Coupling Model of Heat Pump System and Water Tank with Immersed Condenser Coil in HPWH

N. Dai 1, S. Li 1

1School of Energy and Environment
Southeast University, Nanjing 210000, China

SUMMARY
A coupling model consisted of heat pump cycle and water tank with immersed condenser coil was established based on the heat exchange between refrigerant in condenser and water in tank. In first model, heat flux of condenser coil was calculated through heat pump cycle with MATLAB. In second model, water tank was dealt as natural convection flow and heat transfer in a cavity with FLUENT. After a good agreement with experimental data, the coupling model was able to reproduce water-heating and water-using process. Further study was performed to compare the influence of variable-diameter coil and constant-diameter coil on temperature distribution, heat transfer characteristics and COP. It was found that combined properties of variable-diameter coil was better than that of constant-diameter coil in water-heating process. While for water-using process, the improvement was not obvious for variable-diameter coil. Therefore, immersed condenser coil should be optimized in design process to improve combined properties.

INTRODUCTION
Heat pump water heater (HPWH) is a promising technology and becomes increasingly attractive for its high efficiency of making hot water over the years (Chen et al. 2005; Guo et al. 2011; Silva Vieira et al. 2015). The system is mainly composed of vapor-compression cycle and hot water circulation loop, including evaporator, compressor, condenser, water tank and thermostatic expansion valve. By using immersed condenser coil as heat source, heat pump cycle and water tank were integrated together (Prabhanjan et al. 2002).

The computational fluid dynamics (CFD) software package, FLUENT, has become an important method of current research (Cònsul et al. 2004; Jayakumar et al. 2008, 2010). Wang et al. (2006) presented a mathematical model for a cylindrical water tank with a cylindrical condenser as its heat source. The effects of tank dimension and the type of condenser coil on water temperature distribution were discussed. A similar research was conducted by Chuan-Chao et al. (2014) in which the influence of different diameter and different location of condenser coils were studied based on FLUENT. In addition, a new kind of variable-diameter coil structure was put forward in his research and the results showed that the water temperature stratification was weakened, which provided more reference of coil designs.

Despite the convenience of FLUENT to simulate temperature field and velocity field in water tank, there still remains an extensive research effort to be made for the connection with heat pump system. Among these numerical studies, the processing of condenser coil in FLUENT has been paid more attention due to its strong interdependence between the vapor-compression system and the fluid dynamics as well as thermal behavior of the water in tank (Piñeiropontevedra et al. 2012). Shah and Hrnjak (2014) put forward a linked modelling process involving iteration between the CFD model of the water tank and the vapor-compression system model in describing quasi-steady warm up of a heat pump water heating system. However, his model was for wrap-around coil condenser HPWHs. A challenge in our simulation is to establish coupling model containing both vapor-compression cycle and water heating system with immersed condenser coil.

In this study, specific attention was given to the development of a coupling model which captured both the heat transfer in water tank and dynamic progression of the overall vapor-compression cycle. Vapor-compression cycle was developed in MATLAB to obtain the heat flux boundary condition for helically coil and then the two-dimensional flow and heat transfer model of water tank was calculated by FLUENT software. The goal of this coupling model was to study the temperature distribution, heat transfer and COP of system in water-heating and water-using process more accurately, so as to compare the influence of variable-diameter coil and constant-diameter coil on the operating characteristic of HPWH system.

METHODS
Concept of coupling model
Based on the heat exchange between refrigerant in tube and water in tank, the overall vapor-compression cycle and water heater was coupled together. In this model, vapor-compression cycle predicted heat flux of refrigerant-side along the condenser coil. However, a different coordinate system was adopted in the simulation of water tank, so it was necessary to make coordinate transformation for convenience of calculation. The transformation between the coil coordinate system and the master cylindrical coordinate system is given by Rabin and Korin (1996):

\[ z = \frac{z^*}{n} - h_c \]  

(1)

Where \( z \) was vertical direction in the master coordinate system and \( z^* \) was spiral direction in the coil coordinate system.

The condenser coil was treated as internal heat source, regardless of the volume effect. Heat flux was calculated by:

\[ q = \frac{m_r \Delta h_r}{\Delta n \omega \Delta z^*} \]  

(2)

Where \( \Delta z^* \) was the length of condenser coil corresponding to each coil element \( \Delta z^* \).

Flow chart of this coupling model was shown in Fig.1. Assuming an initial heat flux of condenser coil first, then...
waterside temperature and flowrate during heating time were calculated in CFD. Taking waterside temperature distribution into account, MATLAB model was set up to access the heat flux boundary condition for helically coil. Assuming that the heat flux was uniform in the spiral direction, the formulation of average heat flux was given then. The heat flux profile was then updated in the FLUENT and the iterations was repeated again until the residuals of heat flux would ideally converge.

Model of vapor-compression cycle

(1) Model of evaporator

In the evaporator, refrigerant goes through the superheat and two-phase regions and it is described by multi-zone moving boundary model. In each zone of the evaporator, the heat and mass conservation equations are presented:

\[ Q_e = m_r(h_{e,r,o} - h_{e,r,i}) \]  

(3) The heat transferred in each zone to the air is:

\[ Q_a = m_a(h_{e,a,o} - h_{e,a,i}) \]  

(4) The total heat transfer and balance equation is:

\[ Q_e = Q_a = U_e A_e \Delta T_e \]  

(5) In the Eqs. (3)-(5), \( m_r \) and \( m_a \) are mass flow of refrigerant and air. \( h_{e,r,i} \) (\( h_{e,a,i} \)) and \( h_{e,r,o} \) (\( h_{e,a,o} \)) are inlet and outlet refrigerant (air) enthalpy of evaporator. \( U_e \), \( A_e \) and \( \Delta T_e \) are overall heat transfer coefficient, surface area and the temperature difference between refrigerant and air.

(2) Model of compressor

The steady lumped parameter method is adopted for the simulation of compressor. The mass flow of refrigerant \( m_r \) is expressed as:

\[ m_r = \eta_v \frac{V_s}{3600 \rho_v} \]  

(6) Where \( \eta_v \) is volumetric efficiency, \( V_s \) is theoretical displacement volume, and \( \rho_v \) is suction specific volume.

The input power of compressor \( W \) is given as:

\[ W = \frac{m_r(h_{e,r,o} - h_{e,r,i})}{\eta_{co}} \]  

(7) Where \( \eta_{co} \) is total efficiency of compressor, \( h_{e,r,i} \) and \( h_{e,r,o} \) are inlet and outlet refrigerant enthalpy of compressor, respectively.

(3) Model of thermal expansion valve

Assuming the inlet enthalpy and outlet enthalpy of thermal expansion valve are equal.

\[ h_{e,v,i} = h_{e,v,o} \]  

(8) Where \( h_{e,v,i} \) and \( h_{e,v,o} \) are inlet and outlet refrigerant enthalpy of thermal expansion valve, respectively.

(4) Model of condenser coil

Depending on the operation conditions, the condenser can operate with three zones (superheat, two-phase and subcool) and it is described by multi-zone moving boundary model by Sheng et al. (2015).

In each zone of the condenser, the heat and mass conservation equations are presented:

\[ Q_c = m_r(h_{c,r,i} - h_{c,r,o}) \]  

(9) The heat transferred in each zone to the water is:

\[ Q_w = C_p w m_w (T_{w,i} - T_{w,o}) \]  

(10) The total heat transfer and balance equation is:

\[ Q_w = Q_c = U_c A_c (T_{c,i} - T_{c,o}) \]  

(11) In the Eqs. (9)-(11), \( m_r \) and \( C_p w \) are mass flow and heat capacity of water, respectively. \( h_{c,r,i} \) and \( h_{c,r,o} \) are inlet and outlet refrigerant enthalpy of condenser. \( U_c \) and \( A_c \) are overall heat transfer coefficient and surface area. \( T_{w,i} \), \( T_{w,o} \), \( T_{c,i} \) and \( T_{c,o} \) are the inlet water temperature, water side temperature, refrigerant temperature and average water temperature.

\[ U_c = \left( \frac{a_{r}+\frac{1}{a_{w}}}{2} + \frac{a_{r} \ln \frac{d_{r}}{d_{ij}}}{\lambda_p} \right)^{-1} \]  

(12) Where \( a_{r} \) and \( a_{w} \) are the heat transfer coefficient of refrigerant side and water side. \( d_{ij} \) and \( d_{r} \) are the inner and outer diameter of the tube. \( \lambda_p \) is the thermal conductivity of copper tube.

Model of water tank in FLUENT

(1) Basic assumptions

To simplify the issue, the model was assumed as follows:

(a) Since the length of vertical coil part was short and could be neglected, condenser coil was assumed as many small circles in symmetry plane. Therefore, three-dimensional cylindrical water tank could be simplified as an axisymmetric two-dimensional model as shown in Fig.2.

(b) The water flow was laminar (Wang 2016).

(c) The condenser coil was regarded as the variable heat flux boundary and the heat flux was the input by User Defined Function (UDF) feature of FLUENT.

(d) Natural convection flow was modeled with Boussinesq approximation (Gao et al. 2003).

(e) The water tank sidewall was assumed adiabatic.
Figure 2. Simplified model of water tank

(2) Governing equations

Conservation of mass:
\[ \nabla \cdot (\rho \vec{u}) = 0 \]  
\[ \rho = \text{constant} \]
\[ (13) \]

Conservation of momentum:
\[ \frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} = -\frac{\nabla P}{\rho_0} + \nu \nabla^2 \vec{u} - \frac{\Delta \rho}{\rho_0} \]  
\[ (14) \]

Conservation of energy:
\[ \frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T = \alpha \nabla^2 T \]  
\[ (15) \]

(3) Boundary conditions

(a) No-slip condition was imposed at all solid surface walls. That is, the velocity of the fluid at the wall was zero.

(b) Adiabatic thermal condition was applied for the water tank walls, so zero heat flux boundary condition was assigned to every bottom, top and side tank walls. The heat flux of condenser coil surface was the variable heat flux boundary condition.

(c) The initial temperature of water-heating process was natural temperature of cold water.

(d) The initial temperature of water-using process was 50°C. Mass flow rate of hot water was assumed as 6.5 L/min.

(4) Grids generation

Grids were generated by the GAMBIT program. For calculation accuracy, the grids were locally refined near the condenser coil. Away from the coil, the grids were more and more loosened.

RESULTS

Validation

To validate the mathematical model, the experimental data reported by Wang (2006) was used. As shown in Fig.3, numerical results were mostly lower than experimental data for the reason that the length of vertical coil part was neglected in our simplified model. However, the maximal difference between the calculated data and the experimental data for the water temperature was within 10.91%. As the heating process goes on, the difference was reduced to 5% when t=180min. Since a good agreement with the experimental data was observed, the coupling simulation was able to reproduce the heating process of the tank.

Calculation Condition

In this paper, the condenser coil was directly immersed in the tank and the configuration details of the helically coil were illustrated in Table 1. For constant-diameter coil, coil diameter \( D_c \) is 0.16m, number of turns \( N \) is 36 and coil pitch \( h_c \) is 10mm. While for variable-diameter coil, maximum coil diameter \( D_{c,\text{max}} \) is 0.35m, minimum coil diameter \( D_{c,\text{min}} \) is 0.1m, the diameter difference between each adjacent coils \( \Delta D_c \) is 0.01m, number of turns \( N \) is 26 and coil pitch \( h_c \) is 10mm. Moreover, the volume of the stainless steel water tank is 150 L. The wall of the tank is made of aluminum, with 30 mm thick polyurethane thermal insulation layer. Cold water is connected directly with the tap water pipe at the bottom of the tank and hot water comes out from the top of the tank.

Table 1. Main structural parameters of constant-diameter coil and variable-diameter coil

<table>
<thead>
<tr>
<th>Structural parameter</th>
<th>Symbol</th>
<th>Constant diameter coil</th>
<th>Variable diameter coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum coil diameter</td>
<td>( D_{c,\text{min}} )</td>
<td>0.16 m</td>
<td>0.10 m</td>
</tr>
<tr>
<td>Maximum coil diameter</td>
<td>( D_{c,\text{max}} )</td>
<td>0.16 m</td>
<td>0.35 m</td>
</tr>
<tr>
<td>Diameter difference</td>
<td>( \Delta D_c )</td>
<td>0 m</td>
<td>0.01 m</td>
</tr>
<tr>
<td>Inner diameter of tube</td>
<td>( d_{i,c} )</td>
<td>0.01 m</td>
<td>0.01 m</td>
</tr>
<tr>
<td>Outer diameter of tube</td>
<td>( d_{o,c} )</td>
<td>0.12 m</td>
<td>0.12 m</td>
</tr>
<tr>
<td>Coil height</td>
<td>( h_c )</td>
<td>0.7 m</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Coil pitch</td>
<td>( h_c )</td>
<td>10 mm</td>
<td>10 mm</td>
</tr>
<tr>
<td>Number of turns</td>
<td>( N )</td>
<td>36</td>
<td>26</td>
</tr>
<tr>
<td>Total length</td>
<td>( L_c )</td>
<td>19 m</td>
<td>19 m</td>
</tr>
</tbody>
</table>
Variation of water temperature vs height of tank for variable-diameter coil and constant-diameter coil at different heating time were demonstrated in Fig.6. The results showed that the centerline temperature increased along the tank height. For t=60min, the average water temperature was 37.01°C and 38.00°C while the maximum temperature difference in the tank altitude direction was up to 9.00°C and 2.95°C for constant-diameter coil and variable-diameter coil, respectively. With the increase of heating time, the average temperature increased and the maximum temperature difference in the tank altitude direction reduced. For t=180min, the average water temperature was 55.5°C while the maximum temperature difference in the tank altitude direction was only 0.18°C for variable-diameter coil. From the results, variable-diameter coil provided the higher temperature profiles in comparison to the constant-diameter coil design and temperature stratification was almost eliminated.

**DISCUSSION**

Comparison of variable-diameter coil and constant-diameter coil in water-heating process

As shown in Fig.4-5, thermal stratification was also apparent. Temperature contours showed that higher temperature profiles was achieved for variable-diameter coil in comparison to the constant-diameter coil design. Since the water was acting as the cooling medium for the condenser coil, water temperatures near the coil wall may affect overall system performance and this would be discussed in the following section.

**Comparison of variable-diameter coil and constant-diameter coil in water-heating process**

As shown in Fig.4-5, thermal stratification was also apparent. Temperature contours showed that higher temperature profiles was achieved for variable-diameter coil in comparison to the constant-diameter coil design. Since the water was acting as the cooling medium for the condenser coil, water temperatures near the coil wall may affect overall system performance and this would be discussed in the following section.
Comparison of variable-diameter coil and constant-diameter coil in water-using process

The initial condition of water-using process was assumed as the state of water after heating to 50°C. Mass flow rate of hot water was assumed as 6.5 L/min, which was residential water consumption of daily shower. Cold water of 15°C flowed into tank from the bottom while hot water flowed from the upper portion of the tank. Because of the water temperature stratification, hot water was in the upper. In water-using process, hot water flowed out due to the extrusion of cold water.

Figure 8. Variation of water temperature vs time in water-using process

Fig. 8 showed variation of hot water temperature vs water-using time in water-using process. It was shown that variable-diameter coil provided higher temperature profiles in comparison to the constant-diameter coil design. For these two coil designs, water temperature decreased rapidly as time increased and it decreased faster in lower part of the tank. When height of tank x=1.15m, hot water above 45°C could be used for as long as 14 minutes. This was due to the temperature stratification caused by natural convection, so there existed hot water in upper region. At the same time, since diameter of water tank was much larger than diameter of inlet pipe, the influence of cold water flow on upper hot water temperature stratification had a time delay. Based on these two factors, the water that flowed from the top of tank was of higher temperature for quite a long time. With more hot water flowing out and more cold water flowing in, water temperature dropped rapidly. During water-using process, the moment of water temperature dropping rapidly was 10min and 5min for x=1.15m and x=0.6m, respectively. For x=0m, water temperature was only 35°C after 1min and it was mainly due to the mixing of cold water and hot water in lower part of tank.

Figure 9. Comparisons of COP and condenser heat transfer coefficient in water-using process

Fig. 9 showed the comparison of COP and heat transfer coefficient in water-using process. The average $U_c$ of variable-diameter coil was 665.8W/(m²·K), a litter higher than that of constant-diameter coil. With time increasing, water temperature dropped rapidly, which lead to increasing COP from 4.32 to 4.88 for variable-diameter coil. However, difference of COP between these two coil designs was relatively small. From the above, temperature distribution of variable-diameter coil in water-using process was better than that of constant-diameter coil while the improvement of heat transfer performance and COP was not obvious for variable-diameter coil design.

CONCLUSIONS

A numerical investigation of performance analysis on heat pump water heater (HPWH) was carried out. Coupling model was established to study the temperature distribution, heat transfer and COP of system in water-heating and water-using process more accurately, so as to compare the influence of variable-diameter coil and constant-diameter coil on the operating characteristic of HPWH system.

(1) This coupling model could be used as an effective tool to optimize tank parameters at early design stages, thus it may help improve heat transfer performance and aggravate the temperature uniformity in water tank.

(2) In water-heating process, the water temperature in tank was guaranteed to be stable and temperature stratification was almost eliminated for variable-diameter coil design. $U_c$ of variable-diameter coil was 720.5W/(m²·K), much higher than that of constant-diameter coil. Moreover, a higher COP at 4.56 was achieved for variable-diameter coil.

(3) In water-using process, temperature distribution of variable-diameter coil was better than that of constant-diameter coil. However, the improvement of $U_c$ and COP was not obvious for variable-diameter coil.

ACKNOWLEDGEMENT

Shuhong Li and Nannan Dai designed the main analysis; Nannan Dai performed the numerical simulations and wrote the paper.
REFERENCES


Piñeiropontvedra C., Fernándezseara J., Dopazo A., Diz R. 2012. "Simulation and experimental validation of a helical coil used as condenser in a heat pump for domestic water heating in a tank".


