THERMAL STRATIFICATION IN HOT WATER STORAGE TANKS WITH FABRIC STRATIFICATION INLET PIPES

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1. Abstract

Double walled Fabric inlet stratification pipes made of Teflon and Polyester are investigated experimentally with the aim to study the thermal stratification that is build up in a hot water tank. The fabric pipes are mounted in the centre of a transparent circular acrylic tank from the bottom to the top of the tank. The thermal stratification is investigated during charge and discharge with inlet to the fabric pipes through the top of the tank and through the bottom of the tank. The fabric pipes are closed in the end opposite to the inlet. During charge, the outlet is at the bottom of the tank and during discharge, the outlet is at the top of the tank.
The investigations show that the use of fabric inlet stratification pipes significantly improves the thermal stratification compared to the thermal stratification in the tank with no inlet stratification device. This is true both with inlet to the fabric pipes through the bottom and the through top of the tank. The investigations also show that the thermal stratification during charging is build up best with inlet to the fabric stratification pipe through the top of the tank while the thermal stratification during discharge is build up best with inlet to the fabric stratification pipe through the bottom of the tank. Finally, the investigations show that thermal stratification all in all is build up better with inlet to the fabric stratification pipes through the bottom of the tank than with inlet to the pipes through the top of the tank.

2. Introduction

Thermal stratification in hot water storage tanks for solar heating systems can be achieved in different ways. Excellent thermal stratification can be established in the tank when water heated by the solar collectors or water returning from the heating system is lead into fabric stratification inlet pipes through the bottom of the tank. The pipes are made of two concentric mounted fabric pipes with different diameters (Andersen, 2007). With a well performing fabric stratification pipe, the cross section area of the pipe is flexible. The most important function of the fabric stratification pipe is the ability to contract, whereby the cross section area of the pipe is reduced. The contraction is caused by temperature differences and thereby pressure differences between the inside of the fabric stratification pipe and the tank. When the temperature in the fabric stratification pipe is higher than the temperature in the tank, water in the tank flows toward the fabric stratification pipe due to lower pressure in the fabric stratification pipe. Thereby, the cross section area of the fabric stratification pipe is reduced. This leads to a higher velocity inside the fabric stratification pipe and thereby a higher pressure. The fabric stratification pipe contracts until the pressure difference between the inside of the pipe and the tank is eliminated. Consequently, no water from the tank will enter the fabric stratification pipe. Water from the fabric stratification pipe enters the tank at the level, where the tank temperature is the same as the temperature of the entering water. It is very important that the fabric stratification pipe is mounted vertically and that the pipe is closed in the end opposite to the inlet.

However, many tank designs have all the pipe connections in the top of the tank; hence incoming water must enter the fabric stratification pipe through the top of the tank. Fabric stratification pipes made of one fabric layer with inlet to the pipes through the top of the tank have been investigated by Davidson and Adams (1994). They found that the performance was highly dependent on the fabric style and that the performance of fabric pipes over a reasonable range of operation conditions were better that the performance of a rigid porous manifold. The natural forces that make the fabric pipe work with inlet to the pipe through the bottom of the tank are not the same as with inlet to the pipe through the top of the tank. During heating, the incoming water has a low density and will therefore stay at the top of the tank regardless of a fabric stratification pipe or not. During cooling, the pressure in the fabric stratification pipe is higher than the pressure in the tank. Hence natural forces will make the cold water flow towards the tank in all levels. The velocity of the incoming cold water together with the gravity will result in some kind stratification during cooling, but the quality of the stratification is highly dependent on the incoming velocity. Consequently, a high velocity is an advantage during cooling. Also here it is very important that the fabric stratification pipe is mounted vertically and that the pipe is closed in the end opposite to the inlet.

In this paper it is investigated how thermal stratification is build up in hot water storage tanks with fabric stratification pipes during charging and discharging when heated or cooled water enters the fabric stratification pipes through the top or the bottom of the tank. The investigations are carried out with different two layer fabric stratification pipes made of Teflon and Polyester fibres.

3. Experimental investigations

3.1. Experimental set up

Figure 1 shows a picture of the experimental setup consisting of a transparent circular acrylic tank with a diameter of 388 mm and a height of 1270 mm. The tank is not insulated. The fabric stratification pipes are mounted in the centre of the tank and a forced volume flow can enter the stratification pipe either from the bottom or the top of the tank. The outlet can take place from the bottom or the top of the tank. In this way heated or cooled water can be charged at the top or at the bottom of the tank and water can be discharged from the top or the bottom of the tank. The fabric stratification pipes are closed in the end opposite to the inlet.

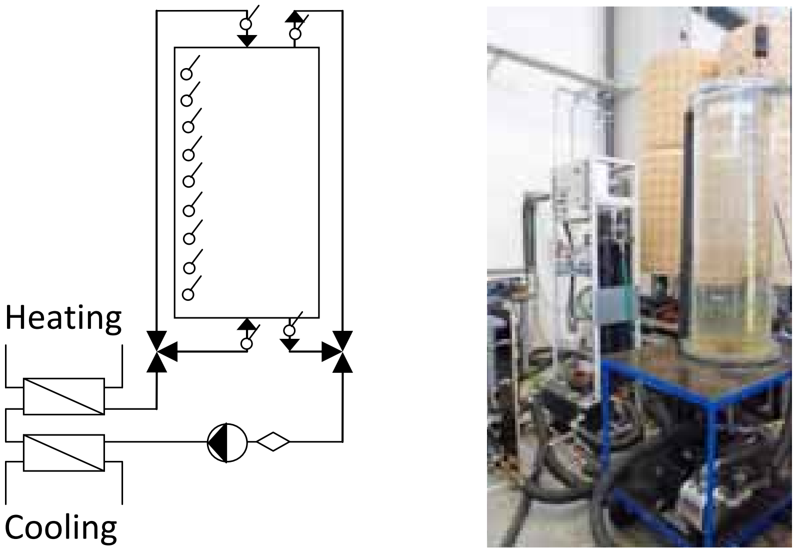

Fig. 1: Experimental set up. Left: A schematic illustration. Right: A photo.

The volume flow rate is measured by Brunata HGQ energy meter. The temperatures are measured with copper-constantan thermocouples type TT. The temperature sensors which are mounted in the tank can be seen in Figure 1 and the sensors are positioned as shown in table 1.

Tab. 1: Sensor positions.

Sensor number	Height from bottom of tank [mm]
1	80
2	220
3	360
4	505
5	645
6	785
7	930
8	1075
9	1210

3.2. Experiments

The thermal behaviour of three different types of fabric inlet stratification pipes made of two concentric fabric pipes with diameters of 30 mm and 50mm is investigated during charging and discharging. The operation conditions are:

- Charging with inlet to the fabric stratification pipe through the bottom of the tank. The start temperature of the tank is around 20°C and the water that enters the fabric stratification pipes is 40°C. The outlet is in the bottom of the tank.
- Discharging with inlet to the fabric stratification pipe through the bottom of the tank. The start temperature of the tank is around 40°C and the water that enters the fabric stratification pipes is 20°C. The outlet is in the top of the tank.
- Charging with inlet to the fabric stratification pipe through the top of the tank. The start temperature of the tank is around 20°C and the water that enters the fabric stratification pipes is 40°C. The outlet is in the bottom of the tank.
- Discharging with inlet to the fabric stratification pipe through the top of the tank. The start temperature of the tank is around 40°C and the water that enters the fabric stratification pipes is 20°C. The outlet is in the top of the tank.

As a reference, the thermal behaviour without inlet stratification pipe is investigated during charging and discharging through the bottom and the top of the tank. The operation conditions are as described above.
The volume flow rate is 4 l/min during charging and discharging. During the experiments, the tank is filled with water to a level of 1225 mm. Hence the water volume is 144.5 litres.

The investigated fabrics are shown in Table 2. The fabrics are obtained from the Danish company Ohmatex ApS during project cooperation (Perers et. al, 2009). The fabrics are knit with yarn made of Teflon and Polyester fibres: Polyvinylidene Fluoride (PVDF) and Polyethersulfone (PES) respectively. These fibres have some excellent qualities, among others high temperature resistance.

Tab. 2: Investigated fabric styles.

Fabric style
440 dtex PVDF
220 dtex*2 PVDF
167/36 PES

3.3. Analysis method

The tank is divided into N horizontal layers with the volume V. The temperature of each volume is measured.
In the analysis of the "momentum of energy", M, the energy of each layer of the tank E_i, is weighted by the vertical distance from the bottom of the tank to the centre of each layer, y_i. The energy of each tank layer and the "momentum of energy" are:

$$E_i = \rho_i \cdot c_i \cdot V \cdot \Delta T_i \qquad \text{(eq. 1)}$$

$$M = \sum_{i=1}^{N} y_i \cdot E_i , \qquad \text{(eq. 2)}$$

During charging, ΔT_i is the temperature difference between layer number i and the start temperature of the tank.
During discharging, ΔT_i is the temperature difference between layer number i and the end temperature of the tank when one tank volume has been exchanged.

A mixing number is derived based on the measured temperature profile and the corresponding ideal stratified and fully mixed temperature profiles.
The mix number is:

$$MIX = \frac{M_{str} - M_{\exp}}{M_{str} - M_{mix}} , \qquad \text{(eq. 3)}$$

M_{str} , $M_{\exp}$ and M_{mix} are the "momentum of energy" of a perfectly stratified tank, of the experiment and of a fully mixed tank respectively. The value of the mix number is between 0 and 1 where 0 corresponds to a perfectly stratified tank and 1 corresponds to a fully mixed tank.

The temperature profiles for the perfectly stratified tank and the fully mixed tank are calculated by means of the measured energy content of the tank. In this way heat losses and the heat capacity of the tank material are accounted for.

In the charging case, the low temperature equals the start temperature of the tank. The lower part of the tank has a volume equal to the total water volume in the tank minus the water volume which has entered the tank during the test. Based on the measured temperatures, the temperature in the upper part of the tank with a volume equal to the water volume which has entered the tank during the test is determined in such a way that the energy of the perfectly stratified tank is equal to the measured energy in the tank.
The temperature of the fully mixed tank is calculated based on the measured energy content of the tank at the time *t*.

In the discharging case, the low temperature equals the end temperature of the tank when the whole volume of the tank has been replaced once. The lower part of the tank has a volume equal to the water volume which has entered the tank during the test. Based on the measured temperatures, the temperature in the upper part of the tank with a volume equal to the total water volume in the tank minus the water volume which has entered the tank during the test is determined in such a way that the energy of the perfectly stratified tank is equal to the measured energy in the tank.
The temperature of the fully mixed tank is calculated based on the measured energy content of the tank at the time *t*.

4. Results

4.1. Experiments

Figure 2 shows the temperature stratification in the tank in different heights after 5 minutes, 15 minutes and 25 minutes during charging test without stratification manifold with inlet through the bottom of the tank (left) and inlet through the top of the tank (right). The outlet is at the bottom of the tank.
Thermal stratification is established in a good way if the inlet is at the top and in a very poor way if inlet is at the bottom.

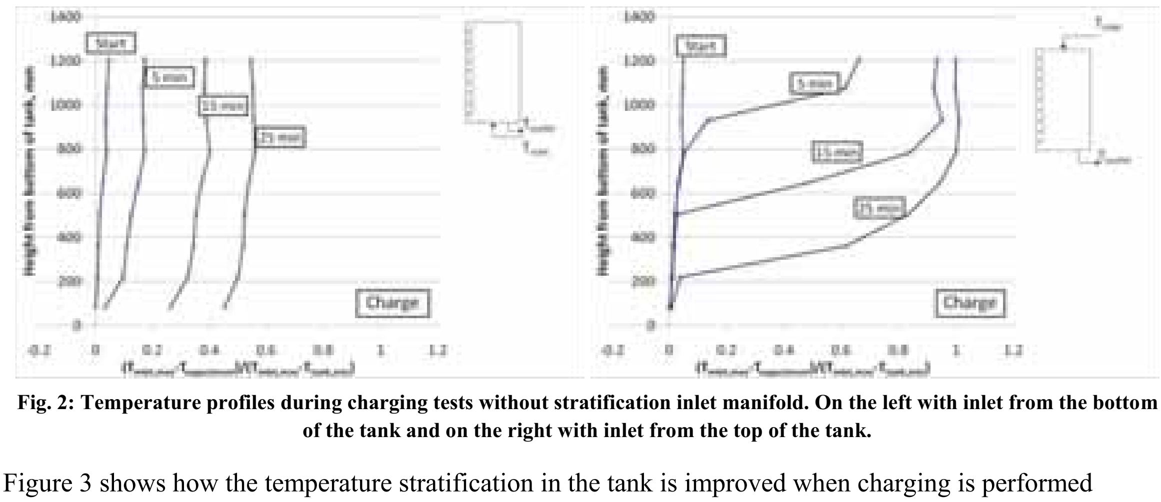

Fig. 2: Temperature profiles during charging tests without stratification inlet manifold. On the left with inlet from the bottom of the tank and on the right with inlet from the top of the tank.

Figure 3 shows how the temperature stratification in the tank is improved when charging is performed through stratification manifolds of two fabric layers. The temperature stratification is significantly improved for the operation conditions with inlet through the bottom of the tank, but an improvement can also be seen for the operation conditions with inlet through the top of the tank. In this case the improved stratification is because the fabric inlet stratifier reduces the inlet velocity and thereby the mixing in the tank.

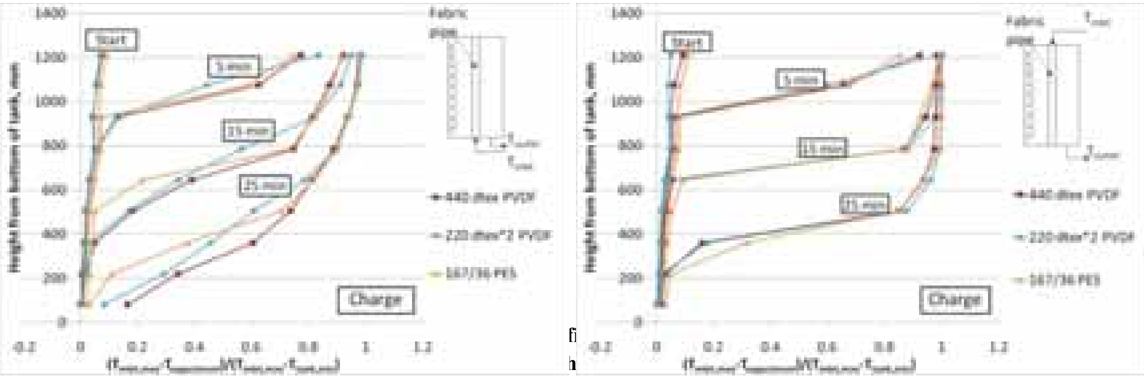

Figure 4 shows the temperature stratification in the tank in different heights after 5 minutes, 15 minutes and 25 minutes during discharging test without stratification manifold with inlet through the bottom of the tank (left) and inlet through the top of the tank (right). The outlet is at the top of the tank.
Thermal stratification is established in a good way if the inlet is at the bottom and in a very poor way if the inlet is at the top.

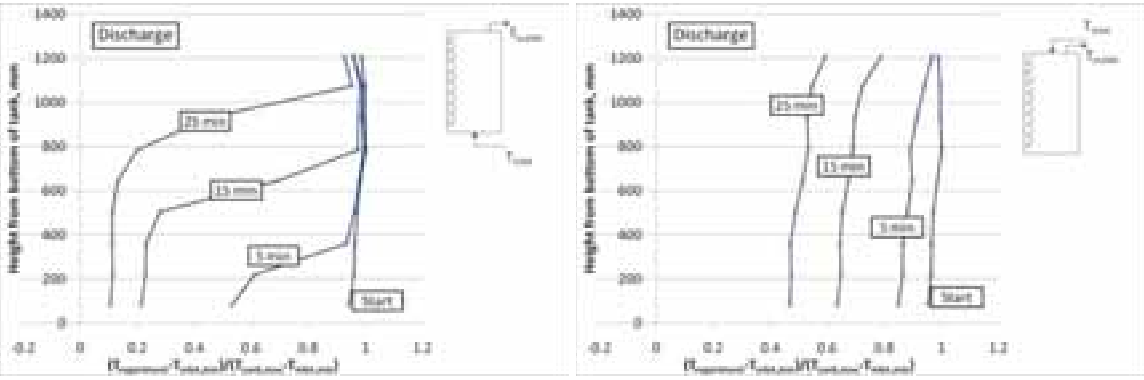

Fig. 4: Temperature profiles during discharging tests without stratification inlet manifold. On the left with inlet from the bottom of the tank and on the right with inlet from the top of the tank.

Figure 5 shows how the temperature stratification in the tank is improved when discharge is performed through stratification manifolds of two fabric layers. The temperature stratification is slightly improved for the operation conditions with inlet through the bottom of the tank and significantly improved with inlet through the top of the tank the tank. The slight improvement of the temperature stratification in the case with discharge through the bottom of the tank is because the two layer fabric pipe reduces the inlet velocity and thereby the mixing in the tank.

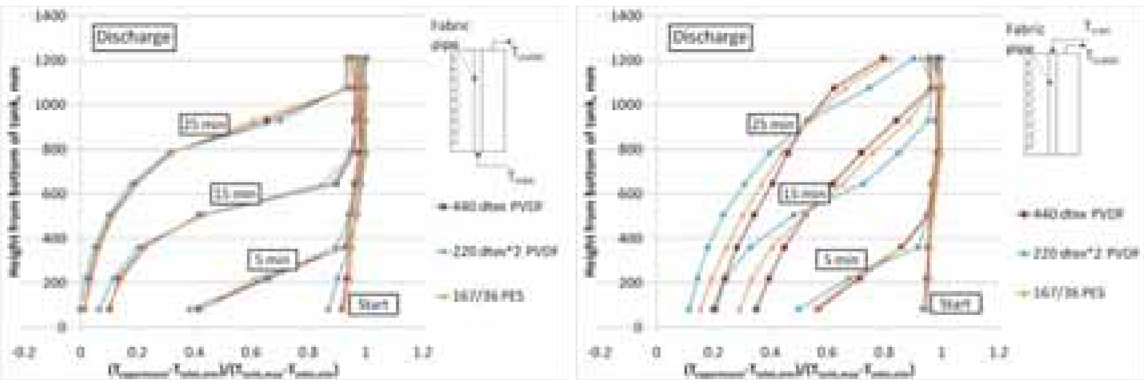

Fig. 5: Temperature profiles during discharging tests with stratification inlet manifold. On the left with inlet to the stratifier from the bottom of the tank and on the right with inlet to the stratifier from the top of the tank.

4.2. Analysis

Figure 6 shows the mix numbers during charge and discharge without inlet stratifiers with inlet from the bottom (left) or the top (right) of the tank. As expected, the mix number is high during charging with inlet from the bottom of the tank and during discharging with inlet from the top of the tank. The mix number is dramatically reduced when charging takes place from the top of the tank and discharging from the bottom of the tank.

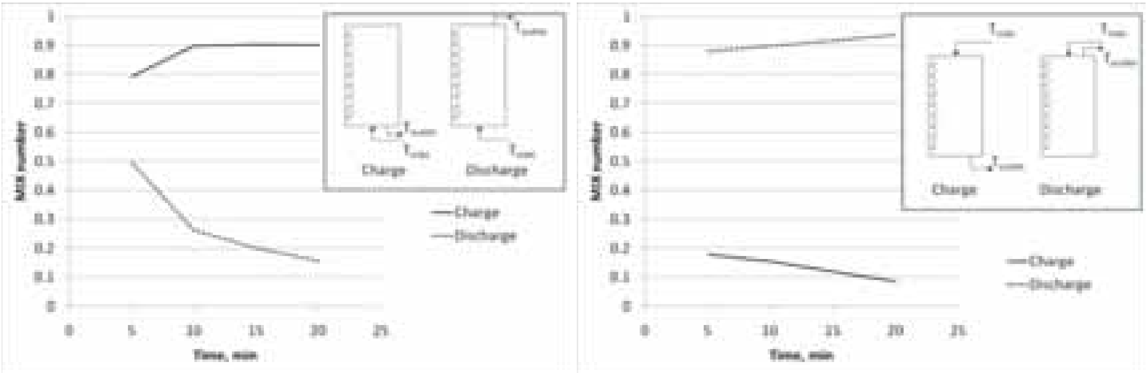

Fig. 6: Temperature profiles during charging tests without stratification inlet manifold. On the left with inlet from the bottom of the tank and on the right with inlet from the top of the tank.

The thermal behaviour of the different fabric pipes with the same operation conditions is very similar and hence only represented by one curve for each applied operation condition.

Figure 7 shows the mix numbers during charge and discharge with inlet stratifiers with inlet from the bottom (left) or the top (right) of the tank. It can be seen that the mix numbers are reduced dramatically when an inlet stratifier is used during charging through the bottom of the tank and during discharging through the top of the tank. It can also be seen that the mix number improves when an inlet stratifier is used during discharging through the bottom of the tank and charging through the top of the tank.

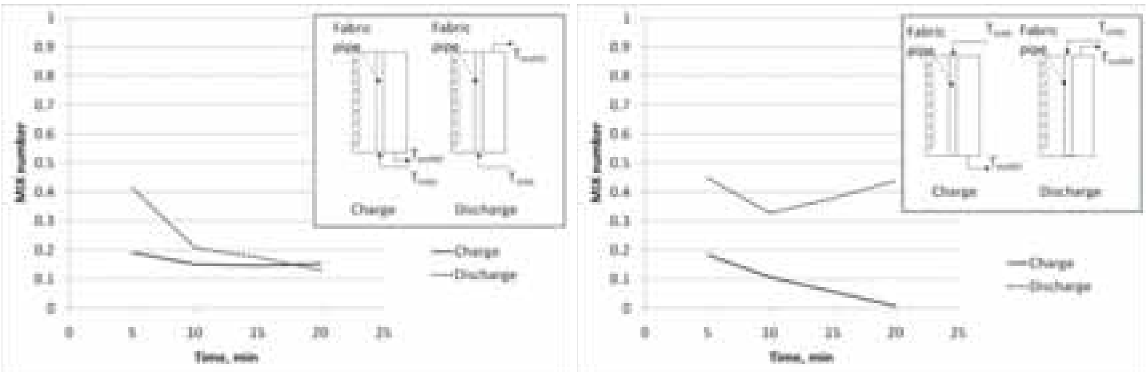

Fig. 7: Mix number during charging tests with stratification inlet manifold. On the left with inlet to the stratifier from the bottom of the tank and on the right with inlet to the stratifier from the top of the tank.

Based on the mix numbers of Figure 7 it is concluded that thermal stratification all in all is established in a better way with the inlet to the stratifier placed at the bottom of the tank than with inlet to the stratifier placed at the top of the tank.

5. Further discussion

Andersen (2007) showed that the theoretical thermal performance of solar heating systems with perfectly stratified tanks is much higher than the thermal performance of similar solar heating systems with non stratified tanks and that the thermal performance improvement was strongly dependent on the solar fraction. The smaller the solar fraction, the higher the thermal performance improvement will be. This conclusion is independent of the system size, the total consumption and the climate.

Figure 8 shows the performance ratio as function of the solar fraction. The performance ratio is calculated as the thermal performance of solar heating systems with perfectly stratified tanks divided with the thermal performance of solar heating systems with non stratified tanks. The dots in the figure represent differently sized solar heating systems under different reference conditions. The solar heating system sizes range from 5 m^2 – 60 m^2 with tank volumes in the range from 0.5 m^3 – 1.5 m^3. The different reference conditions are those used in the International Energy Agency taskforce 32 and Danish climate conditions.

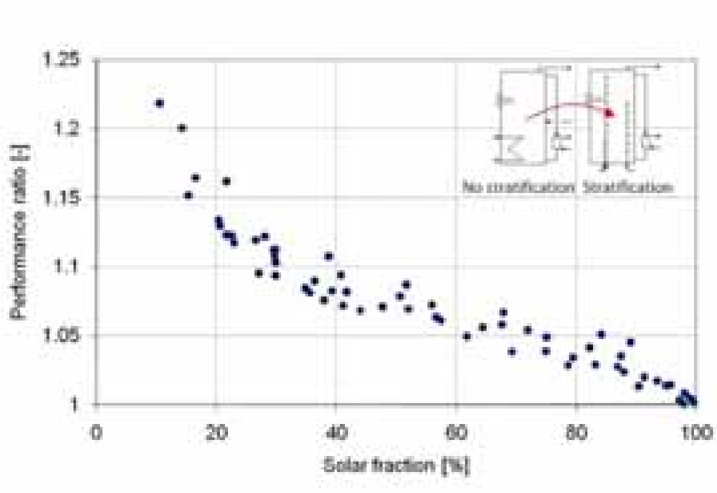

Fig. 8: Performance ratio as function of the solar fraction (Andersen and Furbo, 2008 a).

Further it was shown that the additional solar collector area needed to increase the thermal performance as much as the use of inlet stratifiers would result in, was increasing for increasing solar fraction making fabric inlet stratifiers an attractive solution for increasing the thermal performance.

An inlet at the top of the tank results in perforation of the insulation material encapsulating the hot water tank. This leads to a thermal bridge at the perforation and to a reduction of the thermal performance of solar heating systems. Furbo (1989) showed experimentally that one pipe connection at the top of the tank would increase the heat loss coefficient by 0.3 W/K – 0.5 W/K depending on the design of the pipe and pipe connection. Andersen (2007) showed theoretically that the thermal performance of a small solar heating system with an auxiliary heated volume would decrease by 20 % with a thermal bridge of 0.5 W/K. This makes inlet stratifiers with inlet through the bottom of the tank an attractive solution for increasing the thermal performance.

The weak point of the fabric inlet stratifier is its sensitivity towards correct mounting and the durability. Andersen and Furbo (2008 b) investigated the long time durability of different fabric inlet stratification pipes both in a domestic hot water tank and in a space heating tank. They found that lime in relatively short time destroyed the functionality of the fabric pipes, not by reducing the porosity, but by making the pipes stiff and thereby unable to contract in order to eliminate the pressure difference between the pressure in the pipe and the pressure in the tank. They also found that the amount of deposits in the fabrics was less important than the structure of the deposits.

The fabric styles investigated in this paper have high temperature resistance and are expected to have very high resistance towards lime, dirt and algae deposits. This will be investigated.

6. Conclusion

Three double walled fabric inlet stratification pipes made of Teflon and Polyester fibers are investigated experimentally. The inlet stratification pipes are made of two concentric fabric pipes with diameters of 30 mm and 50 mm. The thermal performance of the pipes is investigated during charging and discharging with a volume flow rate of 4 l/min. Inlet to the stratification pipes is investigated both through the bottom and the top of the tank. During charging, the outlet is at the bottom of the tank and during discharging, the outlet is at the top of the tank. The fabric pipes are closed at the opposite end of the inlet.

The investigations show that thermal stratification is build up in a good way with inlet to the pipe through the bottom of the tank during charging with a high inlet temperature and in a very good way during discharging with a low inlet temperature. When the inlet to the pipes is through the top of the tank, thermal stratification is build up in a very good way during charging with a high inlet temperature and in a poor way during discharging with a low inlet temperature.

All in all, thermal stratification is established in a better way with the inlet to the stratifier placed at the bottom of the tank than with the inlet to the stratifier placed at the top of the tank.

7. Nomenclature

Quantity	Symbol	Unit
Momentum of energy	M	J m
Energy	E	J
Vertical distance	y	m
Volume	V	m^3
Specific heat capacity	c	J kg^{-1} K^{-1}
Density	ρ	Kg m^{-3}
Temperature	T	K
Temperature difference	ΔT	K
Number of tank layers	N	
Mix number	MIX	
Subscripts		
Tank layer	i	
Perfectly stratified tank	*str*	
Experimental tank	*exp, experiment*	
Fully mixed tank	*mix*	
Maximum inlet temperature	*inlet,max*	K
Minimum inlet temperature	*inlet,min*	K
Maximum tank temperature	*tank,max*	K
Minimum tank temperature	*tank,min*	K

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