = 0.9*
	*Flex hose supplies air around beam ends, perforated with 3mm holes*	*Roughness = 0.0015* *(= 2.7*

It is important to point out that the pressure loss in the systems depends on dimensions of the different components and also the size of the wall. The biggest losses seem to occur where there is friction loss in the ducting and dynamic pressure loss over the holes. In smaller apartment with less façade area, the friction loss will be reduced, while the dynamic loss is obtained approximately the same, therefore it is likely that the same setup can be applied to smaller walls and still obtain a balanced air flow when supplied air is 1.2 m3/m2h.

As for the number of hoses and related friction loss, system 1 can be applied on walls that are smaller, as the friction loss will decrease simultaneously with the airflow.

5.2.3 Results and discussion

The measurements from the mock-up test are compared to the calculations in Table 16.

Table 16: Comparison of measurements and calculations of pressure drop and airflow

	Calculated	**Measured**	**Total*****
Pressure drop wall [Pa]	*3.10*	*3.30*	*6.10*
Pressure drop hose system [Pa]	*3.10*	*3.20*	*6.05*
Min. air flow beneath window [m^3/m^2h]	*0.2*	*0.48**	
Min. air velocity beneath window [m/s]	*0.006*	*0.016***	

*Some perforations are sealed; 40% of the flow along the wall (1.2m^3/m^2h) will flow beneath the window

** The same applies to the air velocity where 40% of the main flow along wall (0.036 m/s) will be the velocity beneath the window.

*** Total pressure loss includes the exhaust bottom duct for both loops explained in Figure 58.

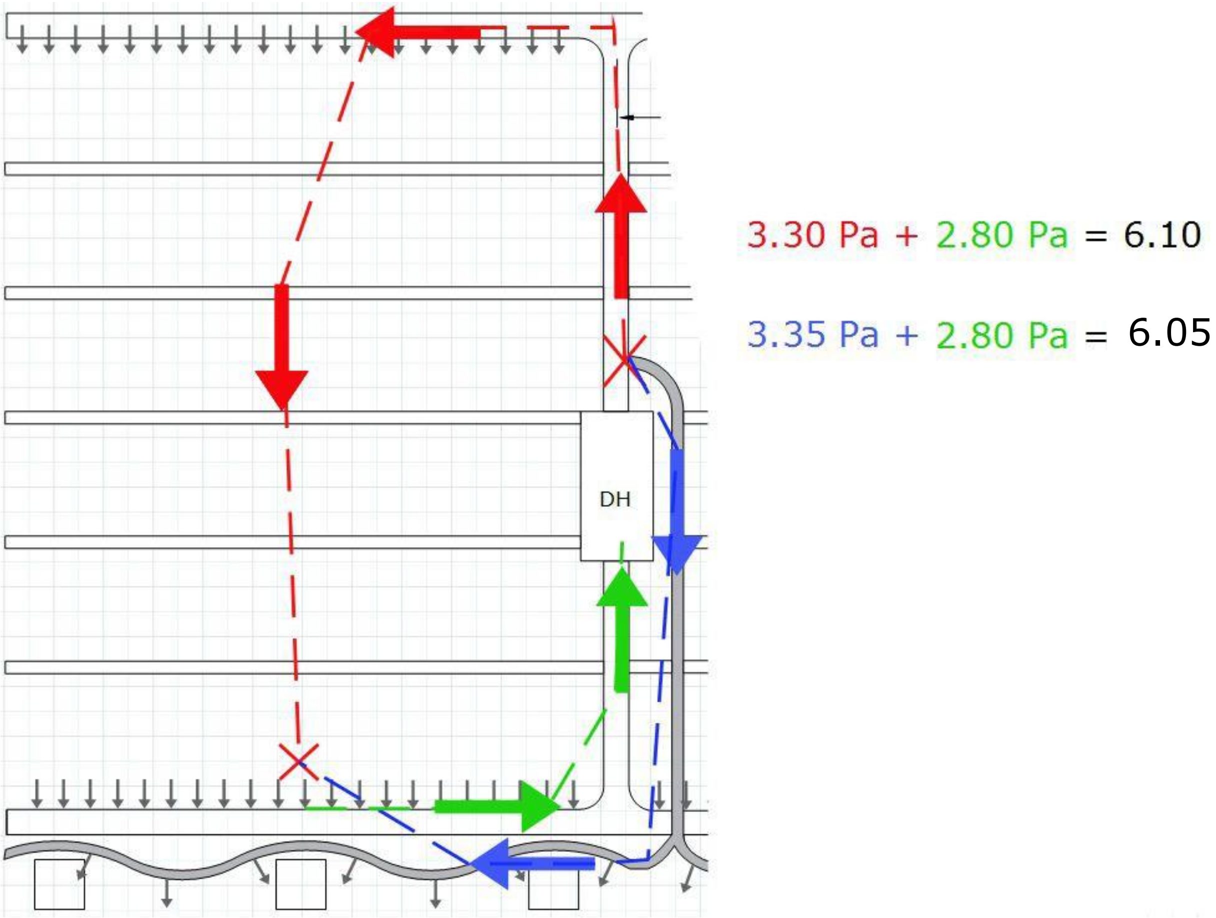


Figure 58: Location of measured pressure loss and total pressure loss of both loops (Layout)

The measured pressure drop in the system is slightly larger than the calculated pressure drop. This may be due to small differences in airflow resulting in differences in pressure loss. Additionally, the friction and dynamic losses can differ from the estimated standard calculations methods to real measurements. Ultimately the measured and calculated pressure difference is very little and it can therefore be concluded that the pressure loss will be around 5-6 pascal for both loops. Furthermore, the smoke test and velocity measurements show much less airflow in the section beneath the window, but the air is not stagnant. To be on the safe side and increase the airflow in this critical location it is recommended to either seal some perforations in the steel profiles, or perform other actions for the same purpose.

5.2.4 Preliminary conclusion of part 2

- *Vapour diffusion in still air is not sufficient enough to keep RH<70% underneath window.*
- *The airflow beneath the window is measured to be approximately 20% of the main airflow. However, an effort to enhance the air flow is still considered necessary to be on the safe side, such as sealing some of the perforations in the bottom steel profiles.*
    - *Initial air velocity: 0.007 m/s*
    - *Air velocity with sealed perforations: 0.016 m/s >> required velocity to keep RH below 70%*
- *Pressure drop in the system is calculated and measured to be approximately around 6 Pascal.*
- *System 2 with dehumidifier installed in the middle will give about 1 Pa less pressure drop to the system.*
- *Friction loss in the hoses should be minimized by either increasing number of hoses or use hoses with larger inner diameter with less friction loss.*

5.3 Part 3 – The dehumidifier

This part will examine the capacity of the dehumidifier, its energy consumption and discussion of solutions to limit its operation time.

The dehumidifier developed by Cotes AS, is customized for dehumidification of walls and the very small volumes of airgaps between external facades and insulation. It is supposed to be able to supply a flow of 16m³/h, and remove the excessive moisture in the air gap between the insulation and brick wall.

The specific flow of 16m³h will be enough to supply a 5 m long wall with the an airflow of 1.2m³/m²h. The two fans have an effect of 5-7 W while the heating coil has an effect of 70W. If the operation time of the dehumidifier is 24/7, the annual energy consumption adds up to be 700kWh in total.

5.3.1 Drying capacity

The capacity of the dehumidifier is important to investigate to ensure that it can remove the necessary amount of moisture. As the dehumidifier is still a prototype and very small compared to other dehumidifiers, it is tricky to measure its actual capacity according to the designers. To get an understanding of the capacity of an adsorption dehumidifier, Figure 59 shows the drying capacity of a much larger dehumidifier of the type Cotes All-round C30E-09, with a nominal airflow of 300m³/h. Basically the chart show that the drying capacity of the dehumidifier depend on the relative humidity and the temperature. The lower temperature and relative humidity the less capacity it has. This is due to the fact that cold air contains less moisture than warm air. Hence, the dehumidifier will have less capacity during winter when the airgap is cool.

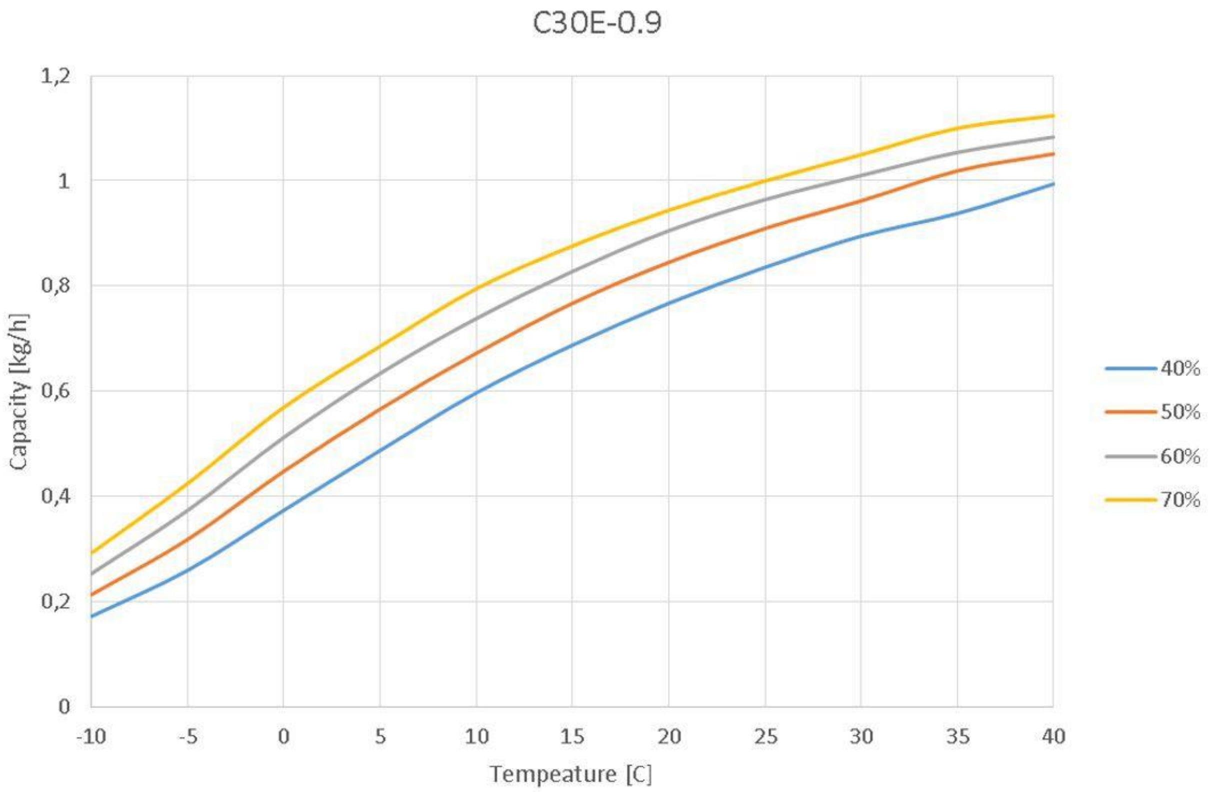


Figure 59: Drying capacity of the adsorption dehumidifier Cotes All-round C30E-09

Testing of the little wall dehumidifier has been conducted by Cotes AS and Anton Ørbæk at DTU measuring capacity of moisture removal for two different situations. The tests work as indicators of what can be expected of the dehumidifier. Both tests show that the capacity is more than enough.

Drying capacity of wall dehumidifier – summer season
The test conducted by Cotes AS has the following situation and drying capacity:

Process in		**Process out**
T=21.2°C	⟶	*T=28.2°C*
RH=30%		*RH=17%*
	Regeneration in	
	T=21.9°C	
	RH=30%	

Measured drying capacity	*0.68 g/kg*
Required drying	*0.40 g/kg*

The process air has a very low initial relative humidity of 30% because it is tested using room air. This is unrealistic considering that the airgap would be much more humid. However, the capacity of the dehumidifier is higher when the relative humidity is higher, meaning the actual capacity during summer would probably be higher. Evidently the capacity plentifully covers the necessary moisture removal. The capacity of 0.68g/kg is more than the calculated excessive moisture content of 0.40g/kg for a north oriented wall during summer (results from chapter 5.1.3.4).

Drying capacity of wall dehumidifier – winter season
The test conducted by Anton Ørbæk at DTU has the following situation and drying capacity:

Process in		**Process out**
T=4.2°C	⟶	*T=15°C*
RH=56%		*RH=23%*
	Regeneration in	
	T=20°C	
	RH=50%	
Measured drying capacity		*0.32 g/kg*
Required drying		*0.15 g/kg*

This situation is representing a situation that can occur during the winter season. The regeneration air would realistically have a RH of less than 50% due to the typical dry indoor environment during winter, so this is to the safe side. Even though the temperature of the process air increases to 15°C it will drop down along the wall, hence the RH of 23% will increase to 50% if the temperature drops to 5°C. The necessary moisture removal for a north oriented wall during winter is 0.15g/kg and is less than the capacity of the dehumidifier.

5.3.2 Airflow capacity

Because of the very little fan effect of 5-7 W, the fan only has a capacity of 5Pa of external pressure which is less than the measured pressure drop of 6 Pa in the system. The fan capacity also limits the airflow of the dehumidifier, which has to be 16m³/h for a 5 meter long wall if the desired airflow is 1.2m³/m²h. It is designed to give the required airflow, however the testing of the prototype by Anton Ørbæk at DTU gave less airflow due to errors and incorrect filters. Initially the dehumidifier will supply 16m³/h with an external pressure loss of 5 Pascal.

If the pressure drop is in reality higher than the capacity of the fan then the airflow will decrease. And as a result of a smaller airflow, the dehumidification will increase and thus supply dryer air. Because of the fact that the airflow of 1.2m³/m²h is quite high compared to the required amount of moisture removal and the drying capacity of the dehumidifier, this is assumed not to be an issue. Additionally, an airflow of 16m³/h is only required when the façade is 5 meter long, which will not be the case of man typical apartments.

The consequences of decreasing the airflow is provided to argue the small risk it may entail. With summer conditions (T=20°C) and an average diffusion of 0.58 g/m²h two airflows are compared and presented in Table 17.

$$MC_{excessive} = \frac{G_v}{V^{\cdot} * _{air}} \quad \text{Eq. 13}$$

$$pv_{sat} = 288.68 * (1.098 + \frac{T}{100})^{8.02} \quad \text{Eq. 14}$$

$$pv_{50\%RH} = 0.5 * pv_{sat} \quad \text{Eq. 15}$$

$$MC_{50\%RH} = 0.622 \frac{pv_{50\%RH}}{pa - pv_{50\%RH}} \quad \text{Eq. 16}$$

$$MC_{sat} = 0.622 \frac{pv_{sat}}{pa - pv_{sat}} \quad \text{Eq. 17}$$

$$MC_{actual} = MC_{50\%RH} + MC_{excessive} \quad \text{Eq. 18}$$

$$RH = \frac{MC_{actual}}{MC_{sat}} \quad \text{Eq. 19}$$

First of all, the excessive moisture content is calculated according to Eq. 13. The saturated vapour pressure and vapour pressure at 50% RH is then calculated according to Eq. 14 and Eq. 15. Moreover the moisture content (MC) of saturated air and air at 50%RH is calculated according to Eq. 16and Eq. 17 with an atmospheric pressure of 101325 Pa. Then the actual MC is the sum of the excessive MC from diffusion and the MC in the dry air of 50% RH. Finally the relative humidity is determined by dividing the actual MC by saturated MC according to Eq. 19.

Table 17: Comparison of increase in RH of two airflow rates

Airflow rate [m³/m²h]	**1.2**	**0.6**
Excessive MC [g/kg]	*0.40*	*0.80*
Actual MC [g/kg]	*7.65*	*8.05*
Increase in RH [%]	*2%*	*4%*

When the airflow is halved to 0.6m³/m²h, the relative humidity only increase with 2% more compared to an airflow of 1.2m³/m²h.

5.3.3 Operation time

The energy consumption of the dehumidifier depends on its operation time. As already stated, the annual energy consumption is 700kWh if the dehumidifier operates 24/7. This is quite a lot compared to the annual energy saving potential of the insulation of around 1500kWh for a 13m² large wall area [estimated calculation in Appendix C].

The operation time depends on how humid the airgap is. Hence, it should be tested in reality to detect any "dry hours", and whether operation time can be limited *to a few hours a day. Moreover, based on the simulation results of vapour diffusion to the interior in chapter 5.1.3.4 the hours of vapour diffusion into the airgap is 82% annually for the worst case. This already cuts the operation time with about 20%.*

When it comes to the matter of noise, the operation time of the dehumidifier can be regulated to fit the residence with a sleep button that will put the dehumidifier to sleep a few hours. Even though the dehumidifier is designed to make as little noise as possible, a humming sound will still be present during operation. The dehumidifier should however turn on automatically when the relative humidity is critical, or after a few hours.

5.3.4 Discussion

The dehumidifier is not fully developed, but when it is it should meet certain requirements based on the investigation. However, the requirements of fan capacity and airflow only apply when the required airflow is 1.2m³/m²h.

1	*External pressure*	*6 Pa*
2	*Nominal airflow*	*16m³/h*
3	*Drying capacity (summer/winter)*	*0.40/0.32*

These requirements apply to a 5 meter long wall which is studied in this report. Hence, if the dehumidifier is fitted to smaller wall areas, the requirement changes slightly. For example, a nominal flow of 16m³/h is not required for a smaller wall. However, as the pressure drop primarily occurs as dynamic losses, the fan still need to withstand the external pressure of 6 Pascal if an airflow of 1.2m³/m²h is required. Ultimately, the system will require the same dehumidifier capacity, regardless of the area due to the pressure drop.

On the other hand, an airflow of 1.2 m³/m²h is calculated to be excessive compared to the actual need of moisture removal. As calculated in chapter 5.3.1 the necessary airflow to keep the relative humidity below 70% is 0.2 m³/m²h. An external pressure exceeding the capacity of the fan will reduce airflow to some extent, but not to such an extent that it will cause the relative humidity to increase to above 70%.

5.3.5 Preliminary conclusion

- *Drying capacity of dehumidifier is nearly 50% greater than the drying demand when desired RH is 50%.*
  - *Winter: 0.32 g/kg > 0.15 g/kg*
  - *Summer: 0.68 g/kg > 0.40 g/kg*
- *The airflow of 1.2m³/m²h is large compared to the necessary demand, which means the decrease in airflow due to the external pressure exceeding the fan capacity with 1 Pa will only result in a little higher increase in RH along the wall.*

5.4 Part 4 – Optimization of the concept and alternative solution

Optimization of the system includes discussion of measures that can limit the energy consumption and operation time of the dehumidifier, in addition to alternative solutions to upgrades of entire apartment buildings.

5.4.1 Required levels of relative humidity – moisture monitoring

In order to avoid the system to use unnecessary energy, the level of relative humidity (RH) should not be lower than what is actually required to prevent mould growth. A RH below 75% is enough to keep the mould away.

Hygrometers measuring RH at critical locations within the wall can be connected to the dehumidifier and control the operation based on the desired RH. Once the hygrometers measure level above 75%, the dehumidifier turns on and removes vapour from the air gap.

Future work will include finding two critical locations in the wall where sensors should be placed and then control the uptime of the dehumidifier. The Retrowall will be tested in test apartments in Denmark and sensors will be integrated in the wall to monitor temperature and relative humidity. Finisterra AS, have provided the wireless moisture monitoring system called Omnisense to be tested at DTU with the intent that it can be used in future test apartments. Different types of sensors are able to measure relative humidity, temperature, dew point temperature and moisture content. The wireless system will record measurements every 5 minutes, and alerts the user by mail if measurements deviate from the pre-set values. Additionally the person in charge of the monitoring can access the readings from home or anywhere because the wireless system records measurements directly to the Omnisense website, which makes it very easy to observe any time.

When a couple of critical locations have been determined from the test apartments, future installation of the RetroWall can have one or a couple hygrometers connected to the dehumidifier which then regulate its operation time.

5.4.2 Ducting with little pressure loss

Optimization of ducting can decrease the pressure drop in the system and hence decrease the required effect of the fan. This can be done by using duct with little pressure loss, larger ducts, adjusting numbers and sizes of perforations, adjusting air flow rate, but in such a way that it will still provide an efficient and equal airflow throughout the wall.

Based on the measuring of the pressure loss in duct and hoses, the pressure can vary a lot due to small changes in the system. Therefor it is believed that with more testing of alternative solutions it is possible to limit the pressure loss and optimize even more.

5.4.3 Alternative ventilation during summer

During summer the RetroWall can in theory use the indoor air as dry air supply to the airgap. This is due to the little to no temperature difference between interior air and brick surface, which will thus keep the RH at about 50% in the air unchanged when applying it to the air gap.

This will however require a new function to the dehumidifier, or alternatively a separate fan only supplying and extracting interior air. If this was possible, the energy consumption of the system could be minimized during summer.

5.4.4 Alternative solutions – retrofitting of a whole apartment building

The RetroWall is initially developed for single walls in historical apartment buildings. However, when upgrading a whole apartment building it would be possible that one large dehumidifier could supply all walls with dry air through high pressure air ducts. For instance, a dehumidifier attached to a high pressure machine could be placed in the basement or in the attic and blow dry air to all floors displayed in Figure 60. In this way, any noise from an integrated dehumidifier is not an issue. This solution can also benefit the often very humid basements to avoid mildew damage to stored assets.

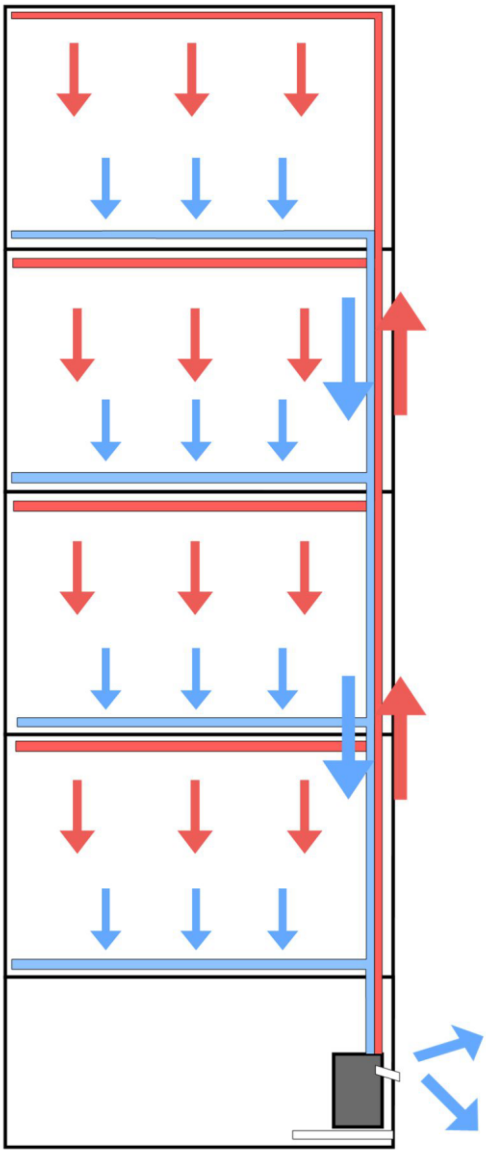


Figure 60: Alternative solution for upgrading of whole apartment buildings

6 DISCUSSION OF INVESTIGATION

A summary of all discussions throughout the investigation is provided to get a better overview and will furthermore be the basis for the final conclusion.

In part 1 the hygrothermal simulations of the RetroWall with wind driven rain (WDR) and the worst case scenario rain exposure coefficient (CR) of 0.5 results in rapid accumulation and an extreme increase in relative humidity after a few years. These results indicate that further actions are needed to prevent mould growth at beam ends. Thus, when dry air is supplied around the beam ends, the simulations show that the moisture content (MC) in the beam end is below the critical level of 20%. This indicates that drying around beam ends will prevent any mould growth at the embedded beam ends.

Even though the CR of 0.5 is most probably not realistic, the extreme accumulation and increase in RH 10 cm into the brick wall is considered so critical, that a lower CR will probably not be as extreme, but still be critical. To back up this assumption, previous research around the topic of moisture issues in embedded wooden beam ends has not found moisture safe solutions when the CR is above 0.1, mentioned in chapter 2.1. Therefore drying around beam ends when the catch ratio is lower is still assumed as a necessary measure.

Moreover, the simulation results of vapour diffusion into the airflow in the gap are compared with the theory of Fick's law, which backs up the accu*racy of the seasonal average vapour diffusion. The results of average seasonal vapour diffusion are therefore used further in the investigation of the airflow.*

In part 2 the investigation of the air flow show the expected restricted airflow beneath the window section. Even though the air was measured to not be stagnant, further action should still be considered to increase the airflow in this particular location to be on the safe side. The examination also shows that the airflow rate of 1.2m³/m²h exceeds the demand. The consequence of a halved airflow is that the RH in the airflow will increase with 4% instead of 2%, which does not pose a risk to mould growth when the dry air is initially at 50% RH. The purpose of this comparison is to argue that even though the external pressure of 6 Pascal is larger than the fan's capacity of 5 Pascal, this will only limit the airflow to a certain extent *and not cause any risk as it would certainly not half the airflow.*

The drying capacity of the dehumidifier is also exceeding the drying demands. Overall, the investigation shows that the solution is moisture safe in theory. A well thought out and airtight solution should thus also be moisture safe in practice. A proposal for an airtight solution for the RetroWall is developed and presented in the conclusion.

7 CONCLUSION AND PROPOSAL FOR A MOISTURE SAFE SOLUTIONS

7.1 Conclusion

The aim of this thesis was to investigate whether the Retrowall is fit for internal façade insulation of historical buildings in terms of moisture, and further to develop a fool proof solution. First of all, all preliminary conclusions throughout the investigation are summarized and listed below. Secondly, the conclusion of this report is presented as proposals for a moisture safe solution based on all investigation around the RetroWall concept. Based on the investigation the RetroWall is a moisture safe solution when dry air is supplied around the beam ends. As emphasized in the discussion, a north oriented wall requires additional attention towards the embedded wooden beam end due to less drying potential.

- *North and west oriented facades require dry air supply around the beam ends*
- *South and southwest oriented facades are moisture safe with the initial conditions of only moisture control along wall*
- *The catch ratio of 0.5 gives unrealistic results, considering the critical conditions for the reference case. Hence, the CR is in reality less than 0.5.*

• *Average required drying, [g/kg]:*	*Winter:*	*0.15*
	Summer:	*0.40*
• *Estimated drying capacity, [g/kg]:*	*Winter:*	*0.32*
	Summer:	*0.68*

- *Vapour diffusion in still air is not enough to keep the section beneath window dry enough.*

• *Required air flow (RH<70%)*		*0.006*
• *Air velocity beneath window [m/s]:*	*Initial model:*	*0.007*
	Forcing the flow:	*0.016*
• *Pressure drop in the system, [Pa]:*		*6*

- *An airflow of 1.2 m^3/m^2h is large compared to the demand*

7.2 Proposals for moisture safe solutions

Proposals for moisture safe solutions are carried out based on the investigation. Solution 1 include dry air supply around beam ends to make sure that any accumulation and relating moisture will not damage the wooden beam end in terms of mould. Solution 2 is a less moisture safe solution without air supply around the beam ends, and can therefore only be applied on walls facing south due to the sun exposure and resulting annual drying to the exterior which does not require dry air supply around beam ends.

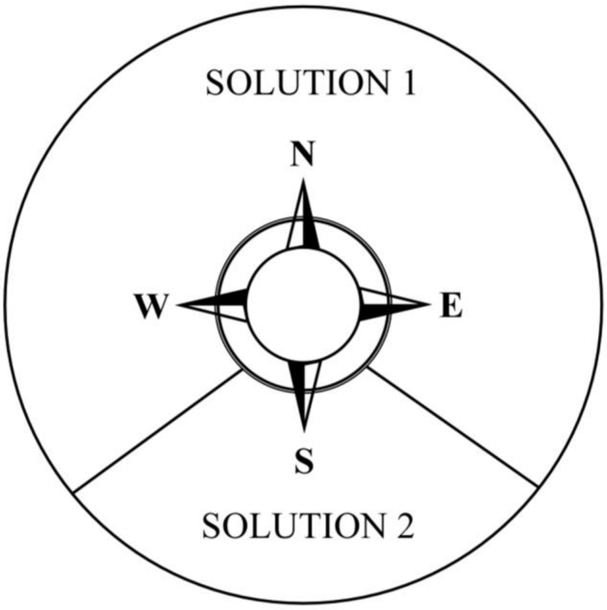


Figure 61: Solution dependent on wall orientation

7.2.1 Solution 1

Solution 1 should be installed at walls towards north, west and east due to the limitation of drying potential to the exterior. Even though the catch ratio of 0.5 is most probably too large, the risk of accumulation in north facing brick walls is still present, which therefore suggest a measure of the additional dry air around the beam ends to be on the safer side. The solution presented in Figure 62 consists of moisture control in the 25mm air gap in addition to hoses that supply dry air around the beams. For this solution to work in the anticipated way, the volume around the beams has to be separated from the volume underneath the floor panels. This can be solved with easy modifiable plates placed in between the beams that are attached and tightened with foam around the edges. The vapour barrier attached to this plate can later on overlap the vapour barrier in the wall construction, which gives an air- and vapour tight solution.

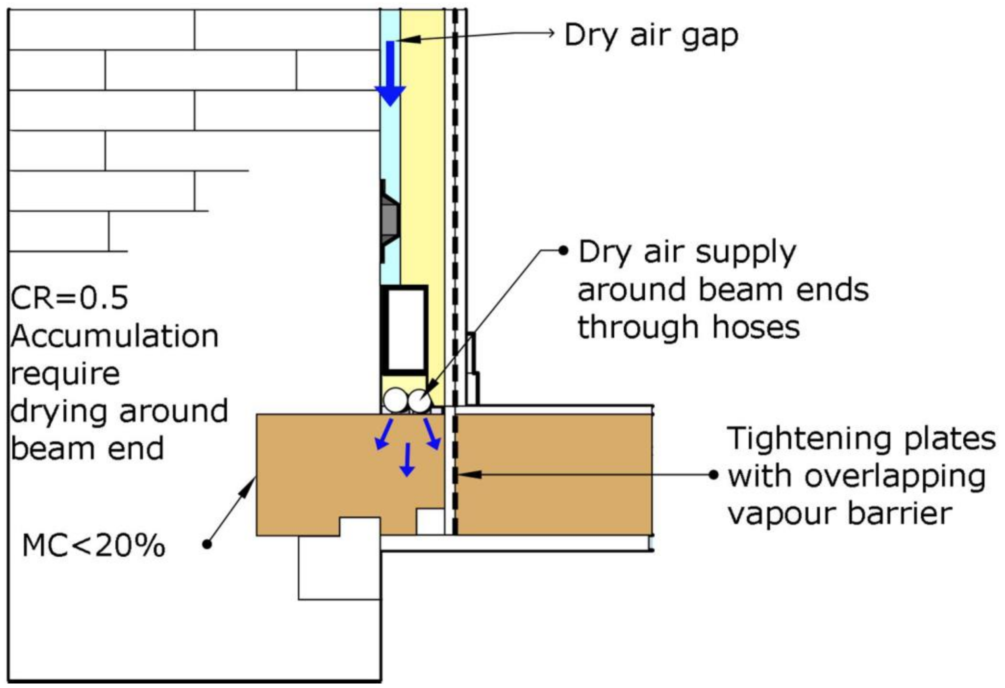


Figure 62: Proposal for solution 1

7.2.2 Solution 2

The second proposal of solution displayed in Figure 63 only applies to facades that are facing south of southwest/east with sufficient sun exposure. This is because the facade dries out over a yearly cycle according to the hygrothermal simulations. The solution corresponds to solution 1, except it does not include the supply air around the beam ends.

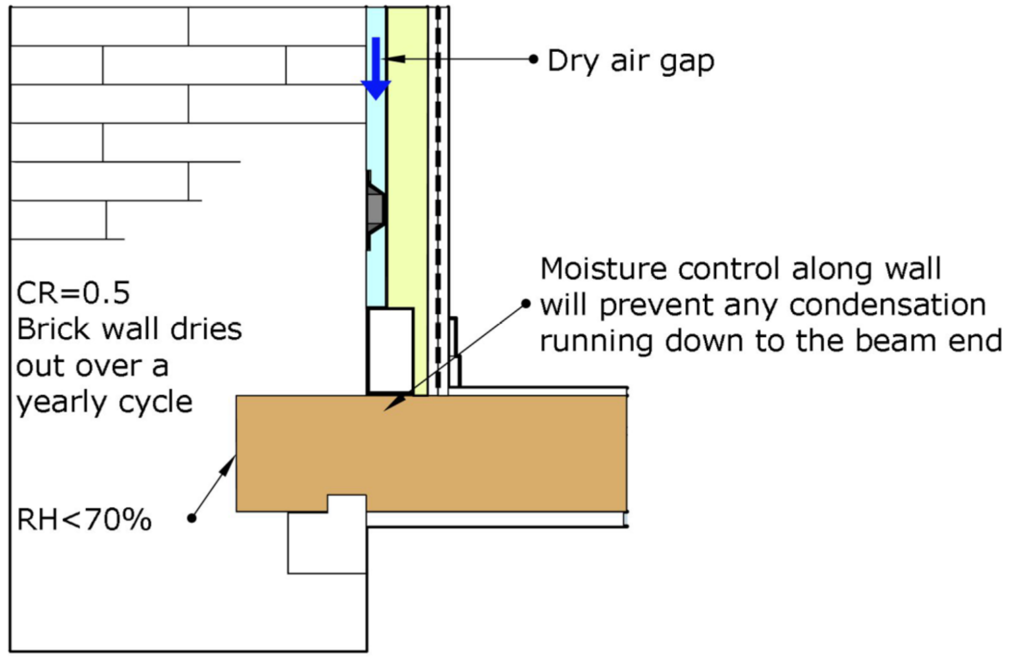


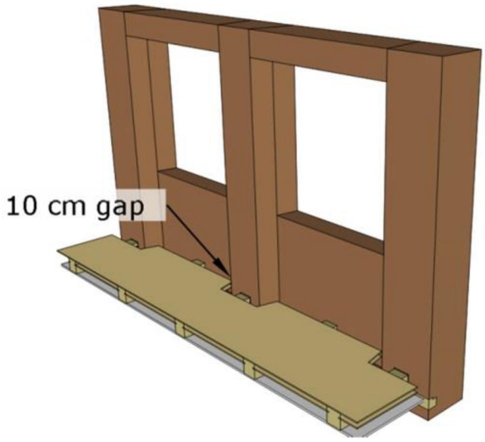
Figure 63: Proposal for solution 2

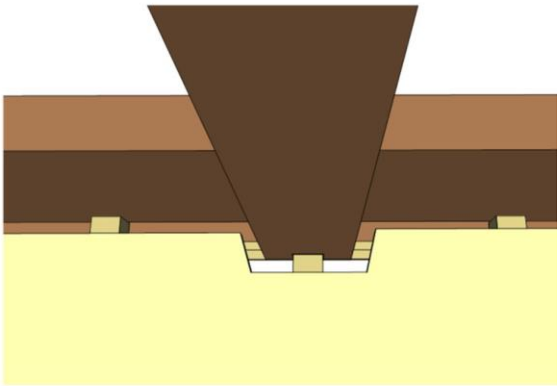
7.3 Step by step – Construction of RetroWall

A step by step on how to build the proposed solution 1 for the RetroWall is provided in this chapter to give a better explanation of the system.

Step 1

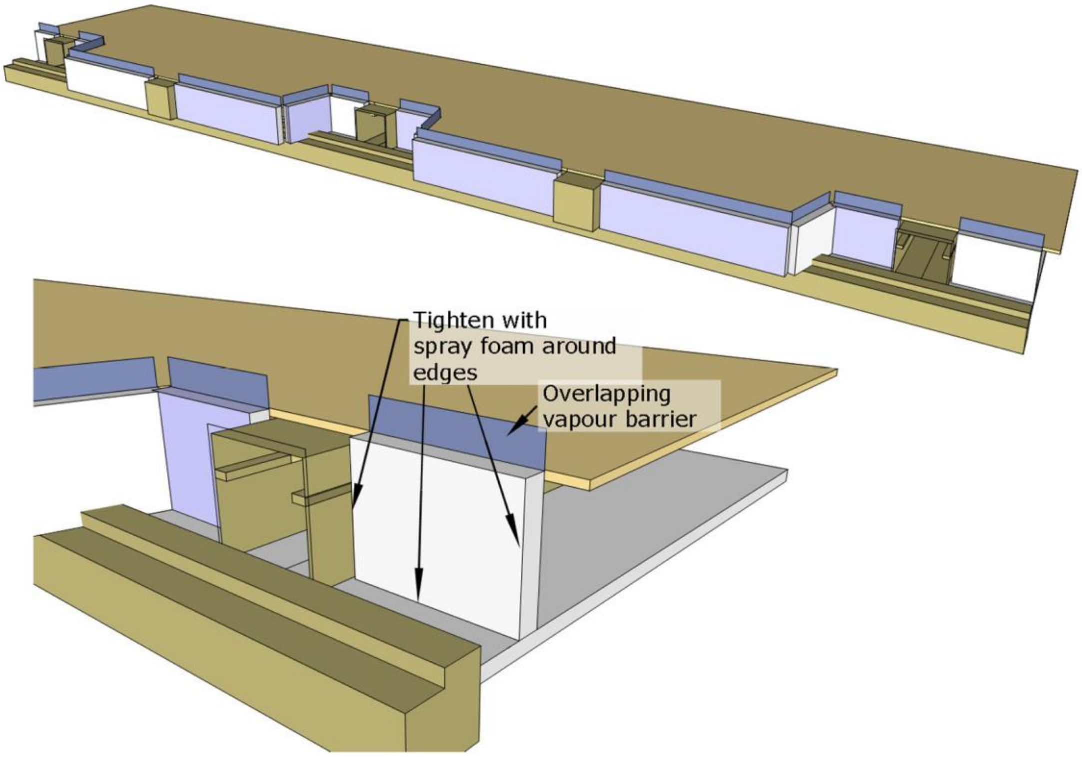
Saw a 10 cm gap off the floor panels along the brick wall with a circular saw





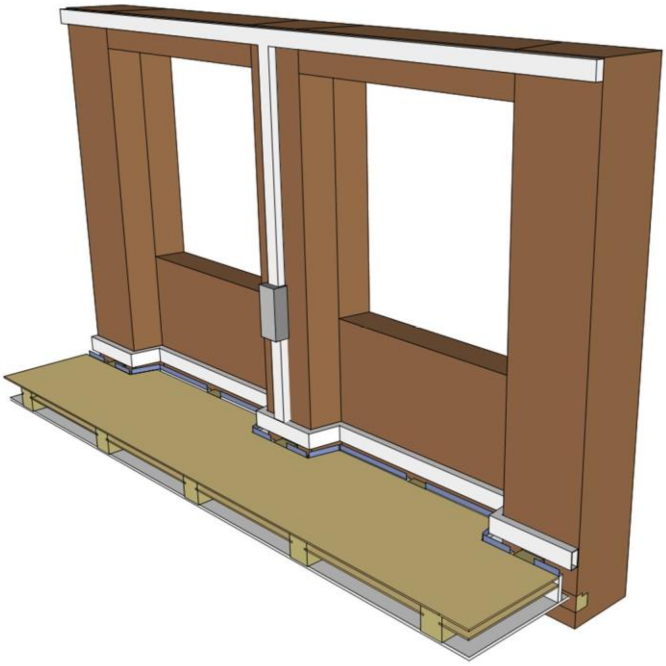
Step 2

Tightening plates fitted between the beams. Tighten edges with spray foam. The vapour barrier sticking up from the edge will overlap the vapour barrier in the wall construction. The plates could either be thick plywood or other material that is easy to cut to fit.



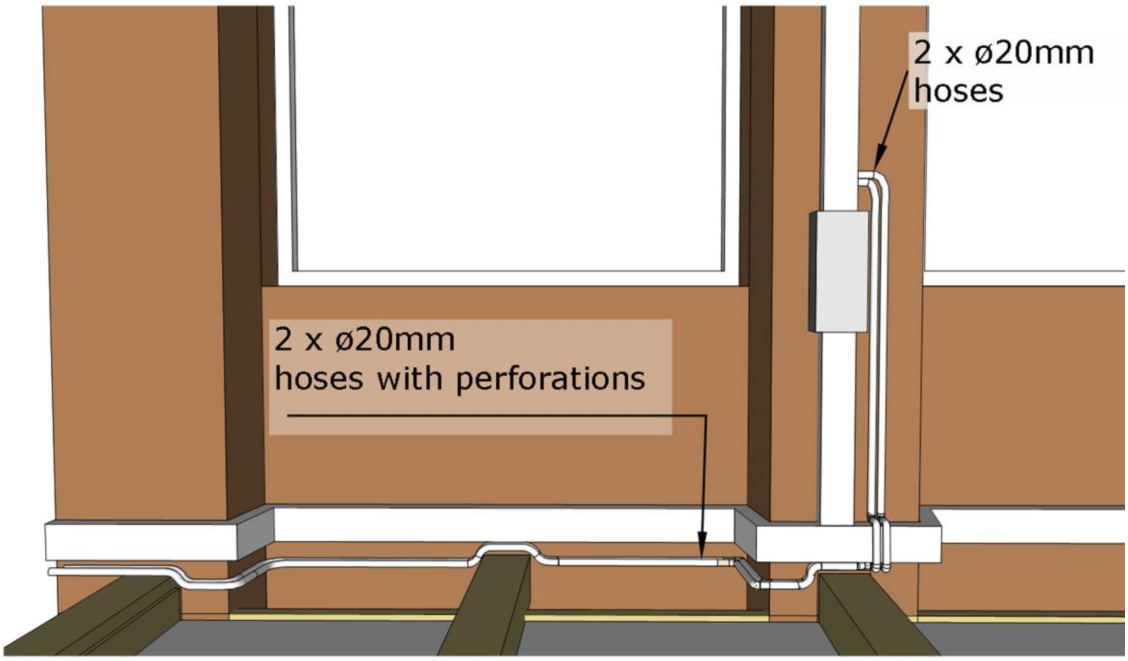
Step 3

Installation of the dehumidifier and standard rectangular pre-perforated ducts (110x54mm)



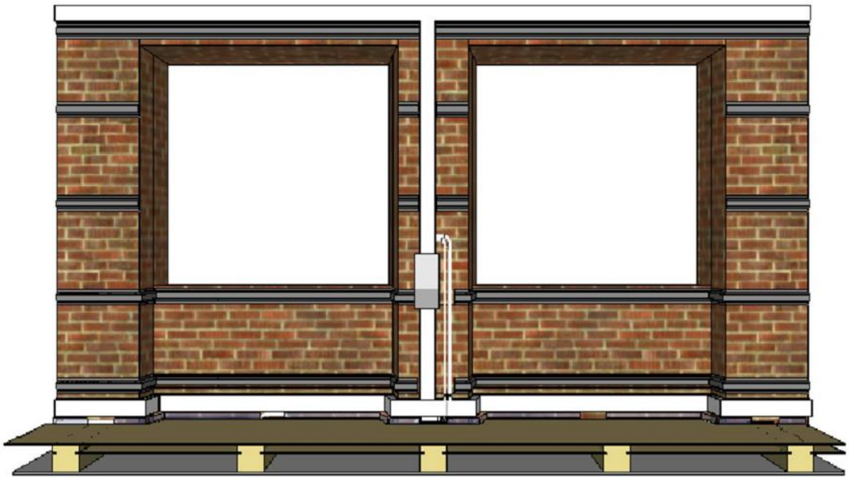
Step 4

Two hoses are connected to the supply duct. Pre-perforated hoses are connected and drawn along the beams underneath the bottom duct.



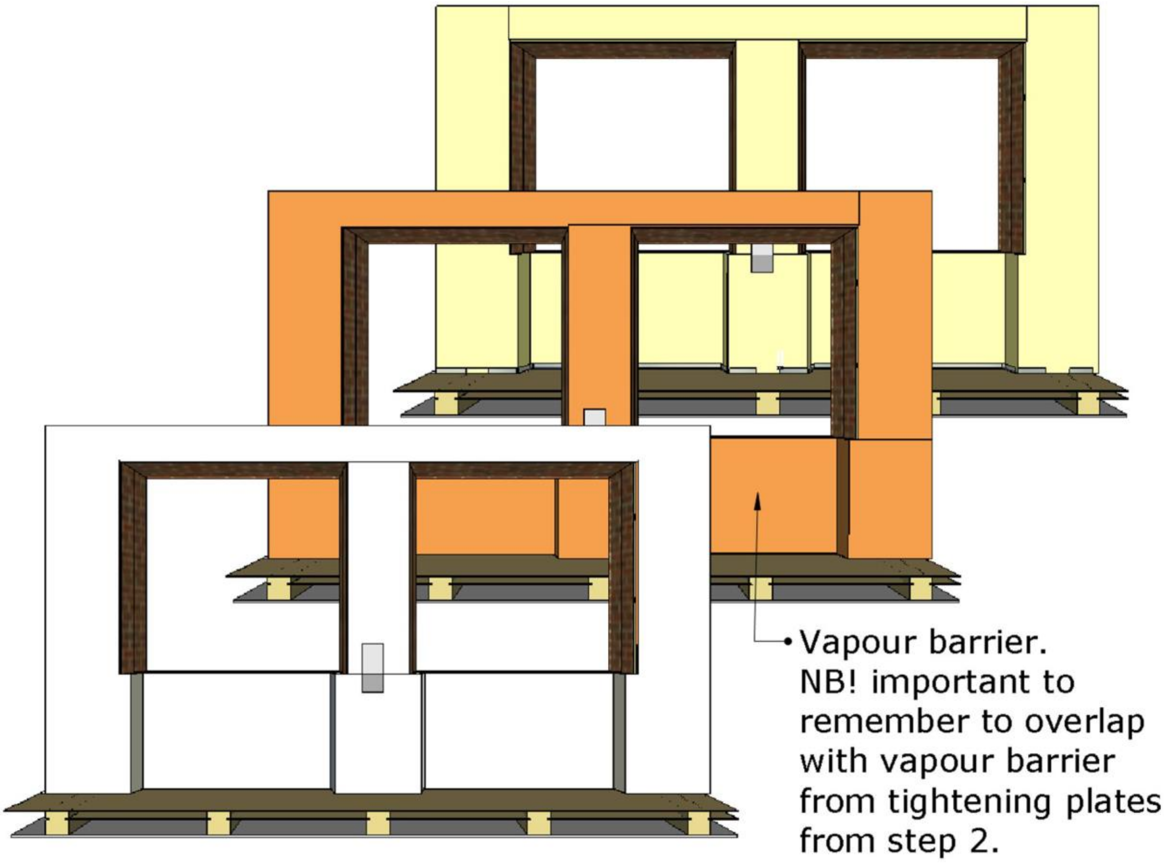
Step 5

Mounting of partition steel profiles along the wall and around windows. 25 mm gap along wall and 15 mm gap around window.



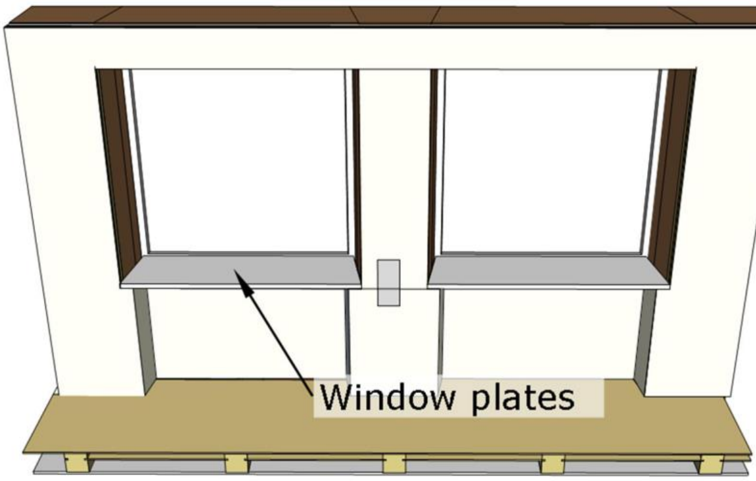
Step 6

Appliance of mineral wool, plywood, vapour barrier and gypsum.



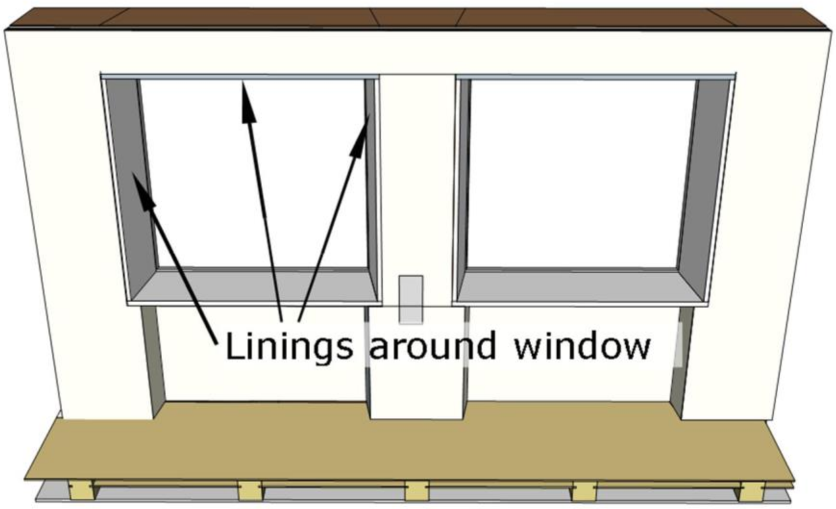
Step 7

Window plates are placed on top of the new wall construction beneath. This will also tighten the vapour barries from the construction beneath.



Step 8

Window linings consist of sandwich elements with insulation and vapour barrier.



8 FUTURE WORK

The results in this report are mostly based on theory, in exception of some measurements conducted related to airflow and pressure drop. Future work will therefore be to investigate the concept in test apartments, which is already planned by Isover. Sensors should be placed at different locations throughout the wall in order to monitor relative humidity, temperature and moisture content in beam ends over time. The monitoring makes it possible to determine critical locations. These critical locations can be the trigger-points controlling the operation time of the dehumidifier.

Moreover, the concept can be optimized by reducing pressure losses in ducting, improving construction method to limit imperfections, as well as to develop solutions for retrofittings of entire apartment buildings.

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10 APPENDICES

Appendix A

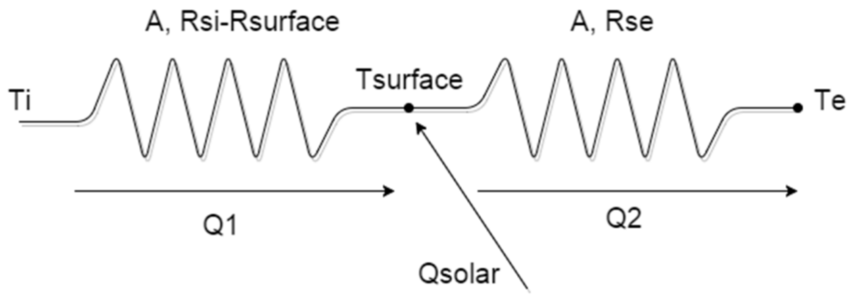
3.2.4 Wetting and drying

The exterior diffusion is calculated using some formulas and assumptions of the surrounding air. A relative humidity of 100% is used a constant boundary for the exterior surface. Furthermore, it is assumed that all global solar radiation strikes the surface.

Assumed conditions when calculating vapour diffusion:

	Interior	**Exterior**
Temperature [°C]	20	0
RH [%]	50	100
Vapour permeability in brick, δ [kg/msPa]	$0.1x10^{-IO}$	

The surface temperature of the brick wall with internal insulation is calculated based on the heat balance with solar radiation: (balance drawn in draw.io)



$$Q1 + Qsolar = Q2$$

$$*\frac{T_i - T_{surface}}{R_{si\text{-}surface}} + Q_{solar} = \quad * \frac{T_{surface} - T_e}{R_{se}}$$

$$T_{surface} = \frac{T_i \frac{A}{R_{si\text{-}surface}} + T_e \frac{A}{R_{se}} + Q_{solar}}{\frac{A}{R_{se}} + \frac{A}{R_{si\text{-}surface}}}$$

Diffusion to the exterior is calculated using the difference between the exterior and surface vapour pressure and the exterior surface diffusion resistance.

$$Z_{surface} = \frac{1}{\beta_{ext}}$$

$$\beta_{ext} = 15x10^{-8}$$

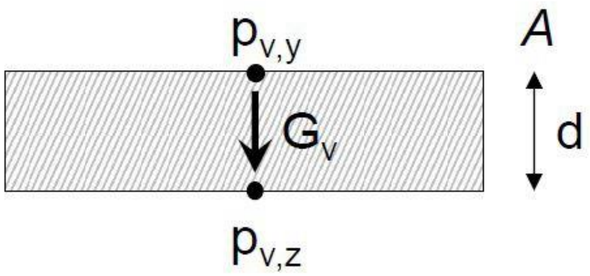
$$Diffusion = \frac{p_{v.surface} - p_{v.e}}{Z_{surface}} * 3600s * 24h$$

Appendix B

5.1.3.4 Moisture removal

Vapour diffusion according to Fick's law

Vapour diffusion into dehumidified air gap in a north oriented wall according to fick's law *[29]. Assuming vapour permeability of historic brick is 0.1E-10 kg/m s Pa.*



Season	d* (m)	Twall/Tgap [°C]	Pv,y/Pv,z [Pa]	Diffusion [kg/m2s]	Diffusion [g/m2h]	Added MC [g/kg]
Winter	0.1	2/3	706/379	3.3E-8	0.12	0.08
Spring	0.1	10/11	1230/656	5.7E-8	0.20	0.14
Summer	0.1	22/20	2643/1169	1.5E-7	0.53	0.37
Fall	0.1	10/11	1230/656	5.7E-8	0.20	0.14

**location of waterfront which is where the brick wall is saturated, collected from simulations*

*** Temperatures at waterfront, and in air gap also collected from simulations*

$$Pv.sat = 288.68(1.098 + \frac{T}{100})^{8.02} \quad \text{Eq. 20}$$

$$pv,y,winter = 288.68(1.098 + \frac{2}{100})^{8.02} = 706\,pa \quad \textbf{Eq. 21}$$

$$pv,z,winter = pv.sat(T=3) * 0.5 = 379\,pa \quad \textbf{Eq. 22}$$

$$G_v, winter = o\frac{pv_y - pv_z}{d} = 3.3E-8 \frac{kg}{m2s} \quad \textbf{Eq. 23}$$

Added moisture content to the airflow of 1.2m3/m2h due to the vapour diffusion is then calculated by dividing the vapour diffusion by the air flow multiplied by the density of air; thus the added moisture content during winter will be 0.08 g/kg.

$$MC.winter = \frac{0.12}{1.2 * 1.2} = 0.08 \frac{g_{water}}{kg_{air}} \quad \text{Eq. 24}$$

The saturated vapour pressure at the waterfront in the brick wall is calculated by xxx. The vapour pressure in the airgap is calculated by multiplying the saturated vapour pressure by 0.5 which represent 50% relative humidity, meaning it is only 50% saturated.

The vapour diffusion can hence be calculated by fick's law of diffusion (eqxxx) using the the *force in vapour pressure difference and distance from waterfront to the air gap.*

5.2.3 Balanced pressure drop

Pressure drop are calculated according to the textbook "Ventilasjonsteknikk" [28].

For a 5 meter long and 2.7 meter high wall, a flow of 16m³/h is required to obtain the necessary flow of 1.2m³/m²h. The ducting consists of rectangular plastic ducts with the dimensions [a x b] 110x54mm. The perforations in the ducts above and below the window are 7mm in diameter every 50mm of duct and ads up to 100 holes.

Air flow rate per hour	$\dot{V}$	**16**	**[m³/h]**
Air flow rate per sec	$\dot{V}$	0.00445	[m³/s]
Air flow per hole	$\dot{V}_{hole}$	0.0000445	[m³/s]
Area of duct	$_{duct}$	0.005	[m²]
Area perforations	$_{perf}$	0.0000384	[m²]

Velocity duct	v	0.89	[m/s]
Velocity hole	v_{hole}	1.16	[m/s]
Kinematic viscosity (20°C)	v_k	15x10-6	[m^2/s]
Air density	p_{air}	1.2	[kg/m^3]

Friction loss

Friction loss will occur everywhere in the wall, and is calculated the following way. The friction factor depends on the Reynolds number, meaning whether it is laminar or turbulent flow.

$$Re = \frac{v * D_h}{V_k}$$ Eq. 25

$$D_h = \frac{2 * a *}{a *}$$ **Eq. 26**

Re < 2300 $$A = \frac{64}{Re}$$ **Eq. 27**

Re > 2300 $$\frac{1}{\sqrt{A}} = 2.0 log * \frac{Re * \sqrt{A}}{2.51}$$ **Eq. 28**

$$\Delta pf = L * A * \frac{p_{air} * v^2}{D^h * 2}$$ **Eq. 29**

When the flow is laminar (Re < 2300), Darcy Eq. 27 is used to find the friction factor. When the flow is turbulent (Re > 2300), Colebrook white Eq. 28 is used by iteration to find the friction factor. The hydraulic diameter for a rectangular duct is found using Eq. 26.

The total friction loss in Pa can then be calculated by Eq. 29, and summed up.

Dynamic loss

Dynamic loss will happen where the flow is disturbed at bends or through perforations.

E.g. the dynamic pressure loss though the perforated holes in the rectangular duct is calculated the following way: in all calculations with perforated holes the single loss factor of 1.81 is used. $(= 1.81$

$$\Delta pd = \{ * \frac{_{air} * v_{hole}^2}{2}$$ **Eq. 30**

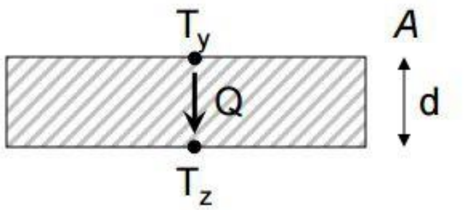
5.3.3 Operation time

The energy saving potential of 1300kWh is an estimate calculated with seasonal situations:

Winter (Dec-Feb)	**Te=0°C**
Spring (Mar-May)	Te=10°C
Summer (June-Aug)	Te=15°C
Autumn (Sept-Nov)	Te=10°C

The heat transfer through the exterior facade depends on the thermal resistance of the façade material. For an uninsulated wall the thermal resistance of a 360mm thick brick wall with 20mm lime plaster is 0.594 m²K/W, and 2.03m²K/W for an insulated wall with 50mm mineral wool.

The heat loss though the wall is determined using the fourier's law of conduction [30].



$$Q = A * \frac{T_y - T_z}{R}$$ Eq. 31

$$R = \frac{d}{A}$$ **Eq. 32**

An uninsulated wall has the following properties and thermal resistance:

	d [m]	**λ [W/mK]**	**R [m²K/W]**
Internal surface			0.13
Lime plaster	0.02	0.82	0.4
Brick	0.36	0.87	0.024
External surface			0.04
Total			0.594

An insulated wall has the following properties and thermal resistance:

	d [m]	λ [W/mK]	R [m^2K/W]
Internal surface			0.130
Gypsum	0.013	0.2	0.065
Plywood	0.016	0.13	0.12
Mineral wool	0.05	0.04	1.25
Lime plaster	0.02	0.82	0.4
Brick	0.36	0.87	0.024
External surface			0.04
Total			2.03

The estimated annual heat loss in kWh through a 5x2.7m large wall:

	Uninsulated wall	Insulated wall
Winter	983	288
Spring	491	144
Summer	245	72
Fall	491	144
Total heat loss	2210	650

The estimated potential energy saving is thus around 1500 kWh annually.

Annex 2

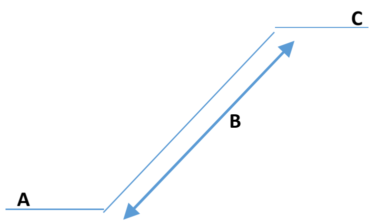
Aars 2016

Luftmængderegulering

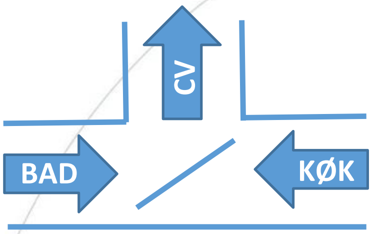
Iht. arbejdsbeskrivelsen ønskes nedestående luftmængderegulering.

<u>Normaldrift</u>

Tidsskema aktiv 24 timer med grundventilation (A), overstyring af luftmængde fra minimum til maksimum efter behov iht. den absolut fugtighed (B). Under hele denne proces vil tre-vejsspjældet være positioneret som på figur. 3 størst lufttilstrømning til badeværelset.



Figur 1 – Luftmængdestyring iht. Tabel 1.



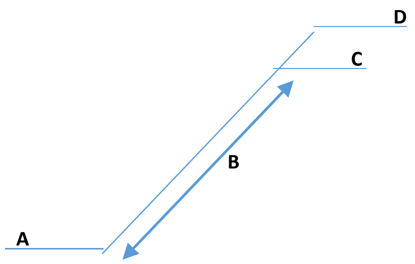
Figur 2 – Indstilling af tre-vejsspjæld ved luftmængdestyring som på figur 1.

Punkt		Luftmængde	Voltindstilling
A	Grundventilation	f.eks. 75 m³/h - (0,3 l/s pr. m² etageareal)	Min volt
B	Fugtstyring (selvregulering)	f.eks. 75-126 m³/h	Min volt – Max volt

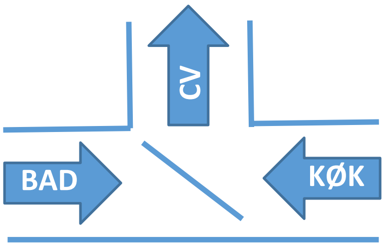
Tabel 1

<u>Boost drift</u>

Ved tryk på kontakt 2 – boost drift (D), øges luftmængde yderligere til ønsket maksimum (boost). Boost funktionen anvender selvvalgt voltindstillinger forskellige fra maksimum voltindstilling til forceret drift (C). Ved denne proces vil tre-vejsspjældet være positioneret som på figur. 4 størst luftttilstrømning til køkkenet.



Figur 3 – Luftmængdestyring iht. Tabel 2.



Figur 4 – Indstilling af tre-vejsspjæld ved overstyring af boost drift, punkt D.

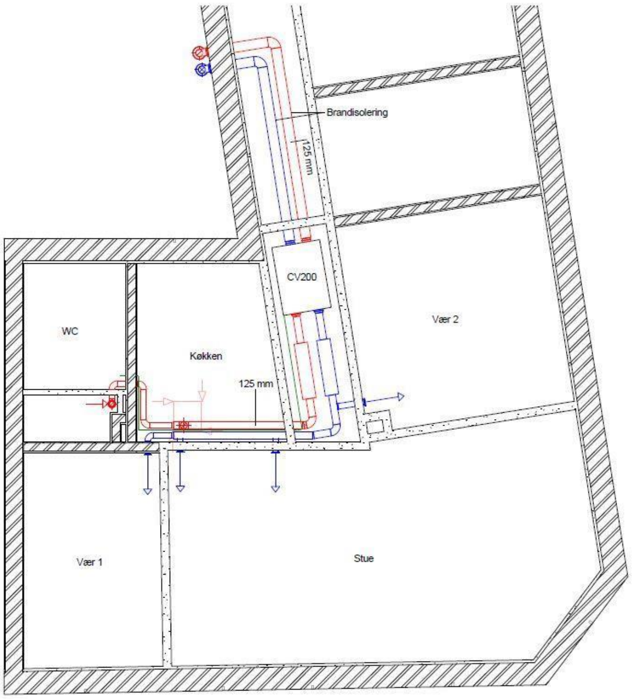
Punkt		Luftmængde	Voltindstilling
A	Grundventilation	f.eks. 75 m³/h - (0,3 l/s pr. m² etageareal)	Min volt
B	Fugtstyring (selvregulering)	f.eks. 75-126 m³/h	Min volt – Max volt
C	Boost drift	f.eks. 198 m³/h (144 + 54 m³/h)	Max volt

Tabel 2

Annex 3

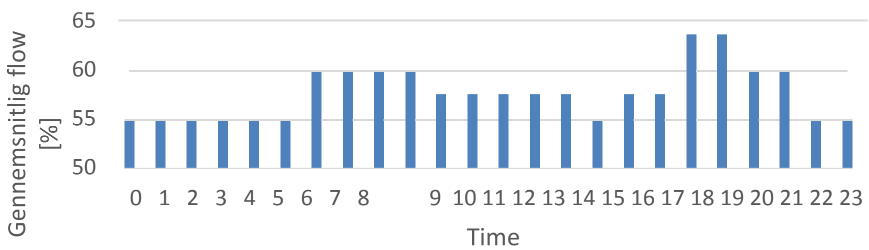
Elforbrug fra decentralt ventilationsaggregat af type CV200C

Dette notat undersøger energiforbruget fra et decentralt ventilationsaggregat af typen CV200C fra Airmaster. Aggregatet forsyner en enkelt lejlighed på Meinungsgade 1 i København. En plantegning af lejligheden med kanalføring fremgår af figur 1, hvor aggregatet er placeret over nedhængt loft i entréen, og indtag/afkast føres ud igennem ydervæggen.



Figur 1: Plantegning med kanalføring af lejligheden.

Til beregning af energiforbruget er der anvendt målinger fra Airmaster, der viser en døgnprofil med gennemsnitsluftmængder en måleperiode. Døgnprofilen fremgår af figur 2.



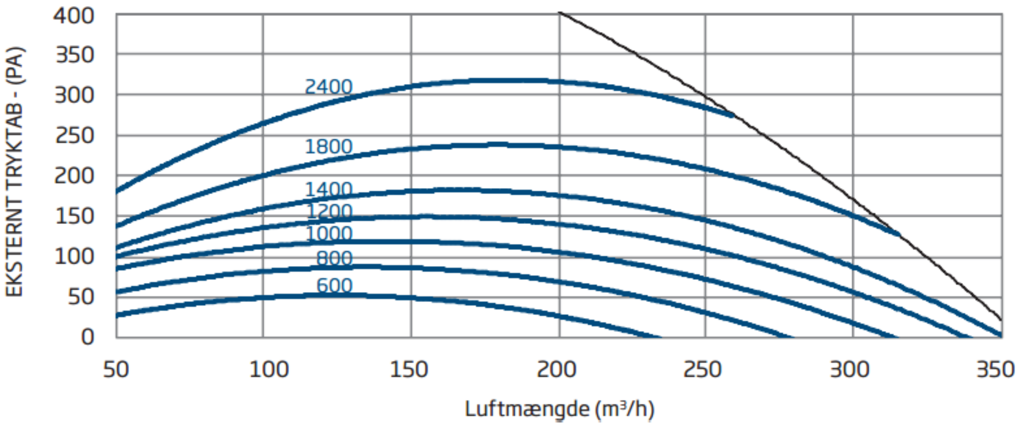
Figur 2: døgnprofil for drift af CV200 på Meinungsgade 1. [Kilde: Airmaster]

Målingerne er fra et CV200 på en anden lejlighed på Meinungsgade 1 og viser luftmængde m.m. for hvert målepunkt, som er placeret med et interval på 8 minutter. En CV200 fra Airmaster har to funktioner, som er beskrevet herunder:

1) Grundventilation – 126 m³/h til- og fraluft. Luftmængden kan øges ved overstyring via fugtstyring. (Udsug 15+ l/s i badeværelse og 20 l/s i køkken)
2) Boost – 250m³/h til- og fraluft. (Udsug 15 l/s i badeværelse og 54,4 l/s i køkken)

Anlægget er indstillet til ventilere med grundventilation som udgangspunkt og øge luftmængden op til 187 m³/h ved overstyring via fugtstyring. Boost funktionen aktiveres ved brug af emhætten hvorved der kun kan udsuges 15 l/s i badeværelset.

SEL-værdien er aflæst af figur 3 og afhænger af luftmængden samt det eksterne tryktab. Det eksterne tryktab i kanalerne er udregnet med MagiCAD. De aflæste værdier fremgår af tabel 1 og er reduceret med 5%, da der anvendes type C af CV200-serien, som har indtag/afkast i enden af aggregatet. Der er udført en parametervariation på størrelsen af kanalerne for at undersøge, om det er økonomisk rentabelt at reducere størrelsen på fordelerkanalerne fra ø125 til ø100.



Figur 3: SEL-værdier for et CV200 anlæg. (For type C skal SEL-værdien reduceres med 5%) [Kilde: Airmaster]

Drift	Luftmængde [m³/h]	125/100 Eksternt tryktab [Pa]	125/100 SEL [J/m³]	100/100 Eksternt tryktab [Pa]	100/100 SEL [J/m³]
Grundventilation	126	52	570	94	855
Boost funktion	250	177	1520	386	2280

Tabel 1: Tryktab og SEL-værdier.

De fundne SEL-værdier regnes om til elforbrug ved at gange med luftmængden for hver måling hvorefter det omregnes til kWh. Resultatet fremgår af tabel 2 for måleperioden. Det årlige elforbrug er udregnet på baggrund af den antagelse af resten af året følger fordelingen i måleperioden.

Elforbrug	Elforbrug [kWh] 125/100	Elforbrug [kWh] 100/100
Elforbrug over måleperiode	15,2	22,9
Årligt elforbrug	217,2	327,1

Tabel 2: Elforbrug fra ventilationsanlægget

Annex 4

Tilbudsbeskrivelse

Hermed følger en nærmere beskrivelse af den til Meinungsgade foreslåede løsning.

Bolig

I Bygningsreglement 2015 forefindes lovkravene til ventilation i beboelsesbygninger omhandlende luftmængde, ventilationsanlægs energimæssige ydelse samt støjniveau fra tekniske installationer. Bygningsreglementets krav til luftmængde i opholdsrum såvel som boligen totalt skal ventileres med minimum 0,3 l/s pr. m². Samtidig skal der kunne udsuges op til 20 l/s fra køkken, 15 l/s fra bade- og wc-rum samt op til 10 l/s fra eksempelvis særskilt wc-rum eller bryggers.

I forhold til ventilationsanlægs energimæssige ydelse der forsyner én bolig er der krav om, at det specifikke elforbrug til lufttransport (SEL) for anlæg med konstant eller variabel luftydelse og varmegenvinding ikke må overstige 1.000 W/(m³/s), samt at temperaturvirkningsgraden som minimum skal være 80 %. Støj fra et ventilationsanlæg må ikke overstige 30 dB(A) i opholdsrum.

Den tilbudte løsning

Løsning på 3 sal består af 1 stk. CityVent 200. Anlægget skal behovsstyres ved hjælp af fugtighed og overstyring via betjeningspanel, og kan overstyres via Airlinq BMS. Dette anlæg er monteret med et 3 vejs-spjæld for bedre at kunne flytte udsugningen til de ønsket steder i huset. (Se vedhæftet)
Der ud over er der på dette anlæg lukke spjæld og varmeflade.
Den samlede luftmængde for den enkelte bolig er dimensioneret for 126/198 m³/h, svarende til BR10 krav.
Der er ved Boost funktion ca. 144 m*³/h I emhætte og 54 m³/h I bad.*
Løsningen på 4 sal består af 1 stk. CityVent 200. Anlægget skal behovsstyres ved hjælp af fugtighed og overstyring via betjeningspanel. (Her har vi mulighed for på sigt at eftermontere et Online modul men dette vil kræve et internet forbindelse.) Dette anlæg er monteret uden et 3 vejs-spjæld, elvarmeflader samt lukke spjæld. Der er ingen indreguleringsrapport men der skulle være ca. 144 m³/h i emhætten og XX i bad. Ved boost funktion.
Den samlede luftmængde for den enkelte bolig er dimensioneret for 126/198 m³/h, svarende til BR10 krav.

Særlige forhold

Vi tager forbehold for uforudsete forhold der kan forstyrre lufttilførslen eksempelvis uhensigtsmæssig placering af indblæsning og udsugning, ligesom det forudsættes, at der er tilstrækkelig opvarmning i lejligheden fra varmeanlæg.

Anlægsbeskrivelse

Airmasters decentrale ventilationsanlæg er konstrueret med komponenter af højeste kvalitet, hvilket er med til at sikre en lang levetid. Ved at benytte nogle af markedets mest energieffektive og pålidelige komponenter fås en støjsvag ventilationsløsning, som samtidig sikrer en høj varmegenvinding og et minimalt energiforbrug.

Decentrale ventilationsanlæg fra Airmaster har som standard en trinløs regulering af luftmængden, hvilket giver en optimal behovsstyring. Der er som standard mulighed for tilslutning af interne eller eksterne sensorer, samt mulighed for sammenkobling og styring af flere ventilationsanlæg fra ét eller flere betjeningspaneler.
Med Airmasters decentrale ventilationsanlæg fås en fleksibel og fremtidssikret ventilationsløsning, som kan tilpasses ethvert behov.

Montage

Anlæggets positionering udføres enten således, at der er direkte adgang til servicelemmen eller således, at der udføres en servicelem under anlægget, mindst i anlæggets størrelse. Der skal ligeledes sikres adgang til komponenter, el-tilslutning og kondensafledning fra anlægget. På baggrund af ventilationsanlæggets position i lokalet foretages en opmærkning af gennembrydninger af konstruktionsdele for ventilationskanalerne. Hullerne bores og der monteres vinkelbeslag på de respektive konstruktioner. Ventilationsanlægget fastgøres til vinkelbeslag. Ventilationskanaler til indtag og afkast tilsluttes, alle gennembrydninger tætnes, funktionslag i væggen/loftet (f.eks. dampspærre) genoprettes, således, at de er fuldt funktionsdygtige, og kanaler kondensisoleres. Lyddæmpere på kanalføringerne monteres lige efter anlægget på alle kanalerne. En eventuel vandvarmeflade tilsluttes varmesystemet, og der foretages en elektrisk tilslutning af ventilationsanlæg, betjeningspanel, eksterne sensorer etc. Kondensafløb fra kondenspumpen eller direkte fra kondensbakken kobles til et spildevandsrør. Der udføres en funktionstest, og der foretages en programmering af ventilationsanlæggets drift i henhold til kundens ønsker.

Styring - Betjening

Orbit betjeningspanel

Som betjeningspanel foreslås Airlinq Orbit. Airlinq Orbit er for brugere der har lidt mere avancerede ønsker til selv at kunne foretage indstilling og programmering fra et betjeningspanel. Med Airlinq Orbit er det muligt at styre anlægget med eksempelvis start/stop, tidsstyring, luftmængde eller indblæsningstemperatur, aktivering af tidsbegrænset datalogning etc., ligesom det er muligt at foretage programmering af anlæggets væsentligste driftsparametre. Det er muligt at koble et Airlinq User Tool fra sin PC op på et Airlinq Orbit betjeningspanel, hvis man ønsker betjening via sin PC.

Viva betjeningspanel

Som betjeningspanel foreslås Airlinq Viva. Airlinq Viva er for brugere der ønsker en let og enkel tilgang til regulering af luftmængde, og som ikke har de store reguleringsbehov derudover. På Airlinq Viva er der tillige mulighed for at starte/stoppe anlæg og eksempelvis indstille feriemode. Det er også muligt at koble et Airlinq User Tool fra sin PC op på et Airlinq Viva betjeningspanel, og her igennem foretage en mere avanceret indstilling.

Styring med Airlinq Orbit i et Airlinq BMS system

I et Airlinq Building Management System (Airlinq BMS) er det muligt at betjene og overvåge op til 20 forskellige ventilationsanlæg ved hjælp af ét Airlinq Orbit betjeningspanel. Med Airlinq Orbit er det muligt at betjene anlæggene individuelt eller gruppevis med eksempelvis start/stop, tidsstyring, luftmængde eller indblæsningstemperatur, aktivering af tidsbegrænset datalogning etc. For hvert enkelt anlæg er det muligt at udlæse status for bl.a. målt CO_2-koncentration, temperaturer, luftmængder, driftstid, prognose for filterskifte etc. Ved hjælp af et Airlinq Orbit betjeningspanel er det derved muligt at betjene og overvåge flere ventilationsanlæg fra ét centralt sted, uden at anlæggene skal integreres i et større digitalt Building Management System (Digitalt-BMS).

Styring – Behovsstyring

Som standard har et Airmaster decentralt ventilationsanlæg indbygget temperaturfølere til registrering af rummets temperatur og tilluftstemperatur. Det modulerende bypassspjæld benyttes til regulering af tilluftstemperaturen såfremt denne overstiger setpunktet. Styringen tager desuden højde for, at indblæsningstemperaturen ikke kan overskride rumtemperaturen med risiko for, at ventilationsanlægget overtager opvarmningen af rummet.

Styring med elektroniske fugtsensorer

Formålet med behovsstyret ventilation er at regulere ventilationsanlæggets ydelse i forhold til det aktuelle behov. Forskning har vist, at det er hensigtsmæssigt at benytte fugt som indikator for indeklimaet i boliger. Tilstedeværelsen af personer, og mange menneskelige aktiviteter i boliger er knyttet til produktion af fugt, f.eks. bad, madlavning, rengøring, tøjvask etc.
Ved hjælp af to indbyggede elektroniske fugtsensorer er det muligt for ventilationsanlægget at regulere luftmængden efter forskellen mellem udendørs og indendørs fugtindhold i luften, dvs. forskellen i absolut fugtighed. Med denne unikke styringsfunktion fra Airmaster opnås en optimal behovsstyret ventilation, hvor det samtidigt kan undgås at overventilere boligen i perioder, hvor udeluften i forvejen har et højt fugtindhold.

Boost funktion

Formålet med boost funktion er forcering af ventilationen ved aktivering af emhætte til en maksimal ønsket luftmængde, fastlagt ud fra tryktab og lydkrav. For at denne funktion kan benyttes skal emhætten være udstyret med et potentialfri relæ og med et så lavt tryktab som muligt. På grund af anlæggets maksimale ydelse anbefales dette kun til boliger med en nødvendig luftmængde på 126 m^3/h, svarende til et køkken og et baderum / wc-rum, jf. BR10.

Kontaktfunktion

Formålet med kontaktfunktion er forcering af ventilationen ved aktivering af en kontakt til en maksimal ønsket luftmængde, fastlagt ud fra tryktab og lydkrav. For at denne funktion kan benyttes skal det være en momentar kontakt til små-signal elektronik, som enten er guldbelagt eller sølvbelagt og forseglet således der ikke kommer ilt dertil.

Styring af varmeflade

- Ved eftervarmeflade med virtuel forvarmefunktion er det muligt at programmere hvorledes den virtuelle varmeflade skal anvendes. Således det er frit om varmefladen ønskes anvendt udelukkende som eftervarmeflade eller som eftervarmeflade med virtuel forvarmefunktion.
    - Hvis eftervarmeflade med virtuel forvarmefunktion anvendes, er det muligt at vælge hvorledes denne funktion skal styres ift. 'comfort mode' (anlægget aktiverer først varmefladen og derefter reducere luftmængden hvis nødvendigt) eller 'green mode' (anlægget reducerer først luftmængden og derefter aktivere varmefladen hvis nødvendigt, med henblik på lavere energiforbrug).

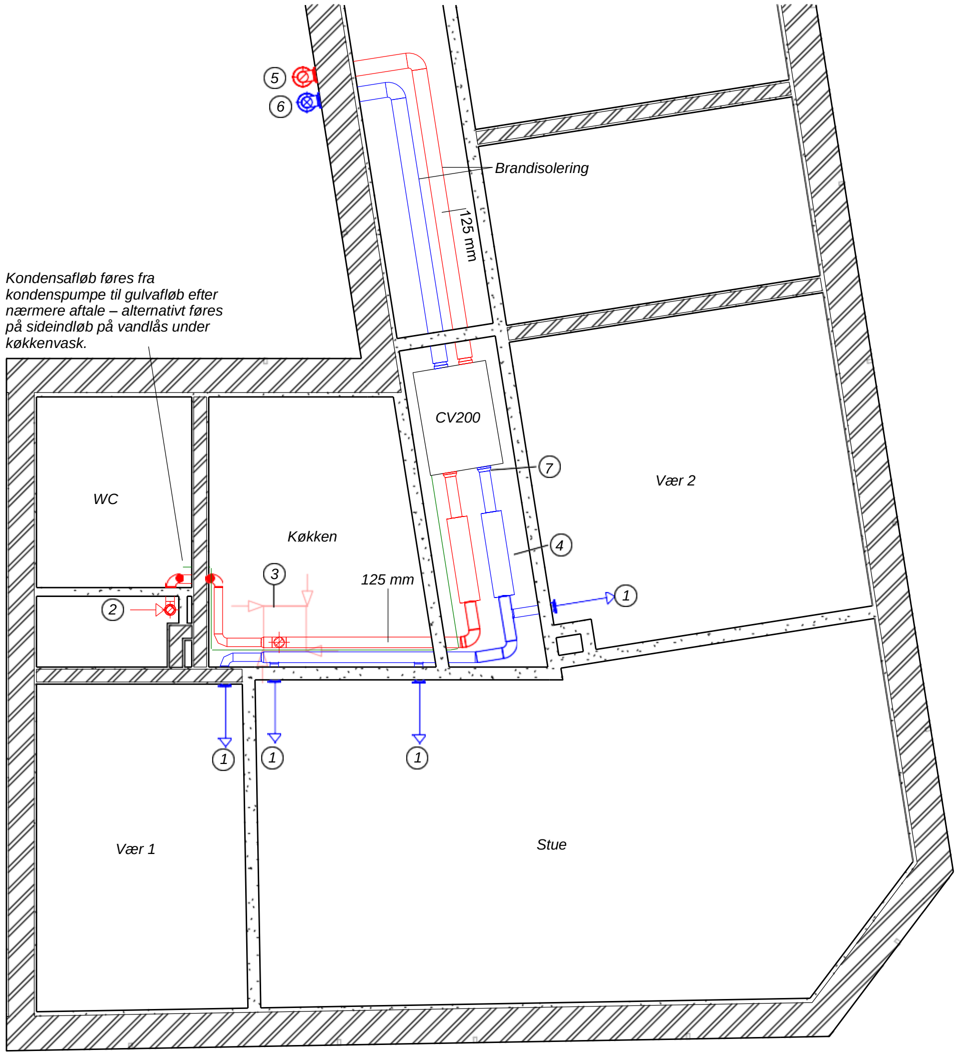
Ventilation in balance®

Vi håber, at det fremsendte tilbud har Deres interesse, og vi står naturligvis til rådighed for yderligere rådgivning.

Med venlig hilsen
Airmaster A/S

Tel. +45 98 62 48 22
Fax. +45 98 62 57 77
info@airmaster.dk

Annex 5



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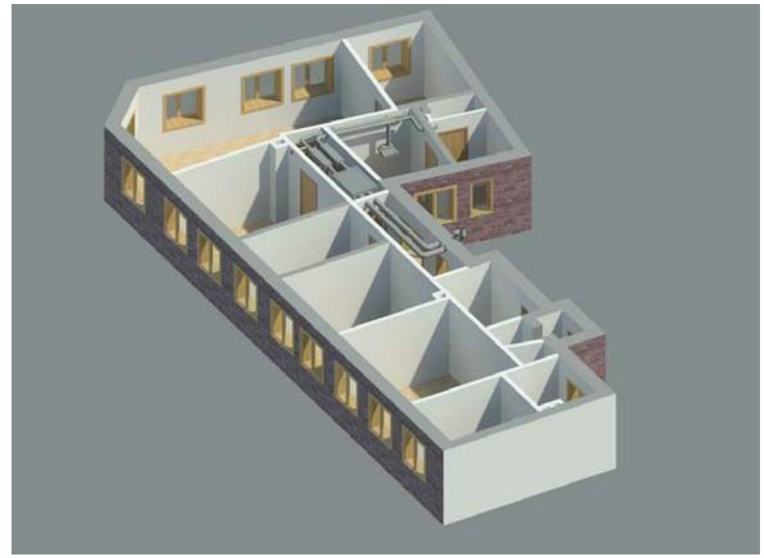
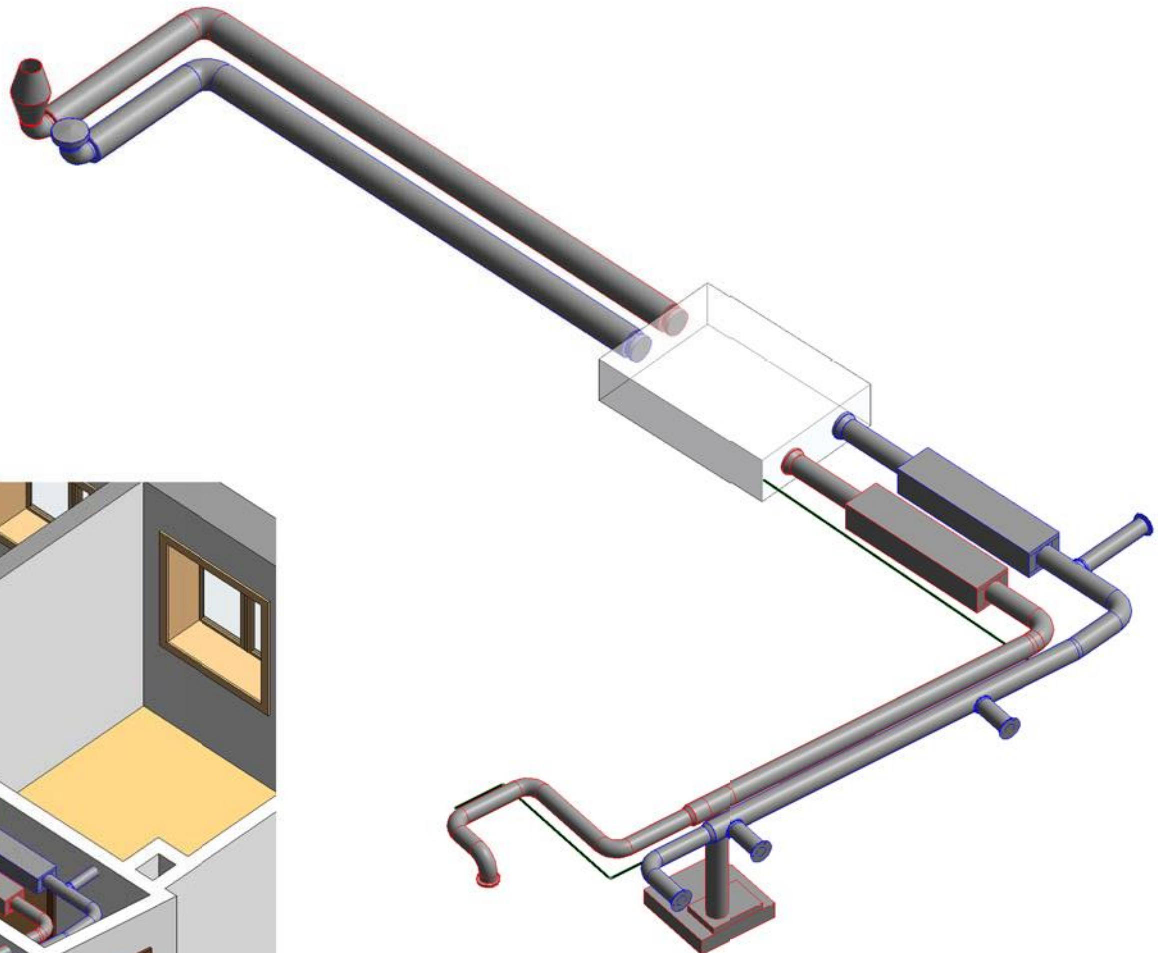


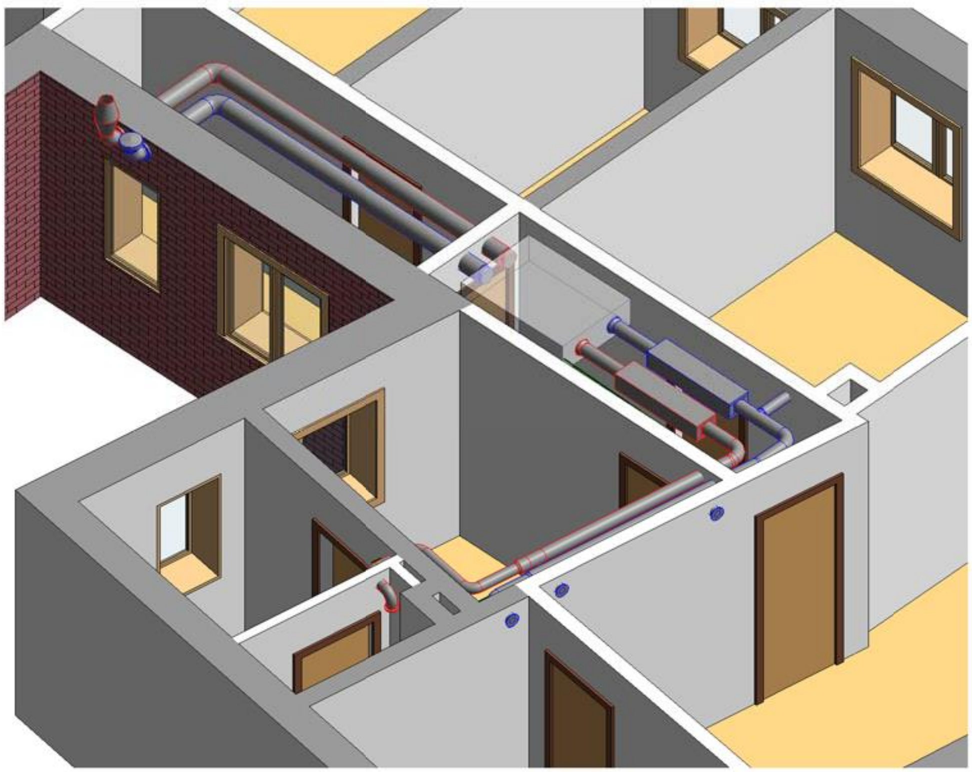
1. Lindab Airy - Ø100 - 31.5 m³/h - Placering under hensyntagen til eksisterende stuk
2. Neotherm Hygro - Ø100 - 54 m³/h
3. Thermex Airgrip - Ø125 - 72 m³/h - Eksakt placering indmåles
4. Lindab LRCA - Ø125
5. Lindab HN - Ø125 - 126 m³/h
6. Øland KH - Ø125 - 126 m³/h
7. Lindab RCU - Ø160-Ø125

Meinungsgade 1 - 4. sal	*Tegn. nr.:* 01
Titel: Plantegning m. ventilation	*Dato:* 06/02/15
Sidenr:	*Skala:* As indicated
Sag.nr.: 93610 Energirigtig komfort	*Udført af:* RH
Rev.: *Rev. dato:*	*KS af:*

Ekolab Aps
Vestergade 48H, 2.tv.
8000 Aarhus C
Tlf: 8613 2016

ekolab





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Titel: Kanalføring			*Dato:* 06/02/15
Sidenr:			*Skala:*
Sag.nr.: 93610 Energirigtig komfort			*Udført af:* RH
Rev.:	*Rev. dato:*		*KS af:*

Ekolab Aps
Vestergade 48H, 2.tv.
8000 Aarhus C
Tlf: 8613 2016

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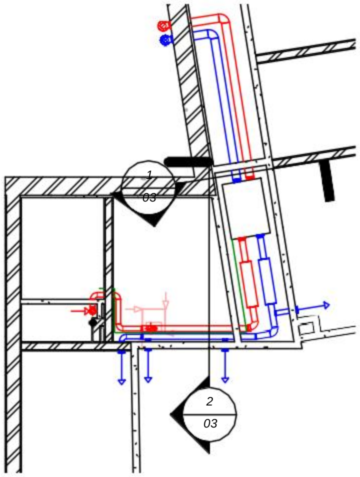

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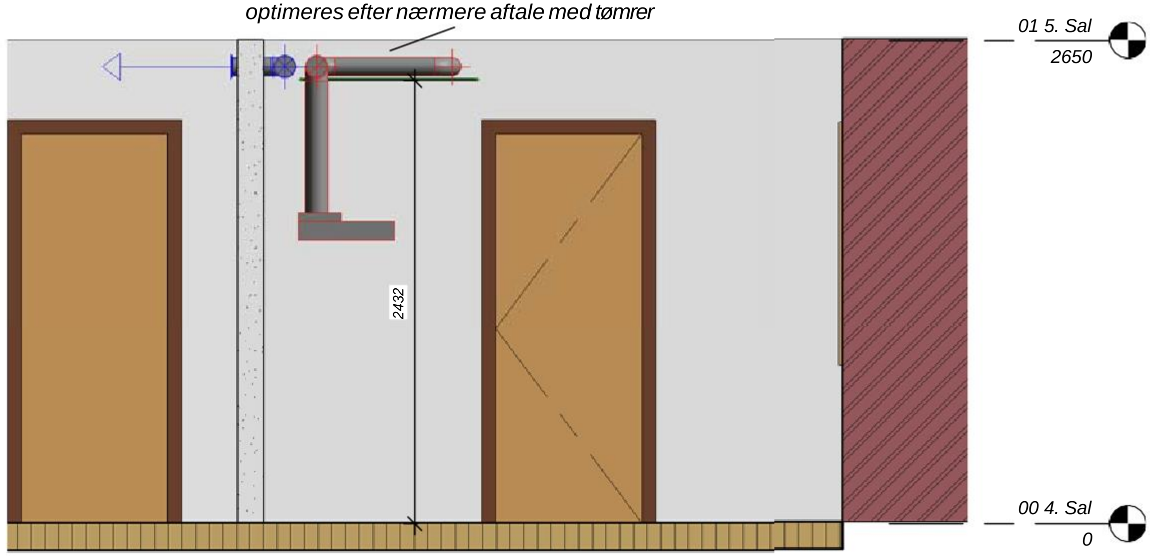
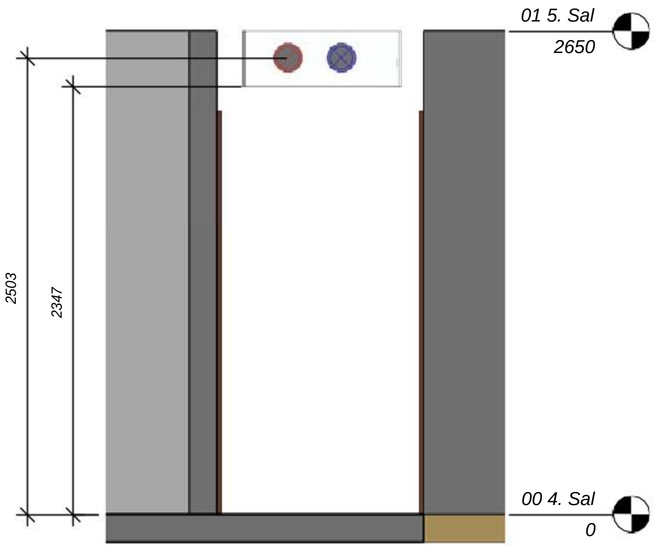


Snit 2 - 1:25



Snit 1 - 1:25

Meinungsgade 1 - 4. sal	Tegn. nr.: 03
Titel: Snittegninger	Dato: 06/02/15
Sidenr:	Skala: As indicated
Sag.nr.: 93610 Energirigtig komfort	Udført af: RH
Rev.: Rev. dato:	KS af:

Ekolab Aps
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