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Development of a hot water tank simulation program with improved prediction of thermal stratification in the tank

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Abstract

A simulation program SpiralSol was developed in previous investigations to calculate thermal performance of a solar domestic hot water (SDHW) system with a hot water tank with a built-in heat exchanger spiral [1]. The simulation program is improved in the paper in term of prediction of thermal stratification in the tank. The transient fluid flow and heat transfer in the hot water tank during cooling caused by standby heat loss are investigated by validated computational fluid dynamics (CFD) calculations. Detailed CFD investigations are carried out to determine the influence of thickness and material property of the tank wall on thermal stratification in the tank. It is elucidated how thermal stratification in the tank is influenced by the natural convection and how the heat loss from the tank sides will be distributed at different levels of the tank at different thermal conditions. The existing equation of the heat loss removal factor used in SpiralSol is evaluated by means of the detailed CFD calculations. A generalized new equation for the heat loss removal factor is obtained by regression. The new equation calculates the heat loss removal factor for a given temperature gradient in the tank, taking into account the influences of tank volume, height to diameter ratio, tank insulation, thickness and material property of the tank and initial thermal conditions of the tank. The equation is validated for a tank volume between 150 l and 500 l, a tank height to tank diameter ratio of 1-5, a tank wall thickness of 1.5 mm to 3 mm for a stainless steel tank and a tank wall thickness of between 3 mm to 5 mm for a normal steel tank. Accuracy and reliability of the SpiralSol program with the improved prediction of heat loss removal factor will be examined in future investigations.

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Keywords: Hot water tank; thermal stratification; tank simulation program; Computational fluid dynamics (CFD) ; Heat loss removal factor

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1. Introduction

Thermal stratification in solar storage tanks has a major influence on the thermal performance of solar heating systems. A high degree of thermal stratification in the storage tank increases the thermal performance of a solar heating system because the return temperature to the solar collector is lowered [2-4]. A lower inlet temperature to the solar collector will increase the efficiency and operating hours of the solar collector. Further, the temperature at the top of the storage will be closer to the desired load temperature. Therefore the auxiliary energy consumption will be decreased which increases the solar fraction [5-6].

Heat loss from the tank sides helps to build up thermal stratification in the tank. Due to heat loss to the surroundings, the fluid close to the tank wall has a lower temperature than the fluid at the centre of the tank. The relative colder fluid flows downwards along the tank wall while the fluid with higher temperature rises up in the centre of the tank.

Thermal stratification and natural convection flow in a vertical cylindrical hot water tank during standby periods were investigated by Fan and Furbo [7, 8]. Transient, three-dimensional CFD models of hot water storage tanks were developed and validated against thermal measurements. The results show that the CFD calculation predicts satisfactorily the water temperatures in the tank during cooling of the tank. The natural convection flow along the tank sides is strongly influenced by the thermal stratification in the tank. Without the presence of thermal stratification, there is a strong downward fluid velocity of 0.003-0.015 m/s, which means that the heat loss from the tank sides will be moved downwards and thus helps to build up thermal stratification in the tank. With the presence of thermal stratification in the tank the buoyancy driven flow is significantly reduced [8].

A simulation program SpiralSol was developed in previous investigations to calculate thermal performance of a solar domestic hot water (SDHW) system with a hot water tank with a built-in heat exchanger spiral [1]. The detailed simulation program can, among other things, calculate thermal stratification in the tank established by heat loss of the tank during standby period. The simulation program will be improved in the paper in term of prediction of thermal stratification in the tank by means of detailed CFD calculations. The influence of thickness and materials of tank wall on thermal stratification in the tank will be elucidated. The ultimate goal of the investigations is to find a simple equation to quantify the exchange of heat loss between tank layers, which can be implemented in the simple multi-node tank simulation model, SpiralSol.

Nomenclature

a	The heat loss removal factor, -.
D	Diameter of the tank, m.
Gr	Temperature gradient in the tank, K/m.
h_{layer}	Distance of the layer to the tank bottom, m.
H	Tank height, m.
I	Layer number countered from the tank bottom, -.
K	Heat loss coefficient of the tank, W/K.
N	The total number of tank layers, -.
Q	Heat transfer, W.
R^2	The coefficient of determination, -.
t	Water temperature in the tank, ºC.
T	Temperature in the tank (T= t+273.15), K.
T_a	The ambient air temperature, ºC.
δ	Thickness of the insulation material, m.
ρ	Water density, kg/m^3.
μ	Dynamic viscosity of water, kg/(ms).
λ	Thermal conductivity of water, W/(mK).

2. The CFD models

CFD calculations were carried out to theoretically investigate the fluid flow in hot water tanks during cooling by heat loss from the tank. A CFD model of the hot water tank was created using the CFD code Fluent 6.3 [9], see Fig. 1. The 150 l tank has a diameter of 0.34 m and a height of 1.68 m. The height to diameter ratio of the tank is 5.0. The tank is made of steel and is insulated with 5 cm mineral wool. In order to better resolve the heat transfer and fluid flow in the region adjacent to the tank wall, a boundary layer mesh is applied so that there is a fine and dense mesh in the area close to the tank wall. The 3D tank model includes the steel tank wall as a solid region and the hot water volume of the tank as a fluid region while the insulation materials are not directly modelled. The tank is insulated with mineral wool with the same thickness for the top surface, the side surface and the bottom surface of the tank. The effect of the insulation materials is considered by the heat loss coefficients obtained by the experiments. Mean average ambient air temperature during the experiment is used as the free stream temperature of the tank surfaces. Water is used as the heat storage media. Properties of water and their dependences on temperature are shown as follows:

Density, [kg/m^3]:

$$\rho = 863 + 1.21 * \mathrm{T} - 0.00257 * \mathrm{T}^2 \tag{1}$$

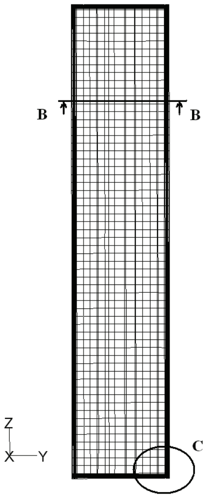
Dynamic viscosity, [kg/(ms)]:

$$\mu = 0.0007 * (\frac{T}{315})^{-5.5} \tag{2}$$

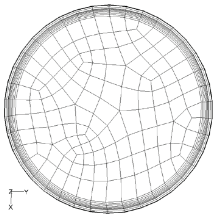
Thermal conductivity, [W/(mK)]:

$$\lambda = 0.375 + 8.84 \times 10^{-4} * T \tag{3}$$

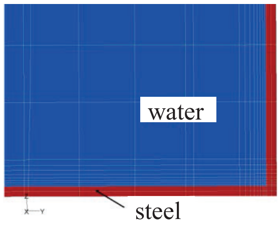
where T is fluid temperature, [K].



A. Vertical cut plane of the tank model



B. Cross section of the tank model



C. A magnified view of the corner

Fig. 1. CFD model of the cylindrical hot water tank

The measured heat loss coefficients for different parts of the tank are used as input to the CFD model. The heat loss coefficients are finely tuned within the measurement inaccuracy so that the heat loss from the tank calculated by the CFD calculation is the same as the measured heat loss. The heat loss coefficient of the top surface, of the side surface and of the bottom surface of the tank insulated with 5 cm mineral wool are given in the equations 4-7 [7].

$$K_{top} = 0.24 + 0.00015 * \mathrm{t} \quad \text{[W/K]} \tag{4}$$

$$K_{side} = 1.75 + 0.00148 * \mathrm{t} \quad \text{[W/K]} \tag{5}$$

$$K_{bottom} = 0.41 + 0.00034 * \mathrm{t} \quad \text{[W/K]} \tag{6}$$

$$K_{total} = 2.4 + 0.00198 * \mathrm{t} \quad \text{[W/K]} \tag{7}$$

where t is the water temperature in the tank, [˚C].

The CFD model was validated against measurements carried out on a hot water tank in previous investigations [7, 8]. Calculation of Rayleigh number shows that the flow is in the laminar region, therefore the laminar model is used in the calculation. Transient CFD calculations are performed with a density of water as a function of temperature, shown in equation (1). A time step in the range of 2-4 s and a cell size of 0.02-0.03 m with a eight row of boundary layer mesh attached to the tank wall are found to be appropriate and are therefore used in the calculations [7,8]. The PRESTO and second order upwind method are used for the discretization of the pressure and the momentum/energy equations respectively. The SIMPLE algorithm is used to treat the pressure-velocity coupling. The transient simulations start from a tank with uniform temperature of 80˚C in the tank. A zero velocity field is assumed at the start of all simulations. The calculation is considered convergent if the scaled residual for the continuity equation, the momentum equations and the energy equation are less than 10^{-3}, 10^{-3} and 10^{-6} respectively. The simulation runs with a time step of 2-4 s and a duration of 24 h. One simulation takes approximately 24-48 hours for a quad-core processor computer with 4 X 3 GHz CPU frequency and 4G memory.

3. The solar domestic hot water system simulation program SpiralSol

SpiralSol is a program for simulation of a solar domestic hot water system with the Danish reference weather data TRY [1]. The program in its original version was developed at Thermal Insulation Laboratory, Technical University of Denmark [1]. The program can calculate the conditions in active solar heating systems in great detail as special weight has been attached to an exact description of the thermal conditions in the storage tank. The program can calculate two designs of the system: Systems in which the auxiliary energy supply system and the solar heat exchanger are placed in the same storage tank and preheating systems (systems in which there is no auxiliary energy supply system in the storage tank). In both cases the solar heat exchanger is a heat exchanger spiral that is mounted at the bottom of the storage tank.

In order to analyze the influence of the buoyancy driven flow on the thermal stratification, the tank is equally divided into a number of layers (N), numbered sequentially from the bottom to the top of the tank, see Fig. 2. Heat loss from the side of the layer I is defined as $Q_{loss}(I)$ calculated based on traditional heat transfer theory while the heat loss moving from the layer above (I+1) to the layer (I) due to the buoyancy driven flow is defined as $Q_{flow}(I)$. A heat loss removal factor $a(I)$ for interface I is defined as the ratio between the heat loss moved down by natural convection and the total amount of heat loss of the layer. The heat loss of the layer includes both heat loss from the side of the tank and the heat loss moved down from the layer above.

$$a(I) = \frac{Q_{flow}(I)}{Q_{flow}(I+1) + Q_{loss}(I+1)} \tag{8}$$

For the top layer N, the heat loss moving from the layer above is replaced by the heat loss from the top of the tank.

$$a(N-1) = \frac{Q_{flow}(N-1)}{Q_{\text{top loss}} + Q_{loss}(N)} \tag{9}$$

Thermal stratification in the tank is characterized by a temperature gradient Gr(I).

$$Gr(I) = \frac{T_{layer}(I+1) - T_{layer}(I)}{h_{Layer}(I+1) - h_{Layer}(I)} \tag{10}$$

where T_{water} (I) is the average fluid temperature of layer I in K, while H_{Layer} (I) is the average height of layer I in m measured from the bottom of the tank.

In SpiralSol, the following equation of heat loss removal factor was used [1]:

$$\alpha(I) = 0.50 - 0.02 * Gr(I) \text{ (if } a\text{(I)<0, } a\text{(I)=0)} \tag{11}$$

Fig. 3 shows the existing equation of heat loss removal factor used in SpiralSol. When there is no temperature gradient e.g. Gr(I)=0, the heat loss removal factor is 0.5, which means that half of the heat loss in the layer is moved to the layer below due to the downward flow along the tank wall. With an increase of temperature gradient, the heat loss removal factor is decreased. When the temperature gradient Gr(I) is larger than 25, the equation 11 gives a negative factor but it is forced to be zero, which means that there is no heat loss moved to the neighbor layer.

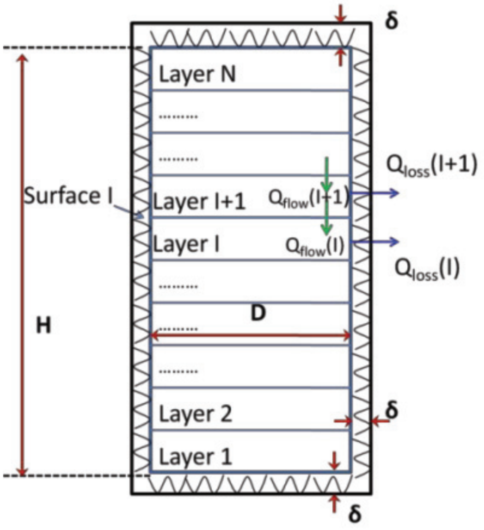


Fig. 2 schematic illustration of a tank consisting of N layers.

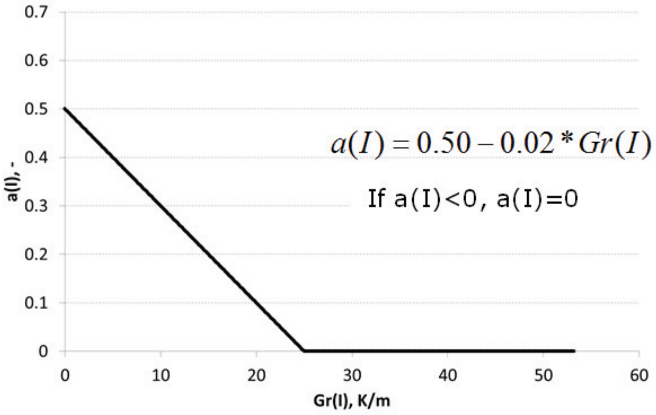


Fig. 3 the existing equation of heat loss removal factor used in SpiralSol.

4. Results and discussion

4.1. Flow pattern in the hot water tank during standby period

The pattern of water movement in the tank due to heat loss from the tank is investigated by CFD calculations. The simulation starts with a tank with a uniform temperature of 80˚C. After 5 hours standby, the tank is cooled to a temperature of 77 ˚C at the top of the tank due to heat loss from the tank. Fig. 4 (Left) shows that the water temperature is 77 ˚C at the majority of the tank while it is decreased to 60 ˚C down to the bottom of the tank. A thermal stratification of approx. 27 K/m has been established at the bottom 1/10 of the tank. Fig. 4 (Right) shows the trajectory of water flow in the tank. Apparent streamlines of water flow can be found close to the tank wall, indicating a downward flow along the wall. While in the rest of the tank, streamlines can be observed from the lower part to the upper part of the tank. In the bottom 1/10 of the tank where there is a thermal stratification, there is almost no streamline, which indicates that the movement of water is limited in the area where there is a thermal stratification.

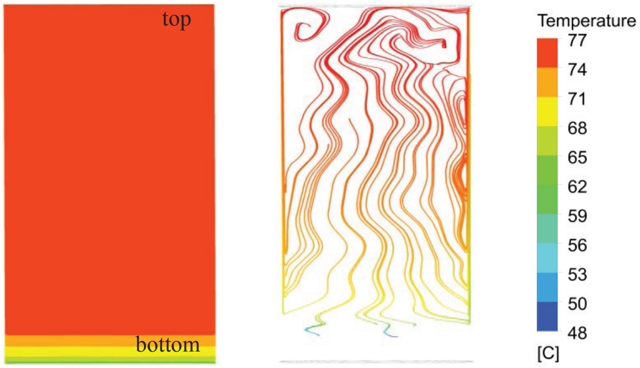


Fig. 4 temperature plot (to the left) and trajectory of water flow (to the right) in the tank after 5 hours standby.

Velocity vectors in the tank after 5 hours standby are shown in Fig. 5. At the upper part of the tank where there is almost no temperature gradient, a downward flow with a relatively higher speed is observed in the area close to the tank wall. The max speed of water flow is in the range of 7-10 mm/s. While at the bottom of the tank with a thermal stratification present, the downward flow is significantly reduced to a value less than 0.1 mm/s. In the rest of the tank, there is an uprising flow with a speed of less than 1 mm/s except in the very top of the tank where a water flow of 2-4 mm/s is seen. It is the downward flow close to the tank wall and the uprising flow in the middle of the tank that move water with a relatively lower temperature to the bottom of the tank, thus establishing thermal stratification in the tank.

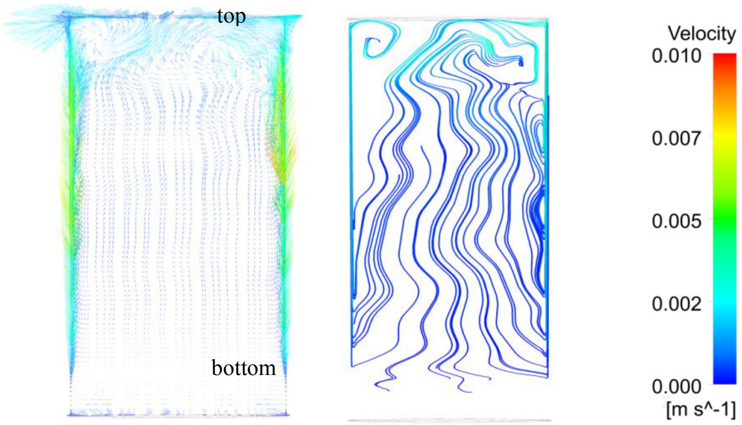


Fig. 5 velocity vectors (to the left) and trajectory of water flow (to the right) in the tank after 5 hours standby

4.2. The new equation of heat loss removal factor

In previous investigations parametric studies using the validated CFD models were carried out to study the influence of tank height to diameter ratio (H/D) and tank volume on thermal stratification in the tank [7]. Twelve tank models with different tank volumes and different height to diameter ratios were built using Fluent 6.3, see Table 1. In these calculations, the default tank wall was 5 mm normal steel. Investigations are carried out in this paper to study water temperatures and fluid flow in a 150 l stainless steel tank with a wall thickness of 1.5-3 mm and in a 150 l normal steel tank with a wall thickness of 3-5 mm. In the investigations a H/D ratio of 5 is used. Design of the six tank models is listed in Table 2.

Table 1. Twelve tank models with different tank volumes and different height to diameter ratios investigated in previous work [7].

Tank volume	Height to diameter ratio, H/D			
	1	2	3	5
150 l	X	X	X	X*
300 l	X	X	X	X
500 l	X	X	X	X

Note: *Tank insulation thickness investigated: without any insulation, with 2 cm, 5 cm and 7 cm mineral wool. Experimental investigation was carried out.

Table 2. Six tank models with different tank materials and different tank wall thicknesses.

Tank material	Height to diameter ratio, H/D				
	1.5 mm	2 mm	3 mm	4 mm	5 mm
Normal steel	-	-	X	X	X*
Stainless steel	X	X	X	-	-

Note: * the reference case

Based on the results of the CFD investigations, a simple equation is obtained by regression that calculates the heat loss removal factor for a given temperature gradient. The equation takes into account the influences of tank volume, tank height to diameter ratio, tank insulation, thickness and property of the tank wall and initial conditions of the tank, see equation (12).

$$Gr(I)\le 0.25:\quad a(I)=0.65-Gr(I)$$

$$Gr(I)>0.25:\quad a(I)=\frac{1}{2.32+1.39D^2H+0.116H/D}\ln\left(\frac{Q_{loss}(I+1)}{8.12H+2.23D+4.71/H/D}\right)Gr(I)^{\frac{T_{layer}(I+1)-T_a}{85.8+39.5D^2H+18.3H/D}-1} \quad (12)$$

where H is the tank height in m; D is the tank diameter in m; $Q_{loss}(I+1)$ is the heat loss from the side of the tank layer $I+1$ in W/m^2. $T_{layer}(I+1)$ is the average water temperature in the tank layer I+1, ºC; T_a is the ambient air temperature, ºC.

Results of the CFD calculations for a 150 l normal steel tank and for a 150 l stainless steel tank are shown in Fig. 6 and Fig. 7 respectively. The heat loss removal factor is calculated at the interfaces for a 24 hours standby period with an interval of three hours. The results show that the lower the temperature gradient, the higher the heat loss removal factor is. At the top of the tank where there is almost no temperature gradient, the heat loss removal factor is around 0.4-0.6, while at the bottom of the tank where there is a temperature gradient the heat loss removal factor is reduced to a value lower than 0.05. A similar trend is observed for both a normal steel tank wall with thickness of 3 mm, 4 mm and 5 mm and for a stainless tank with a wall thickness of 1.5 mm, 2 mm and 3 mm. The dependence of heat loss removal factor on temperature gradient in the tank is not influenced by thickness of tank wall, nor by tank materials. The heat loss removal factor predicted by equation 12 is compared to the factor determined based on CFD calculations. It can be seen from Fig. 6 and 7 that the equation predicts well the factors for all layers of the tank with a maximum difference up to 0.1. The existing equation (11) in SpiralSol overestimates the factor at a temperature gradient lower than 0.4 or higher than 23 while it underestimates the factor at a temperature gradient between 0.4 and 23.

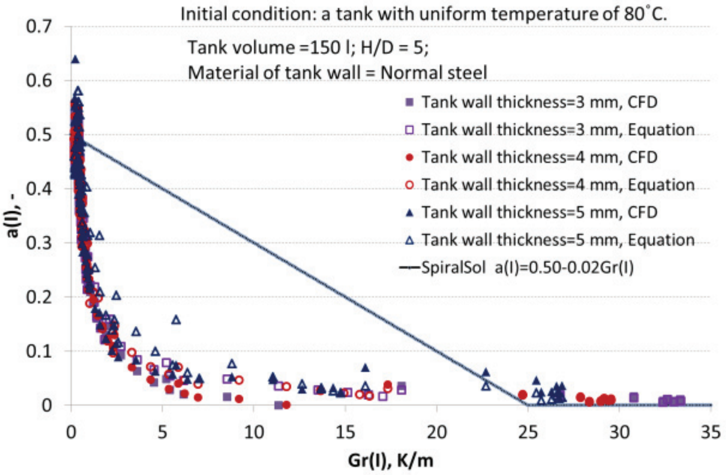


Fig. 6 the heat removal factors for a 150 l normal steel tank with different tank wall thicknesses.

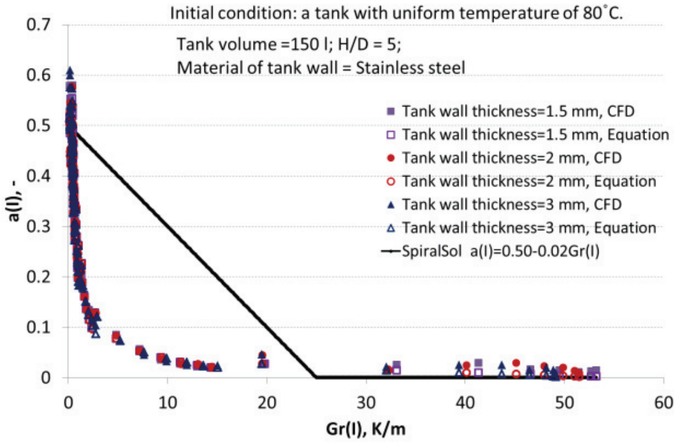


Fig. 7 the heat removal factors for a 150 l stainless steel tank with different tank wall thicknesses.

The confident level of the equation for calculation of the heat loss removal factor (12) is analyzed by means of the coefficient of determination, defined as follows:

$$R^2 = 1 - \frac{\sum\left(a - a_{equation}\right)^2}{\sum\left(a - \bar{a}\right)^2} \tag{13}$$

where a is the heat loss removal factor determined based on CFD calculations; $\bar{a}$ is the average of the heat loss removal factors determined based on CFD calculations; $a_{equation}$ is the heat loss removal factor determined by the equation 12.

The coefficient of determination is calculated for all the investigated tank designs. The results are respectively listed in Table 3 for different tank volumes with different H/D ratios and in Table 4 for different tank materials with different thicknesses. The smallest R^2 is 0.86 while for most cases R^2 is 0.91 or higher. It can be concluded that the new equation 12 can satisfactorily predict the heat loss removal factor based on design of the tank, thermal conditions of the tank and the ambient air temperature.

Table 3 Coefficient of determination, R^2 for different tank volumes and different H/D ratios [7]

Tank volume	H/D			
	1	2	3	5
150 l	0.86	0.96	0.96	0.91
300 l	0.86	0.98	0.96	0.97
500 l	0.92	0.96	0.98	0.98

Table 4. Coefficient of determination, R^2 for different tank materials and different wall thicknesses.

Tank material	Height to diameter ratio, H/D				
	1.5 mm	2 mm	3 mm	4 mm	5 mm
Normal steel	-	-	0.97	0.97	0.91*
Stainless steel	0.95	0.96	0.96	-	-

Note: * the reference case

The equation is now ready to be implemented in the SDHW system simulation program SpiralSol. Thermal performance calculated by the program will in future be compared to measurements. Future investigations will elucidate accuracy and reliability of the program for calculation of temperatures and thermal performance of a SDHW system with a spiral hot water tank.

5. Conclusions and future work

The transient fluid flow and heat transfer in the hot water tank during cooling caused by standby heat loss are investigated by validated computational fluid dynamics (CFD) models. Based on the detailed CFD calculations, a new equation of the heat loss removal factor was obtained by regression. The new equation calculates the heat loss removal factor for a given temperature gradient in the tank with a satisfactory accuracy. Influences of tank volume, height to diameter ratio, tank insulation, thickness and material property of the tank and initial thermal conditions of the tank are considered in the equation. The equation can be used with a good accuracy for a tank volume between 150 l and 500 l, a tank height to tank diameter ratio of 1-5, a tank wall thickness of 1.5 mm to 3 mm for a stainless steel tank and a tank wall thickness of between 3 mm to 5 mm for a normal steel tank. Accuracy and reliability of the SpiralSol program with the improved prediction of heat loss removal factor will be evaluated in future investigations.

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