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Experimental and numerical investigation of the heat transfer in helically coiled tubes heat exchanger and design optimization

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Abstract

In this manuscript, heat transfer enhancement in helically coiled tubes has been investigated numerically and experimentally. Experiments were conducted for immersed helical condenser coil with constant diameter. While for the numerical investigation, the studies were conducted for the immersed condenser coil with conical shape and variable pitch coils. In this study, the effects of the helical condenser coil design on the water temperature and the water velocity have been performed. According to the proposed models, the thermal performance of the helical coil, conical coil and variable pitch coils were compared. The results indicated that the water temperature and the water velocity of variable pitch coils are higher than the conical coil and the constant diameter coil. This work provides that the immersed condenser coil in the water tank is more adequate to have a variable pitch coil.

Keywords: Optimal design; helical coil; conical coil; variable pitch coil; heat transfer; experiments

1. Introduction

During the waste heat recovery from refrigeration machines for residential and commercial hot water production, the helical condenser coils are widely used than the straight tubes **[1]**. Due to the higher heat transfer in the helical condenser coil than the straight tube, there are many researchers reported the natural heat transfer in the helical condenser coil. Missaoui et al. **[2]** performed an experimental and numerical analysis on the heat transfer in the helical condenser coil immersed in the water tank. The results indicated that the performance and the heat transfer of the helical condenser coil with variable pitch are higher in comparison with the normal helical coil. Dai et al. **[3]** investigated the heat transfer in the helical condenser coil immersed in the storage tank. The results indicated that the heat transfer in the helical coils with variable diameters is higher in comparison with the normal helical condenser coil. Missaoui et al. **[4]** studied the heat transfer by changing the coil pitch. The results indicated that the coil pitch presents a direct effect on the water temperature and the water velocity in the cylindrical tank. Ye et al. **[5]** numerically investigated the performance of the heat pump water heater with wrap-around condenser coil. The results indicated that the performance and the heat transfer coefficient of variable pitch coils are increased compared with constant pitch coil. Missaoui et al. **[6]** presented a coupled model of a domestic refrigerator and a water heating unit. The proposed model aims to investigate the influence of helical condenser coil design on the heating performance. Based on the aforementioned literature review, the knowledge about the heat transfer in the helical heat exchanger and the helically coiled tube are very important. Thus, the purpose of this paper is to enhance the heat transfer in the immersed helical condenser coil in the storage tank with modifying the coil shape.

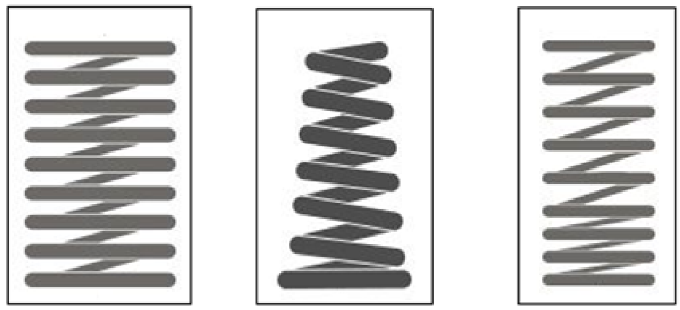
2. System description

Figure 1 shows a coupled unit of a domestic refrigerator and a residential hot water supply. The system consists of 50 L water bath, a compressor, a condenser, an expansion valve and an evaporator. In this study, the test rigs are designed and build for the immersed condenser coil with constant diameter coil. The helical condenser coil used in the experimental study has 0.004 m and 0.006 m of inner and outer tube diameter respectively and has 13 turns. The cylindrical tank is made from plastic with a diameter of 0.38 m and a height of 0.48 m. The interior tank is insulated with 5 cm of glass wool and covered with a stainless steel jacket as shown in the figure 1.

Figure 1. Household refrigerator for water heating

3. Cases study

Figure 2 illustrates three different designs of the immersed helical condenser coil in the water tank. This helical condenser coil is presented under three different shape defined respectively by the normal coil, the conical coil and the variable pitch coil. Therefore, the aim of this study is to analysis the impact of the helical condenser coil designs on the thermal characteristics of the water heating during utilization the waste heat from the refrigeration machines.



(a) Normal coil (b) Conical coil (c) Variable pitch coil

Figure 2. Helical condenser coil design

4. Numerical model

The numerical model is developed using ANSYS Fluent in order to predict the water heating phenomenon under laminar flow regime.

4.1. Boundary conditions

Table 1 shows the boundary conditions of the proposed model of the helical condenser coil and the storage tank for water heating.

Table 1. The main boundary conditions used in the CFD

Thermophysical properties	Values	Condition
Density, ρ	994 [kg/m^3]	Boussinesq
Specific heat, Cp	4183 [J/(kg. K)]	Constant
Thermal conductivity, λ	0.6107 [W/(m. K)]	Constant
Dynamic viscosity, μ	0.0007196 [kg/(m. s)]	Constant
Thermal expansion coefficient, β	0.000347 [1/K]	Constant

4.2. Meshing

For calculation accuracy, the mesh is locally refined near the coil. In the tank bottom, tank top and tank wall the mesh is more and more loosened.

4.3. Mathematical formulation

The Navier-Stokes equations governing the flow of the water on the outer surface of the helical condenser

coil are obtained from the continuity equation, the momentum equation and the energy equation.
The continuity equation is written as follows:

$$\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}=0 \quad (1)$$

The momentum equations are written as follows:

$$\frac{\partial u_x}{\partial t}+u_x\frac{\partial u_x}{\partial x}+u_y\frac{\partial u_x}{\partial y}=-\frac{1}{\rho_{w0}}\frac{\partial P}{\partial x}+v_w\left[\frac{\partial^2 u_x}{\partial x^2}+\frac{\partial^2 u_x}{\partial y^2}\right] \quad (2)$$

$$\frac{\partial u_y}{\partial t}+u_x\frac{\partial u_y}{\partial x}+u_y\frac{\partial u_y}{\partial y}=-\frac{1}{\rho_{w0}}\frac{\partial P}{\partial y}+v_w\left[\frac{\partial^2 u_y}{\partial x^2}+\frac{\partial^2 u_y}{\partial y^2}\right]-g\beta(T_w-T_{w0}) \quad (3)$$

The energy equation is written as follows:

$$\frac{\partial T}{\partial t}+u_x\frac{\partial T}{\partial x}+u_y\frac{\partial T}{\partial y}=\lambda_w\left[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right] \quad (4)$$

5. Model validation

In order to verify the accuracy of the present numerical model, experiments study have been carried out in the laboratory of research Energy, Water, Environment and Process at National Engineering School of Gabes. According to the obtained results, it can be seen that the maximum deviation between the experimental data and the predicted results is less than 3.42%. Therefore, the numerical results are in good agreement with the experimental data.

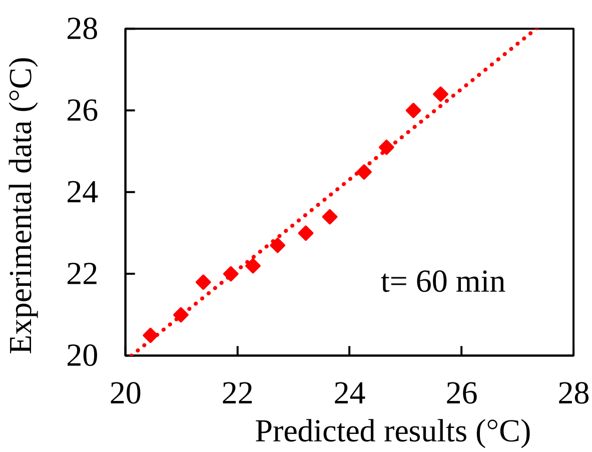


Figure 3. Comparison of measurement and calculation of the water temperature at t=60 min

6. Results and discussion

The temperature distribution of the water in the storage tank for normal coil, conical coil and variable pitch coil at heating time equal to t = 60 min are presented in figure 4. The results confirm that all the water temperature curves increase with the increase of heating time. Indeed, the variable pitch coil presents a higher water temperature in comparison with the two other condenser coils design. These outcomes indicate the effects of the condenser coil design on the water temperature. According to the obtained results, it can be seen that the variable pitch coil provides the higher water temperature profiles in comparison to the conical coil shape and normal helical condenser coil design. This is meanly due to the important heat transfer of the lower part of the condenser coil when reducing the coil pitch in the helical condenser coil with variable pitch.

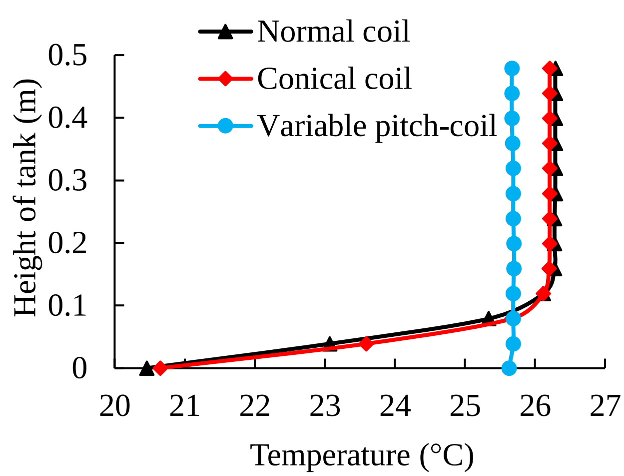


Figure 4. Variation of the water temperature with height of tank under three different condenser coil at t=60 min

Figure 5 shows the water velocity profiles of normal coil, conical coil and variable pitch coils during heating time equal to t=60 min. According to the obtained results, it can be seen that the water velocity of the variable pitch coil is higher than the conical coil and the normal coil. This effect is mainly explained by the heat transfer area of the lower part in variable pitch coil which is larger than that of middle and upper part. So, the water in the lower part of the cylindrical tank is heated quickly. Indeed, the combined properties of the variable pitch coil are better than that of the normal coil and conical coil.

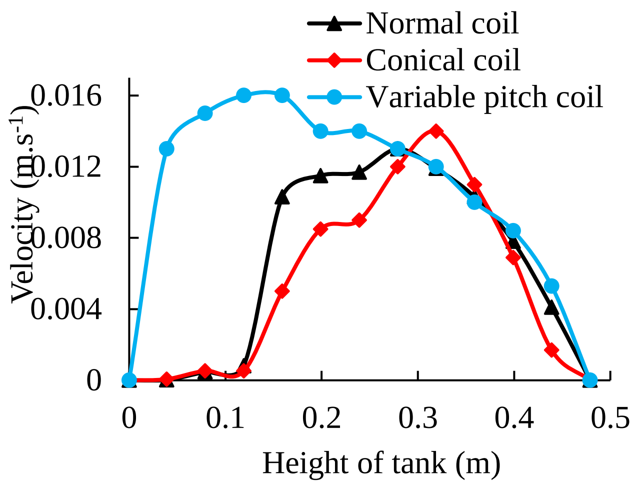
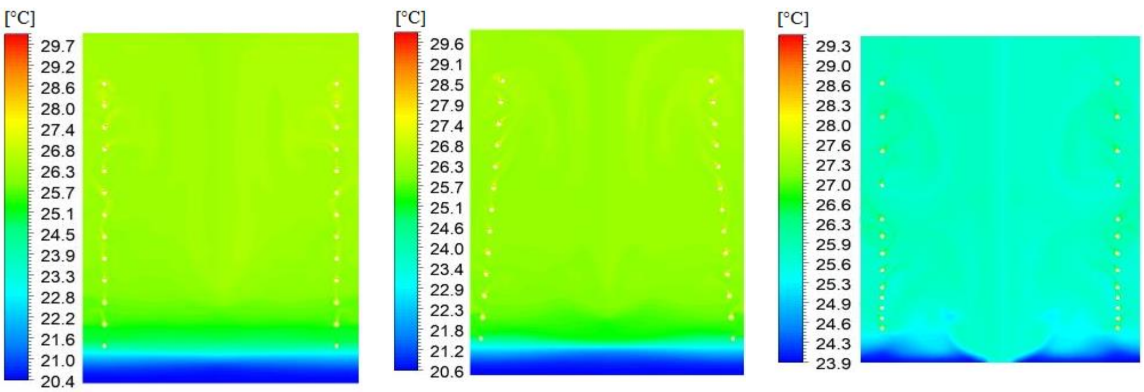


Figure 5. Variation of the water velocity with height of tank under three different condenser coil design at t=60 min

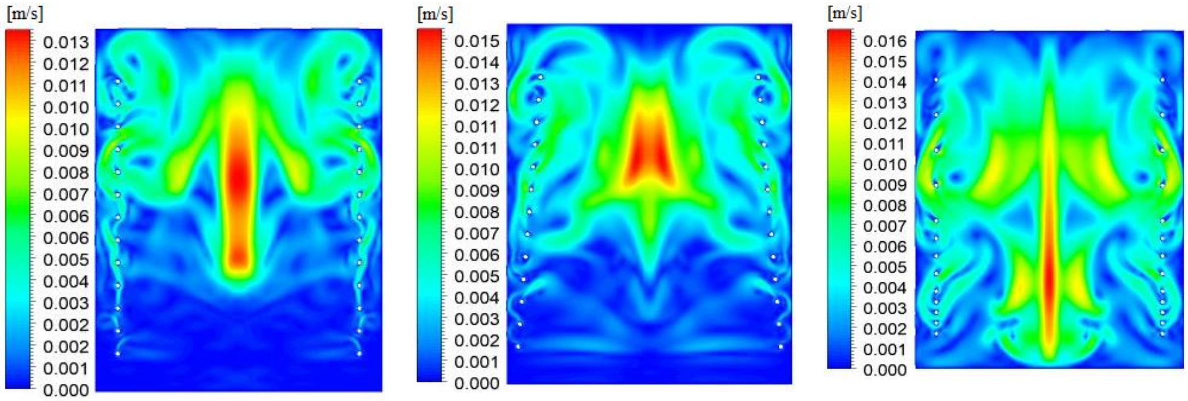
As shown in figure 6, the temperature distribution of the water in the tank are plotted for the normal coil, the conical coil and the variable pitch coil at heating time equal to t = 60 min. The outcomes show that with using helical condenser with variable pitch coil, the natural heat transfer between the coil and the water get improved which leads to improving the water temperature in the tank. Similarly, the obtained results expose the effects of the condenser coil geometry on the water temperature distribution.

Figure 7 illustrates the comparison of the water velocity distribution of the three different condenser coil design consisting of a normal coil, a conical coil and variable pitch coils at the heating time equal to t=60 min. According to the numerical results, it can easily be noted that the water velocity under variable pitch coils is higher compared with the normal coil and conical coil. Indeed, by using the helical condenser coil with variable pitch the velocity is enhanced in the lower and middle part of the tank. This fact reduces the thermal stratification and contributes to accelerate the water heating. The reason of this phenomenon is related to the small pitch in the lower part of the condenser coil.



(a) Normal coil (b) Conical coil (c) Variable pitch coil

Figure 6. Water temperature contours under three different condenser coil design (t=60 min)



(a) Normal coil (b) Conical coil (c) Variable pitch coil

Figure 7. Water velocity contours under three different condenser coil design (t=60 min)

7. Conclusions

In this paper, we have developed experimental and numerical investigation of the heat transfer in helically coiled tubes heat exchanger. The aim is to choose the more adequate design. Use of helical coil heat exchanger with variable pitch coil was seen to increase the temperature and the velocity of the water in the storage tank compared to the helical condenser with constant diameter and the conical coil shape. In addition, the water temperature in the tank was found to be effected by the helical condenser coil geometry.

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