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Improved design of mantle tanks for small low flow SDHW systems

Simon Furbo*,† and Søren Knudsen

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

SUMMARY

Side-by-side tests of two small low flow solar domestic hot water (SDHW) systems based on mantle tanks have been carried out under the same test conditions in a laboratory test facility. The systems are identical with exception of the mantle tanks. One of the mantle tanks has the mantle inlet port located at the top of the mantle and the other mantle tank has the mantle inlet port moved 0.175 m down from the top of the mantle. The thermal performance is almost the same for the two systems in the measuring period of 252 days. The solar fractions were 0.66 and 0.68 for the two systems. The tests showed also that the system with the low mantle inlet perform better than the system with the high mantle inlet in periods with low solar fractions, that is in less sunny periods. Further, calculations with a simulation model for low flow SDHW systems based on mantle tanks showed that mantle tanks currently marketed can be greatly improved by relatively simple design changes: increasing the height/diameter ratio, reducing the mantle height and increasing the insulation thickness on the sides of the tank. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: solar domestic hot water systems; low flow; mantle tank; simulation model; design optimization

1. INTRODUCTION

Investigations by Furbo and Mikkelsen (1987), Hollands (1988), Furbo (1991) and Duff (1996) have shown that low flow systems with a vertical mantle tank are excellent small solar domestic hot water (SDHW) system types, see Figure 1. A simulation model, MANTLSIM, for small low flow SDHW systems with a vertical mantle tank was originally developed by Shah and Furbo (1996) and later modified by Shah and Furbo (1998), Shah (1999) and Shah (2001) at the Technical University of Denmark. MANTLSIM can be used to calculate the yearly thermal performance of a solar heating system based on weather data from the Danish Test Reference Year TRY, Statens Byggeforskningsinstitut (1982). Recently the model was further improved and validated by Knudsen and Furbo (2004) and Knudsen (2004). The improvements were

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*Correspondence to: Simon Furbo, Department of Civil Engineering, Technical University of Denmark, Building 118, DK-2800 Kgs. Lyngby, Denmark.
†E-mail: sf@byg.dtu.dk

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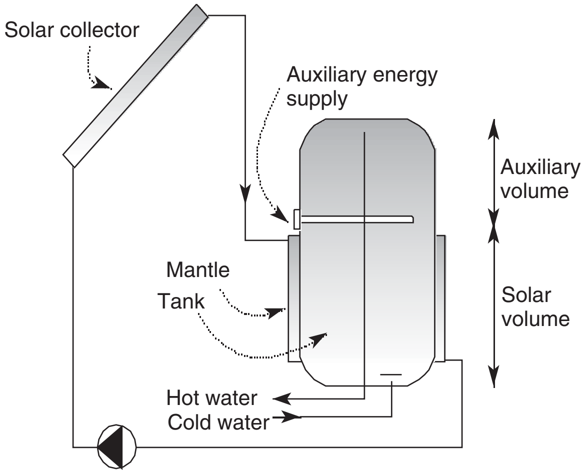

Figure 1. Schematic illustration of a SDHW system based on a vertical mantle tank.

based on detailed studies by Knudsen *et al.* (2005) of the fluid patterns and the heat transfer, both in the vertical mantle and in the inner domestic hot water tank. The studies were carried out by means of Computational Fluid Dynamics (CFD) models. These models were validated by Knudsen (2004) by means of experiments, both with a mantle tank in a heat storage test facility and by means of Particle Image Velocimetry (PIV) measurements with a transparent glass mantle tank.

Parameter analyses were carried out with the CFD models for differently designed mantle tanks under typical operation conditions. Based on the analyses Furbo and Knudsen (2005) developed a number of Nusselt–Reynolds–Rayleigh heat transfer correlations for the heat transfer between the solar collector fluid in the mantle and the inner and outer mantle walls and between the tank wall and the domestic water in the hot water tank.

Thermal stratification is built up in the hot water tank due to natural convection in the tank. By means of CFD calculations for typical operation conditions, Knudsen (2004) developed an empirical method to determine the heat transfer in the hot water tank caused by the natural convection.

Based on CFD calculations for typical operation conditions, an empirical method to determine the mixing inside the mantle caused by the incoming solar collector fluid was developed.

The aforementioned correlations and methods were utilized in MANTLSIM. MANTLSIM was validated by Knudsen (2004) by means of measurements in a test facility for solar heating systems for two low flow solar heating systems with mantle tanks—one with the mantle inlet at the top of the mantle and one with the mantle inlet placed with a distance from the top of the mantle of about one-fourth of the mantle height.

The measurements of the thermal performance of the two low flow systems as well as results of calculations of the yearly net utilized solar energy of low flow SDHW systems with differently designed mantle tanks will be presented in this paper.

Table I. Data for the two SDHW systems tested side-by-side.

Tank design	
Inner tank	
Hot water tank volume (m^3)	0.175
Inner height (m)	1.45
Inner diameter (m)	0.394
Tank wall thickness (m)	0.003
Auxiliary volume (m^3)	0.063
Power of auxiliary energy supply (W)	1200
Mantle	
Mantle volume (m^3)	0.0319
Mantle height (m)	0.7
Mantle gap (m)	0.0335
Position of mantle inlet	Top/0.175 m from top
Inside diameter of mantle inlet (m)	0.0189
Insulation	
Material	Mineral wool
Insulation top (m)	0.13
Insulation side above/below mantle (m)	0.06
Insulation side mantle (m)	0.06
Insulation bottom (m)	0.0
Solar collector	
Area (m^2)	2.51
Start efficiency (dimensionless)	0.801
1st order heat loss coefficient ($W\,m^{-2}\,K^{-1}$)	3.21
2nd order heat loss coefficient ($W\,m^{-2}\,K^{-2}$)	0.013
Incident angle modifier	$1-\tan^{3.6}(\theta/2)$, where θ is the incidence angle
Heat capacity ($J\,m^{-2}\,K^{-1}$)	5339
Tilt (°)	45
Orientation	South
Solar collector loop	
Pipe material	Copper
Outer diameter (m)	0.010
Inner diameter (m)	0.008
Insulation thickness (PUR foam) (m)	0.01
Length of pipe from storage to collector, indoor (m)	4.6
Length of pipe from storage to collector, outdoor (m)	13.3
Length of pipe from collector to storage, indoor (m)	5.1
Length of pipe from collector to storage, outdoor (m)	10.0
Solar collector fluid (propylene glycol/water mixture) (%)	40
Power of circulation pump (W)	50

2. SIDE-BY-SIDE LABORATORY TESTS OF SMALL SDHW SYSTEMS

Two small low flow solar domestic hot water systems with mantle tanks as heat storage were tested side-by-side in a laboratory test facility. The systems are identical, with exception of the mantle tanks. The data for the two SDHW systems are given in Table I. One of the mantle tanks has the mantle inlet port located at the top of the mantle and the other mantle tank has the mantle inlet port moved 0.175 m down from the top of the mantle. In this way it is possible to determine how the mantle inlet position influences the thermal performance of the system. In periods with low solar collector fluid temperatures the incoming solar collector fluid will to a certain degree destroy the thermal stratification in the tank, more in tanks with a high mantle inlet than in tanks with a low mantle inlet. It is therefore expected that a low mantle inlet position will increase the thermal performance in periods with low solar fractions, which is in periods with relatively low solar collector fluid temperatures. Both of the two mantle tanks make use of electric heating elements as auxiliary energy supply systems, and the electric heating elements heat up the top volume to 51°C during all hours. The 2.51 m^2 solar collector in each system is identical. The solar collector loop in both systems is equipped with a circulation pump with a power supply of 50 W to secure a flow rate of about 0.5 l min^{-1} throughout the measuring period. The circulation pump is controlled by a differential thermostat, which measures the temperature difference between the outlet from the solar collector and the bottom of the mantle. The differential thermostat has a start/stop set point at 10/2 K. The two solar heating systems were tested with the same daily hot water consumption of 0.100 m^3. An energy quantity of 1.525 kWh, corresponding to 0.033 m^3 of hot water heated from 10 to 50°C, was tapped from each system three times each day: at 7 a.m., 12 a.m. and 7 p.m. The test period was from the beginning of March to the middle of November 2003 with a duration of 252 days.

The energy tapped from each system is determined by means of measurements with a calibrated Clorius flow meter type Combimeter 1,5 EPD with an accuracy of 1%, of the volume flow rate during hot water draw-offs and by means of measurements with a calibrated copper-constantan thermopile type TT measuring the temperature difference between the cold water entering the tank and the hot water tapped from the tank during the draw-offs. The auxiliary energy supply for each system is measured by means of an electric kWh meter.

The thermal performance of the two systems is compared by the net utilized solar energy and the solar fraction of the systems. The net utilized solar energy is defined as the tapped energy from the system minus the auxiliary energy supply to the tank, and the solar fraction is the ratio between the net utilized solar energy and the tapped energy from the system. The net utilized solar energy is equal to the solar heat transferred to the hot water tank minus the tank heat loss. The energy savings for the systems are therefore somewhat higher than the net utilized solar energies. It is estimated that the accuracy of the measured net utilized solar energy is within 4%.

The measured energy quantities for the two systems are shown in Table II. From Table II, it is seen that the thermal performance of the system is not strongly influenced by the position of the mantle inlet. Both systems had a relatively high solar fraction (0.66–0.68) in the period. The thermal performance for the system with the lower mantle inlet was about 2% higher than

Table II. Measured energy quantities for the two SDHW systems in the period 3/3 2003–10/11 2003.

Energy quantity	SDHW system with top mantle inlet	SDHW system with lower mantle inlet
Hot water draw-off (kWh)	1158	1158
Auxiliary energy supply (kWh)	395	377
Net utilized solar energy (kWh)	763	781
Solar fraction	0.66	0.68

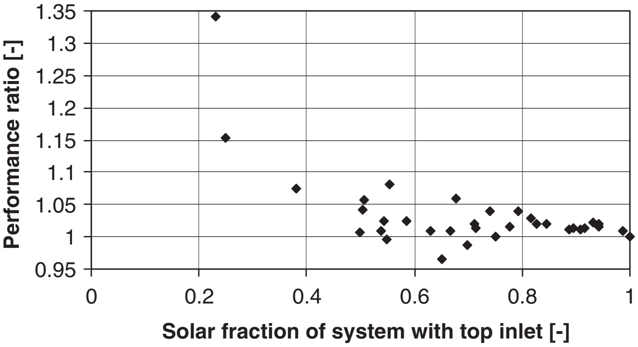

Figure 2. Performance ratio as a function of the solar fraction for the system with the top inlet.

the thermal performance of the system with the top inlet. Considering the measuring accuracy it can be concluded that the thermal performance is the same for the two systems in the measuring period.

At high solar fractions, long periods with high inlet temperatures to the mantle are expected. While the system with the lower mantle inlet has the same thermal performance as the system with the high mantle inlet at high solar fractions, an improvement by moving the inlet down is, due to relative stratification enhancement, expected to appear for smaller solar fractions where lower inlet temperatures are expected.

The 252 days' measuring period have been divided into 36 periods of 7 days. The performance ratio as a function of the solar fraction for the system with the top inlet for the 36 periods is shown in Figure 2. The performance ratio is defined as the ratio between the net utilized solar energy of the system with the lower mantle inlet and the net utilized solar energy of the system with the top mantle inlet.

Figure 2 shows, as expected, that the performance ratio increases for lower solar fractions. However, the performance ratio drops below 1 for two 7-day periods at solar fractions of 0.65–0.70, which can be explained by the distribution of the solar irradiance in these two 7-day periods. Each of the two 7-day periods has 4 days with a clear sky and 3 days more or less overcast, while the other 7-day periods, where the solar fraction is around 0.6–0.7 and the performance ratio is above unity, have clouds every day, which results in lower inlet temperatures to the mantle than on the days with a clear sky. Based on the tendency that the performance ratio increases for lower solar fractions and that the solar fraction was relatively high in most of the measuring periods, it can be concluded that the measurements are consistent with the expectation that the thermal performance of this SDHW system can be somewhat increased by moving the mantle inlet down.

3. MANTLE TANK DESIGN ANALYSIS

Calculations with MANTLSIM were carried out in order to investigate how the thermal performance of a small low flow SDHW system is influenced by the mantle tank design. The mantle tank design analysis is carried out with a commercially available tank, the Danlager 1000 marketed by Nilan A/S, as the standard reference tank. The design analysis is performed in such a way that only one parameter has been changed at a time in the calculation. Table III gives the most important data for the standard reference system.

The circulation pump in the system is controlled by a differential thermostat, which measures the temperature difference between the outlet from the solar collector and the bottom of the mantle. The differential thermostat has start/stop set point at 10/2 K, and the flow rate in the solar collector loop is 0.2 l min^{-1} per m^2 collector.

All the calculations in this chapter are carried out with weather data from the Danish Test Reference Year. The daily hot water consumption is 0.100 m^3 heated from 10 to 50°C, which is tapped from the tank in three equally large parts at 7 a.m., 12 a.m. and 7 p.m. The yearly hot water consumption is 1674 kWh. The auxiliary energy supply system heats the top 0.082 m^3 of the tank to 50.5°C and the indoor air temperature is 20°C.

Table III. Data for the standard reference system.

Tank design	
Inner tank	
Hot water tank volume (m^3)	0.175
Solar volume (m^3)	0.082
Auxiliary volume (m^3)	0.082
Dead volume (m^3)	0.011
Inner height (m)	0.913
Inner diameter (m)	0.494
Tank wall thickness (m)	0.003
Power of auxiliary energy supply (W)	1200
Mantle	
Mantle volume (m^3)	0.0073
Mantle height (m)	0.431
Mantle gap (m)	0.0105
Inside diameter of mantle inlet (m)	0.0244 (3/4″)
Insulation	
Material	PUR-foam
Insulation top (m)	0.075
Insulation side above/below mantle (m)	0.050
Insulation side mantle (m)	0.035
Insulation bottom (m)	0.030
Thermal bridges, tank top (W K^{-1})	0
Thermal bridges, tank bottom (W K^{-1})	0.8
Solar collector	
Area (m^2)	2.5
Start efficiency (dimensionless)	0.801
Heat loss coefficient (W m^{-2} K^{-1})	3.86
Incident angle modifier	$1-\tan^{3.6}(\theta/2)$, where θ is the incidence angle
Heat capacity (J m^{-2} K^{-1})	5339
Tilt (°)	45
Orientation	South

The tank parameters that are investigated are the mantle inlet position, the mantle height, height/diameter-ratio of the tank, the thermal conductivity of the tank material and the insulation of the tank.

Figures 3–7 show calculated yearly net utilized solar energy of the system with the differently designed mantle tank. The standard reference system is marked in the figures. Figure 3 shows the calculated yearly net utilized solar energy of the system as a function of the mantle inlet position. The figure shows that the thermal performance of the system increases for the mantle inlet position moved down from the top of the mantle to a relative position of 0.35 from the mantle top, and that the thermal performance decreases if the inlet position is moved further down. The net utilized solar energy can be increased by 2.5% by moving the inlet port down to a relative position of 0.35. These results are in good agreement with the experimental results from the previous section.

Figure 4 shows the net utilized solar energy as a function of the mantle height. The highest thermal performance is obtained with a mantle height of 0.25–0.30 m. The thermal performance can be increased by 5% by reducing the mantle from 0.43 to 0.27 m. This is not in agreement with earlier theoretical investigations by Shah (1999) and Furbo and Jensen (1995) showing that the top of the mantle is best situated just below the level of the auxiliary volume, because this

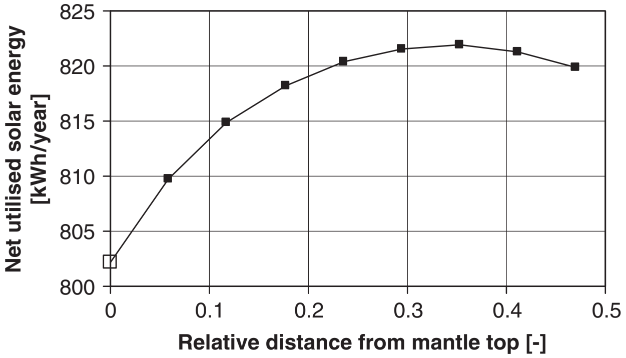

Figure 3. Net utilized solar energy as a function of the mantle inlet position.

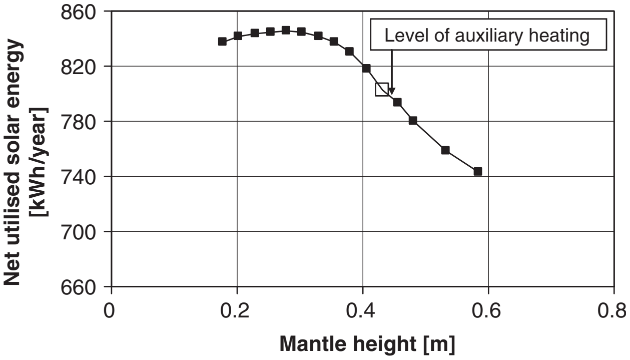

Figure 4. Net utilized solar energy as a function of the mantle height.

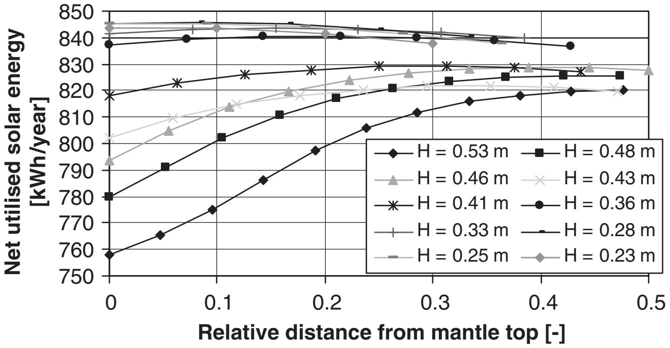

Figure 5. Net utilized solar energy as a function of the mantle inlet position for ten mantle heights.

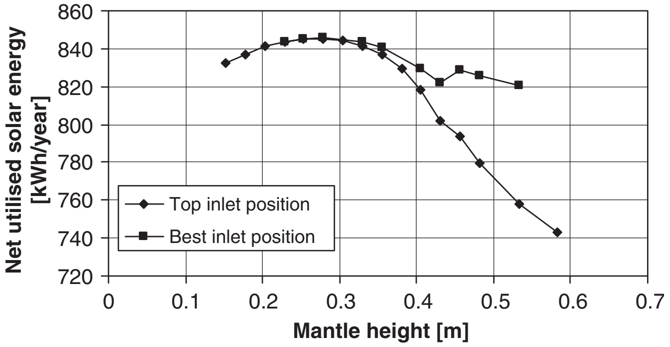

Figure 6. Net utilized solar energy as a function of the mantle height.

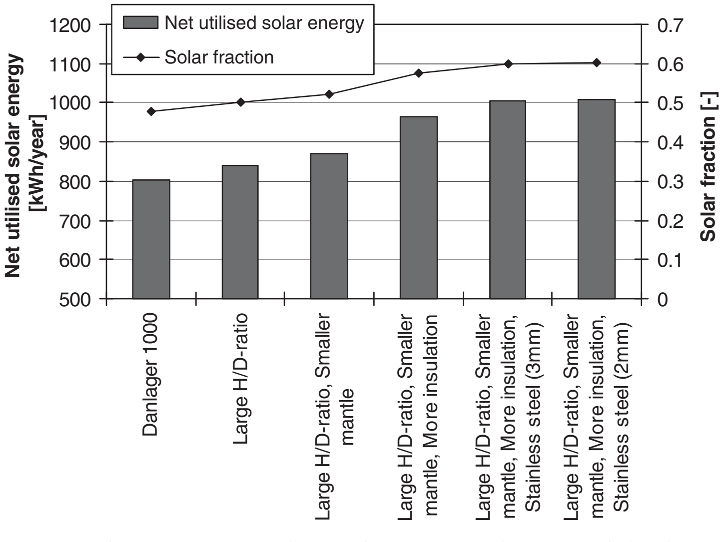

Figure 7. Net utilized solar energy and solar fraction as a function of the different changes in the Danlager 1000 mantle tank.

position maximizes the heat exchange area without the auxiliary energy supply system heating the solar collector fluid in the mantle. If the top of the mantle is located above the level of the auxiliary energy supply system then the auxiliary energy supply system will heat up the mantle fluid and the thermal performance of the system will decrease.

The main reason for the new results is that the simulation model now takes the heat flow in the water in the inner tank into consideration. The heat flow in the water in the inner tank is caused by the upward fluid velocities along the tank wall during supply of heat from the collectors. Therefore the model calculates the thermal stratification which is built up in the hot water tank during periods with supply of heat from the collectors, not only in the mantle level of the tank, but also above the mantle. Another reason is that the mixing, occurring in the mantle caused by differences between the temperature of the incoming solar collector fluid and the temperature of the solar collector fluid, which is already in the mantle, now is taken into consideration by the simulation model. Therefore the simulation model now calculates the heat, which in periods with relatively low solar collector fluid inlet temperatures to the mantle is transferred downwards in the tank. This mixing will equalize temperature differences in the tank resulting in a decreased thermal performance of the system. With a reduced mantle height the influence of this mixing on the thermal performance of the system will be reduced.

The reasons for the increased thermal performance of the system by reducing the mantle height are a reduced tank heat loss due to the smaller mantle surface area and the increased insulation thickness, a decreased equalization of temperature differences in the tank in periods with relatively low solar collector fluid inlet temperatures to the mantle and the fact that the heat transfer area for the heat transfer from the solar collector fluid to the domestic water is not strongly decreased by reducing the mantle height. This is the case because heat by thermal conduction is transferred from the tank wall surrounded by the mantle to the tank wall above the mantle. Consequently, the heat transfer area used for transferring solar heat to the domestic water is a large part of the tank wall. The heat transfer area is influenced by the incoming solar collector fluid temperature. In periods with high temperatures the area is large, in periods with lower temperatures the area is smaller. However, the heat flow model used in MANTLSIM was developed based on CFD-calculations where the mantle covered either the lower half of the tank or all the tank height. The mantle height that gives the highest thermal performance in this study is when the mantle is covering less than one-third of the mantle height. There is a risk that when the mantle gets too small the model is not calculating the natural convection flow in the inner tank correctly and is over-predicting the effect of natural convection.

On the other hand, if these results are true, it opens a new perspective in the mantle tank design because less material can be used making the mantle tank cheaper, less heavy and therefore easier to install if only the bottom third of the tank should be covered by the mantle. There is therefore a need to verify by experiments that the small mantle height is able to create the degree of thermal stratification above the mantle calculated by the model.

Figure 5 shows the net utilized solar energy as a function of different mantle inlet positions (shown as the relative distance from the mantle top) for different mantle heights, H. All other system parameters are equal to the parameters of the reference system. It is seen from the figure that the relative improvement of moving the mantle inlet down is largest for large mantle heights. The improvement in thermal performance is especially large when the top of the mantle is located above the level of the auxiliary energy supply system ($H = 0.53$, 0.48 and 0.46 m), because with these designs the temperature in the upper part of the mantle is always high and therefore the part of the operation time with mantle inlet temperatures lower than the temperature of the solar collector fluid in the top of the mantle will be increased. Consequently, heat from the auxiliary energy supply system will be transferred downwards in the tank. For small mantle heights it has little effect to move the mantle inlet position away from the top of the mantle because with these designs the top of the mantle is relatively far away from the level of the auxiliary energy supply system, and the temperature in the inner tank at the level of the upper part of the mantle is therefore lower.

Figure 6 shows the net utilized solar energy as a function of the mantle height for top mantle inlet position and for the optimum mantle inlet position for each mantle height. It appears that the mantle height of 0.27 m gives the best thermal performance both for top inlet position and when using the best inlet position for each mantle height. Furthermore, it is seen as in Figure 5 that for small mantle heights the top mantle inlet position gives the best thermal performance, and for larger mantle heights the thermal performance can be improved significantly by moving the mantle inlet down to a lower position.

A number of parameter variations have been carried out to reveal how the different tank parameters influence the thermal performance of low flow SDHW systems. In the following it will be elucidated how to improve the design of the Danlager 1000 mantle tank by relatively simple geometrical changes. The change of the design is made in such a way that one parameter is changed at a time in the calculations. Also here the data from Table III are used for the reference system in the calculations.

The following tank parameters are changed: height/diameter ratio of the tank, mantle height, insulation, thermal conductivity of the tank material and the wall thickness of tank and mantle.

Figure 7 shows the net utilized solar energy and the solar fraction as a function of different changes in the mantle tank design. The first bar shows the thermal performance of the system with the Danlager 1000 heat storage with mantle inlet position at the top of the mantle.

The first change is the height/diameter ratio of the tank, which is changed from 2 to 4. The inner height of the hot water tank is for a height/diameter ratio of 4 equal to 1.528 m. The total volume and the ratio between the auxiliary volume and the total volume are kept constant. The second change is the mantle height, which is decreased from 0.72 m, which corresponds to a mantle height with the same relative height as the mantle height in the standard tank, to 0.55 m. The third change is the insulation of the tank. It is assumed that the tank should fit into a cabinet with dimensions $0.6 \times 0.6 \times 2.0\,\mathrm{m}^3$, and by increasing the height/diameter ratio the outer diameter is reduced, and thus the side insulation can be increased by 0.05 m. The fourth change is the tank material, which is changed from normal steel to stainless steel. The thermal conductivity of the tank material is in this way reduced from 60 to $15\,\mathrm{W\,m^{-1}\,K^{-1}}$. The fifth, and last, change is the wall thickness of tank and mantle, which is reduced from 3 to 2 mm.

The change concerning the insulation gives the most significant improvement, while the change of the wall thickness gives the smallest improvement. The net utilized solar energy is increased from 802 to $1009\,\mathrm{kWh\,year^{-1}}$ by applying the mentioned changes in the design. It is an improvement of 26% of the net utilized solar energy.

4. CONCLUSIONS

Calculations with a detailed model have shown that marketed mantle tanks can be greatly improved by relatively simple design changes: by increasing the height/diameter-ratio, by reducing the mantle height, by increasing the insulation thickness on the sides of the tank and by using stainless steel instead of steel as tank material.

The thermal advantage of decreasing the mantle height predicted by the model is of great interest, since the cost of the mantle tank can be decreased by reducing the mantle height. However, it must be mentioned that the model is not validated for small mantle heights. It is therefore recommended to start investigations to test the model with small mantle heights.

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