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TRNSYS Simulation of the Consumer Unit for Low Energy District Heating Net

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Abstract

In the report the performances of two consumer units for low temperature district heating net are investigated using TRNSYS. The TRNSYS model is validated against measurements. The results show that:

1. If there is no heat storage tank the mass flow rate of the district heating flow to the house should be approx. 760 kg/h in order to fulfill the required hot water draw-off profile. For a system with a heat storage tank of 60 l, the mass flow rate can be decreased to 120 kg/h. For a system with a tank of 140 l, the mass flow rate can be decreased to 58 kg/h. For a tank volume of 200 l, a mass flow rate of the district heating flow of 14 kg/h is necessary. The average return temperature from the system is 22.4°C, 23.3°C and 18.2°C for the system with a tank volume of 60 l, 140 l and 200 l respectively.
2. The combisystem can utilize the energy in the return water from the tank therefore decreases the average return temperature of the system to the district heating net can be decreased. The annual energy transferred from the tank to the floor is 553, 660 and 136 kWh for a system with 60 l, 140 l and 200 l tank respectively. The average return temperature of the system is decreased by 2.5, 2.7 and 1.2 K for the combisystem with a tank volume of 60 l, 140 l and 200 l respectively.
3. The daily hot water consumption has a significant influence on the performance of the DHW system. With a reduced hot water consumption of 184 l/day, the average return temperature from the tank will be increased significantly, for instance 16 K for a tank volume of 200 l. With a reduced hot water consumption of 184 l/day and a reduced tank charging flow rate, the average return temperature from the tank will increase 1.0 to 7.1 K for different tank sizes. In order to decrease the return temperature from the tank, the tank charging system shall be smart controlled so that the tank charging flow rate or the control mode can be adjusted with respect to actual daily hot water consumption. An alternative is to combine the tank with the floor heating system so that the energy in the return water from the tank can be utilized for floor heating.
4. The influence of tank material on tank thermal stratification has been investigated. It is shown that a tank with SS316L as construction material will have a slightly better thermal stratification and thus a slightly lower average return temperature than a tank with FE360 as construction material, for instance 0.6 K lower for a tank volume of 200 l. However the cost of SS316L is higher than the cost of FE360. The optimum solution is to use FE360 as tank construction material.
5. The influence of the size of the heat exchanger on thermal performance of the tank is investigated. Three types of heat exchanger are investigated: XB37H60, XB37H90 and XB06H60. It is shown that the system with heat exchanger XB37H60 and XB37H90 can fulfill the DHW demand while the system with heat exchanger XB06H60 can not, therefore XBH37H60 is used as the heat exchanger.
6. The heat loss of the tank is determined by the average tank temperature over the year and the surface area of the tank. The average tank temperature over the year is greatly influence by the standby operation time of the tank. The longer the standby operation time, the higher the average tank temperature over the year. The annual heat loss of the tank is 104 kWh, 181 kWh and 93 kWh for the tank volume of 60 l, 140 l and 200 l respectively. Since it takes much less time for the 60 l and 140 l tanks to be fully charged, the standby time of the two tanks are much longer than

that of the 200 l tank which results in higher average tank temperature, therefore the heat loss of the 60 l tank and the 140 l tank is larger than the heat loss of the 200 l tank. The heat loss of the 140 l tank is the higher than the heat loss of the 60 l tank due to its larger tank surface area.

7. The TRNSYS calculated fluid temperatures in the tank are compared to the measured temperatures at the surface of the tank. The comparison between the calculations and the experiments shows that the calculations agree with the measurements with an underestimated degree of thermal stratification. The reason for the disagreement could be due to the fact that it is not possible to totally avoid numerical diffusion due to the limitation on the node number. Another reason could be the influence on thermal stratification by the natural convection in the tank caused by heat loss from the wall. The natural convection helps to build up thermal stratification in the tank, which is not considered in the TRNSYS tank model.

It must be mentioned that the calculated heat losses will be lower than the tank heat losses in practice. Especially pipe connections in the upper part of the tank will strongly increase the tank heat loss.

1 Model sketch

In the report the performance of two systems are investigated using TRNSYS. One is called separate system where the domestic hot water loop and the space heating loop are parallel connected. The other system is called a two stage system or combisystem where the return water from the heat storage tank is directed to the space heating loop and used for floor heating when the water temperature is higher than the supply temperature to the floor heating system.

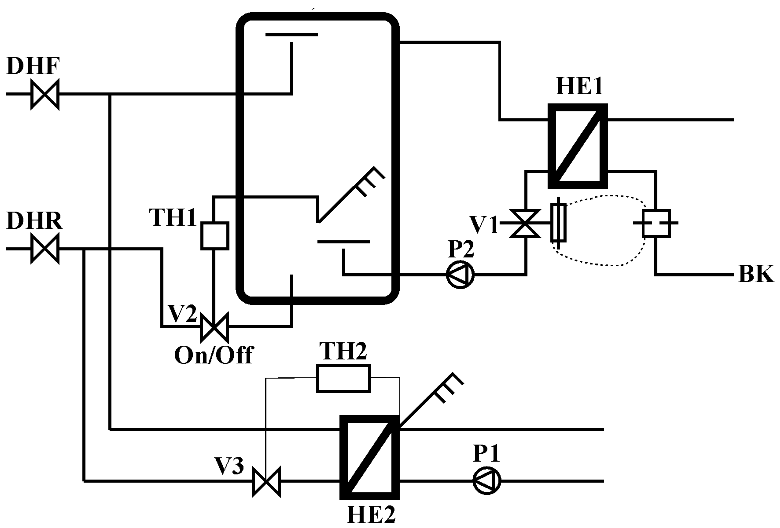

Fig. 1 Model sketch of a system with parallel connected domestic hot water loop and space heating loop

The sketch of the separate system is shown in Figure 1. There are two parallel loops: one for the DHW tank and the other for space heating. The two loops are controlled independently. In the DHW loop, the thermal stratification in the tank is modeled with TRNSYS type 340. Heat loss from the tank is included in the model while heat loss from the pipes and the heat exchanger HE1 is not considered. The charging of the tank is controlled by a thermostat controller based on the temperature of the fluid at the bottom of the tank. The tank is charged if the temperature is lower than or equal to the set point temperature. The charging will be switched off if the temperature is higher than the set point temperature.

The flow rate of the primary loop of HE1 will be adjusted by an iterative feedback controller so that the outlet temperature of the secondary loop (tap temperature) will be 40°C. The tap temperature is lower than the tap temperature of 45ºC as stated in DS439. A warning will be given if the tapped fluid temperature is lower than 39.5°C. It shall be mentioned that heat loss of the pipe from the heat exchange to the tap is not considered.

For the space heating loop, a floor heating system is used. The return temperature is assumed to be 21°C. The space heating demand is averaged out over the day. The flow from the district heating network is calculated based on the daily space heating demand, therefore it varies from day to day. In this model, the heat exchanger for space heating HE2 is not considered.

The sketch of the combisystem is shown in Fig.2. The DHW loop and the space heating loop are the same as in the separate system except that the return water from the heat storage tank is directed to the floor heating loop when the return water temperature is higher than the supply temperature to the floor. The supply temperature to the floor depends on the daily space heating demand. The floor temperature should be high enough so that the space heating demand is covered.

$$((T_{\text{floor, supply}} + T_{\text{floor, return}})/2 - T_{room}) \cdot \mathrm{A}_{\text{room}} \cdot h \geq \frac{\mathrm{E}_{\text{space,daily}}}{24} \cdot 1000 \quad (1)$$

$$T_{\text{floor, supply}} = (\frac{1000 \cdot \mathrm{E}_{\text{space,daily}}}{24 \cdot \mathrm{A}_{\text{room}} \cdot h} + T_{room}) \cdot 2 - T_{floor,return} \quad (2)$$

where $T_{\text{floor, supply}}$ is the supply temperature to the floor, °C ; $T_{\text{floor, return}}$ is the return temperature from the floor, 21°C. T_{room} is the room temperature, 21°C. A_{room} is the floor area, m^2. h is the surface heat transfer coefficient of the floor, 5 W/(m^{2}K). $E_{\text{space, daily}}$ is the daily space heating energy demand, kWh.

As shown in Fig. 2, if the fluid temperature of the return flow from the tank is no less than the $T_{\text{floor, supply}}$, the fluid is directed to the valve V2 and is mixed with the district heat flow from the valve V3 before it enters the floor heating system. If the fluid temperature of the return flow from the tank is less than $T_{\text{floor, supply}}$, the fluid is directed back to the district heating net by the valve V1.

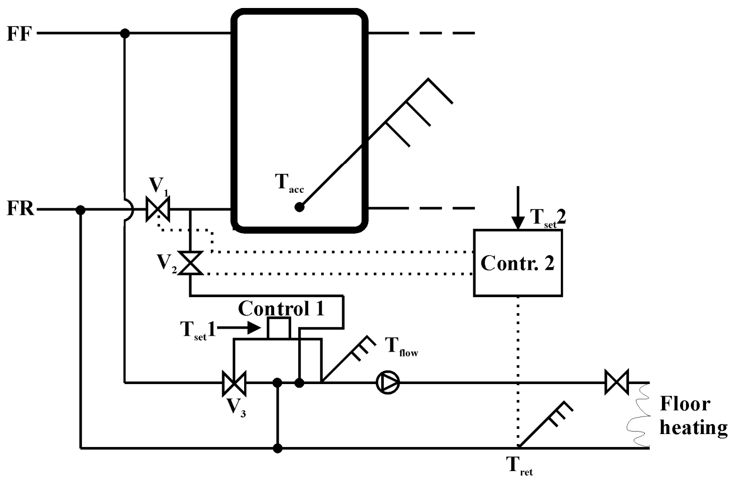

Fig. 2 Model sketch of a two stage system with domestic hot water loop combined to space heating system

Fig. 3 shows outdoor temperature and daily space heating demand of the reference house from January to April. Fig. 4 show flow rate and temperatures of the floor heating system in the model. Cooling of the flow through the floor is shown in Fig. 5.

It can be seen that the supply temperature is charging according to the daily space heating demand while temperature of the return flow from the floor is assumed to be constant at 21°C. The highest supply temperature is 25.8°C in the period from January to April, corresponding to a space heating demand of approx. 42 kWh/day. The supply temperature is decreased with a decreased daily space heating demand. The lowest supply temperature to the floor is set to be 22°C. The flow rate is decreased if the space heating demand is lower than 8.8 kWh/day. In the summer, when there is no space heating demand, the return water from the tank can be utilized to heat up the bathroom for comfort. The energy needed for bathroom comfort is assumed to be 2 kWh/day. The minimum daily space heating demand is set to 2 kWh if bathroom comfort is considered.

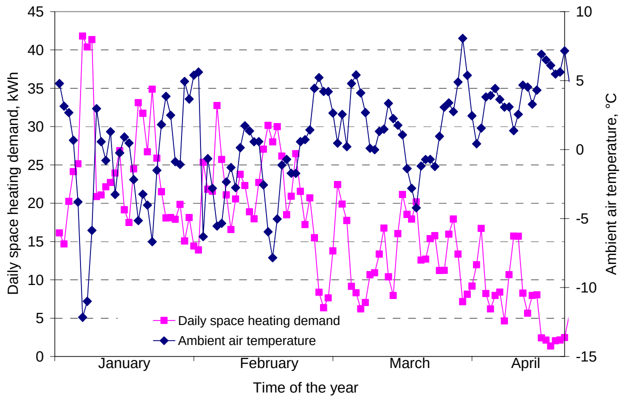

Fig. 3 Ambient air temperature and daily space heating demand from January to April

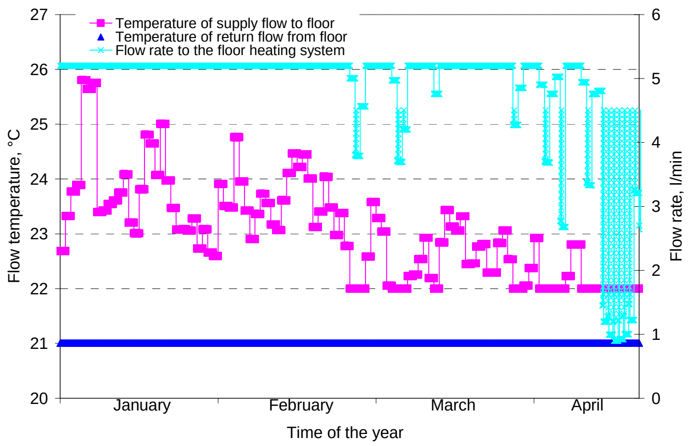

Fig. 4 Fluid temperatures and flow rate of the floor heating system from January to April

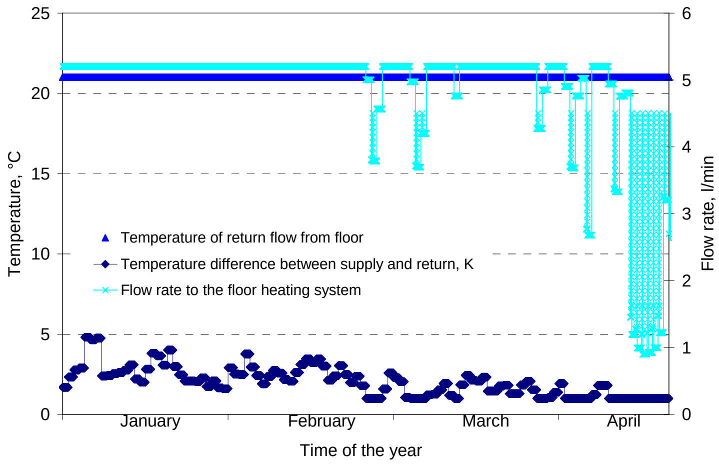

Fig. 5 Temperature difference and flow rate of the floor heating system from January to April

2 Input to model

2.1 Flow from District heating network

The flow from the district heating network has a constant temperature of 50°C. The flows from both loops are fully mixed before the water returns to the network. The temperature of the return flow is obtained by a mass weighted average of the flows over a specified time.

2.2 DHW draw-off profile

The following DHW draw-off profile is assumed.

Type: buildings without bath tub

(1) 4 showers, each with a volume of 42 l. Each shower takes 300 s and there is delay of 20 min between the showers.

(2) 2 kitchen washes for every 3 hours, each wash with a volume of 15 l. Each wash takes 150 s and there is a delay of 20 min between washes.

(3) 4 hand washes for every 6 hours, each wash with a volume of 10 l. Each wash takes 180 s and there is a delay of 20 min between washes.

For all hot water draw-offs, a hot water temperature of 40°C and a cold water inlet temperature of 10°C are used. A combination of 1+2+3 is used in order to be on the safe side. The draw off profile is enforced for 12 hours per day from 6:00 to 18:00. That is different with the standard DS439 which requires that the 12 hours draw-off profile is enforced twice per day. The hot water consumption pattern used is shown in Fig. 6.

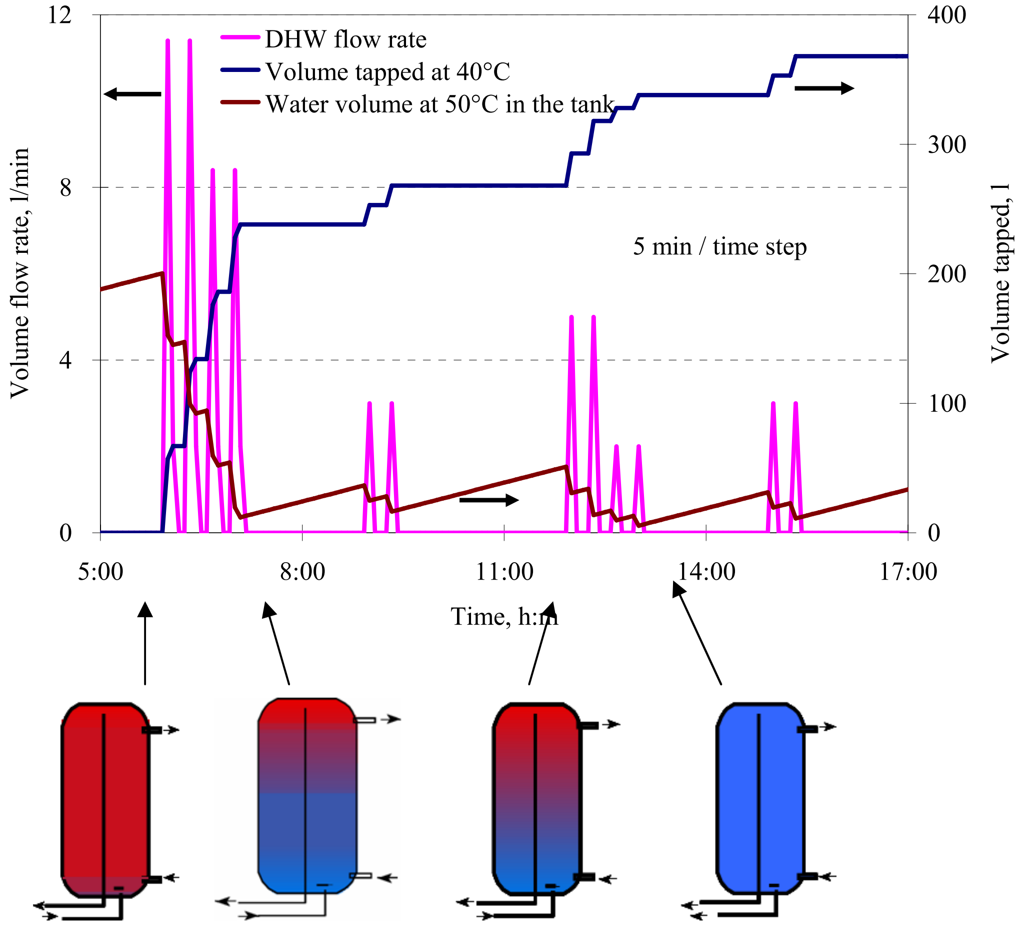

Fig. 6 DHW draw-off profile and status of the heat storage tank for a hot water consumption of 368 l/day. (Tank volume: 220 l)

The principle of the heat storage tank is shown in Fig. 6. The tank is charged with a low flow rate all over the day. Before 6:00 AM, the tank is fully charged. At 6:00 AM, the first draw-off starts. In about 1 hour, the tank is almost emptied. From 7:00 AM to 16:00 PM the tank is continuously charged and is discharged from time to time. At 16:00 PM the tank is emptied again. From 16:00 PM till 6:00 AM of the next day, the tank will be gradually charged and will be full before the start of the first draw-off of the next day.

2.3 Tank model

The buffer tank is supposed to be a cylindrical tank of pressure rating of PN6. By default FE360 is used to produce the tank but the influence of tank stratification by using SS316L as tank material is investigated and presented in chapter 4. The thickness of the tank wall is 1.5 mm.

The diameter of the tank varies with the different tank volumes investigated. The heat loss coefficients from the tank are calculated for the top, bottom and the side respectively, as given in literature (Educational notes, Solar Heating Systems, Simon Furbo).

The heat loss coefficient from the top of the tank is determined by:

$$\frac{\frac{\pi}{4}\left(d_y + e_s\right)^2}{\frac{e_t}{\lambda} + \frac{1}{a_{top}}} \quad \text{W/K} \qquad (3)$$

The heat loss coefficient from the bottom of the tank is determined by:

$$\frac{\frac{\pi}{4}\left(d_y + e_s\right)^2}{\frac{e_b}{\lambda} + \frac{1}{a_{bot}}} \quad \text{W/K} \tag{4}$$

The heat loss coefficient per height unit from the side of the tank is determined by:

$$\frac{\pi}{\frac{1}{2\lambda}\ln\frac{d_y + 2e_s}{d_y} + \frac{1}{a_{side}}\frac{1}{d_y + 2e_s}} l \quad \text{W/K/m} \tag{5}$$

where d_y is the outer diameter of the tank. l is the height of the tank. e_s is the thickness of the side insulation, 0.1 m. e_t is the thickness of the top insulation, 0.1 m. e_b is the thickness of the bottom insulation, 0.1 m. λ is the thermal conductivity of the insulation material, 0.04 W/mK. α_{top} is the heat transfer coefficient of the top surface of the tank, 10 W/m^{2}K. α_{bot} is the heat transfer coefficient of the bottom surface of the tank, 5.88 W/m^{2}K. α_{side} is the heat transfer coefficient of the side surface of the tank, 7.69 W/m^{2}K.

The heat loss coefficients from tanks of different sizes can be calculated with equation [3-5]. As an example the heat loss coefficient from a 200 liter tank is listed in the following table.

Table 1. Heat loss coefficients from a 200 liter tank

Part	top	bottom	side	Total
Unit	W/K	W/K	W/K	W/K
Heat loss coefficient	0.08	0.07	0.95	1.10

The TRNSYS tank model type 340, by far the most advanced model, is used to calculate the thermal stratification of the buffer tank. The tank is divided into a number of equal sized layers. It is assumed that the fluid in each layer is fully mixed and a mixing rate during discharge and charge of 10% and 5% are assumed for the bottom and top of the tank respectively. That is: When the tank is charged 5% of the tank volume at the top of the tank is fully mixed and when the tank is discharged by the hot water draw-off 10% of the tank volume at the bottom of the tank is fully mixed.

In the calculation an effective thermal conductivity of water is used by which the thermal conduction of the tank wall is taken into consideration.

$$\lambda_{effective} = \lambda_{water} + \lambda_{steel} \cdot \frac{\left(d_y^2 - d_i^2\right)}{d_i^2}$$

where $\lambda_{effetive}$ is the effective thermal conductivity of water in the tank; λ_{water} is the thermal conductivity of water; λ_{steel} is the thermal conductivity of tank material; d_y is the outer diameter of the tank; d_i is the inner diameter of the tank.

A fully charged tank is assumed in the start of the simulation. The initial temperature of the whole tank is 50°C. The time step of the TRNSYS calculation is 5 min.

2.4 Space heating demand

The daily space heating demand is calculated based on the reference house 1 shown in Fig. 7, which results in a yearly space heating demand of 3028 kWh for a indoor temperature of 20ºC.

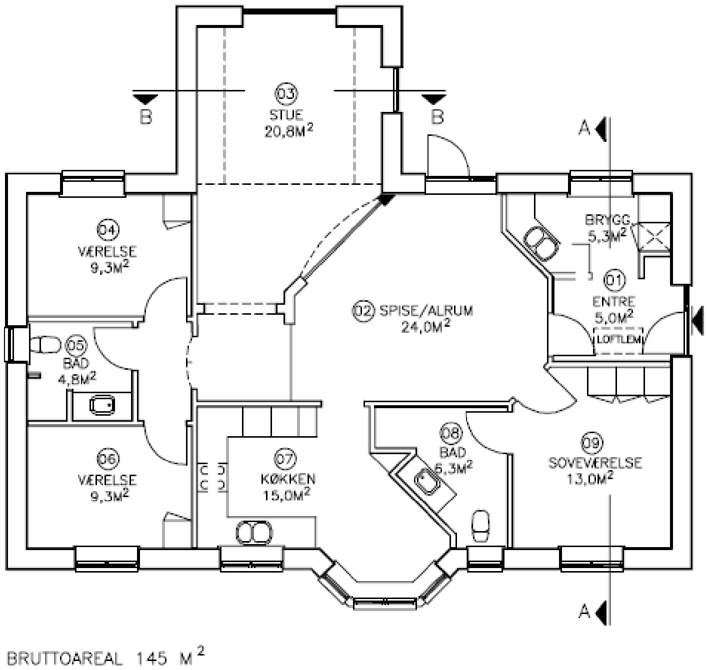

Fig. 7 Illustration of the simulated reference house 1

3 Influence of daily hot water consumption

3.1 Hot water consumption 368 l/day

With the model that is nearly free of numerical diffusion, a good thermal stratification in the tank can be achieved. It is possible to have a tank of 220 l which can fulfill the domestic hot water demand. The temperatures calculated with the model without numerical diffusion are shown in Fig. 8.

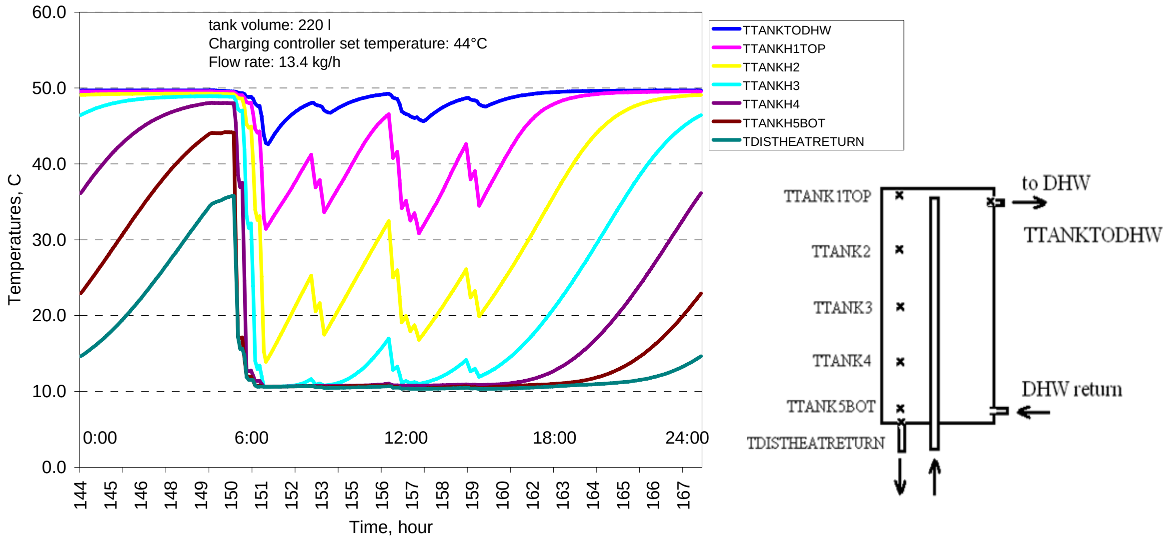

Fig. 8 Temperatures calculated for a daily hot water consumption of 368 l

The results of the calculation with a 220 l tank for the <u>first week of the year</u> are listed in the following table.

Table 2 Results of the first week of the year with a 220 l tank and hot water consumption 368 l/d

Variable	Unit	Value
Reference time	-	First week of the year
Hot water consumption	l	2576
Tank heat loss	kWh	1.9
Energy from district heating	kWh	297
Energy tapped for hot water Consumption	kWh	89
Tank energy change	kWh	-2.7
Energy for space heating	kWh	208
Energy balance	kWh	0.3
Tap warnings	Min	0
Average return temperature of the system	°C	19.9
Average tank return temperature	°C	13.6
Total DH water volume through the tank	l	2141
Water volume from the tank directed to the net with temperature T > 20°C	l	278 (13%)
Water volume from the tank directed to the net with temperature T > 25°C	l	185 (9%)

3.2 hot water consumption 184 l/day

In practice the hot water consumption may be lower than described in the standard. A calculation with a decreased hot water consumption is carried out. The volume of hot water per draw-off is cut by half which results in a total hot water consumption of 184 l per day. The calculated temperatures with a tank charging flow rate of 13.4 kg/h are shown in Fig. 9.

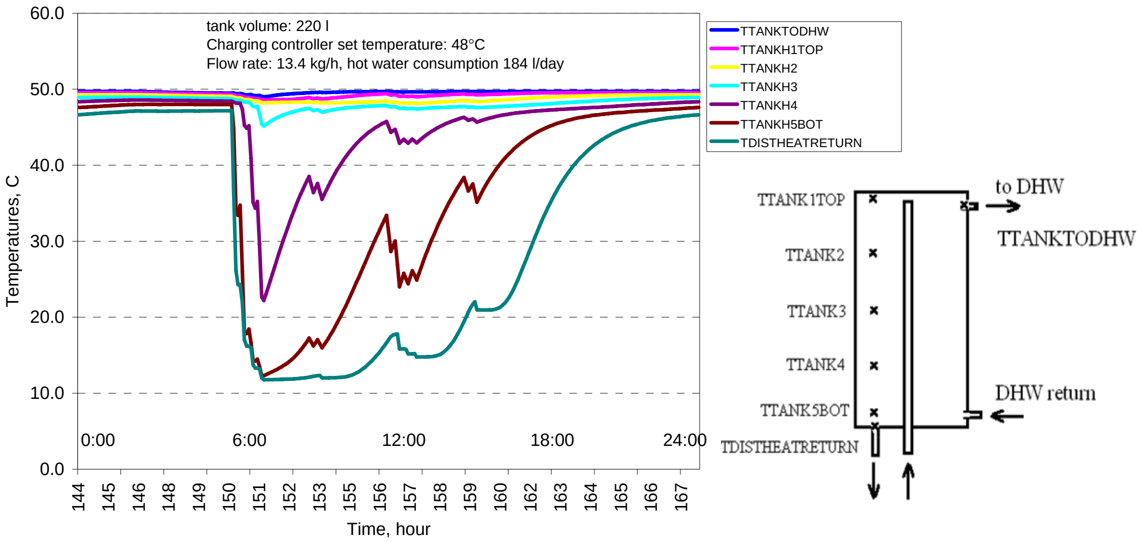

Fig. 9 Temperatures calculated for a daily hot water consumption of 184 l and a tank charging flow rate of 13.4 kg/h.

Compared with Fig. 8, it can be seen that the return temperature from the tank to the district heating network is much higher with a decreased hot water consumption. Since hot water consumption is low, the tank is at most time kept at a high temperature. The tank is frequently charged in order to compensate heat loss from the tank and to keep the tank warm. This frequent charge will deliver water at a high temperature to the district heating network and increase the average temperature of the return flow. The result for the first week of the year is listed in the following table. It can be seen that 1214 liters of the return water from the tank has a temperature higher than 20°C while 996 liters of water has a temperature higher than 25°C.

Table 3 Results of the first week of the year with a 220 l tank, a hot water consumption of 184 l/d and a tank charging flow rate of 13.4 kg/h.

Variable	Unit	Value
Reference time	-	First week of the year
Hot water consumption	l	1288
Tank heat loss	kWh	4.5
Energy from district heating	kWh	257
Energy tapped for hot water Consumption	kWh	45
Tank energy change	kWh	-0.3
Energy for space heating	kWh	208
Energy balance	kWh	0.3
Tap warnings	Min	0
Average return temperature of the system	°C	23.7
Average tank return temperature	°C	29.1
Total DH water volume through the tank	l	2030
Water volume from the tank directed to the net with temperature T > 20°C	l	1214 (60%)
Water volume from the tank directed to the net with temperature T > 25°C	l	996 (49%)

With a hot water consumption decreased by half, it is reasonable to decrease the tank charging flow rate by half. The result of the calculation with a tank charging flow rate of 6.7 kg/h is shown in Fig. 10.

The result for the first week of the year is listed in the following table. It can be seen that 193 liters of the return water from the tank has a temperature higher than 20°C while 79 liters of water has a temperature higher than 25°C. The return temperature from the tank is much lower than for a charge flow of 13.4 kg/h.

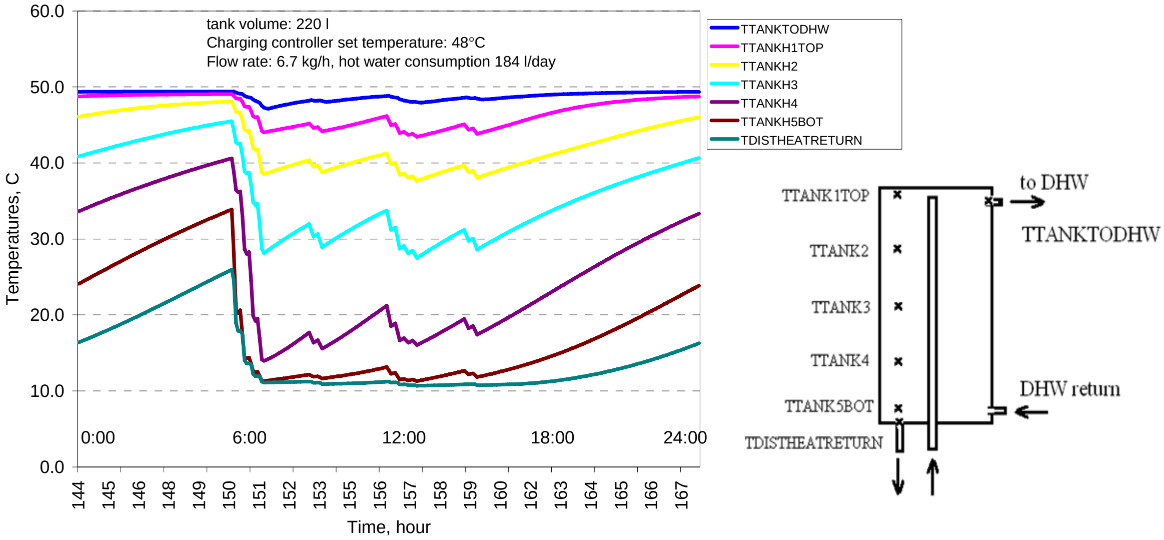

Fig. 10 Temperatures calculated for a daily hot water consumption of 184 l and a tank charging flow rate of 6.7 kg/h

Table 4 Results of the first week of the year with a 220 l tank, a hot water consumption of 184 l/d and a tank charging flow rate of 6.7 kg/h.

Variable	Unit	Value
Reference time	-	First week of the year
Hot water consumption	l	1288
Tank heat loss	kWh	2.7
Energy from district heating	kWh	252
Energy tapped for hot water consumption	kWh	45
Tank energy change	kWh	-3.0
Energy for space heating	kWh	208
Energy balance	kWh	0.3
Tap warnings	Min	0
Average return temperature of the system	°C	20.9
Average tank return temperature	°C	14.7
Total DH water volume through the tank	l	1158
Water volume from the tank directed to the net with temperature T > 20°C	l	193 (17%)
Water volume from the tank directed to the net with temperature T > 25°C	l	79 (7%)

4 Influence of tank materials

The influence of thank material on tank thermal stratification is investigated by replacing the default FE360 with stainless steel SS316L. The temperature calculated for a tank made of FE360 is shown in Fig. 8 while the temperature for a tank with SS316L is presented in Fig. 11.

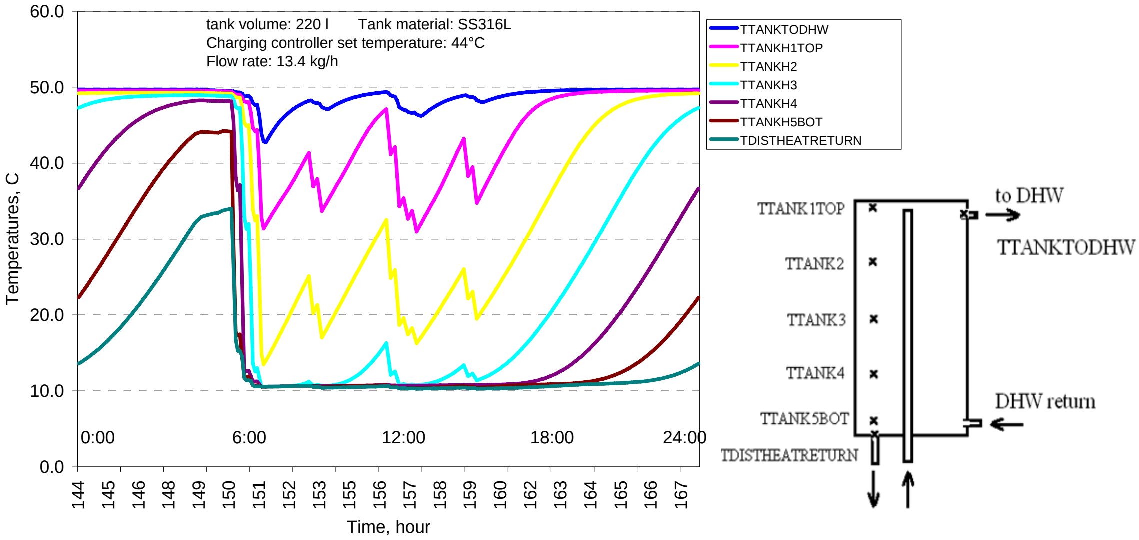

Fig. 11 Temperatures calculated for a daily hot water consumption of 368 l, a tank charging flow rate of 13.4 kg/h using stainless steel SS316L as tank material.

A full comparison for the first week of the year is given in the following table. It can be seen from the table that a tank with SS316L as construction material will have a better tank thermal stratification and thus a lower average return temperature than a tank with FE360 as construction material. 224 liters of the return water from the tank has a temperature higher than 20°C while 135 liters of water has a temperature higher than 25°C. However the cost of SS316L is higher than the cost of FE360. The optimum solution is to use FE360 as tank construction material. For a tank volume of 238 l, the net material saving is approx. 1000 kr if FE360 is used as tank construction material instead of SS316L.

Table 5 Comparison of different tank materials.

Tank material		FE360	SS316L
Reference time	-	First week of the year	
Hot water consumption	l	2576	2576
Tank heat loss	kWh	1.9	1.9
Energy from district heating	kWh	297	297
Energy tapped for hot water Consumption	kWh	89	89
Tank energy change	kWh	-2.7	-2.7
Energy for space heating	kWh	208	208
Energy balance	kWh	0.3	0.3
Tap warnings	Min	0	0
Average return temperature of the system	°C	19.9	19.8
Average tank return temperature	°C	13.6	13.0
Total DH water volume through the tank	l	2141	2106
Water volume from the tank directed to the net with temperature T > 20°C	l	278 (13%)	224 (11%)
Water volume from the tank directed to the net with temperature T > 25°C	l	185 (9%)	135 (6%)

5 Influence of the size of the heat exchanger

In the above investigations, the heat exchanger type Danfoss XB37H-90 is by default used as HE1 for DHW supply. Some of the system parameters are given as follows:
HE1 DHW:
Type: Danfoss XB37H-90 (90 plates, 1 path);
Height H=52.5 cm
Width W=12.5 cm
Depth D=15.0 cm
The heat exchange capacity rate as a function of the mass flow rate of the secondary loop is shown in the Fig. 12.

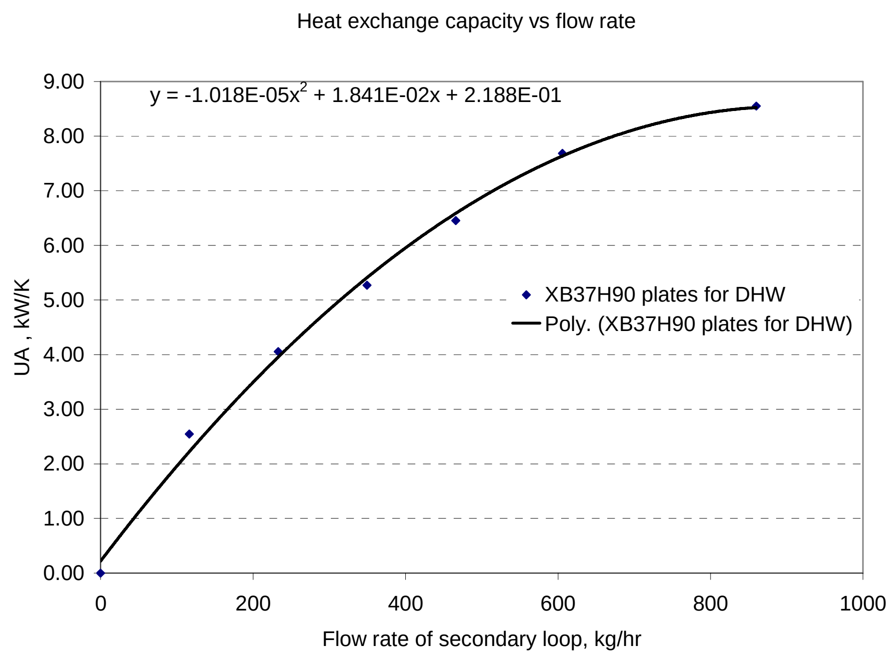

Fig. 12 Heat exchange capacity rate of the heat exchanger type XB37H 90 for DHW supply (HE1)

How thermal stratification of the tank is influenced by the type of heat exchanger is investigated. The performance of heat exchangers type XB37H 60 and XB06H60 are then investigated.
The configuration of the heat exchanger type XB37H60 is:
Type: Danfoss XB37H-60 (60 plates, 1 path)
H=52.5 cm; W=12.5 cm; D=10.0 cm
The heat exchange capacity rate as a function of the mass flow rate of the secondary loop is shown in Fig. 13.

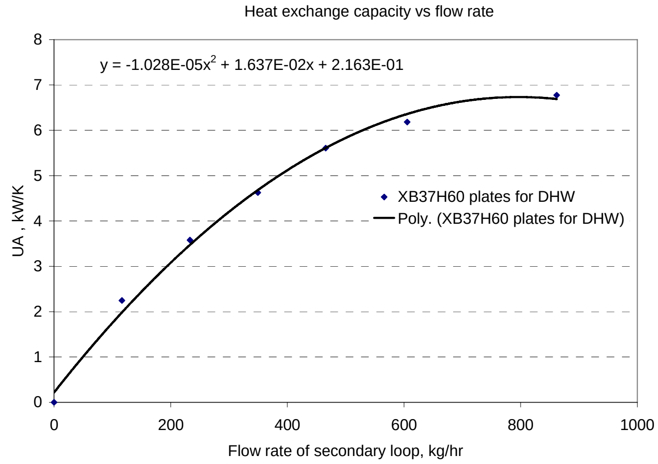

Fig. 13 Heat exchange capacity rate of the heat exchanger XB37H60 for DHW supply (HE1)

The temperature calculated for a system with heat exchanger XB37H60 for hot water supply is given in Fig. 14. It can be seen that the use of XB37H60 as HE1 does not influence the calculated temperatures.

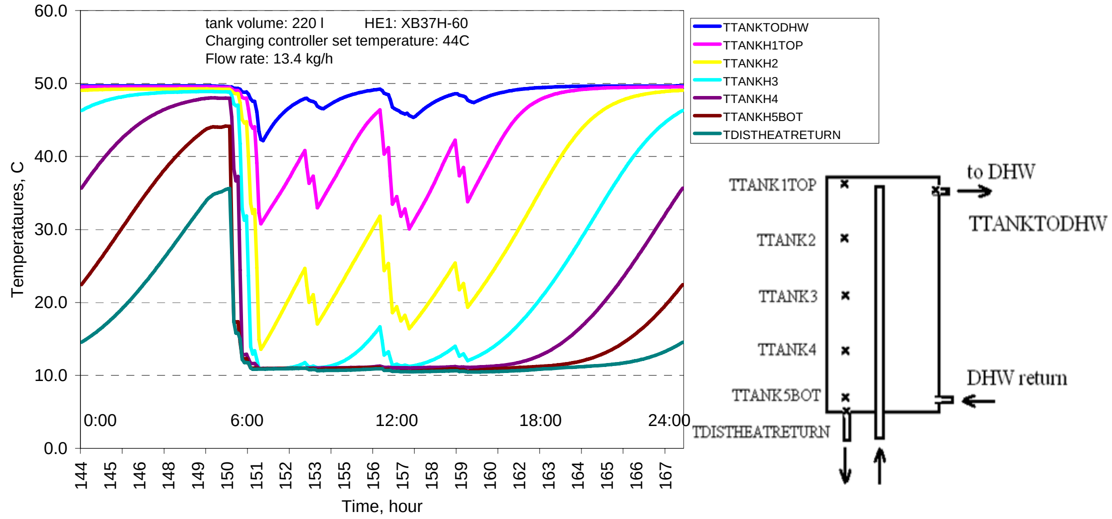

Fig. 14 Temperatures calculated for a daily hot water consumption of 368 l

The configuration of the heat exchanger type XB06H60 is:

Type: Danfoss XB06H-60 (60 plates, 1 path)

H=32 cm; W=10 cm; D=8.7 cm

The heat exchange capacity rate as a function of the mass flow rate of the secondary loop is shown in Fig. 15.

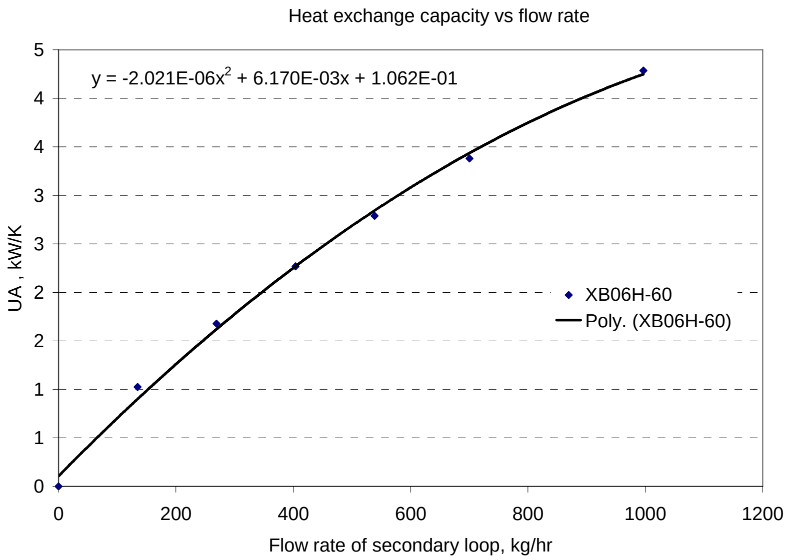

Fig. 15 Heat exchange capacity rate of the heat exchanger XB06H60 for DHW supply (HE1)

A full comparison of the results with heat exchanger XB37H 90, XB37H 60 and XB06H60 for the first week of the year is given in the following table. It can be seen that the systems with heat exchanger XB37H60 and with XB37H60 are able to cover the 12 h standard hot water demands, while the system with the heat exchanger XB06H60 is not sufficient to provide required standard hot water consumption profile. Therefore only XB37H60 will be used in later calculation.

Table 6 Comparison of different types of heat exchangers.

Heat exchanger		XB37H90	XB37H60	XB06H60
Reference time	-	First week of the year		
Hot water consumption	l	2576	2576	2576
Tank heat loss	kWh	1.9	1.9	1.6
Energy from district heating	kWh	297	297	288
Energy tapped for hot water consumption	kWh	89	89	83
Tank energy change	kWh	-2.7	-2.7	-3.7
Energy for space heating	kWh	208	208	208
Energy balance	kWh	0.3	0.3	0.2
Tap warnings	Min	0	0	62
Average return temperature of the system	°C	19.9	20.0	21.0
Average tank return temperature	°C	13.6	13.7	18.1
Total DH water volume through the tank	l	2141	2147	2273
Water volume from the tank directed to the net with temperature T > 20°C	l	278 (13%)	278 (13%)	188 (8%)
Water volume from the tank directed to the net with temperature T > 25°C	l	185 (9%)	185 (9%)	45 (2%)

6 Influence of tank charging mass flow rate

The minimum required tank volume is determined for different tank charging mass flow rates. A 12 h standard hot water consumption profile is used. The tank charging controller set temperature is 48°C. XB37H60 is used as the heat exchanger (HE1) for domestic hot water production. The required tank volumes are listed for different tank charging mass flow rates in the following table. It can be seen that if there is no heat storage tank the mass flow rate of district heating flow has to be approx. 760 kg/h in order to fulfill the demand of simultaneous draw-off of shower and kitchen wash. If a tank volume of 60 liter is used as the heat buffer for DHW supply, the required mass flow rate can be decreased to 120 kg/h. If a tank volume of 140 liter is used as heat storage, the required mass flow rate is decreased to approx. 58 kg/h. If a tank of 200 liter is used, the required mass flow rate can be decrease to 14 kg/h which is the flow rate when the charging of the tank is averaged out all over the day.

Table 7 A list of minimum tank volume for different tank charging flow rates.

Tank charging flow rate	Minimum tank volume	Tank heat loss	Average tank return temperature	Total Water volume through the tank	Water volume directed to the net with T > 20°C	Water volume directed to the net with T > 25°C
(kg/h)	(l)	kWh	°C	l	l	l
14	200	1.8	14.7	2205	347	267
20	193	3.1	18.8	2530	732	637
30	179	3.7	21.5	2788	1098	885
40	165	3.8	23.9	3048	1487	1180
50	152	3.7	23.8	3033	1508	1154
60	136	3.4	23.3	2966	1680	1015
70	123	3.1	24.2	3060	1860	1318
80	109	2.9	23.4	2961	1720	1220
90	93	2.6	23.2	2930	1635	1110
100	79	2.3	22.1	2805	1533	1083
120	60	2.0	22.3	2816	1510	1300
760*	0	-	16°C**	-	-	-

Note: The table is based on calculation of the first week of the year.

* the required mass flow rate of district heating flow is calculated for a return temperature of 16°C.

** The temperature is the average return temperature from the heat exchanger during tapping only.

It can be seen from Fig. 16 that the average return water temperature from the tank is the lowest, 14.7°C for a tank volume of 200 liters. With a decrease of tank volume of 70 liters, the return water temperature increases to 24.2°C. The return water temperature slightly decreases to 22.3°C if a tank of 60 liters is used as the heat buffer. The relatively high return temperature of the tank of 130 liters can be explained by the high return temperature of the tank during standby period. For a tank of 200 liters it takes approx. 13 hours to fully charge the tank, therefore there is almost no standby period. While for a tank of 130 liters, the required tank charging flow rate is higher and the tank volume is smaller, therefore it takes much less time (approx. 1 hour) to fully charge the tank. Due to heat loss of the tank on standby, the tank will be charged from time to time to keep the tank warm which increases the average temperature of the return fluid to the district heating net. Since the standby time of the 60 l tank is insignificantly different with the 130 l tank and the surface area of the 60 l tank is significantly smaller than the surface area of the 130 l tank, the standby heat loss of a 60 l tank is smaller compared to that of a 130 l tank, therefore the average return temperature of the system with a 60 l tank is lower than that of the system with a 130 l tank.

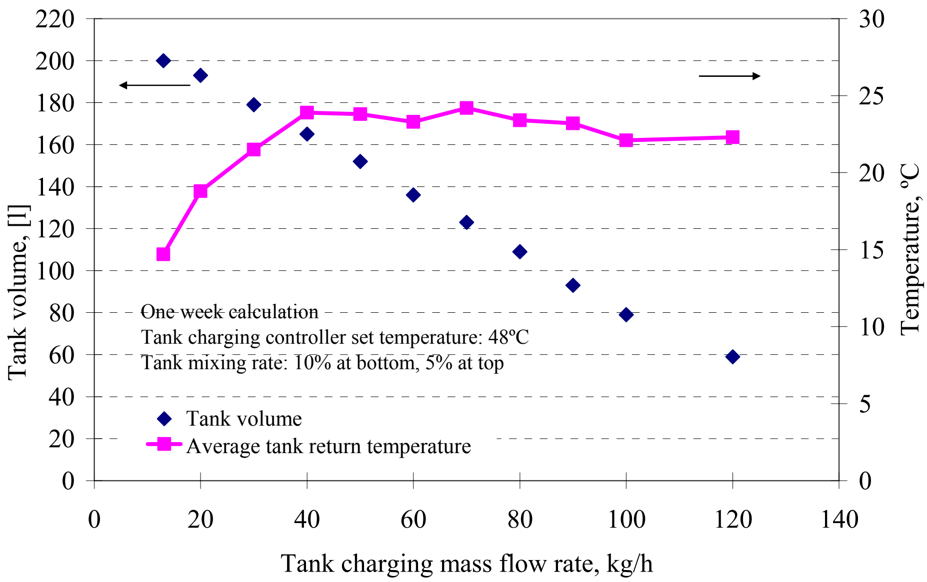

Fig. 16 Required tank volume and average tank return temperature as a function of tank charging mass flow rate.

7 Different scenarios

7.1 Domestic hot water consumption 368 l/day

7.1.1 No heat storage tank

If there is no storage of domestic hot water, the power of the heat exchanger should be able to provide simultaneous draw-off of shower (17.6 kW) and kitchen wash (12.6 kW), which is 30.2 kW in all. The supply fluid temperature of the district heating flow is 50°C. If the return fluid temperature from the heat exchanger can be as low as 16°C, the flow rate of the district heating flow to the house should be approx. 760 kg/h in order to provide sufficient power for shower and kitchen wash.

7.1.2 60 l Tank

If a tank of 60 l is used as the heat storage tank, the required mass flow rate of district heating flow is 120 kg/h. The result of the yearly calculation of the separate system and the combisystem is shown in the following table. The annual heat loss of the tank is 104 kWh. Since the tank is frequently charged, there is a large amount of return water from the tank with a temperature higher than 25°C. The average temperature of return water from the tank is 22.6°C over the year. The average return temperature to the district heating net is 22.4°C.

A combisystem is used to utilize the heat in the return water of the tank for space heating. It is shown that approx. half of the return water with a temperature higher than 25°C can be used for floor heating which correspond to a yearly energy quantity transferred from the tank to the floor of 553 kWh. The average return temperature to the district heating net is decreased by 2.5K.

Table 8 Comparison of yearly calculation of a separate and combined system.

Variable	Unit	Separate	Combisystem
Reference time	-	yearly	
Tank charging flow rate	kg/h	120	120
Hot water consumption	l	134320	134320
Tank heat loss	kWh	104	104
Energy from district heating	kWh	7792	7797
Energy tapped for hot water consumption	kWh	4661	4661
Tank energy change	kWh	-0.07	-0.07
Energy for space heating	kWh	3026	3031*
Energy imbalance	kWh	0.25	0.24
Tap warnings	Min	0	0
Average return temperature of the system	°C	22.4	19.9
Average tank return temperature	°C	22.6	-
Total DH water volume through the tank	l	149062	149062
Water volume from the tank directed to the net with temperature T > 20°C	l	80270 (54%)	41340 (28%)
Water volume from the tank directed to the net with temperature T > 25°C	l	69320 (47%)	33780 (23%)
Energy transferred from the tank to the floor heating loop	kWh	-	553

Note: * the slightly higher than necessary energy for space heating is due to simplification of the model. The energy in the return water from the tank is sometimes higher than the space heating energy demand of the house, therefore the supply temperature to the floor is slightly higher than necessary, resulting in a surplus of energy for space heating.

7.1.3 140 l Tank

If a tank of 140 l is used as the heat storage tank, the required mass flow rate of district heating flow is 58 kg/h. The annual heat loss of the tank is 181 kWh. The average temperature of return water from the tank is 24.0°C over the year. The average return temperature to the district heating net is 23.3°C.

If a combisystem is used to utilize the heat in the return water of the tank for space heating, approx. half of the return water with a temperature higher than 25°C can be used for floor heating which correspond to a yearly saved energy of 660 kWh. The average return temperature to the district heating net is decreased by 2.7 K.

Table 9 Comparison of yearly calculation of a separate and combined system.

Variable	Unit	Separate	Combisystem
Reference time	-	yearly	
Tank charging flow rate	kg/h	58	58

Hot water consumption	l	134320	134320
Tank heat loss	kWh	181	181
Energy from district heating	kWh	7868	7874
Energy tapped for hot water consumption	kWh	4661	4661
Tank energy change	kWh	-0.25	-0.25
Energy for space heating	kWh	3026	3033*
Energy imbalance	kWh	0.18	0.17
Tap warnings	Min	0	0
Average return temperature of the system	°C	23.3	20.6
Average tank return temperature	°C	24.0	-
Total DH water volume through the tank	l	159626	159626
Water volume from the tank directed to the net with temperature T > 20°C	l	86362 (54%)	52572 (33%)
Water volume from the tank directed to the net with temperature T > 25°C	l	58150 (36%)	28613 (18%)
Energy transferred from the tank to the floor heating loop	kWh	-	660

Note: * the slightly higher than necessary energy for space heating is due to simplification of the model. The energy in the return water from the tank is sometimes higher than the space heating energy demand of the house, therefore the supply temperature to the floor is a slightly higher than necessary, resulting in a surplus of energy for space heating.

7.1.4 200 l Tank

If a tank of 200 l is used as the heat storage tank, the required mass flow rate of district heating flow is 14 kg/h. The annual heat loss of the tank is 93 kWh. The average temperature of return water from the tank is 15.1°C over the year. The average return temperature to the district heating net is 18.2°C.

If a combisystem is used to utilize the heat in the return water of the tank for space heating, approx. half of the return water with a temperature higher than 25°C can be used for floor heating which correspond to a yearly saved energy of 136 kWh. The average return temperature to the district heating net is decreased by 1.2 K.

Table 10 Comparison of yearly calculation of a separate and combined system.

Variable	Unit	Separate	Combisystem
Reference time	-	yearly	
Tank charging flow rate	kg/h	14	14
Hot water consumption	l	134320	134320
Tank heat loss	kWh	93	93
Energy from district heating	kWh	7779	7779
Energy tapped for hot water consumption	kWh	4662	4662
Tank energy change	kWh	-2.4	-2.4
Energy for space heating	kWh	3026	3026

Energy imbalance	kWh	0.29	0.13
Tap warnings	Min	0	0
Average return temperature of the system	°C	18.2	17.0
Average tank return temperature	°C	15.1	-
Total DH water volume through the tank	l	116783	116783
Water volume from the tank directed to the net with temperature T > 20°C	l	21134 (18%)	10799 (9%)
Water volume from the tank directed to the net with temperature T > 25°C	l	16258 (14%)	7033 (6%)
Energy transferred from the tank to the floor heating loop	kWh	-	136

Table 11 Summery of a separate system with different tank sizes for a hot water consumption of 384 l/day.

Tank size	liter	60	140	200
Reference time	-	yearly		
Tank charging flow rate	kg/h	120	58	14
Hot water consumption	l	134320	134320	134320
Tank heat loss	kWh	104	181	93
Energy from district heating	kWh	7792	7868	7779
Energy tapped for hot water consumption	kWh	4661	4661	4662
Energy for space heating	kWh	3026	3026	3026
Average return temperature of the system	°C	22.4	23.3	18.2
Average tank return temperature	°C	22.6	24.0	15.1
Total DHwater volume through the tank	l	149062	159626	116783
Water volume from the tank directed to the net with temperature T > 20°C	l	80270 (54%)	86362 (54%)	21134 (18%)
Water volume from the tank directed to the net with temperature T > 25°C	l	69320 (47%)	58150 (36%)	16258 (14%)

Table 12 Summery of a combisystem with different tank sizes for a hot water consumption of 384 l/day.

Tank size	liter	60	140	200
Reference time	-	yearly		
Tank charging flow rate	kg/h	120	58	14
Hot water consumption	l	134320	134320	134320
Tank heat loss	kWh	104	181	93
Energy from district heating	kWh	7797	7874	7779
Energy tapped for hot water consumption	kWh	4661	4661	4662
Energy for space heating	kWh	3031*	3033*	3026
Average return temperature of the system	°C	19.9	20.6	17.0
Total DHwater volume through the tank	l	149062	159626	116783

Water volume from the tank directed to the net with temperature T > 20°C	l	41340 (28%)	52572 (33%)	10799 (9%)
Water volume from the tank directed to the net with temperature T > 25°C	l	33780 (23%)	28613 (18%)	7033 (6%)
Energy transferred from the tank to the floor heating loop	kWh	553	660	136

7.2 Domestic hot water consumption 184 l/day

The influence of decreased hot water consumption on the system performance is investigated. By default the daily hot water consumption is 364 l/day. In the following calculations the daily hot water consumption and the tank charging flow rate are reduced by half. The yearly calculations of a separate system and a combisystem system are listed in table 13 and 14 respectively. From table 13 and table 8, 9 and 10, it can be seen that with a reduced hot water consumption the average tank return temperature increases 5.5 K, 7.1 K and 1.0K for the 60 l, 140 l and 200 l respectively.

Table 13 Results of a yearly calculation of a separate system with a hot water consumption of 184 l/day.

Tank size	liter	60	140	200
Reference time	-	yearly		
Tank charging flow rate	kg/h	60	29	6.7
Hot water consumption	l	67160	67160	67160
Tank heat loss	kWh	104	188	121
Energy from district heating	kWh	5461	5545	5475
Energy tapped for hot water consumption	kWh	2331	2331	2331
Tank energy change	kWh	-0.1	-0.24	-2.92
Energy for space heating	kWh	3026	3026	3026
Energy imbalance	kWh	0.28	0.25	0.26
Tap warnings	Min	0	0	0
Average return temperature of the system	°C	25.7	27.0	18.9
Average tank return temperature	°C	29.1	31.1	14.1
Total DH water volume through the tank	l	99863	114240	58544
Water volume from the tank directed to the net with temperature T > 20°C	l	71145 (71%)	86386 (76%)	8382 (14%)
Water volume from the tank directed to the net with temperature T > 25°C	l	63850 (64%)	70503 (62%)	1480 (3%)

The combisystem can utilize the energy in the return flow from tank for floor heating and therefore decrease the average return temperature to the district heating net. For a system with 60 l tank, the average return temperature to the net is decreased by 3.2 K by the use of combisystem. The temperature decrease for the system with 140 l and 200 l tank is 3.5 K and 0.7 K respectively. It can be seen that there is not much decrease of the average return temperature of the system with 200 l tank due to the fact that the return temperature from the tank, 18.9°C is already quite low.

Table 14 Results of a yearly calculation of a combisystem with a hot water consumption of 184 l/day.

Tank size	liter	60	140	200
Reference time	-	yearly		
Tank charging flow rate	kg/h	60	29	6.7
Hot water consumption	l	67160	67160	67160
Tank heat loss	kWh	104	188	121
Energy from district heating	kWh	5468	5549	5475
Energy tapped for hot water consumption	kWh	2331	2331	2331
Tank energy change	kWh	-0.1	-0.24	-2.92
Energy for space heating	kWh	3033	3030	3026
Energy imbalance	kWh	0.26	0.2	0.2
Tap warnings	Min	0	0	0
Average return temperature of the system	°C	22.5	23.5	18.2
Average tank return temperature	°C	-	-	-
Total DHwater volume through the tank	l	99863	114240	58544
Water volume from the tank directed to the net with temperature T > 20°C	l	37500 (38%)	44996 (39%)	5768 (10%)
Water volume from the tank directed to the net with temperature T > 25°C	l	31420 (31%)	35363 (31%)	608 (1%)
Energy transferred from the tank to the floor heating loop	kWh	647	811	10

7.3 Calculation of the combisystem with consideration of bathroom comfort

In the calculation the energy needed for bathroom comfort is assumed to be 2 kWh/day. The energy for bathroom comfort is only considered when the energy demand for space heating is less than 2 kWh/day, for example in summer.

7.3.1 A 12 h standard hot water consumption (368 l/day)

Yearly calculation of the combisystems

Tank volume	l	200	100
Reference time	-	yearly	
Tank charging flow rate	kg/h	14	87
Hot water consumption	l	134320	134320
Tank heat loss	kWh	93	143
Energy from district heating	kWh	8111	8197
Energy tapped for hot water consumption	kWh	4662	4661
Energy for space heating	kWh	3359	3392
Average return temperature of the system	°C	16.7	19.2
Total DH water volume through the tank	l	116850	158000
Water volume from the tank directed to the net with temperature T > 20°C	l	2611 (2%)	27702 (18%)

Water volume from the tank directed to the net with temperature T > 25°C	l	8 (0%)	15188 (10%)
Energy transferred from the tank to the floor heating loop	kWh	242	1016

7.3.2 A reduced hot water consumption (184 l/day)

Yearly calculation of the combisystems with reduced hot water consumption

Tank volume	l	200	100
Reference time	-	yearly	
Tank charging flow rate	kg/h	14	87
Hot water consumption	l	67160	67160
Tank heat loss	kWh	231	151
Energy from district heating	kWh	5925	5858
Energy tapped for hot water consumption	kWh	2331	2331
Energy for space heating	kWh	3364	3375
Average return temperature of the system	°C	21	23.0
Total DHwater volume through the tank	l	106080	120870
Water volume from the tank directed to the net with temperature T > 20°C	l	21435 (20%)	37221 (31%)
Water volume from the tank directed to the net with temperature T > 25°C	l	13006 (12%)	28442 (24%)
Energy transferred from the tank to the floor heating loop	kWh	1019	1185

7.3.3 Yearly calculation of the combisystems with reduced hot water consumption and adjusted tank changing flow rate

Tank volume	l	200	100
Reference time	-	yearly	
Tank charging flow rate	kg/h	6.7	43.5
Hot water consumption	l	67160	67160
Tank heat loss	kWh	121	147
Energy from district heating	kWh	5465	5855
Energy tapped for hot water consumption	kWh	2331	2331
Energy for space heating	kWh	3017	3378
Average return temperature of the system	°C	18.1	21.7
Total DHwater volume through the tank	l	58478	104062
Water volume from the tank directed to the net with temperature T > 20°C	l	3461 (6%)	28108 (27%)
Water volume from the tank directed to the net with temperature T > 25°C	l	10 (0%)	24389 (23%)
Energy transferred from the tank to the floor heating loop	kWh	18	1129

8 Experiments

Experiments with a 200 l tank were carried out in order to validate the Trnsys models. The comparison of the temperatures during charging and discharging of the tank are shown in Fig. 17-20. It can be seen from Fig. 17 that the calculation agrees with the measurement with an underestimated degree of thermal stratification. The reason for the disagreement is that it is not possible to totally avoid numerical diffusion due to the limitation on the node number. Another reason of the disagreement is natural convection in the tank caused by heat loss from the wall. The water close to the tank wall will be cooled down creating a downward flow along the wall to the bottom of the tank. The warm water in inner part of the tank rises up, therefore improving thermal stratification in the tank. The flow due to natural convection is not considered in the model. The calculated energy content of the tank is similar to the measured value. It can be concluded that the Trnsys type is able to calculate thermal stratification in the tank although the degree of stratification is a bit underestimated. This is to be considered on the safe side.

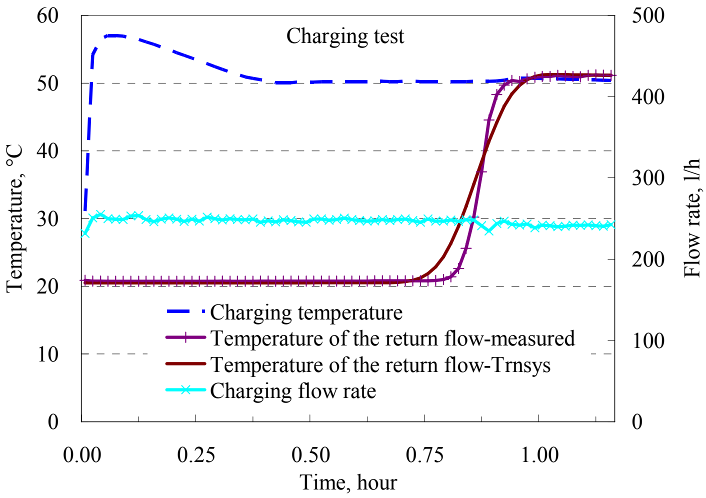

Fig. 17 Supply and return temperature of the charging flow in the charging test.

Fig. 18 shows temperatures at different levels of the tank. The temperature from calculation is the average water temperature of the layer. The measured temperature is the surface temperature of the tank. The distance between the sensors is 0.2 m. It can be seen that the calculation agrees well with the measurement.

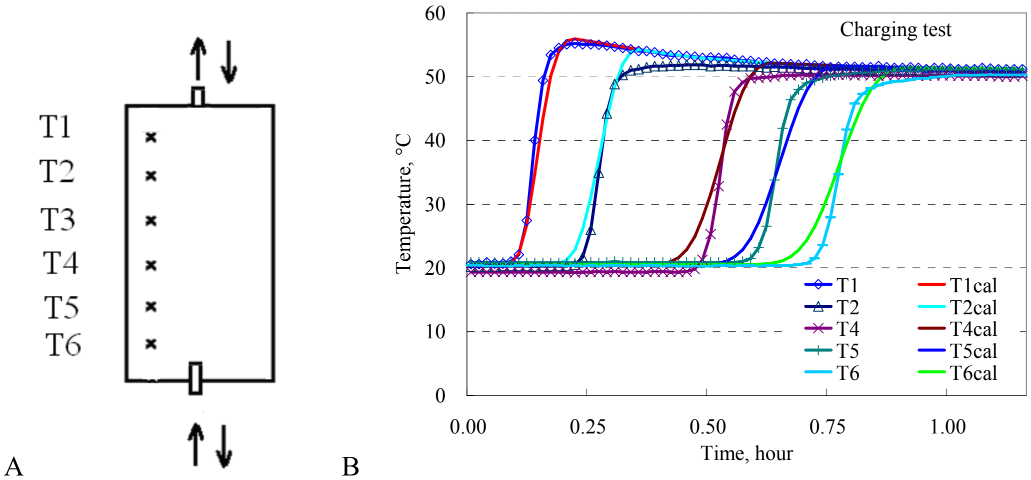

Fig. 18 (A) Positions of the temperature sensors; (B) Calculated fluid temperature and measured tank surface temperature in different levels of the tank in the charging test.

The discharging test is carried out with a uniform temperature of 50ºC as a start. The domestic hot water is provided by heating cold water from 10 ºC to 40ºC by the district heating fluid from the tank through a heat exchanger. A hot water of 38 l is tapped in one draw-off. When the tank is discharged, the cold water enters the bottom of the tank and the hot water leaves the tank from the top. The inputs to the model are the temperature of the flow from the heat exchanger and the volume flow rate. When there is no hot water draw-off, the tank is charged with a constant flow rate of 15 l/h. The temperature of the charging flow is 50-51ºC. The inputs to the model are the temperature of the charging flow and the flow rate of the charging flow. The tank can either be charged or discharged. Fig. 19 shows flow rate during discharging by curve with + and flow rate during charging by curve with x. When the tank is discharged, the cold water inlet temperature at the tank bottom is given as input. The hot water supply at the tank top is validated against measurement. The calculated temperature is 0-1 K lower than the measurement for the first five and the 7th draw-offs. For the 6th and the 8th draw-off, the temperature is underestimated by 0-2.4 K. When the tank is charged, the temperature at the top of the tank is used as input. The calculated temperature at the bottom of the tank is compared to the measurement. It is shown that the difference between the calculation and the measurement is within 2.5 K.

Fig. 20 shows temperatures at different levels of the tank. The temperature from calculation is the average water temperature in the layer. The measured temperature is the surface temperature of the tank. The positions of the sensors are shown in Fig. 18 (A). It can be seen that the calculation is able to predict the temperatures in different tank levels with satisfactory accuracy.

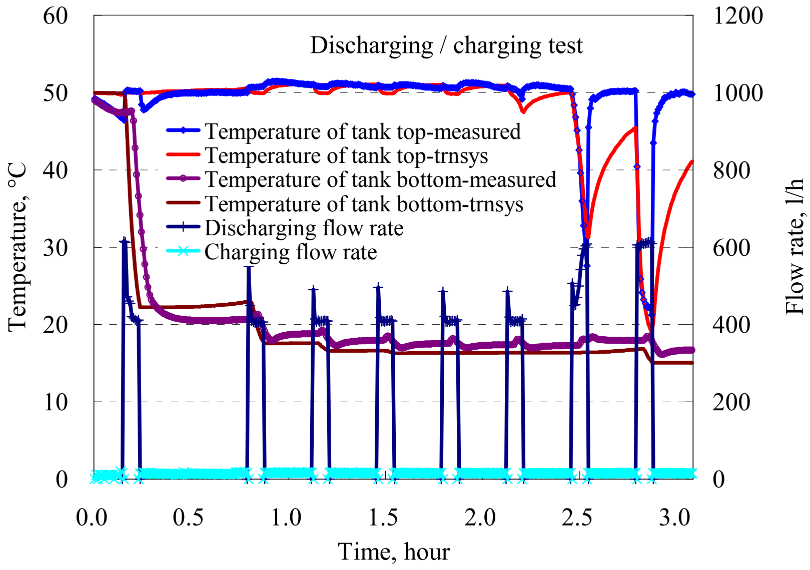

Fig. 19 Temperatures and flow rates during discharging/charging test.

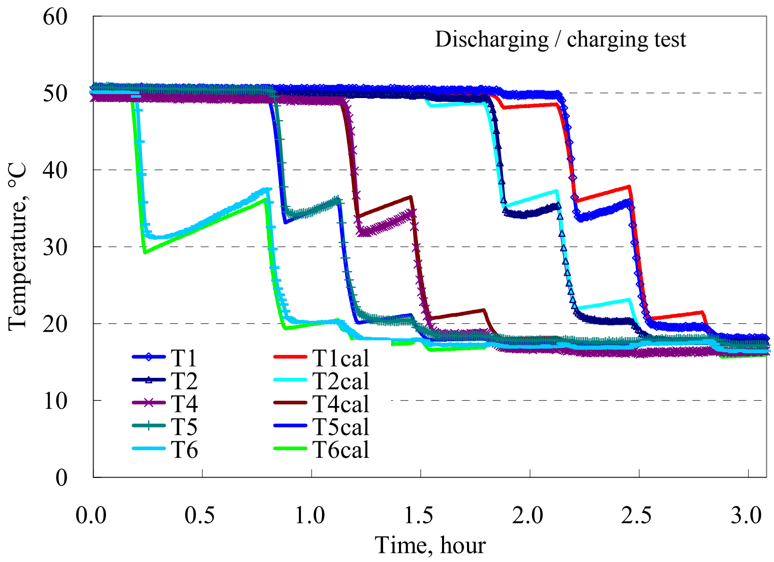

Fig. 20 Calculated fluid temperatures and measured tank surface temperatures in different levels of the tank in the discharging/charging test.

9 Conclusion

1. Calculations show that if there is no heat storage tank the mass flow rate of the district heating flow to the house should be approx. 760 kg/h in order to fulfill the required hot water draw-off profile. For a system with a heat storage tank of 60 l, the mass flow rate can be decreased to 120 kg/h. For a system with a tank of 140 l, the mass flow rate can be decreased to 58 kg/h. For a tank volume of 200 l, a mass flow rate of the district heating flow of 14 kg/h is necessary. The average return temperature from the system is 22.4°C, 23.3°C and 18.2°C for the system with a tank volume of 60 l, 140 l and 200 l respectively.

Table 15 Summary of the yearly calculation with a hot water consumption of 368 l/day.

<table>
<tr><td colspan="2">Tank size</td><td>liter</td><td>0</td><td>60</td><td>140</td><td>200</td></tr>
<tr><td colspan="2">Required mass flow rate of the district heating flow</td><td>kg/h</td><td>760</td><td>120</td><td>58</td><td>14</td></tr>
<tr><td colspan="2">Tank heat loss</td><td>kWh/year</td><td>-</td><td>104</td><td>181</td><td>93</td></tr>
<tr><td>Separate system</td><td>Average return temperature of the separate system</td><td>°C</td><td>-</td><td>22.4</td><td>23.3</td><td>18.2</td></tr>
<tr><td rowspan="2">Combined system</td><td>Energy transferred from the tank to the floor heating loop</td><td>kWh/year</td><td>-</td><td>553</td><td>660</td><td>136</td></tr>
<tr><td>Average return temperature of the combined system</td><td>°C</td><td>-</td><td>19.9</td><td>20.6</td><td>17.0</td></tr>
</table>

2. The combisystem can utilize the energy in the return water from the tank therefore decreases the average return temperature of the system to the district heating net can be decreased. The annual energy transferred from the tank to the floor is 553, 660 and 136 kWh for a system with 60 l, 140 l and 200 l tank respectively. The average return temperature of the system is decreased by 2.5, 2.7 and 1.2 K for the combisystem with a tank volume of 60 l, 140 l and 200 l respectively.
3. The daily hot water consumption has a significant influence on the performance of the DHW system. With a reduced hot water consumption of 184 l/day, the average return temperature from the tank will be increased significantly, for instance 16 K for a tank volume of 200 l. With a reduced hot water consumption of 184 l/day and a reduced tank charging flow rate, the average return temperature from the tank will increase 1.0 to 7.1 K for different tank sizes. In order to decrease the return temperature from the tank, the tank charging system shall be smart controlled so that the tank charging flow rate or the control mode can be adjusted with respect to actual daily hot water consumption. An alternative is to combine the tank with the floor heating system so that the energy in the return water from the tank can be utilized for floor heating.
4. The influence of tank material on tank thermal stratification has been investigated. It is shown that a tank with SS316L as construction material will have a slightly better thermal stratification and thus a slightly lower average return temperature than a tank with FE360 as construction material, for instance 0.6 K for a tank volume of 200 l. However the cost of SS316L is higher than the cost of FE360. The optimum solution is to use FE360 as tank construction material.
5. The influence of the size of the heat exchanger on thermal performance of the tank is investigated. Three types of heat exchanger are investigated: XB37H60, XB37H90 and XB06H60. It is shown that the system with heat exchanger XB37H60 and XB37H90 can fulfill the DHW demand while the system with heat exchanger XB06H60 can not, therefore XBH37H60 is used as the heat exchanger.
6. The heat loss of the tank is determined by the average tank temperature over the year and the surface area of the tank. The average tank temperature over the year is greatly influence by the standby operation time of the tank. The longer the standby operation time, the higher the average tank temperature over the year. The annual heat loss of the tank is 104 kWh, 181 kWh and 93 kWh for the tank volume of 60 l, 140 l and 200 l respectively. Since it takes much less time for the 60 l and 140 l tanks to be fully charged, the standby time of the two tanks are much longer than that of the 200 l tank which results in higher average tank temperature, therefore the heat loss of the 60 l tank and the 140 l tank is larger than the heat loss of the 200 l tank. The heat loss of the 140 l tank is the higher than the heat loss of the 60 l tank due to its larger tank surface area.

7. The TRNSYS calculated fluid temperatures in the tank are compared to the measured temperatures at the surface of the tank. The comparison between the calculations and the experiments shows that the calculations agree with the measurements with an underestimated degree of thermal stratification. The reason for the disagreement could be due to the fact that it is not possible to totally avoid numerical diffusion due to the limitation on the node number. Another reason could be the influence on thermal stratification by the natural convection in the tank caused by heat loss from the wall. The natural convection helps to build up thermal stratification in the tank, which is not considered in the TRNSYS tank model.

It must be mentioned that the calculated heat losses will be lower than the tank heat losses in practice. Especially pipe connections in the upper part of the tank will strongly increase the tank heat loss.