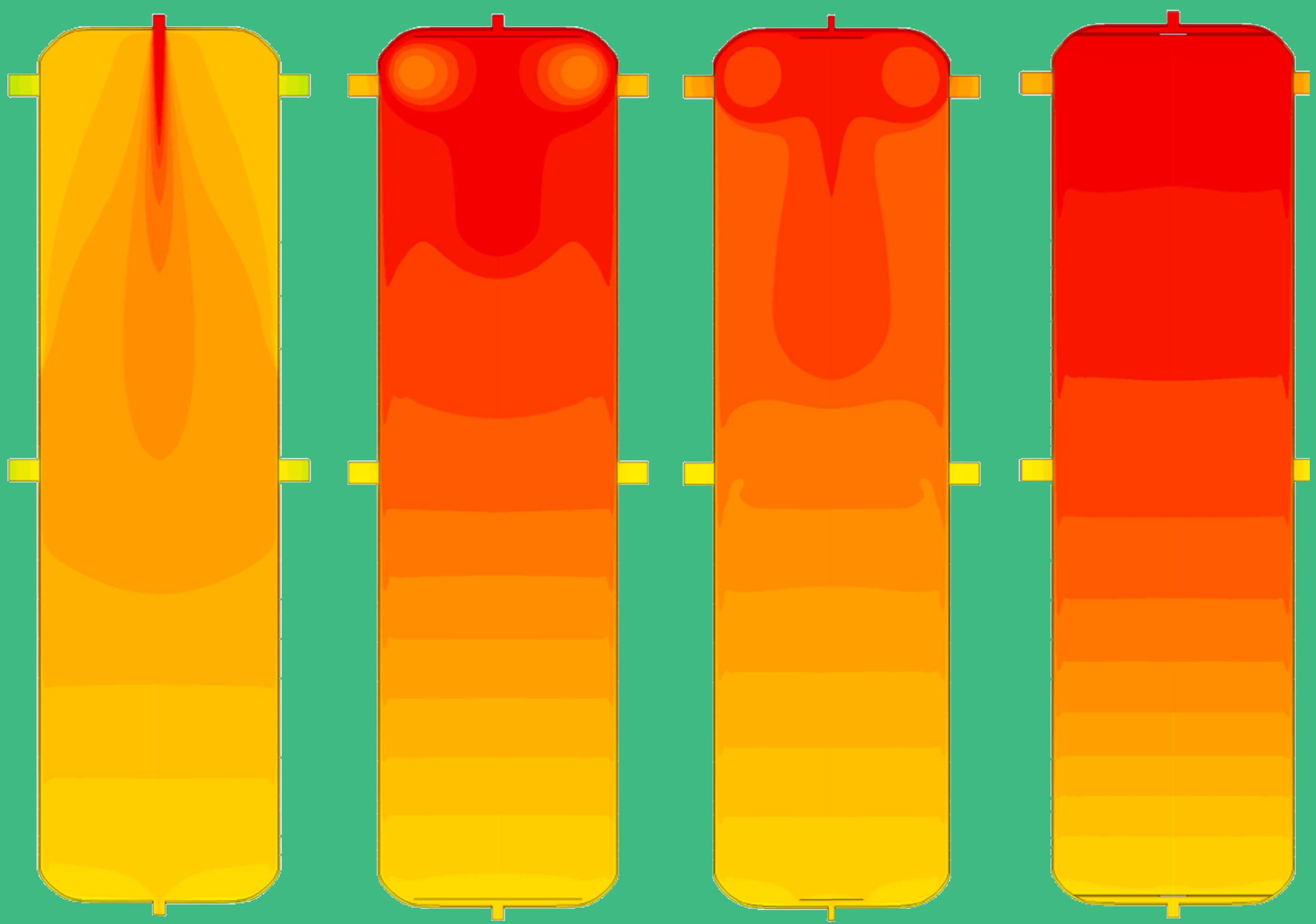
DTU Civil Engineering
March 2020
R-432

Effect of tank design on COP

Highly Efficient and Simplified Thermodynamic Cycle with Isolated Heating and Cooling - Cost Optimized (ISECOP)

Ioannis Sifnaios
Simon Furbo



Contents

Introduction 1

Methodology 2

Small tanks hot side 4

Small tanks cold side 15

Large tanks hot side (the cold side was not investigated) 20

Appendix A - Design Guidelines 24

Introduction

This investigation was done as part of the ISECOP project (Energiforskning grand number: 64017-05102), where a heat pump was used for heating and cooling two storage tanks simultaneously, as it is presented in Figure 1. The part of the system investigated using Computational fluid Dynamics (CFD) is the one marked with a red square in Figure 1. In order to make the modelling easier, the hot and the cold side of the heat pump were individually simulated, following the same methodology presented below. The objective of this project was to examine the effect of the tank design on the COP of the tank-heat pump system during charge and discharge. Parameters such as the tank geometry, flow rate, diffuser plate geometry and tank material were investigated using CFD, in order to determine the effect of these parameters on the final performance of the system.

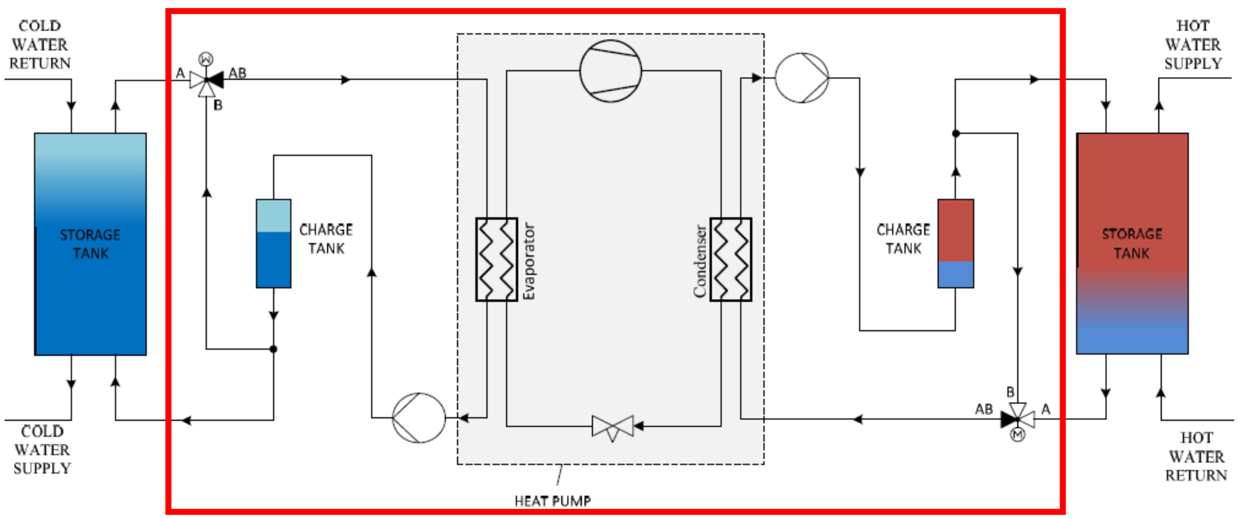


Figure 1: The ISECOP concept

Nomenclature

d	diameter [m]
h	height [m]
m_{steel}	mass of steel [kg]
m_{water}	mass of water [kg]
Cp_{steel}	specific heat capacity of steel [kJ/(kg K)]
Cp_{water}	specific heat capacity of water [kJ/(kg K)]
$T_{initial,\ steel}$	average temperature of tank's steel at start of charge operation [K]
$T_{final,\ steel}$	average temperature of tank's steel at end of charge operation [K]
$T_{initial,\ water}$	average temperature of tank's water at start of charge operation [K]
$T_{final,\ water}$	average temperature of tank's water at end of charge operation [K]
Q	amount of heat stored in tank [kJ]
V	Volume [L]
ρ	Water density [kg/m^3]
Q_C	Heat output from the condenser
W	Power consumption of compressor

Abbreviations

COP	Coefficient Of Performance
CFD	Computational Fluid Dynamics
UDF	User Defined Function

Methodology

The investigated system consists of an 8.9 kW heat pump connected to a 109.6 L vertical cylindrical storage tank. The fluid used in this heating system was water. The tanks used were made of steel with a wall thickness of 2.5 mm at the sides of the tank and a wall thickness of 3 mm at the top and the bottom of the tank.

Since the heat pump's characteristics were known, calculations were performed and the temperature increase of water passing through the heat pump was determined for a given volume flow rate. It was assumed that the inlet temperature of the heat pump was equal to the outlet temperature of the tank and that the outlet temperature from the heat pump was equal to the inlet temperature of the tank. That way, water from the tank outlet would pass through the heat pump and after being heated up (or cooled down), would return to the inlet of the tank without having any thermal losses from the pipes. Figure 2 shows the inlet temperature of the tank as a function of the outlet temperature of the tank based on heat pump operation.

A User Defined Function (UDF) was written in ANSYS Fluent in order to create the temperature profile for the inlet of the tank. The UDF found the area averaged temperature at the outlet of the tank and then increased it based on the curve presented in Figure 2. Afterwards, the UDF applied the obtained temperature to the inlet of the tank. The temperature range of the charge operation was from 35 °C to 75.3 °C. For the discharge operation, cold water of 35 °C was supplied at the bottom of the tank and hot water located at the top of the tank was discharged. The temperature range of the discharge operation was from 75.3 °C to 60 °C.

In order to make a fair comparison between the various solutions tested, a control method was developed, which stopped the simulation (either the charge or the discharge) when the temperature at the inlet/ outlet of the tank reached a specific value. The control temperatures were 75.3 °C and 60 °C for the charge and the discharge respectively. In this way, the energy content of the tanks at the end of the charge/ discharge was almost the same and it was mainly affected by the heat transfer between the water and the tank wall and by mixing. Therefore, the charge/discharge duration of the tested solutions was not exactly the same.

The investigated parameters were:

- Tank dimensions (variations in the height/diameter ratio)
- Diffuser designs
- Tank wall material (scenario with a hypothetical material having zero specific heat capacity and thermal conductivity – meaning no heat transfer between the water and the tank wall, no possibility to store heat in the tank walls, no heat loss and no downwards heat transfer through the tank walls).

The same methodology was used for the tank located on the cold side of the heat pump.

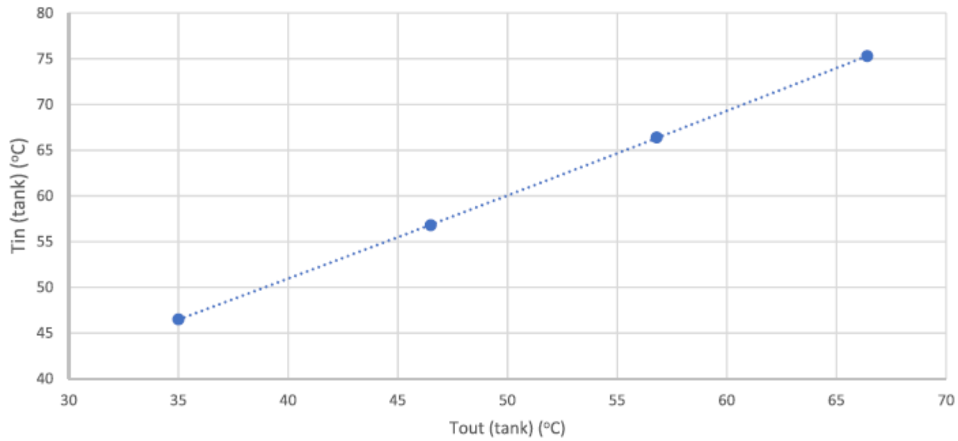


Figure 2: Correlation between tank's inlet and outlet temperature based on heat pump operation for "small tanks hot side"

COP calculation

In order to evaluate the performance of each system under investigation, two different COP expressions were developed; namely, COP during charge and COP during one full cycle of operation (charge and discharge):

COP during charge: $COP_1 = \frac{Total\ heat\ in\ the\ tank\ by\ end\ of\ charge}{Total\ electricity\ consumption\ for\ heat\ pump}$

COP for charge and discharge: $COP_2 = \frac{Total\ tapped\ energy}{Total\ electricity\ consumption\ for\ heat\ pump}$

Where the "heat in the tank by end of charge" is calculated by the equation:

$$Q = \left[m \cdot C_p \cdot \left(T_{final} - T_{initial}\right)\right]_{water} + \left[m \cdot C_p \cdot \left(T_{final} - T_{initial}\right)\right]_{steel}$$

The "total tapped energy" is the energy removed from the tank during discharge:

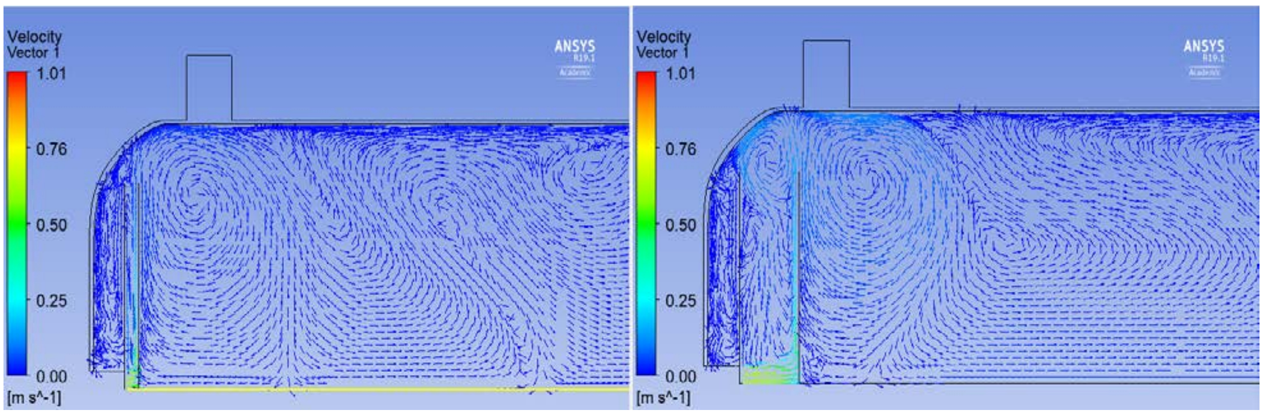
$$Q = \rho \cdot C_p \cdot \Delta T \cdot V$$

The "total electricity consumption" is calculated using the COP equation:

$$COP = \frac{Q_c}{W}$$

Small tanks hot side

The initial diffuser design for the tank was a two-plate diffuser as it can be seen in Figure 3. However, some initial investigations indicated that a 2-plate diffuser created a “dead volume” between the bottom plate of the diffuser and the tank. For this reason, it was decided to investigate single plate diffuser designs in order to utilize the entire tank volume. In addition, it was noticed that if the distance between the top plate of the diffuser and the inlet was increased, a larger mixing region inside the tank was created. This can be observed in Figure 3, where the velocity vectors inside the tank are presented for a 2-plate diffuser having different distances between the plates.



(a) *(b)*

Figure 3: Velocity vector profiles for 2-plate diffusers of 13 cm radius having a distance of (a) 1 cm and (b) 4 cm

Based on the initially obtained results, it was decided to investigate four different diffuser scenarios, which are presented in Table 1. A schematic of the investigated diffusers is presented in Figure 4.

Table 1: Tested tank diffusers

	Scenario A	**Scenario B**	**Scenario C**	**Scenario D**
Description	No diffuser present inside the tank	Single plate diffuser (large)	Single plate diffuser (small)	Perforated single plate diffuser having the same diameter as the tank
Distance from inlet/outlet [m]	-	0.01	0.01	0.01
$d_{diffuser}/d_{tank}$	-	0.73	0.3	1
d_{pipe} inlet/outlet [m]	0.022	0.022	0.022	0.022

“Scenario D” had a 2 mm thick plate with a porosity of 5%, corresponding to 66 holes of a diameter 0.0075 m spread uniformly over the plate area. It also has to be stated that “Scenario D” had a small non-perforated cyclic region with a diameter of 0.044 m in front of the inlet, in order to block the direct inlet of water jet in the tank. The red area in Figure 4(c) represents the perforated part of “Scenario D” plate, which had an outer diameter of 0.276 m.

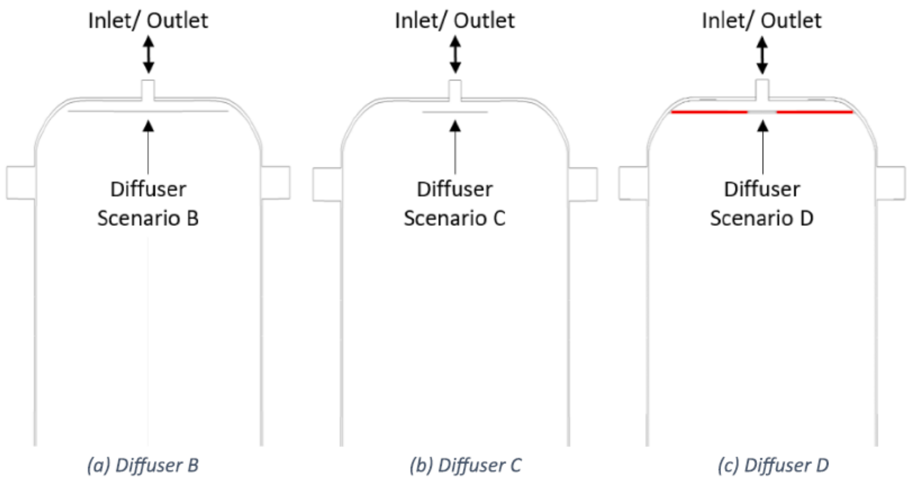


Figure 4: Diffuser designs mounted on the tank top

These diffusers were mounted in three different tank designs, which had different height to diameter ratios. The dimensions of the tanks are presented in Table 2.

Table 2: Investigated tank dimensions

Parameter	Tank 1	Tank 2	Tank 3
Height to diameter ratio, h/d [-]	3.64	2	1
Height, h [m]	1.25	0.82	0.52
Diameter, d [m]	0.34	0.41	0.52
Tank volume, V [L]	109.6	109.6	109.6

Two different charge and discharge modes were investigated. The difference between the two modes was the flow rate in the tank loop and consequently the duration of the charge and discharge operation. Mode 1 had a flow rate of 0.24 kg/s and Mode 2 had a flow rate of 0.12 kg/s. In the results presented in this report, Mode 1 is referred as “high” case and Mode 2 as “low” case. These two flow rates were applied to all tested tank geometries.

In Figure 5-16, the results of the CFD simulations are presented by a number of curves. A theoretical ideal curve was drawn on each figure in order to compare each case with the ideal scenario. This curve shows how the figure would look like if there were no tank material, no thermal conduction, no heat loss and no mixing inside the tank. The heat storage tank is heated up in 3 heating cycles. In each heating cycle, there is a temperature rise approx. 9.4–11.5 K. The ideal curve for charge has a staircase shape because the ideal tank has a uniform temperature and perfect thermal stratification in the tank. The tank will be heated up as plug flow in 3 steps. In a similar way, the ideal curve for discharge has a knee shape. Due to the heavy insulation of the tank (U=0.22 [W/m^2 K]), heat loss of the tank is expected to have a minor impact on the results of the simulations. For this reason, it is deliberately not discussed in this report.

In Figure 5, the temperatures at the outlet of the tank during the charge operation can be seen. The “ideal case”, which has the highest degree of stratification, has a staircase shape. However, the result shows that, none of the simulated cases was similar to the “ideal case”. This means that the obtained results were affected by mixing and thermal conduction. Comparing the simulation results, the effect of mixing can be easily spotted, since all investigated scenarios had similar thermal conduction effect. It can be seen that for the case without a diffuser (Tank 1A high) a high degree of mixing occurs inside the tank (relatively straight curve). On the contrary, the case having a perforated plate diffuser (Tank 1D high), had the most stratified temperature profile, getting the closest to the "ideal case".

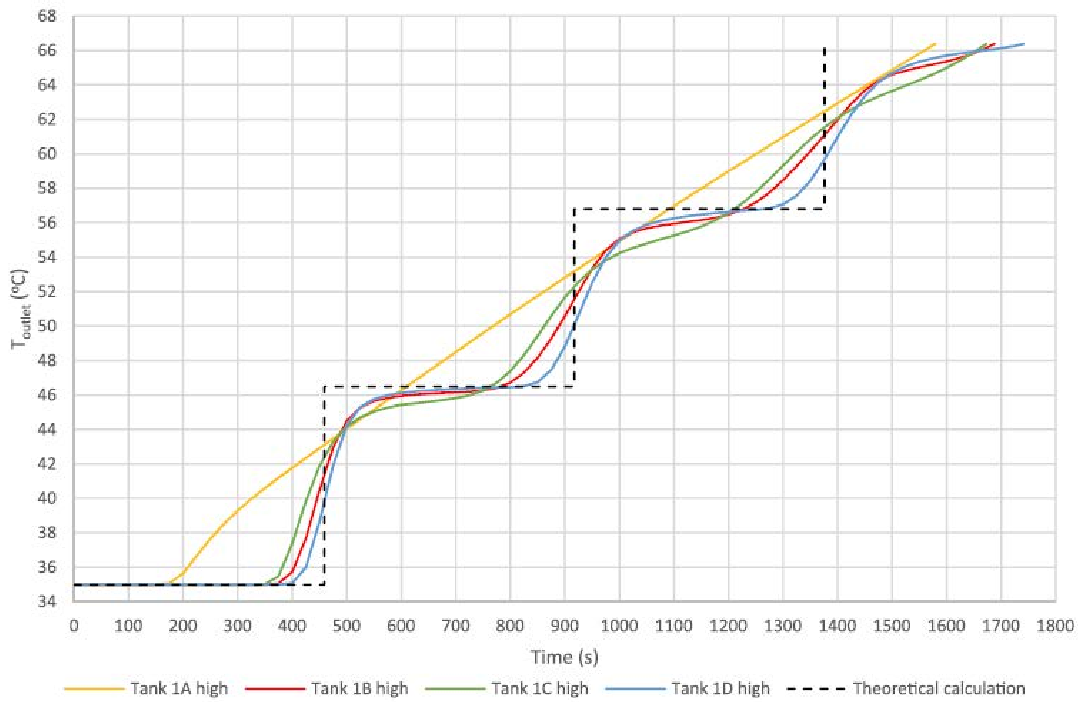


Figure 5: Average temperature at tank outlet during charge – high flow rate (h/d = 3.64)

Figure 6, presents the tapped energy versus the outlet temperature during discharge operation. It can be observed that the simulation results are very different compared to the "ideal case". The reason is that, in the "ideal case", the whole tank has the same temperature during discharge due to the assumption that there is no vertical thermal conduction in the tank and no mixing with the low-temperature water entering in the bottom of the tank, whereas this is not the case in real-life situations. In addition, in the "ideal case", since tank material is not considered, energy is not stored in the tank walls leading to a lower energy content compared to the simulated cases. It can be observed that in "Tank 1A high", most of the tank's volume has a temperature of 69 °C due to mixing, leading to a "knee" shaped curve. The case with the smallest amount of mixing, Tank 1D, was the one able to provide the highest tapped energy during discharge.

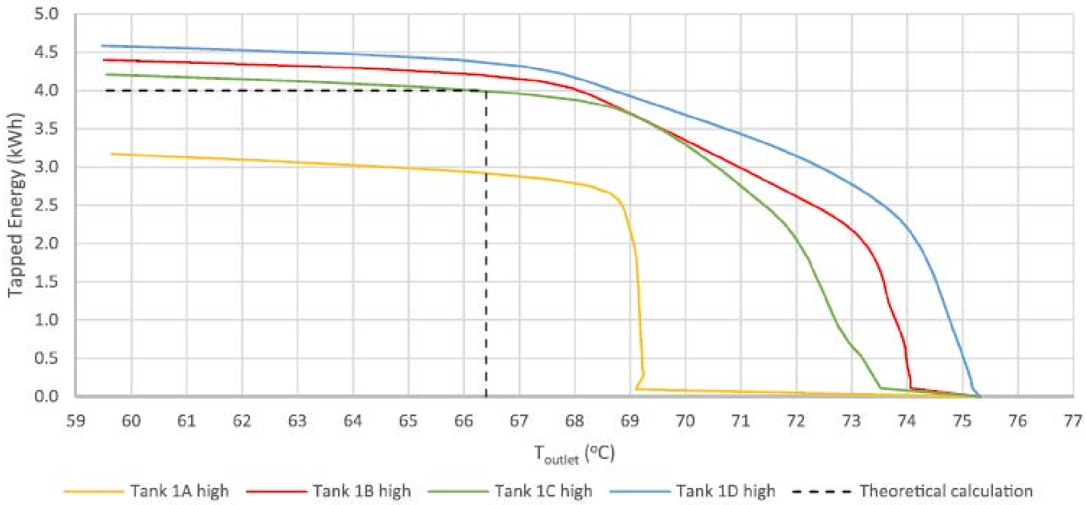


Figure 6: Tapped energy during discharge for a given outlet temperature – high flow rate (h/d = 3.64)

Similar results were obtained for the low flow rate, as it can be seen in Figure 7 and Figure 8. The major difference was found for the tank without a diffuser (Tank 1A). It can be observed that for the low flow rate the curves "Tank 1A low", for both charge and discharge, came closer to the other diffuser results, unlike for the high flow rate, due to lower mixing. Since the effect of low flow rate on the results was only obvious for the tank without a diffuser (Tank 1A), it was decided not to present the low flow results for the other h/d tested, for space saving purposes.

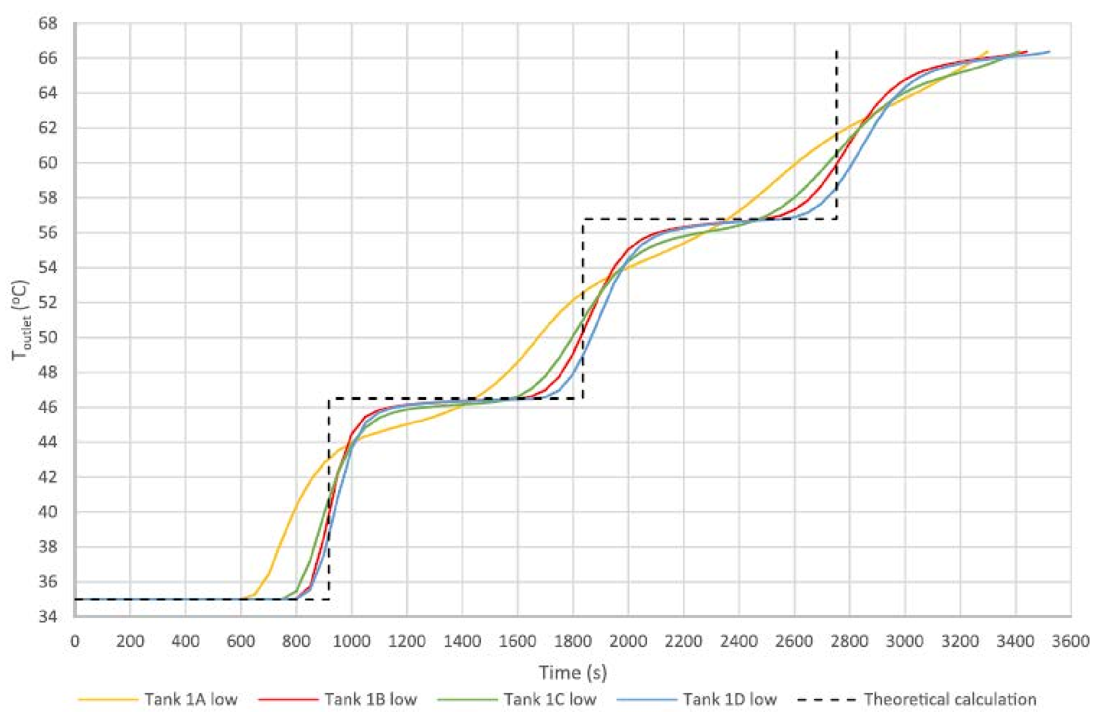


Figure 7: Average temperature at tank outlet during charge – low flow rate (h/d = 3.64)

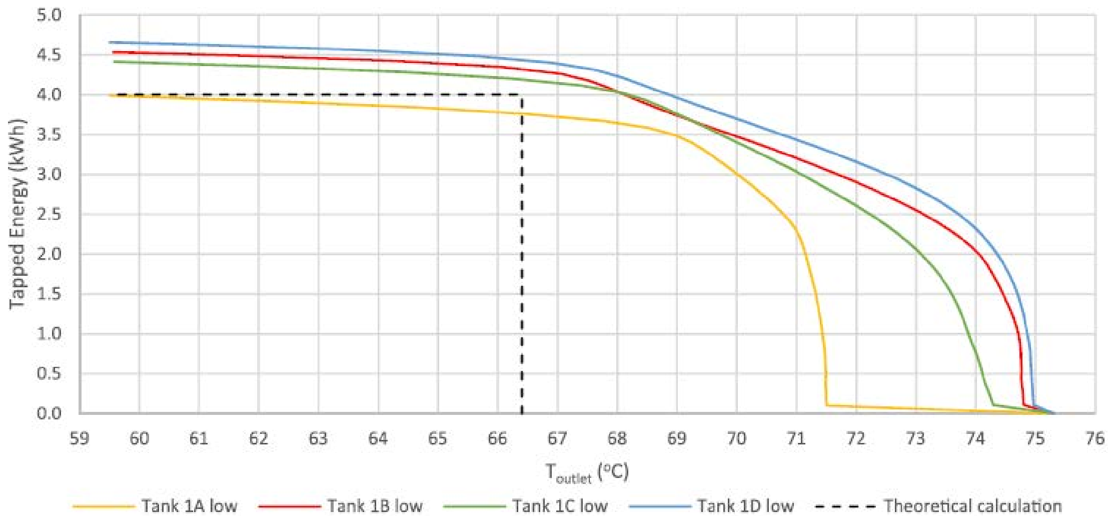


Figure 8: Tapped energy during discharge for a given outlet temperature – low flow rate (h/d = 3.64)

The effect of the diffuser designs on the mixing in the tank is shown in Figure 9, where the velocity vectors close to the top of the tanks during charge are presented. “Tank 1A high” and “Tank 1C high” have a larger region of high velocities compared to the other two solutions where the high water velocities are limited close to the inlet. It can also be observed that water recirculation zones are developed in all cases except “Tank 1D high”. Finally, in all cases, the cooling of water close to the tank walls is visible, creating a down-flow of cooler water with relatively high velocity. Similar flow patterns were seen for the low flow cases but with relatively lower maximum velocity magnitudes.

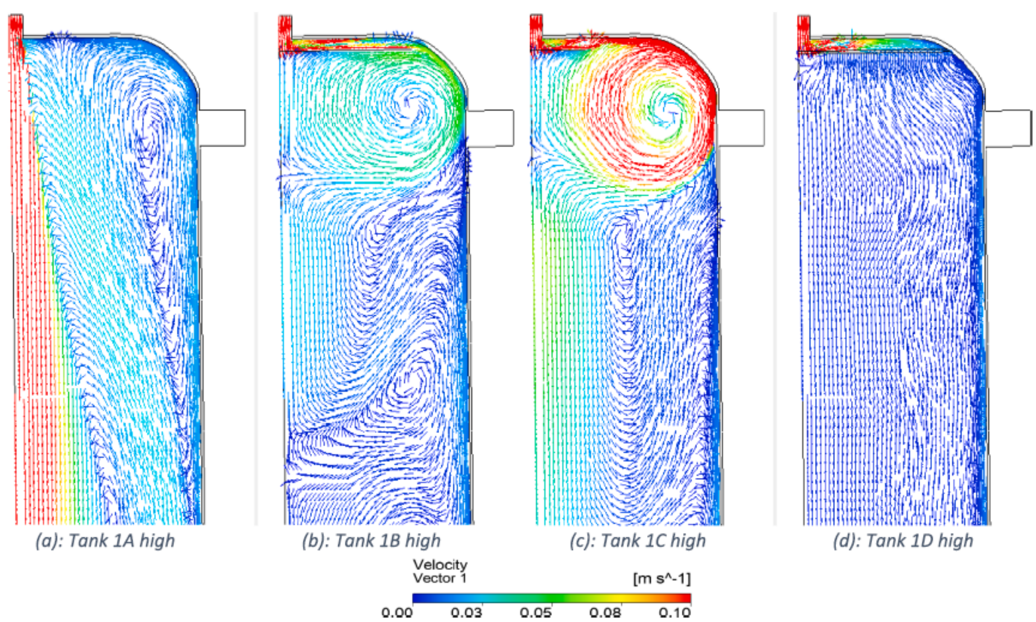


Figure 9: Velocity vectors at the top part of the tanks during charge (Tank 1, h/d=3.64)

The velocity vectors shown in Figure 9 have a direct impact on the temperature contours inside the tank as it can be seen in Figure 10. The results show that the slim-tall tank is able to create thermal stratification in the tank in all cases, regardless of the amount of mixing, due to the high height to diameter ratio of the tank. This is obvious in Figure 10(a) where, in spite of the high degree of mixing at the top of the tank, a relatively large temperature gradient is established at the bottom of the tank. Similar temperature contours were observed for low flow conditions.

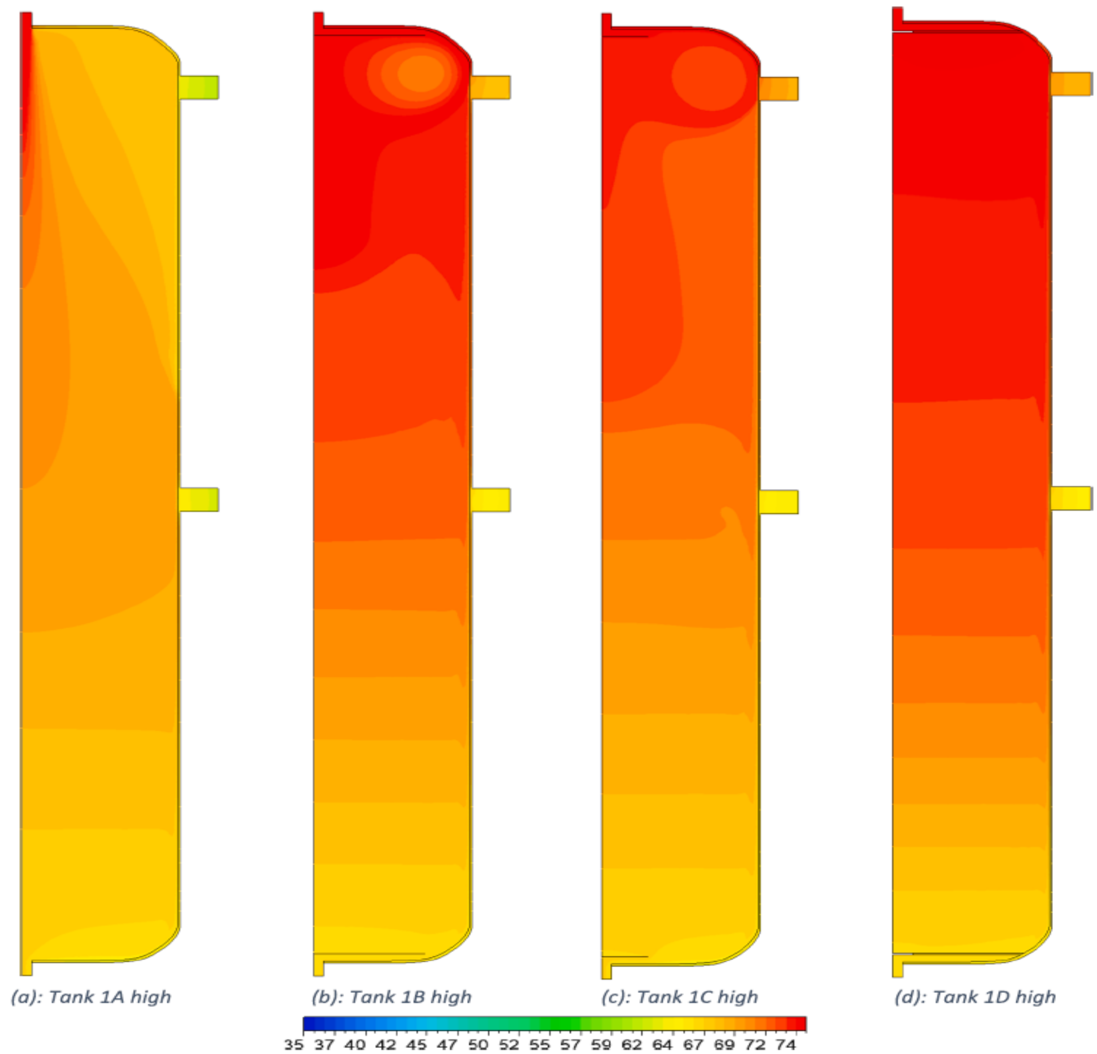


Figure 10: Temperature contours (ºC) inside the tanks at the end of charge (h/d= 3.64 tanks)

The two COPs of the system were calculated and presented in Table 3. “Tank 1B high” has the highest COP_1 and “Tank 1D high” and “Tank 1D low” have the highest COP_2. The reason of the difference is that COP_1 takes into account only the temperature at the bottom of the tank but not the entire temperature profile inside the tank. This can also be seen in Figure 10(a), (b) and (c), where although the tanks are thermally stratified in the bottom of the tank, the top of the tank is not stratified. This difference in the temperature profile affects COP_2; therefore, it is more accurate to evaluate the performance of the system based on COP_2.

Generally, as it was expected since the tank is well-insulated, lower flow rates give higher COP_2 due to lower degree of mixing inside the tank. However, the highest COP_2 was the same for “Tank 1D high” and “Tank 1D low” proving that when using a diffuser design that minimizes mixing, the results become less dependent on the flow rate. In addition, it can be seen that there is a small difference (around 1%) between the best performing solutions (Tank 1B and Tank 1D). The maximum difference in COP for the cases having a diffuser was 4.5%, when comparing “Tank 1C high” and “Tank 1D high”, which occurred due to different amounts of mixing inside the tank. Comparing the best performing diffuser cases (Tank 1D) to a case without a diffuser (Tank 1A high), an increase of up to 32% can be obtained in the COP of the system.

During discharge, since the temperature range of the tapped water is from 75.3 to 60 °C and the water entering the bottom of the tank is 35 °C, it can be expected that due to mixing, it will not be possible to discharge the entire volume of the tank. That will lead to an amount of energy being left in the tank. This residual energy is presented in Table 3 for each simulated scenario. It can be observed that the solutions having the highest COP are the ones having the lowest residual energy in the tank at the end of the discharge. This is also an indication of the amount of mixing in the tank, since lower mixing with the cold water entering the bottom of the tank leads to more energy being tapped and thus less residual energy in the tank.

Table 3: COP and residual energy calculation for h/d=3.64 tank for high and low flow rate

Case	COP_1	COP_2	Residual Energy [kWh]
Tank 1A high	3.50	2.45	1.28
Tank 1B high	3.56	3.20	0.40
Tank 1C high	3.55	3.09	0.53
Tank 1D high	3.49	3.23	0.34
Tank 1A low	3.51	2.95	0.65
Tank 1B low	3.51	3.22	0.35
Tank 1C low	3.52	3.16	0.41
Tank 1D low	3.46	3.23	0.34

Similar results were obtained for tanks having h/d=2 and are presented in Figure 11 and Figure 12, and the corresponding COPs in Table 4. The results for h/d=1 tanks are presented in Figure 13 and Figure 14, and the corresponding COPs in Table 5.

Table 4: COP and residual energy calculation for h/d=2 tank for high and low flow rate

Case	COP_1	COP_2	Residual Energy [kWh]
Tank 2A high	3.48	1.92	1.73
Tank 2B high	3.58	3.13	0.46
Tank 2C high	3.56	2.98	0.67
Tank 2D high	3.57	3.17	0.43
Tank 2A low	3.51	2.69	0.96
Tank 2B low	3.55	3.17	0.40
Tank 2C low	3.52	3.07	0.53
Tank 2D low	3.52	3.18	0.42

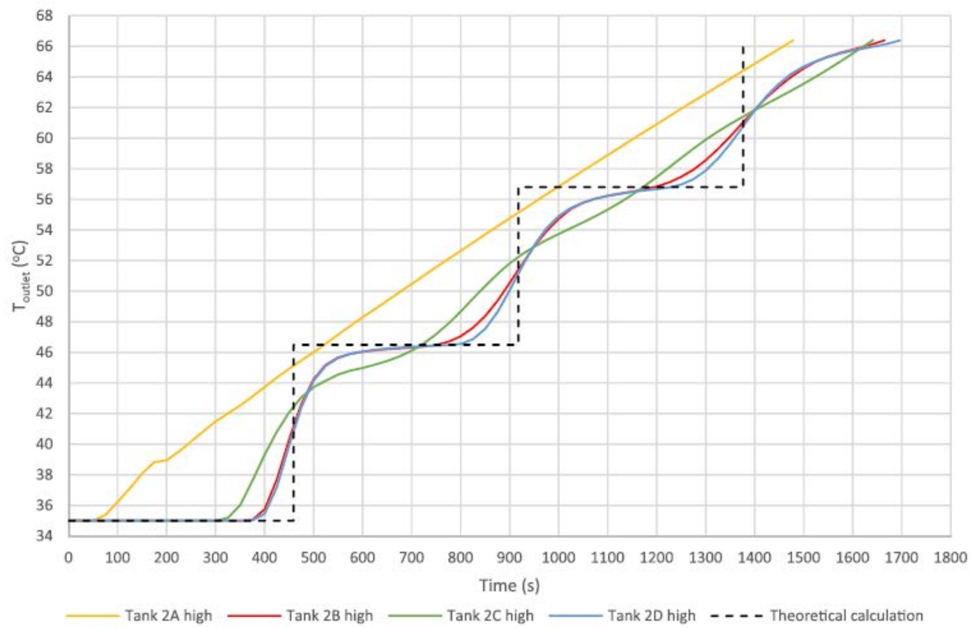


Figure 11: Average temperature at tank outlet during charge – high flow rate (h/d = 2)

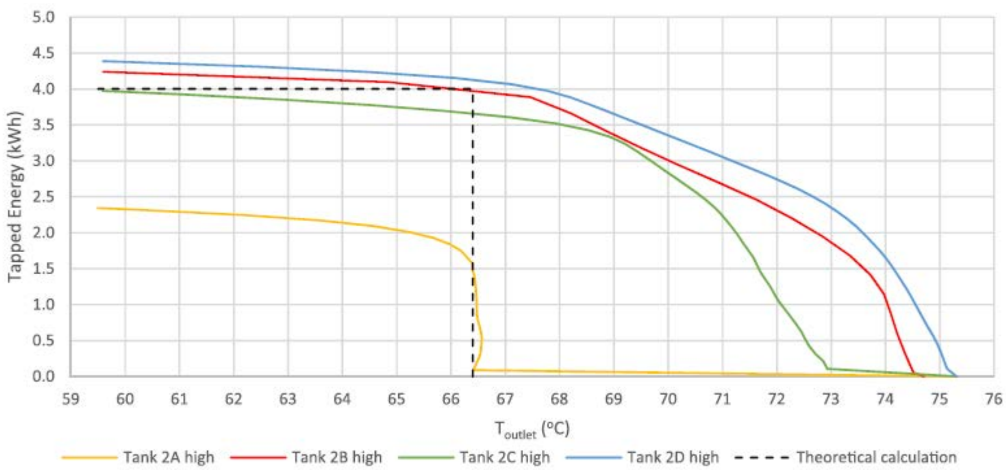


Figure 12: Tapped energy during discharge for a given outlet temperature – high flow rate (h/d = 2)

Table 5: COP and residual energy calculation for h/d=1 tank for high and low flow rate

Case	COP_1	COP_2	Residual Energy [kWh]
Tank 3A high	3.38	0.98	3.35
Tank 3B high	3.51	3.04	0.55
Tank 3C high	3.46	2.82	0.84
Tank 3D high	3.48	3.09	0.52
Tank 3A low	3.39	2.22	1.46
Tank 3B low	3.47	3.07	0.56
Tank 3C low	3.44	2.95	0.68
Tank 3D low	3.46	3.13	0.48

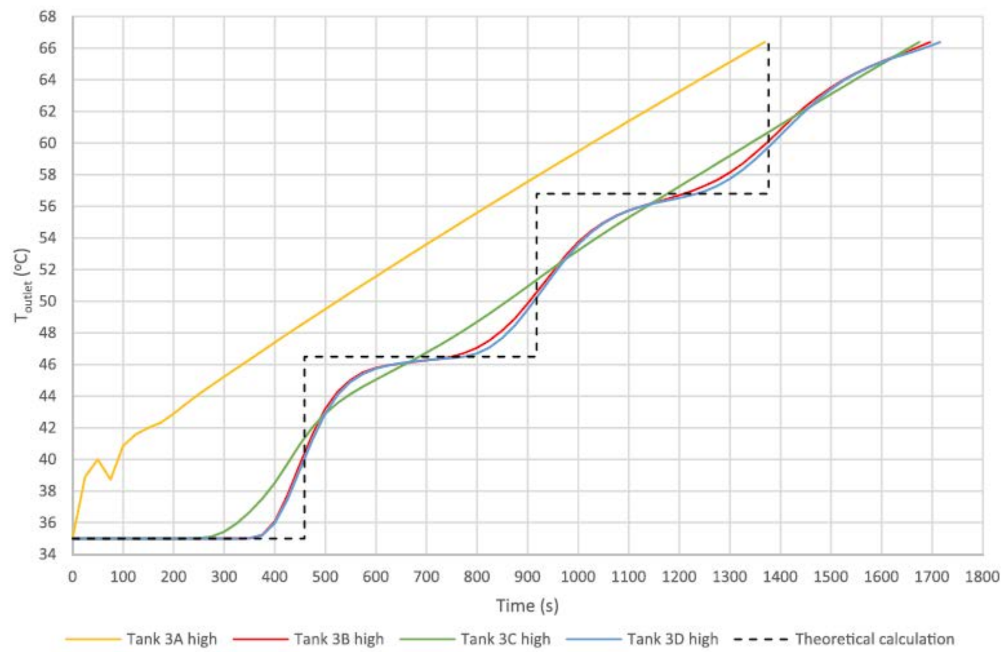


Figure 13: Average temperature at tank outlet during charge – high flow rate (h/d = 1)

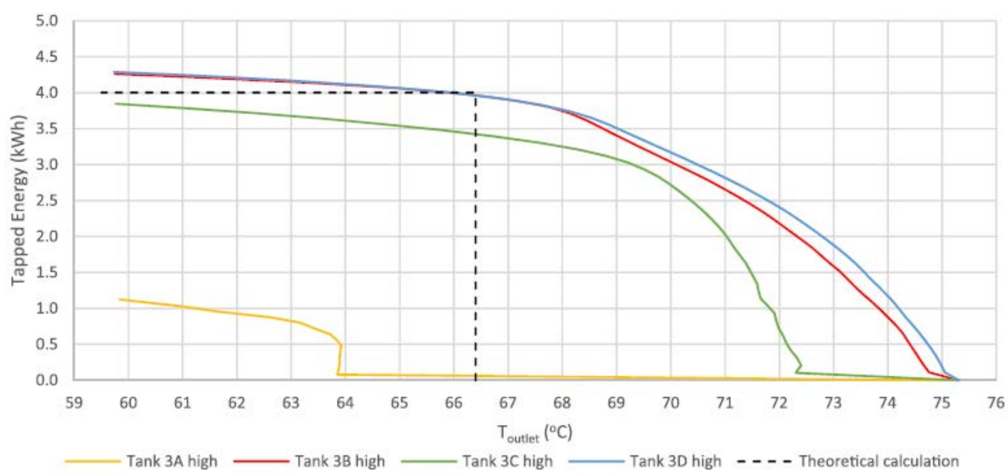


Figure 14: Tapped energy during discharge for a given outlet temperature – high flow rate (h/d = 1)

An ideal case without any tank material was tested. The absence of material meant that the simulated case had no heat transfer between the water and tank wall and no possibility to store heat in the tank walls. As it can be seen in Figure 15 and Figure 16, the "No material-Tank 1D high" case, came very close to the "ideal case". The difference between the "ideal case" and the simulation occurs due to mixing inside the tank and thermal conduction downwards in the tank water.

In Table 6, the simulated case having the highest COP is presented, along with the same case without tank material and the "ideal case". It can be observed that when there is no heat transfer between the water and tank wall, no vertical conduction and no mixing inside the tank (ideal case), the system COP after a charge-discharge cycle is 3.69. When the effect of mixing and vertical thermal conduction in the water are taken into account (No material-Tank 1D case), even if the case is optimized regarding mixing, the obtained COP is decreased by approximately 9%. If heat transfer to the tank wall is also taken into account

(Tank 1D high case), then the obtained COP is lowered by another 5% (so approximately 14% in total). In addition, in Table 6, it can be seen that the "ideal case" is the only one that has a COP_2 larger than COP_1. The reason for this is that, it is the only case where the entire volume of the tank can be discharged since there is no mixing with the cold water and no heat transfer to the tank walls. This fact, combined also with the low electricity consumption (since it takes less time to charge the tank compared to the simulated cases) led to a higher COP_2. It can also be observed that the "ideal case" is able to discharge the whole volume of the tank leaving no residual energy due to the absence of mixing, while this is not the case for the other solutions.

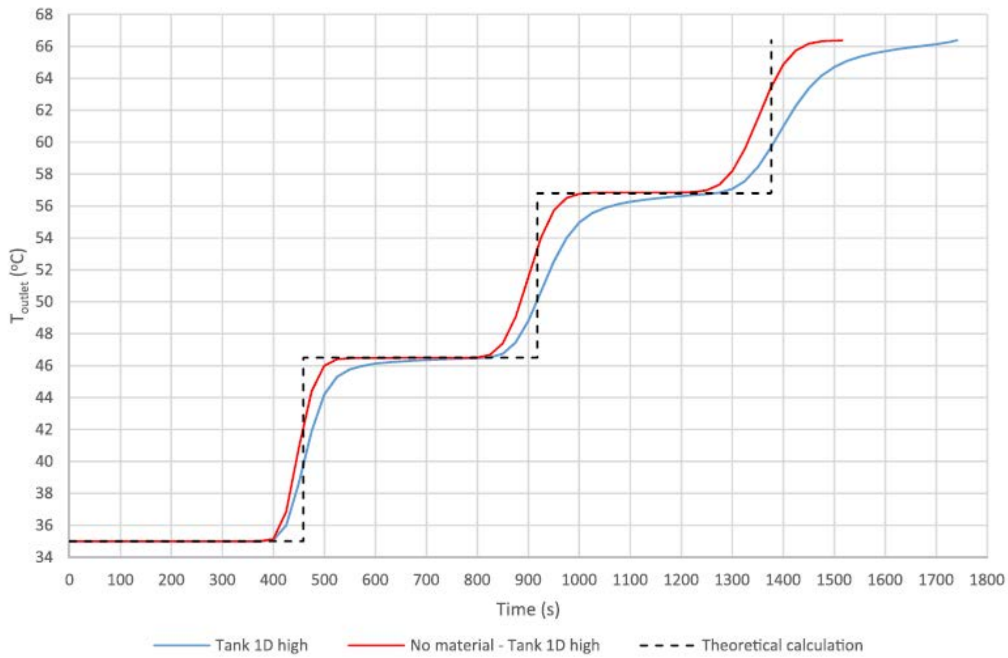


Figure 15: Average temperature at tank outlet during charge for cases with and without tank material – high flow rate (h/d=3.64)

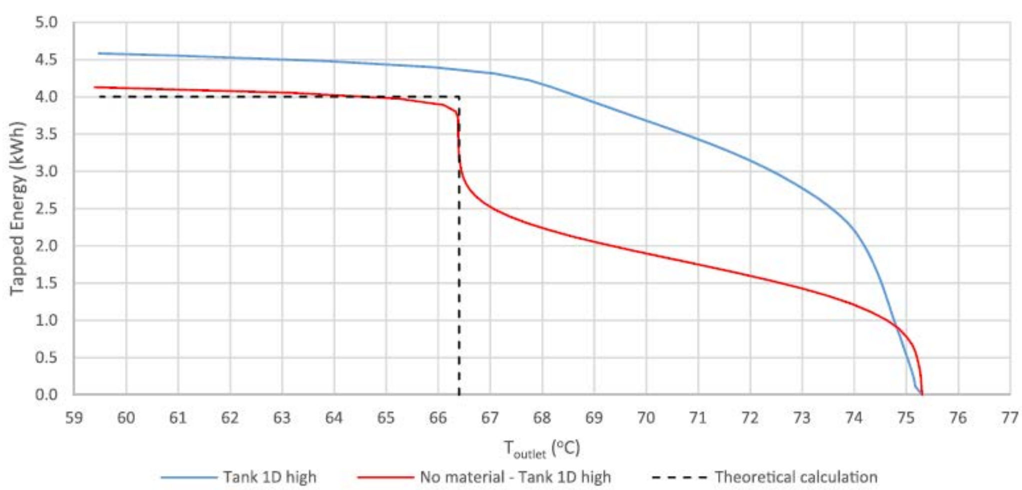


Figure 16: Tapped energy during discharge for a given outlet temperature for cases with and without tank material – high flow rate (h/d=3.64)

Table 6: COP and residual energy comparison between best performing cases

Case	COP_1	COP_2	Residual Energy [kWh]
Tank 1D high	3.49	3.22	0.34
No material – Tank 1D high	3.54	3.38	0.2
Ideal Case	3.65	3.69	0

<u>Conclusions on small tanks, heating operation:</u>

- There is a direct connection between the stratification in the tank and the COP of the system, as higher degree of thermal stratification lead to higher COP.

- For the ideal case where there is no mixing and no vertical thermal conduction in the tank and no heat loss from the tank, the system COP after a charge-discharge cycle is 3.69. When the effect of mixing is taken into account, the obtained COP of the system is decreased by approximately 9%. If heat transfer to the tank wall and vertical thermal conduction are also taken into account, the obtained system COP is lowered by another 5%.

- The COP of a heating system with high flow rates can be significantly increased by a diffuser plate installed in the tank with a small distance to the inlet/ outlet.

- The maximum difference in COP for the cases having a diffuser was 4.5%, when comparing "Tank 1C high" and "Tank 1D high", which occurred due to different amounts of mixing inside the tank.

- Comparing the best performing diffuser cases (Tank 1D) to a case without a diffuser (Tank 1A high), an increase of up to 32% can be obtained in the COP of the system.

- The best performing system studied was the system based on an insulated tall and slim tank with a high h/d ratio of 3.64 and a perforated plate diffuser.

- The best performing diffuser consisted of a 2 mm thick plate with a porosity of 5%, corresponding to 66 holes of a diameter 0.0075 m spread uniformly over the plate area. The diffuser had also a small non-perforated cyclic region with a diameter of 0.044 m in front of the inlet, in order to block the direct inlet of water jet in the tank.

- The performance of the suggested system was not affected by the tested variations in flow rate.

Small tanks cold side

Only Case 1 (40 – 9.7 °C) and Case 4 (25 – 2.6 °C) were simulated using CFD. During discharge, the "stop" temperature was 17 °C. The tank volume was approximately 110 l, similar to heating operation. The water flow rate in the system was 0.24 kg/s. The temperatrue at the tank's outlet during charge and discharge are presented in Figure 18 and Figure 19 respectively, and the corresponding COPs in Table 7.

Table 7: Performance of Case 1 and Case 4 – cold side

	Case 1	Case 4
COP_1 [-]	4.98	4.01
COP_2 [-]	4.41	6.6
Residual Energy [kWh]	0.386	0.104

The correlation between the tank's inlet and outlet temperature based on the heat pump operation for cooling for Case 1 and Case 4, is illustrated in Figure 17.

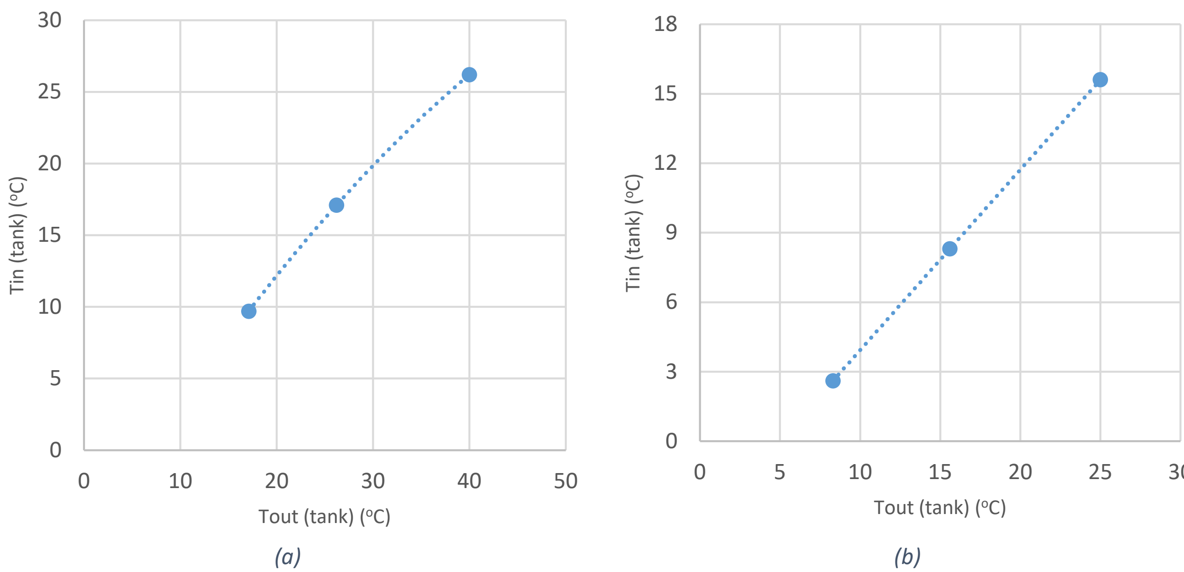


Figure 17: Correlation between tank's inlet and outlet temperature based on heat pump operation for (a) Case 1 and (b) Case 4

Case 4 has a much higher COP because the discharge temperature (17 °C) is much closer to the initial temperature of the tank (25 °C). Generally, it is difficult to compare in a "fair" way these two scenarios for two main reasons:

1) The temperature range is different (ΔT1 = 30.3 °C while ΔT4 = 22.4 °C)
2) The ΔT of each pass through the heat pump is different (Case 1 approx. 10.1 °C while Case 4 approx. 7.5 °C)

In order to get a better idea of the amount of mixing inside the tank the Richardson number for each time-step of the calculation was calculated both for charge and discharge operation.

If Richardson number is higher than 1 then the buoyant forces are stronger than the mixing forces inside the tank. It can be seen in Figure 20 that Ri number is much higher than 1 indicating low levels of mixing in the tank. The only case where Ri number gets close to 1 is towards the end of Case 4 charge. This happens because the temperature is close to 3 °C and density differences become very small.

Generally it could be said that the tank is satisfactorily stratified and thus, even when the temperature approaches 0 °C (and thus density differences are small) there is still a stratified result.

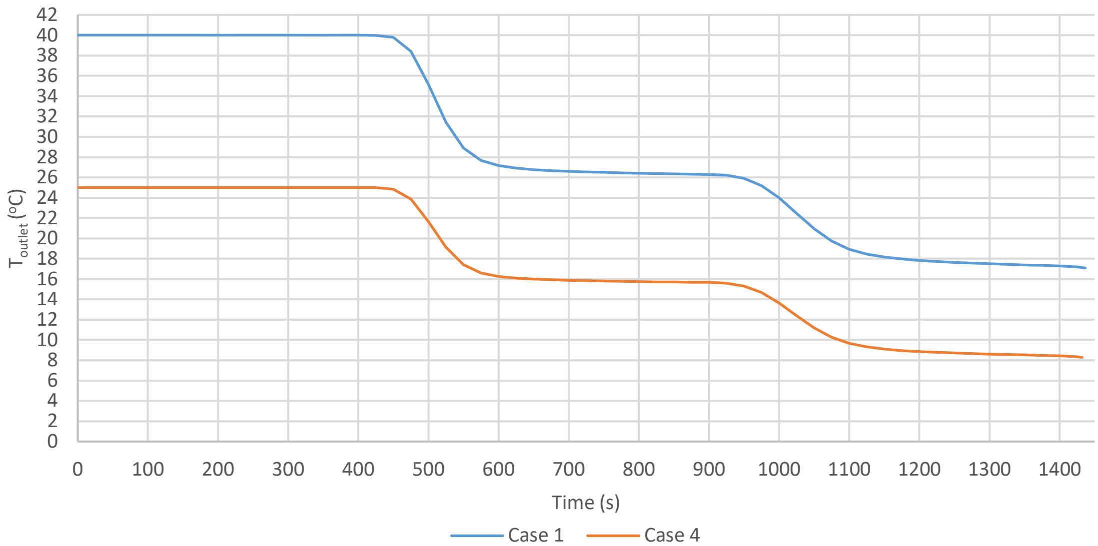


Figure 18: Average temperature at tank outlet during charge – cold side

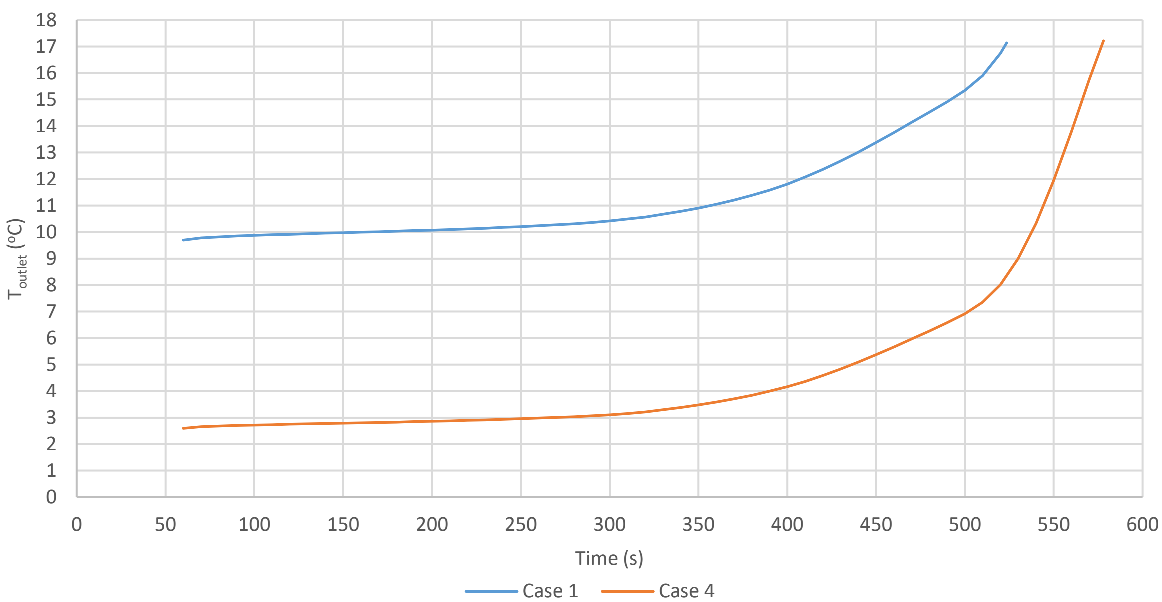


Figure 19: Average temperature at tank outlet during discharge – cold side

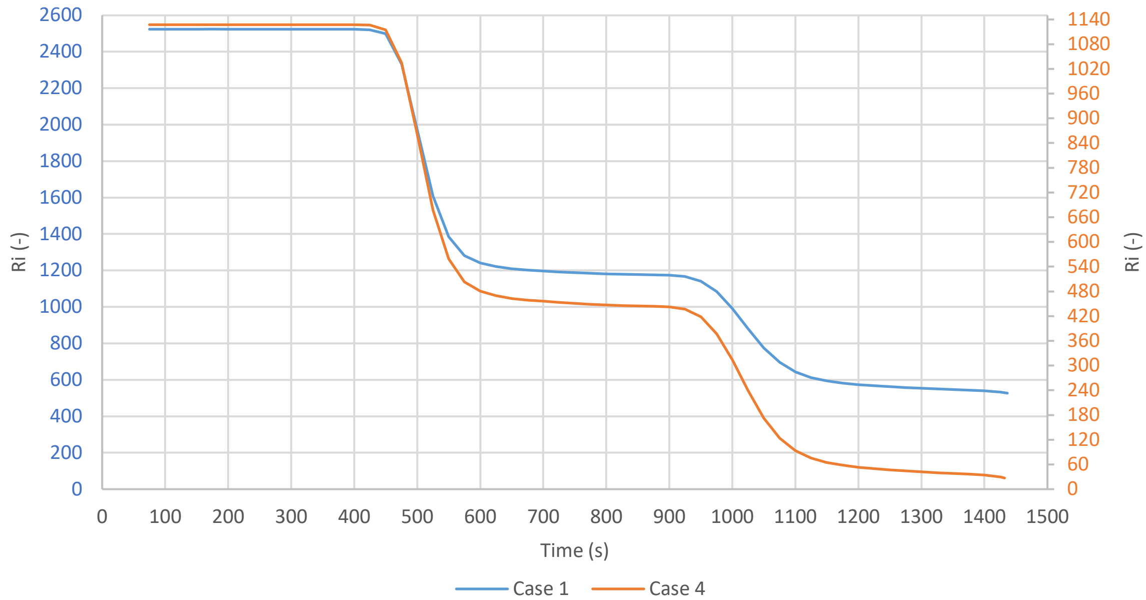


Figure 20: Richardson number during charge – cold side

Various h/d ratios were investigated for Case 4 (T= 25 – 2.6 °C), as well as a case with no tank material. The average temperature at tank outlet during charge is presented in Figure 21 and the corresponding COPs in Table 8.

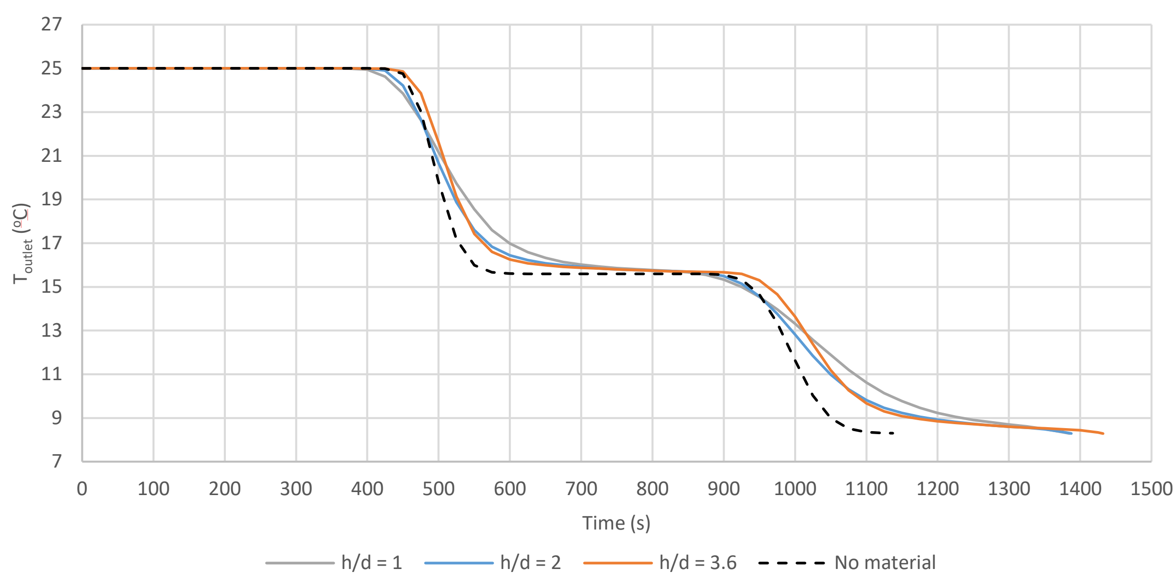


Figure 21: Average temperature at tank outlet during charge – cold side for various h/d ratios

Table 8: Performance of Case 4 for various h/d ratios

	COP_2	Residual energy [kWh]
h/d =1	2.71	0.15
h/d =2	2.72	0.13
h/d = 3.6	2.8	0.1
h/d = 3.6 (no material)	2.96	0.05

Case 1 was also investigated for 2 passes of water through the heat pump, instead of three, meaning that the cooling range of this operation would be from 40 – 17 °C (instead of 40 – 9.7 °C). The discharge range was from 17 – 26 °C. This process was investigated for 3 full cycles of charge-discharge and is presented in Figures 22 and 23.

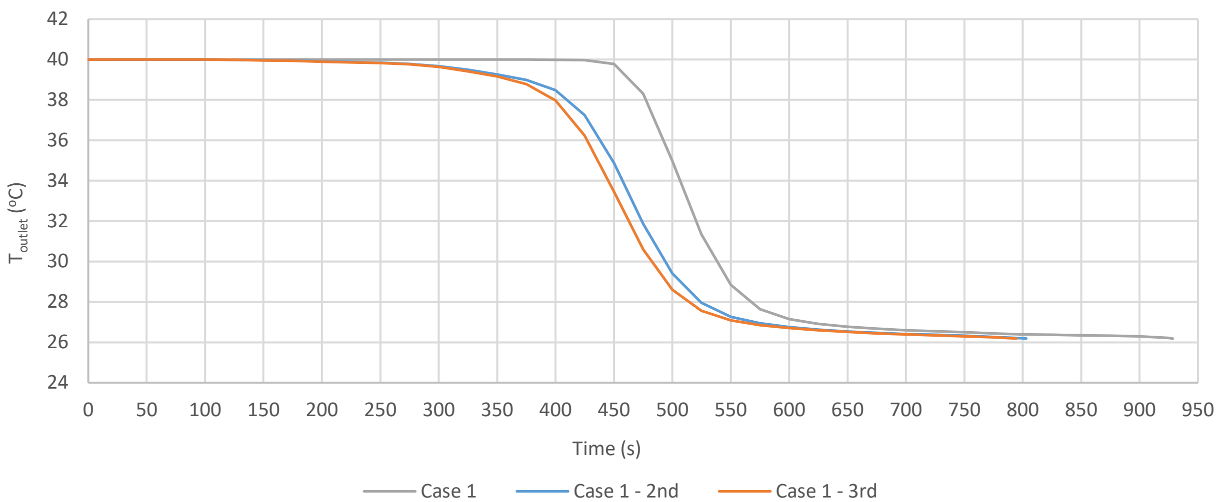


Figure 22: Average temperature at tank outlet during charge – cold side for multiple operation cycles

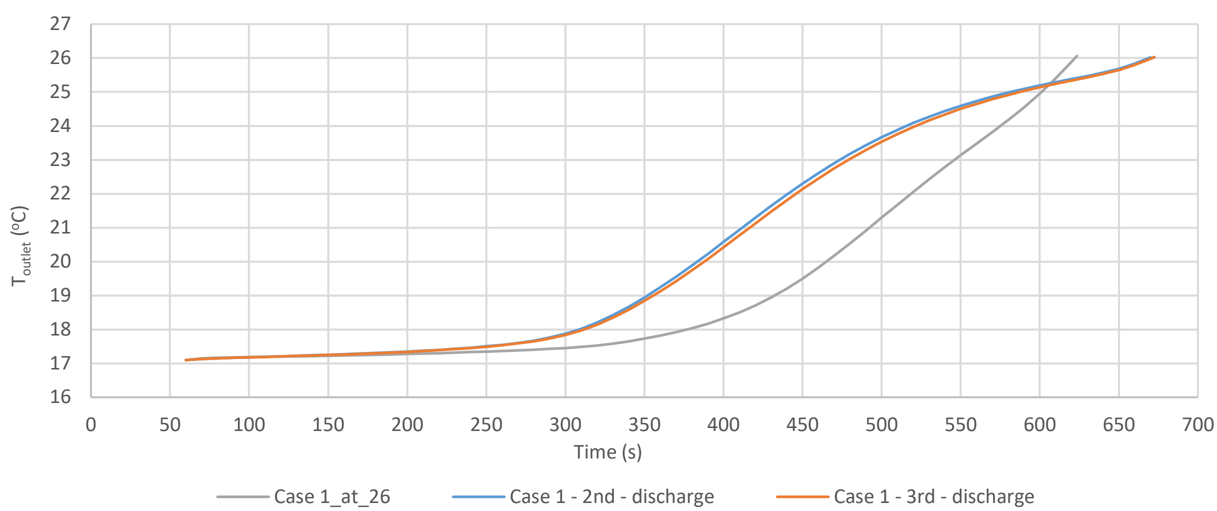


Figure 23: Average temperature at tank outlet during discharge – cold side for multiple operation cycles

The obtained COP_2 and residual energy of Case 1 (40 – 17 °C) for multiple charge-discharge cycles is presented in Table 9.

Table 9: Performance of Case 1 for multiple charge-discharge cycles

	COP_2	Residual Energy [kWh]
Case 1 – 2 passes – charge- 1st	4.32	-
Case 1 – discharge – 1st	3.90	0.22
Case 1 – 2 passes – charge – 2nd	4.33	-
Case 1 – discharge – 2nd	4.16	2.35
Case 1 – 2 passes – charge – 3rd	4.32	-
Case 1 – discharge – 3rd	4.25	2.36

Conclusions on small tanks, cooling operation:

- Similar to heating, a tall-slim tank gives the best stratification.
- The absence of tank wall material (no heat capacity, no thermal conductivity) gives the highest COP for both cooling and heating operation.
- The differences in obtained COPs for tanks of various h/d ratios are not that profound compared to heating operation.
- Tanks with h/d = 1 and 2 performed almost equally well, unlike heating operation.
- Stratification is not easily established when water temperatures drop below 10 °C due to small differences in water density at these temperatures. However, a tall-slim tank (h/d ≥ 3.64) still manages to produce a stratified profile inside the tank.

Large tanks hot side (the cold side was not investigated)

Furthermore, larger systems were investigated, where a 300 kW heat pump was used and tank volumes of 0.5 and 6.5 m^3. The h/d ratio of these tanks was 3. The flow rate in this system was 7.3 l/sec and tank charge was from 40 – 80 ^oC. A similar approach as for the hot side of the small tanks section was followed. Details for the investigated tanks are presented in Table 10.

Table 10: Investigated cases for large tanks hot side

Parameter	Case 1L	Case 4L
Height [m]	1.844	4.221
Diameter [m]	0.615	1.407
Volume [m^3]	0.547	6.563
Duration of charge operation [min]	5	60

Cases 1 and 4 were simulated using CFD, having a perforated plate diffuser. Scenarios with no tank material, for investigating the effect of the material on the results were also performed. The obtained COP_2 and residual energy are presented in Table 11.

Table 11: Material effect on cases 1L and 4L

Cases	COP_2	Residual Energy [kWh]
Case 1L – perf. plate	4.53	2.94
Case 1L – perf. plate – no material	4.59	2.87
Case 4L – perf. plate	4.75	55.5
Case 4L – perf. plate – no material	4.81	52

Due to the high flow rate, it was decided to attempt to optimize the diffuser plate for Case 4L. The examined parameters for optimizing the diffuser were:

- The position of the diffuser plate (0.02 m, 0.08 m and 0.2 m from the inlet)
- The porosity of the plate (1%, 5%, 10%, 20%)
- Keeping constant the plate width (0.002 m) and the diameter of the holes of the plate (0.011 m)

In Figures 24 and 25, the average temperature at the tank outlet during charge is presented for perforated plates having 1% and 5% porosity for various distances from the inlet. The names of the curves, e.g. P_1_D_02, correspond to a perforated plate of 1% porosity at a distance of 0.02 m from the inlet/outlet of the tank etc.

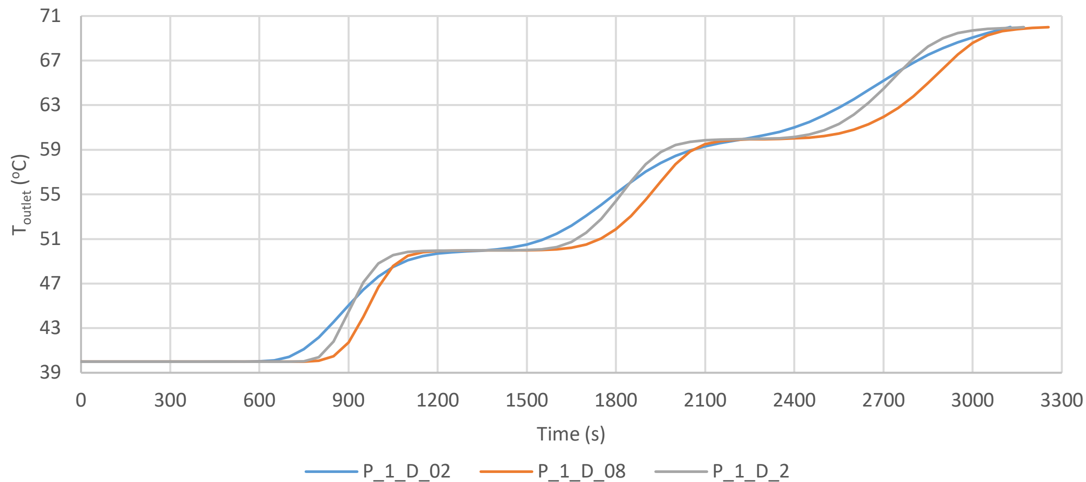


Figure 24: Average temperature at tank outlet during charge – 1% porosity for various distances from the inlet

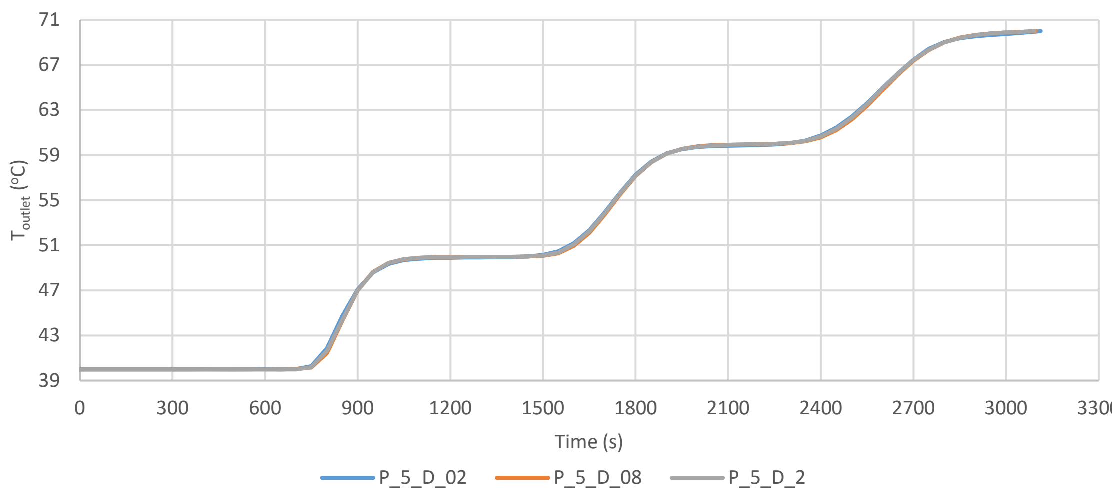


Figure 25: Average temperature at tank outlet during charge – 5% porosity for various distances from the inlet

The same results were obtained for cases having 5%, 10% and 20% porosity and for that reason they are not presented. In addition, only the case having 1% porosity seems to be affected by the distance of the perforated plate from the inlet, where a distance of 0.08 m seems to give the lowest temperature compared to the other two and thus the lower COP. Selecting this distance all the porosity scenarios were investigated, calculating the corresponding COP. The results are presented in Table 12.

Table 12: Performance of perforated plates at a 0.08 m distance from the inlet/outlet for various porosities

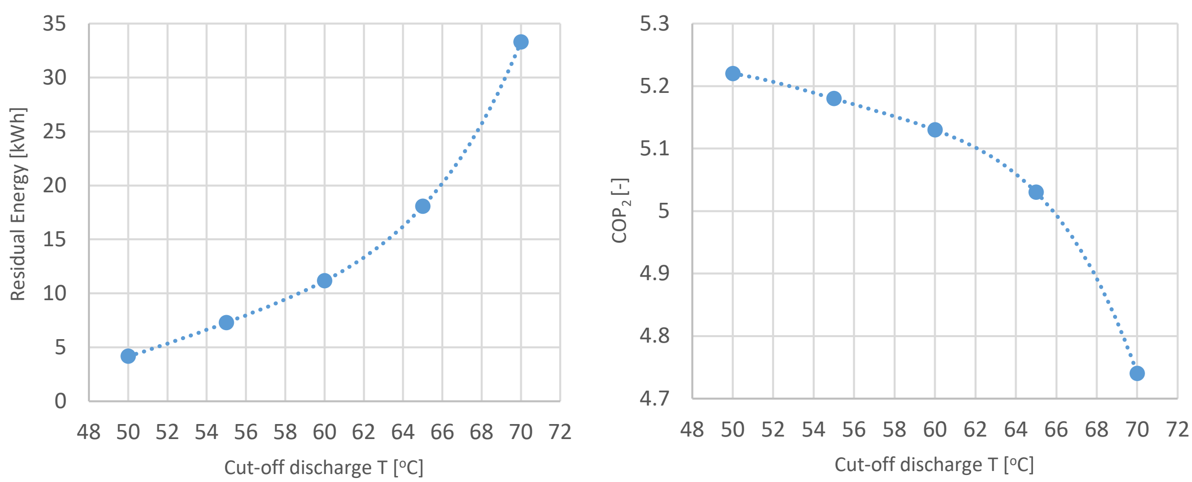
	1% - 0.08 m	5% - 0.08 m	10% - 0.08 m	20% - 0.08 m	Ideal Case
COP_2 [-]	4.74	4.67	4.67	4.66	5.67
Total pressure in tank [bar]	1.6	0.06	0.04	0.04	0
Residual Energy [kWh]	31.8	32.5	32.5	44.6	0

Due to the high flow rate, the diffuser plate having 1% porosity created a much larger pressure inside the tank compared to the other cases. For this reason, in an attempt to decrease the pressure, some scenarios were simulated having two perforated diffuser plates. The plates' characteristics were selected after a sensitivity analysis as the combination that increased the COP without increasing the total pressure in the tank. The first plate had a 10% porosity at a distance of 0.02 m from the inlet and the second had 3% porosity at a distance of 0.12 m from the inlet. In addition, scenarios with different discharge temperatures were investigated. The obtained COPs and residual energy are presented in Table 13.

Table 13: Diffuser performance for various discharge levels for Case 4L

		Discharge to 70 °C	Discharge to 65 °C	Discharge to 60 °C	Discharge to 55 °C	Discharge to 50 °C	Ideal Case
2 perforated plates (10% + 3% porosity)	COP_2	4.74	5.03	5.13	5.18	5.22	5.67
	Residual Energy [kWh]	31.3	18.1	11.2	7.3	4.2	0
	Total pressure tank [bar]			0.08			
1 perforated plate (5% porosity)	COP_2	4.67	4.97	5.08	-	-	5.67
	Residual Energy [kWh]	32.5	19.6	13.5	-	-	0
	Total pressure tank [bar]			0.06			

The temperature where discharge stopped was correlated to residual energy and COP2, as it is seen in Figure 26.



(a) (b)

Figure 26: Correlation of the temperature where discharge stopped with (a) the residual energy and (b) the COP_2

The performance of Case 4L was also investigated for multiple charge-discharge cycles in order to evaluate the system's COP in real-life operation. The obtained results are summarized in Table 14.

Table 14: COP and residual energy for multiple charge-discharge cycles for Case 4L

	Charge (1^{st} time)	Discharge (1^{st} time)	Charge (2^{nd} time)	Discharge (2^{nd} time)	Charge (3^{rd} time)	Discharge (3^{rd} time)
COP [-]	5.39	4.67	6.07	5.22	6.07	5.22
Residual Energy [kWh]	-	32.54	-	32.53	-	32.53

The reason for the increase in COP after the first charge-discharge cycle is that, due to the residual energy, the initial temperature of the tank is approx. 45 ^oC (and not 40 ^oC as in the first cycle). That leads to a smaller charge duration and thus lower electricity consumption, giving a higher system COP.

Conclusions on large tanks, heating operation:

- The lower the diffuser plate porosity, the better the COP of the system due to lower mixing inside the tank.

- A diffuser plate with 1% porosity has the highest COP but increases the total pressure in the tank, reaching 1.6 bar. If higher porosity diffuser plates are used (e.g. 5% or 10%), due to higher mixing in the tank, the COP is decreased, but also the total pressure is decreased, reaching 0.04 bar.

- A two-perforated-plate scenario (3% + 10% porosity) has the same COP as a 1% porosity plate, while maintaining a low pressure in the tank. However, this solution might increase the cost of the system due to higher material usage. For this reason, the solution that is recommended for achieving a high performance and maintain a low pressure in the tank at a low cost is a diffuser plate having 5% porosity.

- Generally, results similar to the small tanks were obtained.

Appendix A - Design Guidelines

Based on the results of this project, some guidelines were written regarding the design of the tank and the tank's diffuser, as well as selection of key system parameters for achieving maximum stratification in the tank. These guidelines can be applied for both heating and cooling applications. The parameters that are taken into consideration are:

- The height/diameter ratio of the tank
- The diffuser design
- The tank wall material
- The flow rate
- The duration of the charging of the tank

Height/diameter (h/d) ratio

In order to obtain the best possible stratification, tanks with high h/d ratios have to be used. In this report, the tested h/d ratios were 1, 2 and 3.64. The best performing h/d ratio was the highest tested; namely 3.64. It is believed that a higher h/d ratio (e.g. 4) would give even better results. However, since an increase in the h/d ratio would also increase the price of the tank, a rational selection should be done taking also the cost of the tank into consideration.

In general, a tank with a high h/d ratio has larger heat losses compared to one with a low h/d ratio. In this report though, all tanks were well insulated (U=0.22 [W/m^2 K]) so heat losses had minor effect on the results.

Diffuser design

All double-plate diffusers create a "dead" water volume between the bottom plate and the bottom of the tank, which cannot be charged or discharged. For this reason, single-plate diffuser designs are superior compared to double-plate, regardless the design, because they can utilize the entire tank volume.

The location of the diffuser plate should be as close as possible to the tank inlet (e.g. 2 cm). This way, the mixing region in the tank is minimized.

For single-plate diffusers, the diffuser plates should have a diameter as large as possible, reaching the tank walls for minimizing the mixing region.

Perforated single plate diffusers give the best stratification and minimize the mixing inside the tank, compared to other single or double plate diffusers. Generally, the lower the diffuser plate porosity, the better the COP of the system due to lower mixing inside the tank.

A diffuser plate with 1% porosity has the highest COP but increases the total pressure in the tank. If higher porosity diffuser plates are used (e.g. 5% or 10%), due to higher mixing in the tank, the COP is decreased, but also the total pressure is decreased.

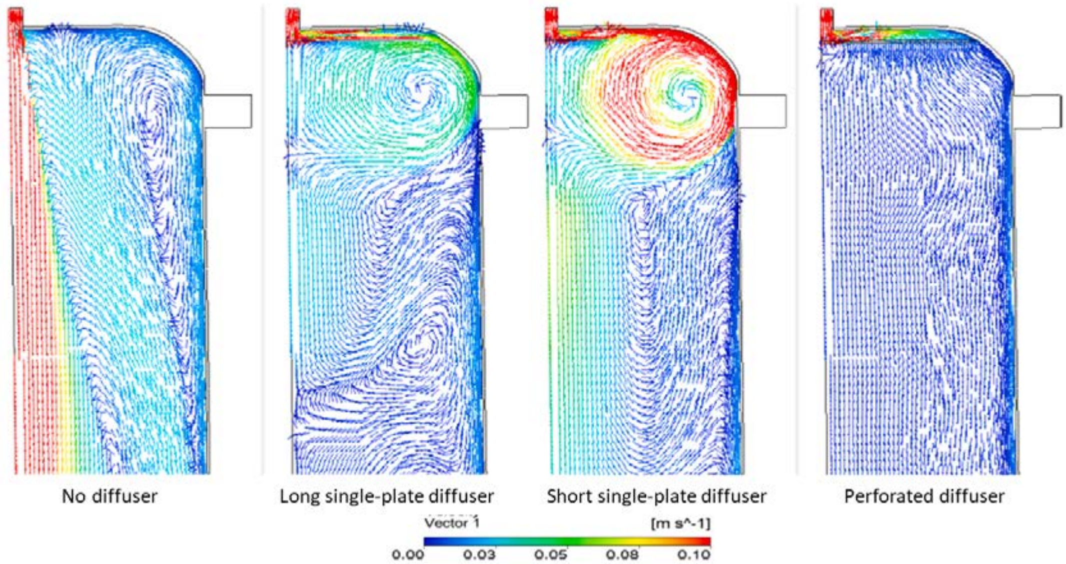


Figure A.1: Velocity vectors at the top part of the tanks during charge for various diffuser designs

A two-perforated-plate scenario (10% + 3% porosity) has the same COP as a 1% porosity plate, while maintaining a low pressure in the tank. However, this solution might increase the cost of the system due to higher material usage.

For this reason, the solution that is recommended for achieving a high performance and maintain a low pressure in the tank at a low cost, is a single diffuser plate having 5% porosity, corresponding to 66 holes of a diameter 0.0075 m spread uniformly over the plate area. It is also suggested for the diffuser to have a small non-perforated cyclic region with a diameter of 0.044 m in front of the inlet (if the inlet is a ¾" pipe, otherwise, a larger non-perforated region might be necessary), in order to block the direct inlet of water jet in the tank.

<u>Tank wall material</u>

In all the investigated cases, for both heating and cooling operation, absence of tank material was beneficial for stratification. In the simulations, a hypothetical material was used, having zero specific heat capacity and thermal conductivity – meaning that there was no heat transfer between the water and the tank wall, no possibility to store heat in the tank walls, no heat loss and no downward thermal conduction in the tank walls. In a real life scenario, any material with lower specific heat capacity and thermal conductivity than steel or stainless steel, which are mostly used in tanks, would create a better stratification in the tank.

However, a number of other parameters have to be taken into consideration like:

- How much would the material actually increase the performance?
- How large pressure will it have to withstand?
- How stable is it for multiple charge-discharge cycles?
- What is the cost and lifetime of the tank?

Flow rate

For a 110 l tank, it was proven that a flow rate in the range of 0.12 – 0.24 kg/s gave the same results, provided that an optimized diffuser is used (e.g. high diameter single-plate or perforated). This proves that, although smaller water velocities create better stratification, with the use of an appropriate diffuser, higher flow rates can be used producing an equally good stratified tank.

Charge duration

A charge duration of 20 – 30 minutes is suggested. Longer durations (corresponding probably to lower flow rates) are likely to affect stratification positively but at the same time heat losses from the tank to the ambient start becoming significant.

In this project, the ISECOP concept was investigated, where a heat pump was used for heating and cooling two storage tanks simultaneously. When the desired temperature was reached in the tanks, the water was discharged and used for industrial purposes. Water charging (heating or cooling) was done gradually so large flow rates were necessary in order to have multiple water passes through the heat pump. However, this created poor thermal stratification in the tanks while, for the optimal performance of this method, a highly stratified tank was of major importance.

The objective of this project was to examine the effect of the tank design on thermal stratification and as a result, on the COP of the tank-heat pump system during charge and discharge. Parameters such as the tank geometry, flow rate, diffuser plate geometry and tank material were investigated using Computational Fluid Dynamics (CFD), in order to determine the effect of these parameters on the final performance of the system. Consequently, guidelines on tank design were proposed.

DTU Civil Engineering

Brovej 118
2800 Kgs. Lyngby
Tel. +45 4525 1700
www.byg.dtu.dk

ISBN: 87-7877-531-0