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Numerical Simulations of Temperature and Velocity Fields in the Storage Tank with the Three-Coil Heat Exchanger

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Abstract

This article presents the results of the numerical investigation of the thermal stratification in the hot water storage tank. The exchanger consists of three tube coils that are immersed in the storage tank of hot water. Two coils—lower and upper—are designed to warm the water in the tank using the water as a heating medium. Another coil—uses the refrigerant for the waste heat transfer. The temperature stratification device is mounted in the thermal storage tank. The device's task is to improve the thermal stratification level of heated water. The performed numerical simulations allowed us to obtain the temperature and velocity fields in the storage tank under the conditions of the work of coils filled with water. Calculations were made in the case of the use of the stratification device under the operating conditions of the upper and lower coils with water.

Keywords

stratification device, numerical calculations, temperature stratification, coil heat exchanger

1. Introduction

Thermal stratification is when a temperature gradient is created in the storage tank which, which leads to the layered structure of the fluid, and the results from the density of the hot and cold fluid. Stratification is based on the buoyancy mechanism. Due to this, there will always be a level of natural-induced thermal stratification in an accumulation tank. Thermal stratification is actively maintained—no mixing of the thermal layers occurs. However, in hot water storage tanks, achieving a suitable temperature stratification requires the use of stratification devices.

Thermal stratification in hot domestic storage tanks is an effective method to improve the efficiency of the heating systems used. It concerns the systems when the available source of energy is irregular or when a time lag exists between the heat production and the demand for heat. An increase in the total efficiency of the system may be achieved by a good thermal performance of the accumulation tank, which in turn depends on the appropriate degree of temperature stratification in the tank.

The water in an accumulation tank is heated by the working medium. The heat transfer to the stored water occurs by direct mixing or through the heat exchanger mounted in a storage tank. The problem of thermal stratification in storage tanks using both heat transfer processes for water heating has been the subject of various experimental and numerical investigations. A short review of the selected literature positions about the subject considered was presented. In [1], Lavan and Thompson experimentally studied the temperature stratification in hot water storage tanks—the two plexiglass cylindrical vessels. The results received have been correlated to predict the system efficiency in terms of Reynolds number at the inlet of the tank, a tank Grashof number, and the ratio of the tank length to its diameter. Another work [2] presented the results of experimental investigations on the effect of the ambient and the operating conditions on the temperature stratification in the accumulation tanks with different geometries. Adequate correlation has also been obtained. The thermal behavior and stratification of storage tanks with different aspect ratios during the operation in the static mode have been studied experimentally and reported by Khalifa et al. [3]. In turn, the results of numerical investigations can be found among others in Altuntop and others [4–7]. In [4], Altuntop et al. studied the effect of using different obstacles on thermal stratification in a cylindrical hot water storage tank. The authors applied numerical simulations and experimental validation of the results was received. It has been concluded that placing obstacles in the accumulation tank provides better temperature stratification compared with the case without obstacles. The

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paper [5] reported the results of the research of geometrical parameters effect on thermal stratification within a cold storage tank. The authors investigated nine two-dimensional models with the use of numerical simulations. The exergy analysis has been applied for the quantification of the level of thermal stratification in each model considered. In turn, the work [6] included the results of numerical study of heat transfer mechanisms during the charging process of thermal stratified storage tank applied in a specific adsorption heat pump cycle. In the last cited article [7], the authors discussed the problem of factors that significantly influence the thermal performance of stratified thermal storage systems for heating and cooling applications. Five fully insulated tanks with different geometries were numerically simulated to determine the effect of the considered factors on the mixing process and thermocline formation.

The present work is a continuation of the previous research on the special type of the three-coil heat exchanger applied in the accumulation tank [8–13]. Two coils—lower and upper—are designed to warm the water in the tank using the water as a heating medium. Another coil—equipped with a special buffer layer with the nanofluid—uses the refrigerant for the waste heat transfer. The preliminary design of the exchanger has been presented in Smusz and Wilk [8]. The correlations of heat transfer coefficients in curved tubes, pressure drop correlations for the fluid flow through helical coil tubes, and the correlations describing the heat transfer process in the buffer layer with nanofluid have been applied in the calculations of thermal power of the exchanger. In [9], Smusz and Wilk analyzed the issue of thermal resistance of the buffer layer filled with nanofluid mounted on the third coil of the exchanger. The results of thermal resistance calculations received based on numerical simulations have been presented. The next work on the storage tank with a three-coil heat exchanger concerned the experimental investigations [10–12]. The papers [10, 11] included the selected results of thermal characteristics of the system analyzed obtained on the industrial stand intended for experimental research of the storage tank with the heat exchanger considered. The experiments presented by Wilk and Smusz [10, 11] were conducted during the operation of the heat exchanger coil filled with refrigerant. In turn, the paper [12] included the analysis of the temperature stratification in the accumulation tank under conditions of water heating in a storage tank using water coil heat exchangers. In the last quoted work [13], Smusz presented the results of numerical simulations in the form of velocity and temperature field in the storage tank considered. The presented simulations have been performed in the case of water heating in the tank using a coil with refrigerant and with and without the stratification device application.

In the present work, the authors performed the numerical study to obtain the temperature and velocity fields in the storage tank under the conditions of the operation of coils filled with water. Calculations were made in the case of the use of the stratification device. The temperature distribution along the tank has been obtained at 5, 10 and 20 min after the start of heating of water in the storage tank.

2. The Hot Water Storage Tank with the Coil Heat Exchangers

The hot water storage tank analyzed comprises three vertical finned coils. Two coils—upper and lower—are designed to warm the domestic hot water in the accumulation tank using water as a heating factor. The refrigerant from the air-conditioning system is a heating factor in the third coil. The third coil is additionally equipped with a special buffer layer filled with the nanofluid. The purpose of the buffer layer is to prevent the possible leakage of the refrigerant. The nanofluid used reduces the thermal resistance of the buffer layer. The appropriately shaped stratification device is mounted inside the storage tank. It is a two-diameter pipe with a tapered connection. Eight horizontal slots are located on the pipe at different levels. The visualization of the coils and the stratification device used in the accumulation tank are shown in Figure 1. In turn, Figure 2 presents the geometry of the stratification device applied. The characteristic dimensions of the accumulation tank and the coil exchangers applied are given in Table 1.

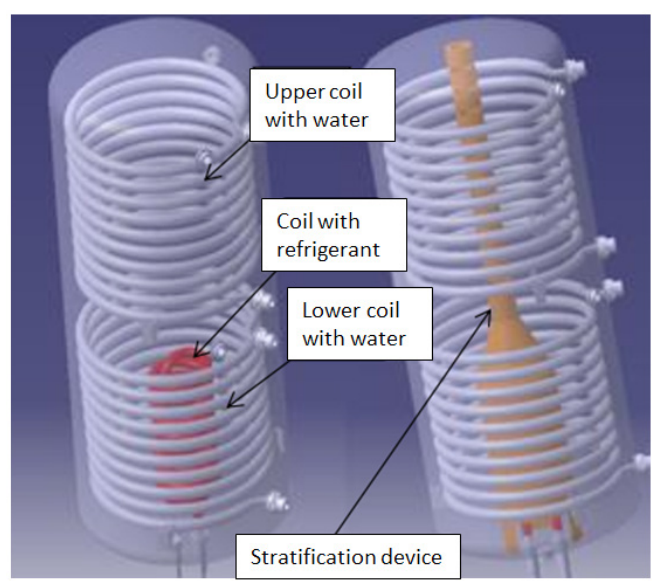

Figure 1. The geometry of the three-coil heat exchangers and the stratification device applied in the domestic hot water storage tank.

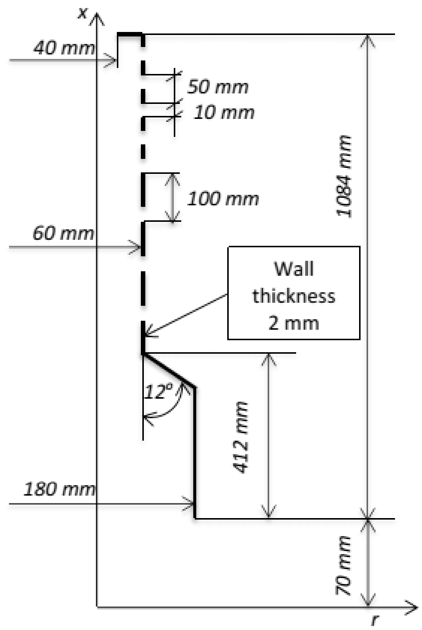

Figure 2. The stratification device geometry.

3. Numerical Simulations

In the present case, the processes of transient heat transfer occurring during the water heating in the considered storage tank have been examined. The system of constitutive equations including the continuity equation, Navier–Stokes equation, and energy equation has been solved numerically. The finite element method has been applied with the use of COMSOL multiphysics CFD software.

The computational domain has been created based on the geometry of the tank and the coil heat exchangers (see Table 1). In turn, the geometry of the stratification device shown in Figure 2 has been applied in numerical simulations. Since the accumulation tank, the coils, and the stratification device are characterized by axial symmetry, the real three-dimensional system has been simplified to the two-dimensional axisymmetric computational domain, which is shown in Figure 3. The computational domain has been meshed with triangle, quadrilateral, and edge elements with a smooth transition to avoid rapid changes in the density of the mesh that could generate numerical errors. The total number of elements used was 798,220.

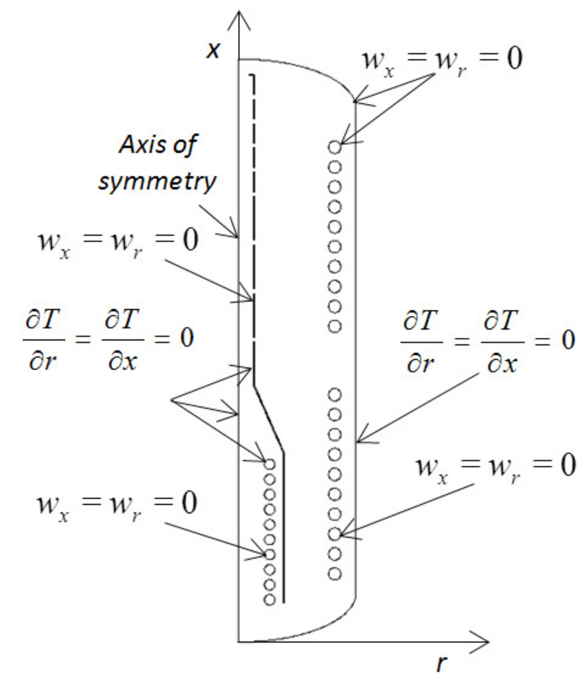

Figure 3. The 2D-dimensional computational domain for the storage tank with the boundary conditions specified on the wall of the tank, stratification device, coil with refrigerant, and the working coils with water.

Table 1. Characteristics dimensions of the storage tank and the coil heat exchangers applied

Characteristics of the tank	**Value**	
Volume	0.21 m^3	
Diameter	0.48 m	
Height	1.206 m	
Tank shell height	1.00 m	
Head tank height	0.103	
Height-to-diameter ratio	2.5	
Characteristics of the coil heat exchangers	**With water**	**With refrigerant**
Diameter	0.385 m	0.126 m
Pitch of coil	0.041 m	0.031 m
Number of coil turns	10	10
Outer diameter of the coil pipe	0.0185 m	0.016 m

While the water in the accumulation tank has been heating, the processes of transient heat transfer occurring in the tank have been studied. Conditions of the operation of the coils filled with water have been taken into consideration.
In the numerical calculations, the Reynolds-averaged Navier–Stokes equations have been solved with the use of standard *k–e* turbulence model. This model has been successfully applied in numerical analysis of thermal stratification in a study by Hussain and Lee [14]. The use of standard *k–e* turbulence model gave a realistic result that has been reported by Abdelhak et al. [15]. The assumed turbulent convection in the storage tank has been previously analyzed [13].
The initial temperature of water in the tank has been assumed uniform as 25.5°C. The temperature of the water in the coils was 41°C. Due to the high thermal conductivity of the material of coils wall, the thermal resistance was low and the temperature difference across the wall thickness was assumed to be negligible.
Boundary conditions for the case considered at all solid walls had a form of no-slip condition:

$$w_x = w_r = 0 \tag{1}$$

The adiabatic thermal condition at the surface of the coil with the refrigerant and the external walls of the tank has been assumed:

$$\frac{\partial T}{\partial x} = \frac{\partial T}{\partial r} = 0 \tag{2}$$

The case of operating the upper and the lower coils was studied separately, and the condition (2) was also valid at the surface of the lower coil (see Figure 3) while the upper coil was working inversely.
Since there was a difference in water density, the flow through the storage tank was driven by buoyancy forces. Thus, the buoyancy term in the momentum equation has been modeled with the use of Boussinesq approximation [6, 16, 17]:

$$f = (\rho - \rho_{\text{ref}})g. \tag{3}$$

4. Results and Discussion

Based on the numerical calculations, the velocity and temperature fields for water that was heated in the accumulation tank have been obtained. The simulations have been performed for two cases: (1) when the upper coil was operating and (2) when the lower coil was operating. Figure 4 presents the velocity fields in the accumulation tank received at 20 min after turn on the operation of lower and upper coils, respectively. Figures 5 and 6 present the temperature fields in the tank 3, 15 and 20 min after turn on the coils.

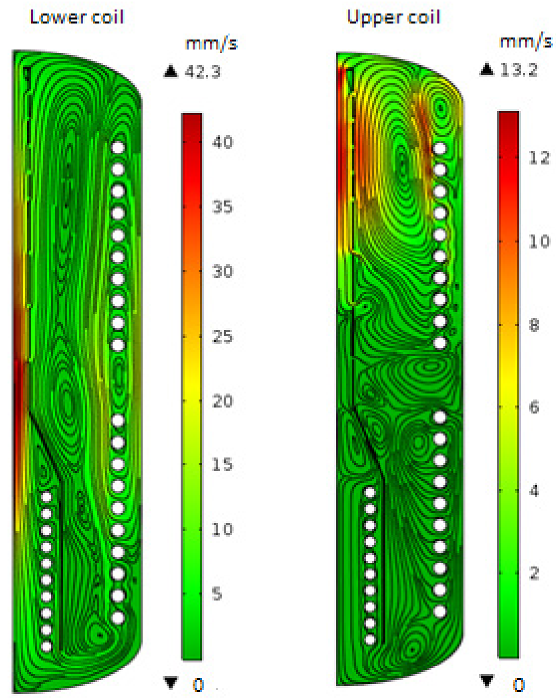

Figure 4. The 2D-dimensional velocity field and streamlines at 20 minutes after the turn on the coil.

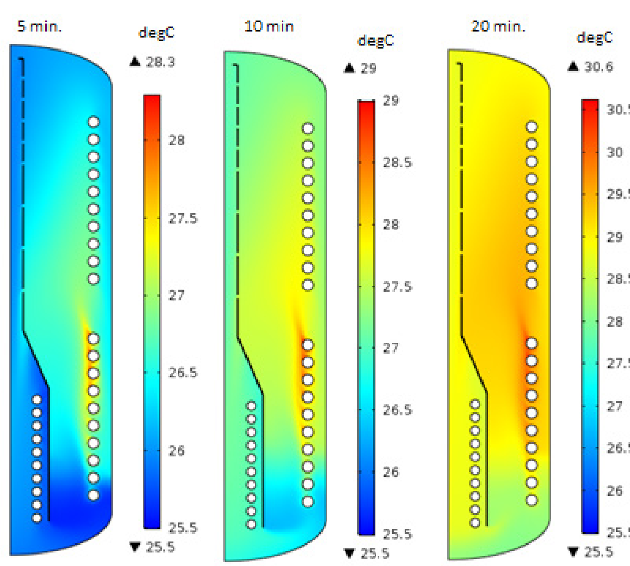

Figure 5. The temperature field in the tank after turn on the lower coil.

As shown in Figure 4, for the lower coil, the velocity of the water in the tank and the circulation level are much higher than those for the upper coil.
The large-scale vortices created in the tank induce intensive

mixing of the water and contribute to the equalization of temperature (Figure 5). The hot water rises upwards and intensifies circulation throughout the tank. This, in turn, increases the mixing of cold and hot water and reduces the level of stratification.

The upper coil generates more number of vortices, but on a smaller scale. Also, the velocity of the water in the tank is considerably lower than for the lower coil. The mixing ratio of water is reduced and the level of stratification is higher (Figure 6).

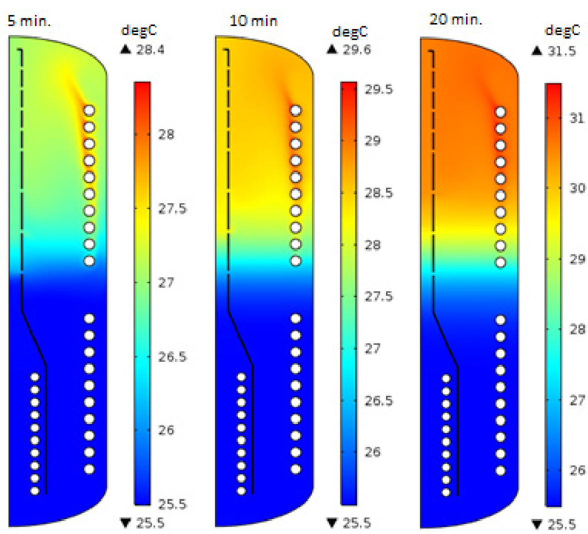

Figure 6. Temperature field in the tank during the operation of the upper coil

5. Conclusions

The main target of this work was the modeling of the heat transfer and fluid flow in the storage tank equipped with three heating coils and stratification device. Transient numerical simulations have been carried out to investigate the temperature distribution and velocity fields of the water during the operation of the upper and lower coils. During the operation of the upper coil stratification was observed, but the thermocline thickness depends on the time. This was mainly due to mixing and the heat conduction between hot and cold layers of the water. When the bottom coil heats the water in the tank, the buoyancy force pushes the water up. This causes a strong mixing of the water in the tank and has a very negative impact on the stratification.

Nomenclature

F	body force (N/m^3)
g	gravitational acceleration (m/s^2)
w	velocity (m/s)
T	temperature (°C)
Greek symbols	
r	density (kg/m^3)
Subscripts and superscripts	
x and *r*	coordinates
ref	reference

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