Thermal stratification built up in hot water tank with different inlet stratifiers

Dragsted, Janne; Furbo, Simon; Dannemand, Mark; Bava, Federico

Published in:
Solar Energy

Link to article, DOI:
10.1016/j.solener.2017.03.008

Publication date:
2017

Document Version
Peer reviewed version

Citation (APA):
Dragsted, J., Furbo, S., Dannemand, M., & Bava, F. (2017). Thermal stratification built up in hot water tank with different inlet stratifiers. Solar Energy, 147, 414-425. DOI: 10.1016/j.solener.2017.03.008

Thermal stratification built up in hot water tank with different inlet stratifiers

Janne Dragsted[1*], Simon Furbo[1], Mark Dannemand[1], Federico Bava[1]

[1]Department of Civil Engineering, Technical University of Denmark, Building 118, Brovej, DK-2800 Kgs. Lyngby, Denmark

[*]*Corresponding email:jaa@byg.dtu.dk*

Keywords: Hot water tank, Thermal stratification, Inlet stratifiers, Laboratory tests

ABSTRACT

Thermal stratification in a water storage tank can strongly increase the thermal performance of solar heating systems. Thermal stratification can be built up in a storage tank during charge, if the heated water enters through an inlet stratifier.

Experiments with a test tank have been carried out in order to elucidate how well thermal stratification is established in the tank with differently designed inlet stratifiers under different controlled laboratory conditions.

The investigated inlet stratifiers are from Solvis GmbH & Co KG and EyeCular Technologies ApS. The inlet stratifier from Solvis GmbH is a rigid plastic pipe with holes for each 30 cm. The holes are designed with flaps preventing counter flow into the pipe. The inlet stratifier from EyeCular Technologies ApS is made of a flexible polymer with openings all along the side and in the full length of the stratifier. The flexibility of the stratifier prevents counterflow.

The tests have shown that both types of inlet stratifiers had an ability to create stratification in the test tank under the different test conditions. The stratifier from EyeCular Technologies ApS had a better performance at low flows of 1-2 l/min and the stratifier for Solvis GmbH & Co KG had a better performance at 4 l/min. In the intermediate charge test the stratifier from EyeCular Technologies ApS had a better performance in terms of maintaining the thermal stratification in the storage tank while charging with a relative low temperature.

INTRODUCTION

The thermal performance of a solar heating system is strongly influenced by the thermal stratification in the heat storage. Previous investigations showed that the thermal performance is increased by increasing thermal stratification (Van Koppen et al. 1979, Hollands et al. 1989, Hahne et al 1998, Han et al 2009).

Thermal stratification in solar storage tanks can be established both during charge and during discharge periods from the tank.

During discharge of a storage tank, the heat is discharged from a fixed level of the tank. For a solar domestic hot water (SDHW) system, the fixed level is at the top of the storage tank. For a solar combi (SC) system the level is just above the auxiliary energy supply in the storage tank. Thermal stratification in a domestic hot water tank is best established during discharge, if cold water enters the bottom of the tank during hot water draw offs without any mixing (Lavan et al. 1977, Shah and Furbo 2003, Jordan and Furbo 2005, Furbo and Shah 2005), and in a hot water tank for combined space heating and domestic hot water supply, if the returning water from the heating system enters the tank through an inlet stratifier (Weiss 2003, Andersen and Furbo 2006). Additionally, thermal stratification can be established in an even better way by discharging the solar storage tank from different levels (Furbo et al. 2005).

During charge, thermal stratification in a hot water tank can be established by an auxiliary energy supply system or by the thermal energy coming from the solar collectors. The heat from the auxiliary energy supply system is normally transferred to the top of the tank. The heat from the solar collectors is ideally transferred to the “right” level of the tank which is the level where the tank temperature matches the temperature of the incoming fluid transferring the solar heat to the tank. Investigations have shown that for small SDHW systems, thermal stratification is built up in an excellent way during charge with solar heat if vertical mantle tanks are used (Furbo and Mikkelsen 1987, Shah and Furbo 1998, Knudsen and Furbo 2004, Furbo and Knudsen 2006). Thermal stratification in hot water stores for large SDHW systems and for SC systems can be successfully established during charging by means of inlet stratifiers (Weiss 2003, Furbo et al. 2005).

Inlet stratifiers can be designed in different ways. For instance, inlet stratifiers can be vertical polymer pipes with openings without or with non-return valves on the openings, securing that water can only flow out of the pipes into the tank. Other designs are porous tube manifolds mounted in the storage tank (Wang et al. 2015, Wang et al 2016). Here the flexibility and permeability of the porous tube manifold ensures stratification. Also valves designed for the inlet, which can allow the water to enter in the right level according to temperature of the incoming water and temperature in the tank (van Ruth 2016), can be used. Inlet stratifiers can also be vertical fabric pipes or vertical polymer film pipes with one or more layers and with openings in different levels. Due to the flexibility of the fabric and polymer inlet stratifiers, the horizontal cross section area of the inlet stratifiers can be decreased strongly in the lower levels of the stratifiers, if the water entering the stratifier from the bottom is warmer than the water in the lower levels of the tank. This decrease in cross section prevents cold water from being sucked into the stratifier and the incoming water flows towards the upper levels of the tank inside the stratifier without being mixed with cold water from the tank.

Differently designed hot water stores and inlet stratifiers have earlier been tested in laboratory test facilities using different test methods with different test conditions. The aim was to elucidate how well thermal stratification is built up in hot water stores during typical operation. This has been done to compare the performance of the different hot water stores and inlet stratifiers (Phillips et al. 1982, Davidson et al. 1994, Rosen et al. 2001, Shah et al. 2005, Andersen and Furbo 2006, Andersen et al. 2007, Andersen et al. 2007, Panthalookaran et al. 2007, Brown et al. 2011, García-Marí et al. 2013).

A perfectly working inlet stratifier operates in such a way that the incoming water is guided to the exact level in the tank where the temperature is the same as the incoming water, without any heat exchange between the water in the tank and the incoming water.

In this article a comparison based on measurements between well-known designs of inlet stratifiers and a new design of inlet stratifier is presented. The performances are investigated for both charge tests with a high inlet temperature and intermediate charge tests with different inlet temperatures.

METHODOLOGY

Scope of investigations

Two tests have been carried out for each of the tested stratifiers; top charge and intermediate charge tests of a hot water tank.

The top charge test is where the tank is heated from cold state with an inlet temperature of 50 °C through the stratifier until the whole volume has been exchanged. The intermediate test is where the tank again is heated from cold state with first an inlet temperature of 50 °C through the stratifier exchanging half of the volume in the tank. Then the inlet temperature is lowered to 30 °C and the rest of the volume is exchanged through the stratifier.

The tests were carried out with different volume flow rates, typically used in small low flow solar heating systems. Analysis on how well thermal stratification was established during the tests are presented.

Geometry and operating conditions

The tests were carried out in a transparent polymer test tank with an inner diameter of 240 mm and a height of 1500 mm, see Figure 1. The test tank consists of two cylindrical polymer cylinders separated by an air gap of 25 mm to reduce the heat loss from the tank.

The temperatures of the water at different levels inside the tank were measured by 12 copper/constantan thermocouples, type TT, see Figure 1. The test facility allowed the water to be circulated from the bottom of the tank through a heat source and then back into the tank through the stratifier. The volume flow rate and the temperature of the incoming water were kept constant during a test. The volume flow rate was measured by a Brunata flow meter/energy meter. The inlet temperature of the incoming water entering through the stratifier and the ambient air temperature were also measured with copper/constantan thermocouples type TT.

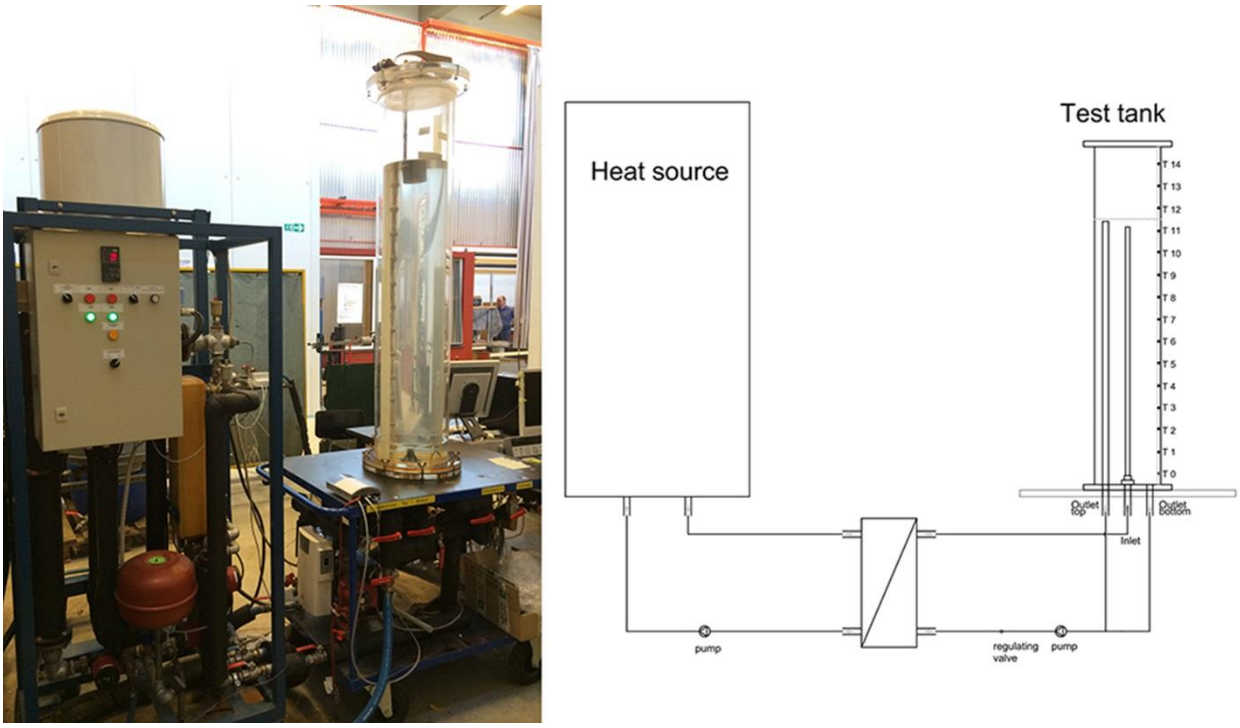

Figure 1. Photo and schematic sketch of polymer test tank with an inlet stratifier connected to a heat storage test facility. The tank has 15 temperature sensors.

The tank was filled with 54 l of water and the entire volume was exchanged during each test. There was air above the water inside the tank, as shown on the schematic sketch in Figure 1.

The tank was heated from a uniform cold temperature of about 20 °C, and the measurements were recorded with a time step of 10 seconds.

All tests started as soon as the warm water from a previous charge test had been replaced by cold water, so that the warm polymer walls only had limited time to release the heat stored in the walls. This assured that all tests were carried out starting with warm tank walls and ending with warm tank walls, and consequently assured energy balance in the tests.

Heat loss from the tank

It was assumed that the small volume and the double walled test tank, as well as the short durations of the tests, resulted in low heat losses. Due to the low tank heat losses and the low heat capacity of the polymer tank material, the tank design did not significantly influence the thermal stratification built up in the test tank during the tests.

Applied calculations

The measured data of the top charge tests are analysed by means of a so called MIX number determined during each charge test (Davidson et al. 1994, Andersen et al. 2007, Haller et al. 2009).

The MIX number in the top charge test was determined by a quantitative "momentum of energy" analysis method. The tank was divided into N = 12 equally sized horizontal layers, each of them having a volume V_i. The temperature in each volume was measured as described in Figure 1. The "momentum of energy" of layer i M_i is determined by:

$$M_i = \rho_i \cdot Cp_i \cdot V_i \cdot T_i \cdot Y_i \qquad (1)$$

where ρ_i is the density of water at the temperature T_i [kg/m³]

Cp_i is the specific heat capacity of water at the temperature T_i [J/kg K]

V_i is the water volume of layer i [m³]

T_i is the temperature of the water in the layer i [K]

Y_i is the vertical distance from the bottom of the tank to the middle of layer i [m]

The "momentum of energy" for the tank M is:

$$M = \sum_{i=1}^{N} M_i \qquad (2)$$

where N is the number of layers in the tank [-]

During each top charge test the "momentum of energy" for the tank was determined based on the measured temperatures. Additional "momentum of energies" for the tank was calculated assuming a fully mixed tank M_{mix} and an ideally stratified tank M_{str}.

The MIX number is determined by:

$$MIX = \frac{M_{str} - M}{M_{str} - M_{mix}} \tag{3}$$

M_{str} and M_{mix} are calculated during each time step of the top charge test.

When M_{str} is calculated, the tank is divided in two parts. The volume of the upper part is equal to the water volume which has entered the tank and the volume of the lower part is equal to the tank volume minus the upper volume. The temperature of the upper volume is equal to the volume weighted average temperature of the entering water. The temperature of the lower part is equal to the water temperature of the tank at the start of the test.

The calculation of the fully mixed tank, M_{mix}, is carried out by determining the water volume entering the tank during the time step in question. The mixed temperature by the end of the time step is then determined based on the weighted energy of the water entering the tank and the energy of the water remaining in the tank.

As suggested by (Haller et al. 2009) the stratification efficiency is defined as:

$$\text{Stratification efficiency } = 100 \cdot (1 - MIX) \tag{4}$$

For a perfectly stratified tank the stratification efficiency is 100%, while the stratification efficiency is 0% for a fully mixed tank. The stratification efficiency is always between 0% and 100%.

It should be mentioned that the above defined method is different from the methods used or described by (Davidson et al. 1994, Andersen et al. 2007, Haller et al. 2009). This method disregards both the influence of the tank heat loss and the heat capacity of all other parts of the test tank than the water. This is reasonable due to the relatively low heat loss of the test tank, the short test periods and the low specific heat capacity of the polymer tank. Theoretical investigations indicated that the stratification efficiency was only affected up to 2% if the heat loss was considered.

It is only possible to use the described method for top charge teste and not the intermediate charge test, because the method relies on the momentum of energy. In the intermediate charge test the volume exchanged with 50 °C water will overshadow the results of the inlet of the 30 °C and therefore not indicate whether or not the tested stratifiers are able to deliver the water at the right level of the tank.

Therefore the energy content in each layer of the test tank is calculated for each time step during the intermediate charge test, showing if energy was lost or gained in the laying question. The ideal stratification during intermediate charge test is where the energy content in the top layers is unfazed by the incoming 30 °C water, and the energy content is increased in the lower layers.

Stratifiers tested

Tree different inlet stratifiers have been tested: Two SOLVIS stratifiers and one stratifier from Eyecular Technologies. Also a PEX pipe was tested. The PEX pipe was a simple rigid pipe with an inner and outer diameter of 16 mm and 20 mm respectively and an opening in the top, see Figure 2-A. The SOLVIS stratification inlet pipe was a rigid polymer pipe with three openings with “non-return” valves for each 30 cm height. One SOLVIS pipe had an opening in the top, see Figure 2-B, the other had a T-piece at the top, see Figure 2-C. The SOLVIS stratification inlet pipes are from Solvis GmbH & Co KG (Krause and Kühl 2001).

The stratifier from EyeCular Technologies was a flexible inlet stratifier with openings in many levels along the length of the stratifier, see Figure 2-D.

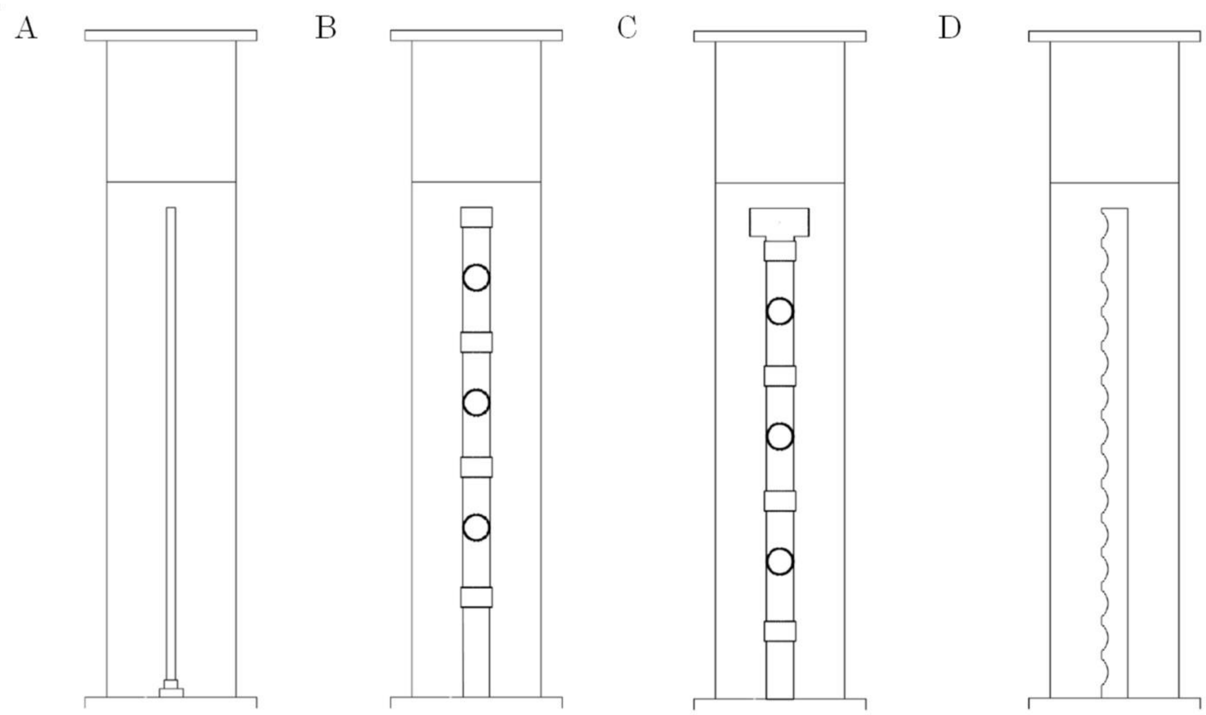

Figure 2. Tested inlet stratifiers. From left to right: PEX pipe, Solvis without T-pipe, Solvis with T-pipe and EyeCular Technologies stratifier.

The distance between the surface of the water and the top of the upper outlets/openings of the four inlet stratifiers was 6 cm. This means that the water during charge tests could enter the tank from the stratifiers at the same level, through the top of in the PEX pipe, through the top and the T-pipe of the SOLVIS pipes and through the top of the EyeCular Technologies stratifier. In this way a fair comparison between the inlet stratifiers was possible.

RESULTS

Top charge test

Figure 3, Figure 4 and Figure 5 show the results from the tests with the four tested inlet stratifiers. The measurements are shown with dimensionless temperatures on the x-axis and the height of the tank on the y-axis during the charge test. The results are shown after 15 l, 30 l and 45 l of water is replaced.

$$Dimensionless\ temperature = \frac{T - T_{tank,start}}{T_{inlet} - T_{tank,start}} \qquad (5)$$

where T is the temperature in the layer in question [°C]

$T_{tank,start}$ is the start temperature in tank [°C]

T_{inlet} is the inlet temperature [°C]

The dimensionless temperature is used in order to eliminate the differences of the start temperatures and the inlet temperature for the different tests.

The volume flow rates during the tests were 1 l/min, 2 l/min and 4 l/min.

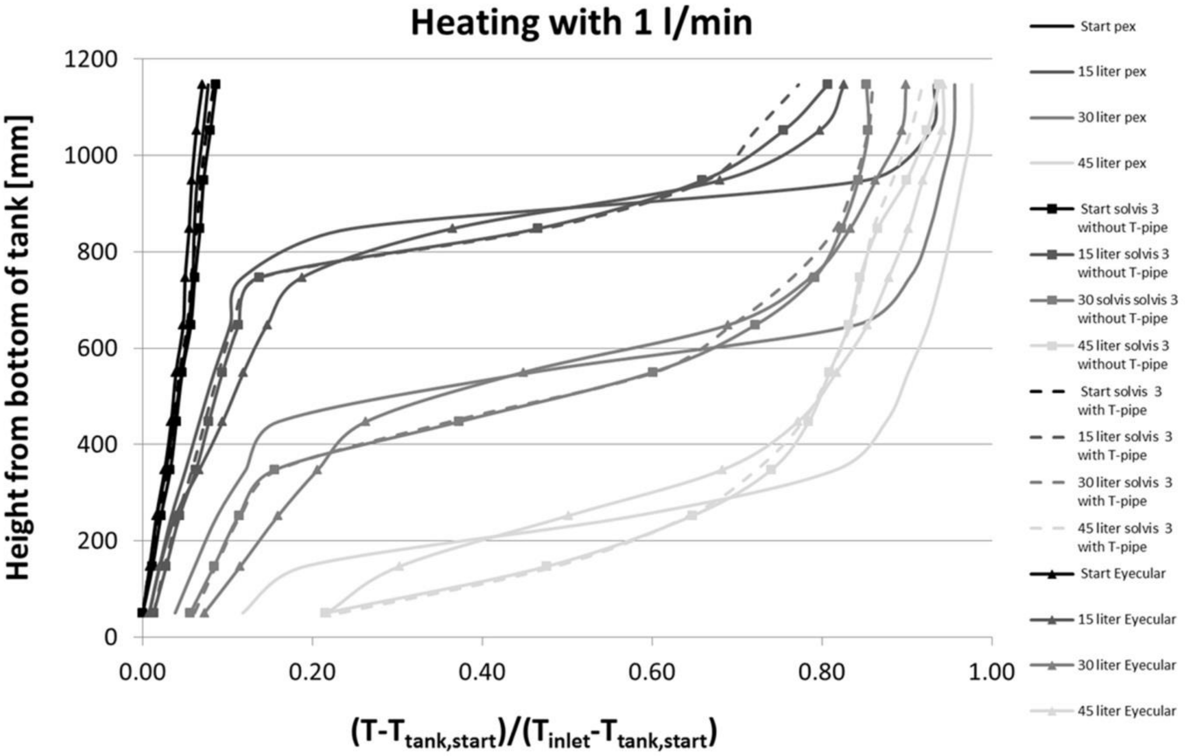

Figure 3. Dimensionless temperature profiles during charge tests for the four inlet stratifiers with a volume flow rate of 1 l/min.

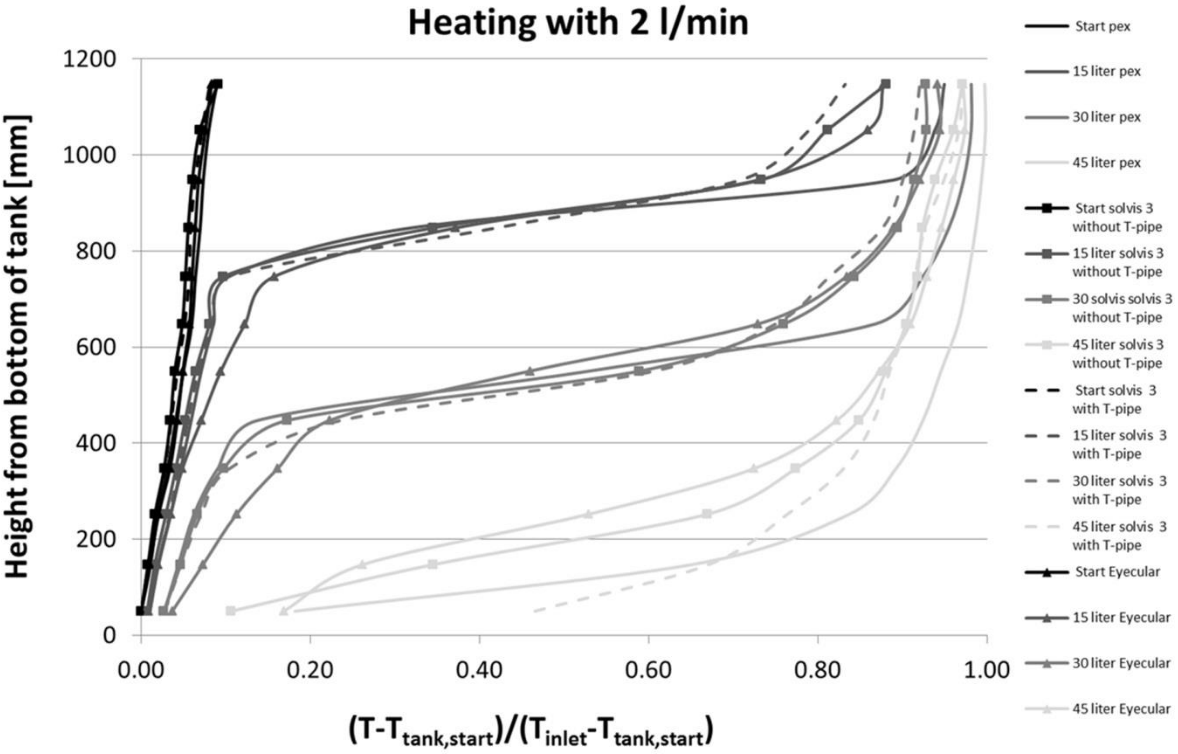

Figure 4. Dimensionless temperature profiles during charge tests for the four inlet stratifiers with a volume flow rate of 2 l/min.

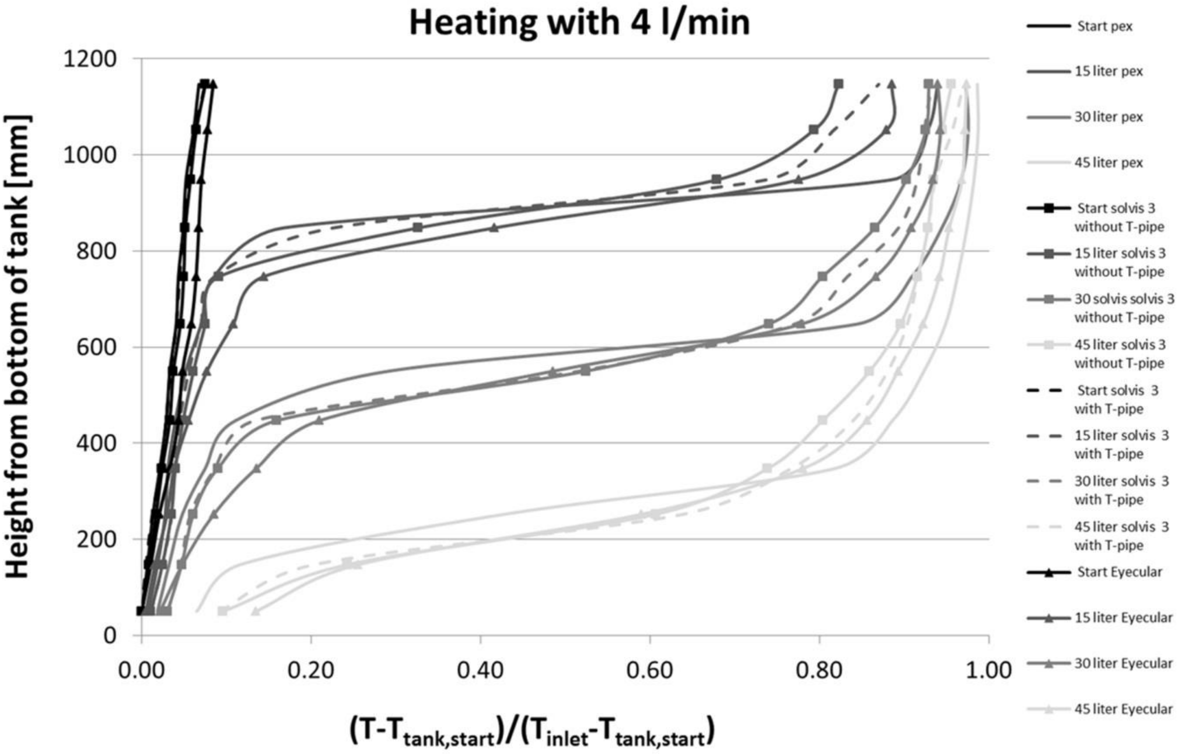

Figure 5. Dimensionless temperature profiles during charge tests for the four inlet stratifiers with a volume flow rate of 4 l/min.

From the figures it can be observed that thermal stratification in the tank was built up in a good way for all the tested inlet stratifiers at all the tested flow rates.

The thermal stratification was established best by the PEX pipe, since it achieved the highest temperature at the top of the tank while little increase in temperature was achieved in the lower levels in the tank after 15 l, 30 l and 45 l. The SOLVIS stratifiers both delivered high temperatures at the top of the tank but also an increase in temperature in the lower part of the tank which is best seen after 30 l has been exchanged with a volume flowrate of 1 l/min, see Figure 3. The stratifier from Eyecular also delivered a higher temperature at the top of the tank than the SOLVIS stratifiers, but again an increase in temperature is seen in the lower part of the tank, again best seen after 30 l at 1 l/min, see Figure 3.

Figure 6 shows the stratification efficiencies for the 12 tests. The stratification efficiencies after a full replacement of the water volume in the 54 l tank ranged from 68% to 92% with the highest efficiencies for the PEX pipe with 92 % at 2 l/min. The thermal stratification for the SOLVIS stratifiers was delayed because of the relatively large water content in the stratifier (about 3 l), which is seen for all flowrates on Figure 6.

The stratification efficiencies are higher for 4 l/min than for 2 l/min and 1 l/min.

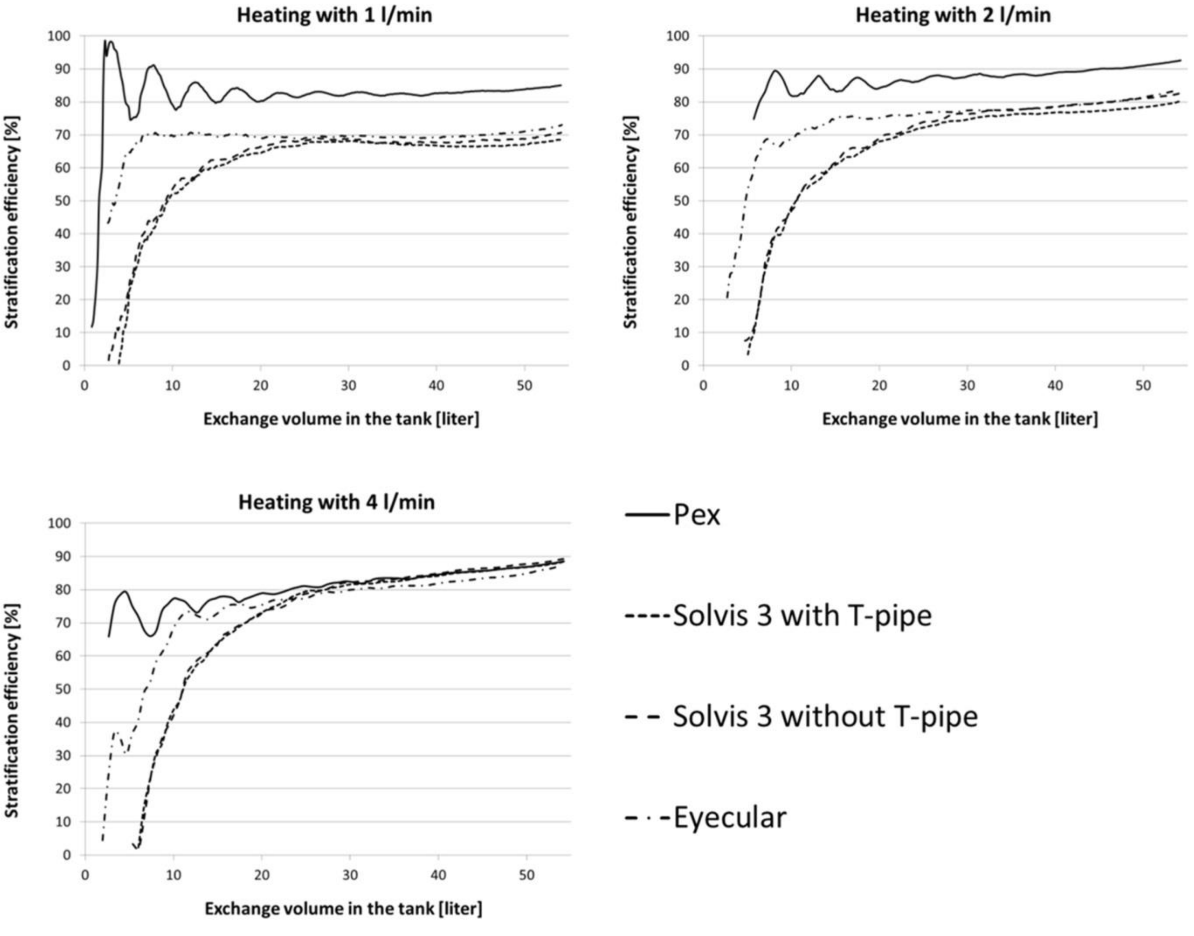

Figure 6. Stratification efficiencies during charge tests for four different inlet stratifiers with a volume flow rate of 1 l/min, 2 l/min and 4 l/min.

The stratification efficiencies of the SOLVIS stratifiers and the EyeCular stratifier were similar, see Table 1. The PEX pipe has as expected the best stratification efficiency at 1 l/min and 2 l/min. At 4 l/min the SOLVIS stratifier has a slightly higher efficiency than the PEX pipe.

The SOLVIS stratifiers and the Eyecular stratifier both performed well at the tested flow rates. At 1 l/min and 2 l/min the best result is achieved with the stratifier from EyeCular, see Table 1. At 4 l/min the best result is with the SOLVIS stratifier without the T-pipe. Of the two SOLVIS stratifiers the one without the T-pipe performs the best compared with the one with the T-pipe, see Table 1.

Table 1 Stratification efficiency after a full replacement of the water volume at flow rate 1 l/min, 2 l/min and 4 l/min.

	Flowrate		
	1 l/min	2 l/min	4 l/min
Pex - reference	85 %	92 %	88 %
Solvis with T-pipe	68 %	80 %	88 %
Solvis without T-pipe	70 %	82 %	89 %
EyeCular	72 %	83 %	87 %

Intermediate charge test

The intermediate charge test is where the test tank is first heated with 50 °C water until half of the volume is exchanged, then the inlet temperature is lowered to 30 °C and the rest of the volume is exchanged, see Figure 7 where the temperature profiles are shown for the flow rate of 1 l/min. The results show that all three stratifiers are working well and that the Pex-pipe is not suitable as a stratifier. This is seen be the decrease in temperature in the top layers of the test tank when the inlet temperature is lowered to 30 °C.

The temperature profiles for the flow rates of 2 l/min and 4 l/min show the same tendency.

The results are shown on Figure 8, Figure 9 and Figure 10 for the flow rates 1 l/min, 2 l/min and 4 l/min with the four stratifiers. The figures give the power transferred to each of the 12 layers in the test tank during the intermediate charge test. Layer 0 represent the bottom of the tank and layer 11 the very top layer. The inlet temperature is given on alternate y-axes.

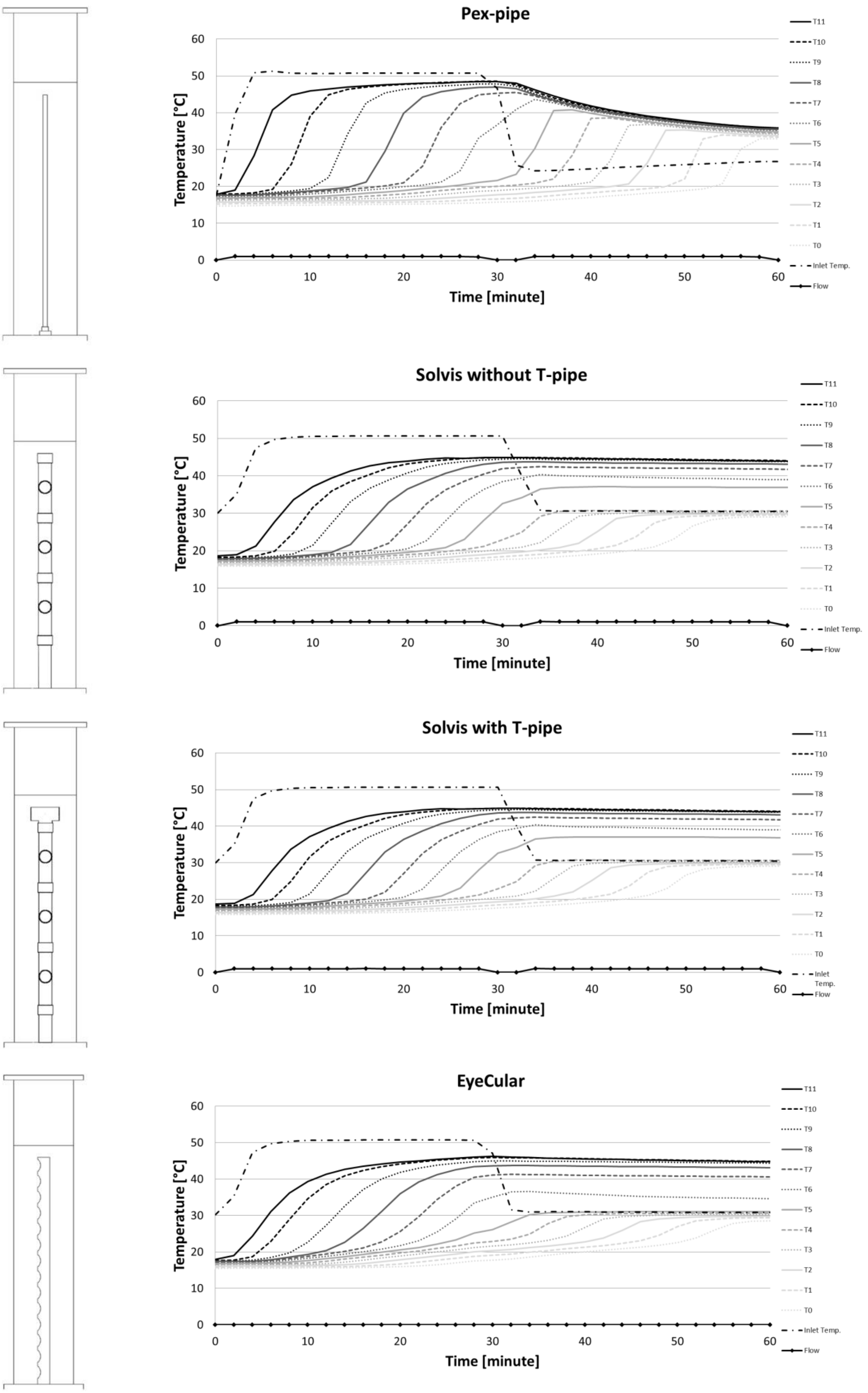

Figure 7. Temperature measurements from intermediate charge of the four devices at a flow rate of 1 l/min.

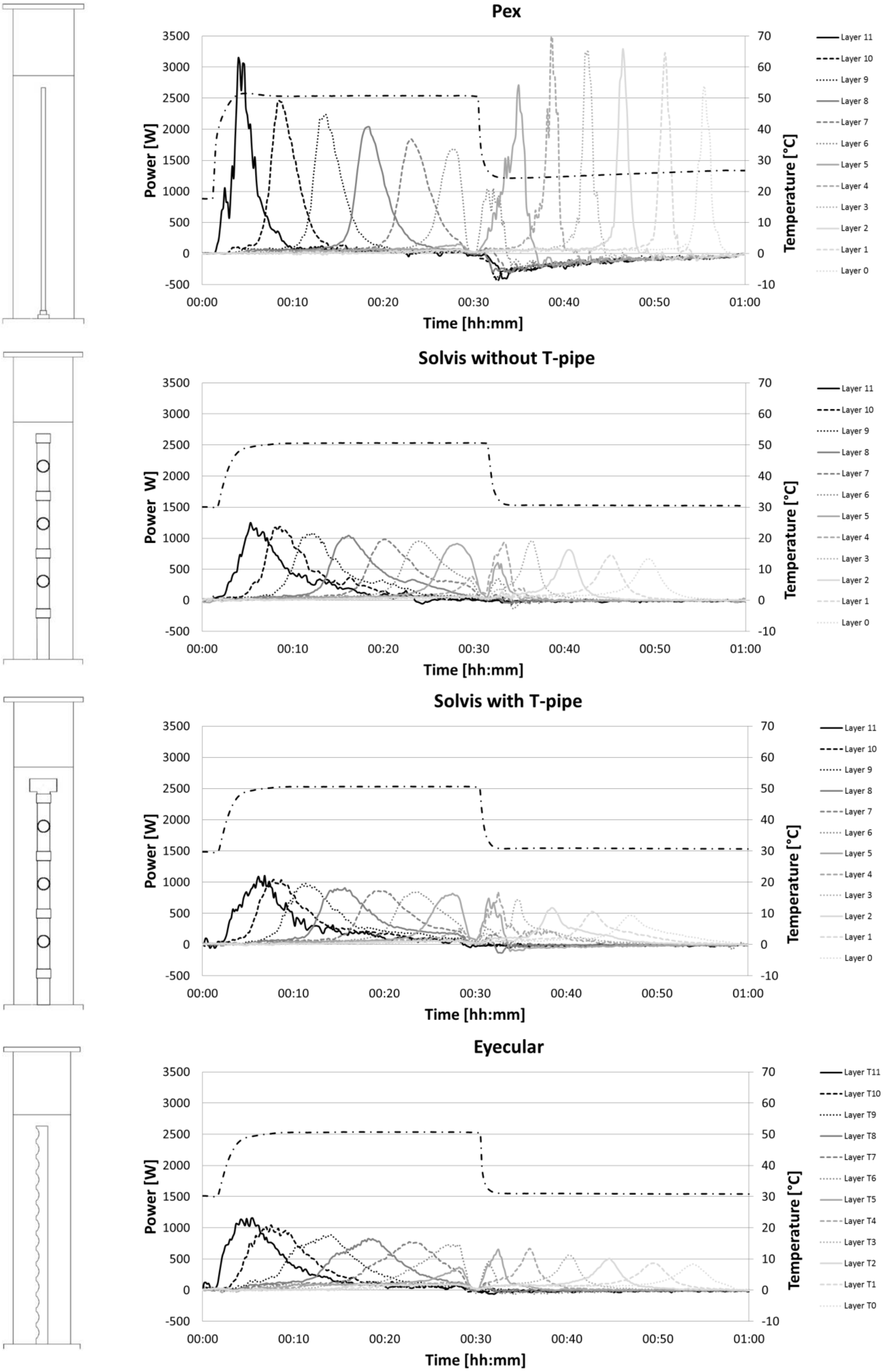

Figure 8. Power transferred to each layer for the intermediate charge for the four inlet devices at a flow rate of 1 l/min.

The results with the flow rate of 1 l/min, see Figure 8, show that the pex-pipe performs poorly as expected. This is seen by the negative heat transfer for the upper layers of the tank when the inlet temperature is lowered to 30 °C, explained by the fact that the pex-pipe only has one opening at the top leading the colder water to the top of the test tank. The colder water mixes with the 50 °C water lowering the tank temperature at the top.

The results with the 3 stratifiers show that when the inlet temperature is lowered to 30 °C there are larger negative heat transfers in the upper layers for the SOLVIS stratifiers compared with the EyeCular stratifier. This indicates that a part of the 30 °C water has entered higher in the tank than what would have been ideal. This is explained by the fixed and limited openings in the SOLVIS pipes, not ensuring the incoming water to enter the tank at the right level. However, the durations of the periods with the XXX negative heat transfer are short.

Table 2 Lost and gained energy in each layer from the period of the intermediate charge test with inlet temperature of 30°C and flow rate of 1 l/min.

Layer number	Pex-pipe kJ	Solvis with T-pipe kJ	Solvis without T-pipe kJ	EyeCular kJ
Layer 11	**-232**	**-21**	**-18**	**-26**
Layer 10	**-235**	**-17**	**-15**	**-18**
Layer 9	**-225**	**-9**	**-13**	**-10**
Layer 8	**-212**	**-12**	**-11**	**-9**
Layer 7	**-183**	6	**-7**	**-7**
Layer 6	**-22**	11	1	**-5**
Layer 5	252	34	64	93
Layer 4	276	184	129	146
Layer 3	291	198	180	163
Layer 2	306	209	194	177
Layer 1	320	219	206	192
Layer 0	325	223	214	201

In Table 2 the total lost and gained energy for the period when the inlet temperature is 30 °C is given for each layer in the tank. Here it can be seen that the overall lost energies from the upper layers for both SOLVIS stratifiers are slightly lower than that for the stratifier from EyeCular, indicating the temperatures in the top of the tank with the EyeCular stratifier is slightly more affected with the inlet temperature lowered to 30°C.

The results from the Pex-pipe show that the Pex-pipe is not suitable as a stratification device, and is here included as a reference to show how mixing will influence the intermediate charge test results.

The results with a flow rate of 2 l/min seen on Figure 9 are similar to the result with 1 l/min. Again larger peaks of lost energy are seen for the SOLVIS stratifiers and not for the stratifier from EyeCular.

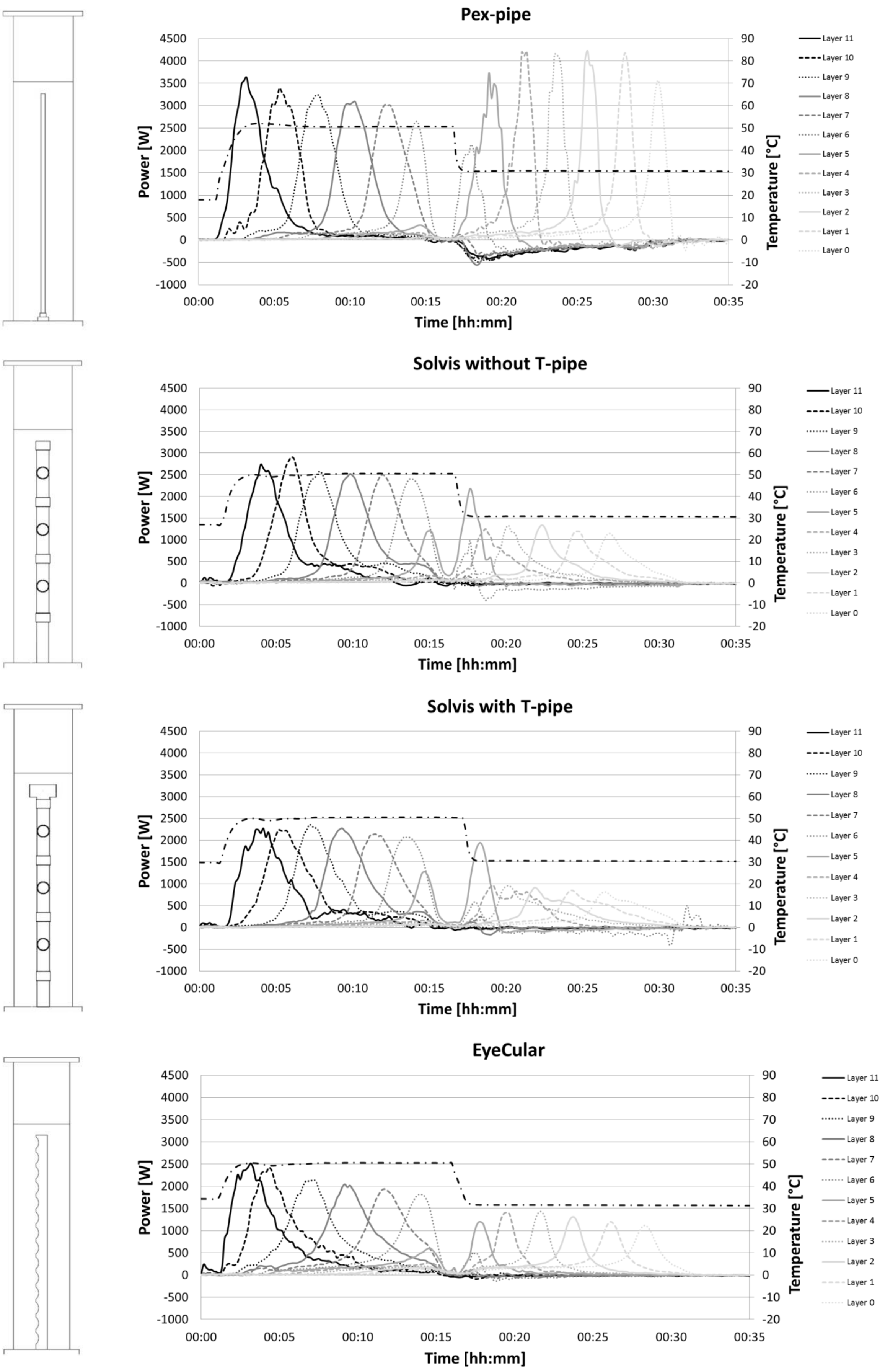

Figure 9. Power transferred to each layer for the intermediate charge for the four inlet devices at a flow rate of 2 l/min.

The total lost and gained energy for 2 l/min are seen in Table 3. For both SOLVIS stratifiers it can be seen that there is lost energy from layer 6 and gained energy in layer 7 above layer 6. This indicates that level where the 30 °C water enters the tank is not the right level according to the temperature, again explained by the limited inlets to the tank through the SOLVIS stratifiers.

The total lost energy in the upper layers for the stratifier from EyeCular is here lower than the total lost energy in the upper layers for the SOLVIS stratifiers. For 1 l/min it was the other way around.

Table 3 Lost and gained energy in each layer from the period of the intermediate charge test with inlet temperature of 30°C and flow rate of 2 l/min.

Layer number	Pex-pipe kJ	Solvis with T-pipe kJ	Solvis without T-pipe kJ	EyeCular kJ
Layer 11	**-183**	**-14**	**-14**	**-16**
Layer 10	**-185**	**-13**	**-11**	**-14**
Layer 9	**-182**	**-8**	**-14**	**-6**
Layer 8	**-169**	**-10**	**-5**	**-6**
Layer 7	**-138**	10	3	**-8**
Layer 6	74	**-50**	**-56**	**-4**
Layer 5	321	123	160	124
Layer 4	354	226	231	175
Layer 3	376	230	236	198
Layer 2	393	232	239	215
Layer 1	402	235	243	232
Layer 0	285	222	232	235

The results from the Pex-pipe again show it is not suitable as a stratification device.

On Figure 10 the result are shown for flow rates of 4 l/min. The same tendencies are seen here as for 2 l/min. The energies lost from the upper layers for the SOLVIS stratifiers are increased which can be seen on the figures by the increase in negative values when the inlet temperature is changed to 30 °C.

For 4 l/min it can be seen that more energy is lost from the upper layers through the stratifier from EyeCular than for the lower flow rates.

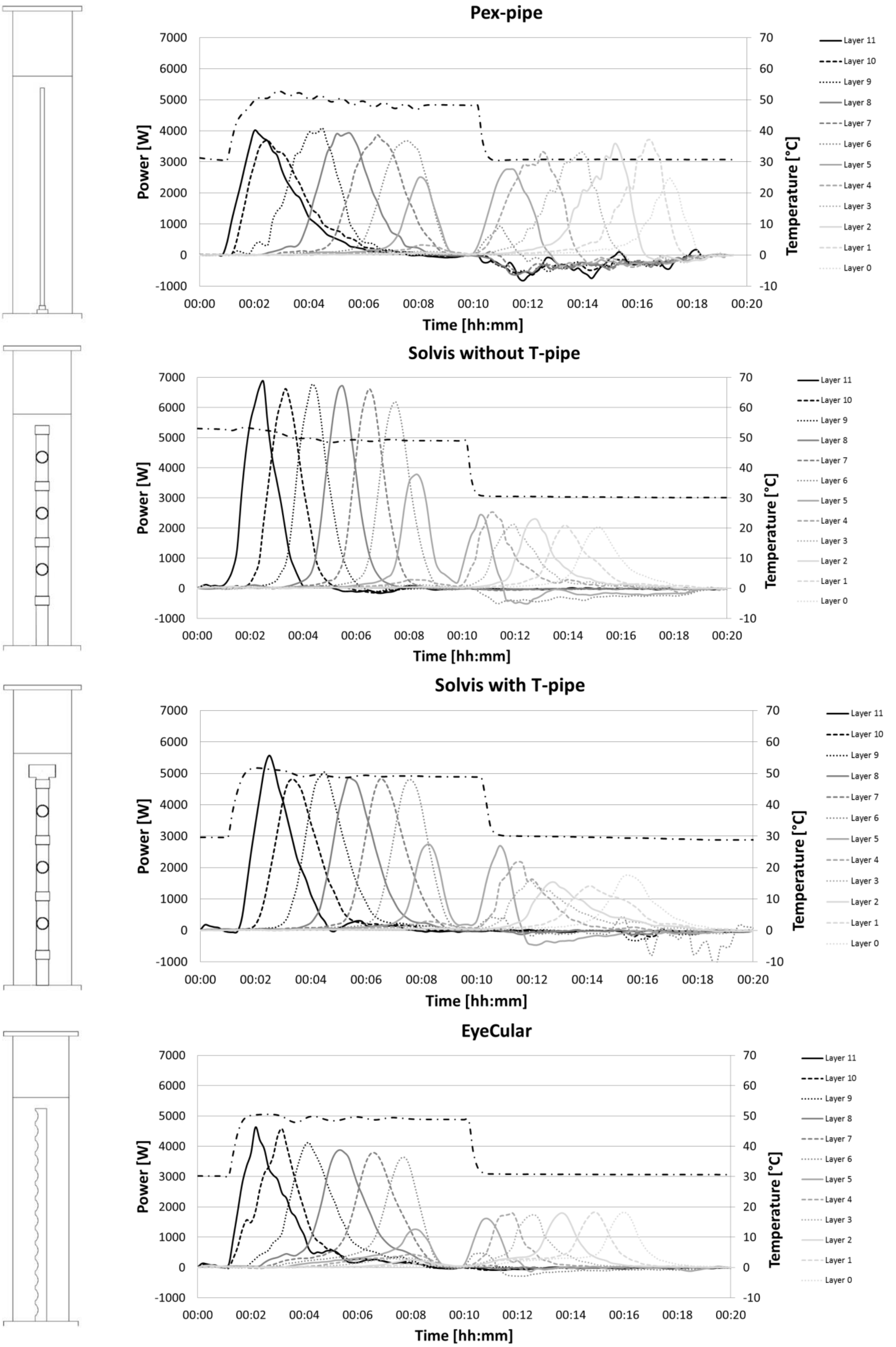

Figure 10. Power transferred to each layer for the intermediate charge for the four inlet devices at a flow rate of 4 l/min.

In Table 4 the total energies lost and gained for each layer during the period with an inlet temperature of 30 °C are shown. Again it can be seen that the stratifier from EyeCular performs better than the both stratifiers from SOLVIS.

Table 4 Lost and gained energy in each layer from the period of the intermediate charge test with inlet temperature of 30°C and flow rate of 4 l/min.

Layer number	Pex-pipe kJ	Solvis with T-pipe kJ	Solvis without T-pipe kJ	EyeCular kJ
Layer 11	**-147**	**-11**	**-4**	**-12**
Layer 10	**-145**	**-21**	**-5**	**-11**
Layer 9	**-145**	**-30**	**-3**	**.5**
Layer 8	**-143**	**-22**	**-5**	**.4**
Layer 7	**-124**	**-16**	**-9**	**-6**
Layer 6	**-43**	**-33**	**-66**	**-30**
Layer 5	196	82	103	105
Layer 4	361	251	239	166
Layer 3	388	244	222	186
Layer 2	398	239	186	202
Layer 1	396	234	66	219
Layer 0	203	230	15	221

Over all the intermediate charge tests show that for flow rates between 2 l/min and 4 l/min the Eyecular stratifier performs better than both SOLVIS stratifiers, since the temperatures of the upper layers are influenced less for the EyeCular stratifier than for the SOLVIS stratifiers. At a flow rate of 1 l/min both stratifiers from SOLVIS performs slightly better than the stratifier from EyeCular.

DISCUSSION

The small, high and slim polymer tank design combined with the applied method of analysis reduced the influence of the test tank design on the test results.

The experimental investigations elucidated the suitability of differently designed inlet stratifiers during the tests in a clear way. The tests can therefore be useful in connection with development of inlet stratifiers.

However, it must be mentioned that it is assumed that the method used to determine the stratification efficiency somewhat underestimates the stratification efficiency. The reason is that a hot water volume is always available inside the inlet stratifier during the charge test and that the heat content of this water volume first will be released to the tank after the end of the charge period. It is therefore assumed that for increasing water content of the stratifier, the underestimation of the stratification efficiency increases. The method therefore may have resulted in a slightly too low stratification efficiencies especially for the SOLVIS stratifiers, which had relatively high water volumes of about 3 l.

CONCLUSIONS

Laboratory tests in a test tank with different inlet stratifiers were carried out with the aim to elucidate how well thermal stratification was established under controlled laboratory conditions. A modified analysis method was used to determine stratification efficiencies for the inlet stratifiers.

The test tank and the test method form a good basis for development of inlet stratifiers and for a comparison of different inlet stratifiers.

All the tested stratifiers performed well in the top charge tests. The stratifier from Eyecular performed better that the SOLVIS stratifiers at 1 l/min and 2 l/min. At 4 l/min both SOLVIS stratifiers performed better that the EyeCular stratifier.

For the intermediate charge test the limited number of inlets to the tank through the SOLVIS stratifiers affect the energy content in the upper layers negatively by decreasing the energy content when the inlet temperature in changed to 30 °C.

For intermediate charge tests, the EyeCular stratifier had a better performance compared to the SOLVIS stratifiers for flow rates between 2 l/min and 4 l/min.

The stratifier from EyeCular had slightly higher heat losses along the length of the stratifier compared to the two SOLVIS stratifiers. The heat loss is reduced with increasing flow rates and had little impact on the overall performance.

REFERENCES

Andersen E., Furbo S. 2006. Fabric inlet stratifiers for solar tanks with different volume flow rates. Proceedings EuroSun 2006 Congress, Glasgow, Scotland.

Andersen E., Furbo S. 2007. Theoretical comparison of solar water/space heating combi systems and stratification design options. Journal of solar Energy Engineering, Vol. 129, issue 4, pp. 438-448.

Andersen E., Furbo S., Fan J. 2007. Multilayer fabric stratification pipes for solar tanks. Solar energy, Vol. 81, pp. 1219-1226.

Andersen E., Furbo S., Hampel M., Heidemann W., Müller-Steinhagen H. 2007. Investigations on stratification devices for hot water stores. International Journal of energy research, Volume 32, issue 3, pp. 255-263.

Andersen E., Jordan U., Shah L.J., Furbo S. 2004. Investigations of the SOLVIS stratification inlet pipe for solar tanks. In: EuroSun 2004 Proceedings, Freiburg, Germany, Vol. 1, pp. 076-085.

Brown N. M., Lai F. C. 2011. Enhanced thermal stratification in a liquid storage tank with a porous manifold. Solar Energy, Vol. 85, pp. 1409-1417.

Davidson J.H., Adams D.A., Miller J.A. 1994. A coefficient to characterize mixing in solar water storage tanks. Transaction of the ASME. Journal of Solar Energy Engineering 116, pp. 94-99.

Furbo S., Andersen E., Thür A., Shah L.J., Dyhr Andersen K. 2005. Advantages by discharge from different levels in solar storage tanks. Solar Energy 79 (5), pp. 431-439.

Furbo S., Knudsen S. 2006. Improved design of mantle tanks for small low flow SDHW systems. International Journal of Energy research, Vol: 30, Issue 12, pp. 955-965.

Furbo S., Mikkelsen S.E. 1987. Is low flow operation an advantage for solar heating systems?. In: Advances in Solar Energy Technology, Vol. 1., Pergamon Press, Oxford, pp. 962-966.

Furbo S., Shah L.J. 2005. How mixing during hot water draw-offs influence the thermal performance of small solar domestic hot water systems. Proceedings ISES Solar World Congress 2005, Orlando, USA.

Furbo S., Vejen N.K., Shah L.J. 2005. Thermal performance of a large low flow solar heating system with a highly thermally stratified tank. Journal of Solar Energy Engineering, transaction of the ASME, Vol. 127, Issue 1, pp. 15-20.

García-Marí E., Gasque M., Gutiérrez-Colomer R. P., Ibáñez F., González-Altozano P. 2013. A new inlet device that enhances thermal stratification during charging in a hot water storage tank. Applied Thermal Engineering, Vol. 61, pp. 663-669.

Hahne E., Chen Y. 1998. Numerical study of flow and heat transfer characteristics in hot water stores. Solar Energy, Vol. 64, pp. 9-18.

Haller M.Y., Cruickshank C.A., Streicher W., Harrison S.J., Andersen E., Furbo S. 2009. Solar Energy, Vol. 83, number 10, pp. 1847-1860.

Han Y.M., Wang R.Z., Dai Y.J., Thermal stratification within the water tank. Renewable and sustainable Energy Reviews 13, pp. 1014-1026.

Hollands K. G. T., Lightstone M. F. 1989. A review og low-flow, stratified-tank solar water heating sysytems. Solar Energy, Vol. 43, number 2, pp. 97-105.

Jordan U., Furbo S. 2005. Thermal Stratification in Small Solar Domestic Storage Tanks caused by Draw-offs. Solar Energy, Vol. 78/2, pp. 291-300.

Knudsen S., Furbo S. 2004. Thermal stratification in vertical mantle heat exchangers with application to solar domestic hot water systems. Applied Energy, Vol. 78/3, pp. 257-272.

Kraus T., Kühl L. 2001. Solares Heizen: Koncepte, Auslegung und Praxiserfahrungen.

Lavan Z., Thompson J., 1977. Eperimental study of thermally stratified hot water storage tanks. Solar Energy, Vol. 19, pp. 519-524.

Shah L.J., Andersen E., Furbo S. 2005. Theoretical and experimental investigations of inlet stratifiers for solar storage tanks. Applied Thermal Engineering 25 (14-15), pp. 2086-2099.

Shah L.J., Furbo S. 1998. Correlation of Experimental and Theoretical Heat Transfer in Mantle Tanks used in Low Flow SDHW Systems. Solar Energy, Vol. 64 (4-6), pp. 245-256.

Shah, L.J., Furbo S. 2003. Entrance effects in solar storage tanks. Solar Energy 75, pp. 337-348.

Panthalookaran V., Heidemann W., Müller-Steinhagen H. 2007 A new method of characterization for stratified thermal energy stores. Solar Energy, Vol. 81, pp. 1043-1054.

Phillips W. F., Dave R. N. 1982. Effects of stratification on the performance of liquid-based solar heating systems. Solar Energy, Vol. 29, number 2 pp. 111-120.

Rosen M. A. 2001. The exergy of stratofed thermal energy storages. Solar Energy, Vol. 71 number 3, pp. 173-185.

van Ruth N. J. L, New type of valve for solar solar thermal storage tank stratification. Energy Procedia 91, pp. 246-249.

van Koppen C.W.J., Thomas J.P.X, Veltkamp W.B. 1979. The Actual benefits of Thermally Stratified Storage in a Small and medium Size Solar System. In: Proceedings of ISES Solar World Congress, Atlanta, USA, pp 579-80.

Wang S., Davidson J. H. 2015. Selection of permeability for optimum performance of a porous tube thermal stratification manifold. Solar Energy, Vol 122, pp. 472-485.

Wang S., Davidson J. H. 2016. Fluid-structure interaction in flexible porous stratification manifold. Journal of Solar Energy Engeneering, Vol 138.

Weiss W. (Ed.) 2003. Solar Heating Systems for Houses. A design Handbook for Solar Combisystems. James & James Ltd. Solar heating and Cooling Executive Committee of International Energy Agency (IEA).