Performance analysis and optimization of wrap-around condenser in an air source heat pump water heater system: Numerical and experimental investigation

Haijian Zhou[a], Youwen Chen[b], Mingwen Luo[b], Hengyi Zhao[c], Fen Zhong[a],

Naiping Gao[a,*]

[a]School of Mechanical Engineering, Tongji University, Shanghai 201804, China
[b]*Hefei R&D department of Commercial Air Conditioner Division , Member of Midea Group, Hefei 230088, China*
[c]*International Copper Association Shanghai Office, Shanghai 200020, China*

Abstract

In this paper, a study on geometric parameter of a wrap-around condenser for a water tank with 200 L capacity has been conducted using experimental and numerical methods. Numerical results are well validated by the experimental ones with a total time deviation less than 2% as the same volume of water was heated to 55 °C. For the wrap-around condenser copper coils with different structural parameters, the average COP (coefficient of performance) of air source heat pump water heater (ASHPWH) varies from 3.8 to 4.6 under the standard condition. Copper tubes with smaller diameter (i.e. 5mm and 7mm) were found to outperform these with larger diameter by improving the heat transfer efficiency and reducing initial copper costs. Moreover, it suggests a better heating performance of the copper coils wrapped around the bottom and lower part of the water tank. This study suggests that given the proper pipe parameters such as location, spacing and turns, a higher average COP of air source heat pump water heater can be achieved and the total heating time is decreased relatively.

Keywords: air source heat pump water heater; wrap-around water tank; condensing copper pipe; numerical simulation; structure optimization

1. Introduction

Air source heat pump is vigorously promoted as an advanced energy-saving technology in China and around the world, makes an indispensable part of the new energy industry. The development of air source heat pump industry, could contribute to the realization of energy saving, emission reduction targets, and utilization of renewable energy. At the same time, expansion in the demand of hot water supply for living and space heating can potentially benefit from implementation of air source heat pump technology.

As one of the core components of the heat pump water heaters, the water tank is the key research object among water heater enterprises. At present, there are two types of water tank, either the condenser coil is immersed in the water tank or the condenser coil is wrapped around the tank. The heat transfer efficiency of immersed condenser is relatively higher, while it is more prone to cause serious corrosion problem and refrigerant leakage. The wrap-around condenser is relatively safer and more reliable, and if combined with proper enamel tank optimization design and effective heat insulation methods, the warp-around condenser can

* Corresponding author. Tel.: +86-13817847420; fax: +86-21-65983867.
E-mail address: gaonaiping@tongji.edu.cn.

also achieve good hot water production and meet the requirements of relevant standards. This paper presents a water tank simulation to predict the heating time of air source heat pump water heaters. A 200 L wrap-around water tank model is numerically studied using CFD (Computational Fluid Dynamics) techniques.

Several models of heat pump water heaters have been developed, but few of them dealt with the water tank. Morrison et al. [1] presented an experimental method for rating ASHPWH, and the water tank and the condenser formed from a wrap-around coil were evaluated. Guo et al. [2] conducted an experimental and simulation research in addition to operation optimization of ASHPWH, the experimental results indicated that the average COP ranged from 2.82 to 5.51 under typical conditions. Oussama et al. [3] presented a dynamic simulation to predict the performance of an ASHPWH, the mathematical model consists of submodels of the basic system components, and the model was coded into MATLAB software. Stephen et al. [4] presented a robust mathematical multiple linear regression models, and the simulation application was developed in Simulink of MATLAB.

2. Description and modelling of the problem

2.1. Physical model

Because the structure of the water tank is more complex, it is necessary to simplify. According to the 1:1 model, a 200 L tank is shown in Figure 1. We selected a 200 L ASHPWH as the test object, the structure parameters of the copper tube: the diameter is 7 mm, 39 turns, pipe spacing is 10 mm, and the simulation object has the same parameters as the tested object. The copper tube wrapped at the bottom and side of the enamel tank, in order to increase the heating area, it will be processed into a D-type structure. Figure 2 is the water tank axisymmetric pattern, that is, take the water tank over the axis of the half-section model. In order to ensure the accuracy of the simulation results, the thermal insulation material on the outside of the water tank is added and using Fluent software to simulate the water tank model. The software package of ICEM-CFD was used to build the mesh of the two dimensional model. The grid type inside the water tank was quadrilateral, and the copper coil region was densified. The total number of meshes is about 40,000 and the mesh quality is above 0.4 (1 is the highest quality).

Fig. 1. Schematic diagram of 3D model structure of water tank

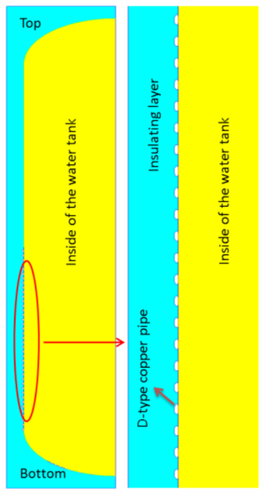


Fig. 2. Schematic diagram of 2D model structure of water tank

2.2. Basic assumptions

Taking into account the feasibility of numerical simulation, the following assumptions are adopted in the process of establishing mathematical models.

The water was heated from 15 °C to 55 °C, and the water temperature in the water storage tank approximated to a linear curve with the measured water temperature in the heating process. In the heating process, the condensing temperature of the ASHPWH increases, the temperature rises with time according to experimental test data obtained by polynomial fitting:

$$T = 0.0042\tau + 301.98 \tag{1}$$

Where T is the water temperature and τ is the heating time.

In the numerical calculation of natural convection in closed space, the Boussinesq assumption is used to deal with the buoyancy force term due to the temperature difference.

$$\rho = \rho_0 \left[1 - \beta(T - T_0)\right] \tag{2}$$

Where β is the average expansion of water, T_0 is the reference temperature and ρ_0 is the density corresponding to T_0.

The condensation process of heat pump water heaters is divided into superheated area, two-phase area and subcooled area. In order to simplify the calculation, it is assumed that all the refrigerant passing through the copper coils during heating is in the two-phase region. Referring to the results of Hu et al. [5], the convective heat transfer coefficient of R410a is obtained.

The water in the tank depends on the density difference to form natural convection, and the Rayleigh number of the natural convection is analyzed:

$$Ra = \frac{g \cdot \alpha \cdot L^3 \cdot \Delta T}{\upsilon^2} \cdot \mathrm{Pr} \tag{3}$$

Where g is the gravitational acceleration, α is the volume expansion coefficient, L is the wall size, ΔT is the temperature difference of the wall and fluid surface, ν is the fluid viscosity, Pr is the Prandtl number. Substituting the relevant data into the formula yields the result $Ra=2\times10^{12}>10^9$, so the water tank is in the turbulent flow region, and the simulation being used turbulence model.

We also ignore the thermal contact resistance between the copper pipe wall and the water tank wall. The third kind of boundary conditions is adopted in the insulation material, and the natural convection coefficient of the air and the wall of the heat preservation material is about $3 W/m^2\cdot K$. Using the unsteady simulation settings, the time step is set to be 1 second. In order to transfer the 2D results to 3D, the Axisymmetric option is selected. According to the requirements of some standards, the simulation starts from 0 second; the inlet water temperature is 15 °C; the flow velocity in the water tank is 0 m/s. The simulation is finish when the water is heated to 55 °C.

3. Results and discussion

Figure 3 is the numerical simulation results and experimental test results, that is, the trends of water temperature with the heating time. It can be seen from the figure that the heating time of experimental test is 170 minutes, numerical simulation result is 167 minutes, and the error is 1.8%. It also can be seen from the figure that the average temperature of the two-dimensional water tank model is higher than the experimental test at first 45 minutes, and they are basically coincident after that. So the 2D numerical simulation results are approximately equal to the experimental results, which prove the feasibility of the 2D axisymmetric model.

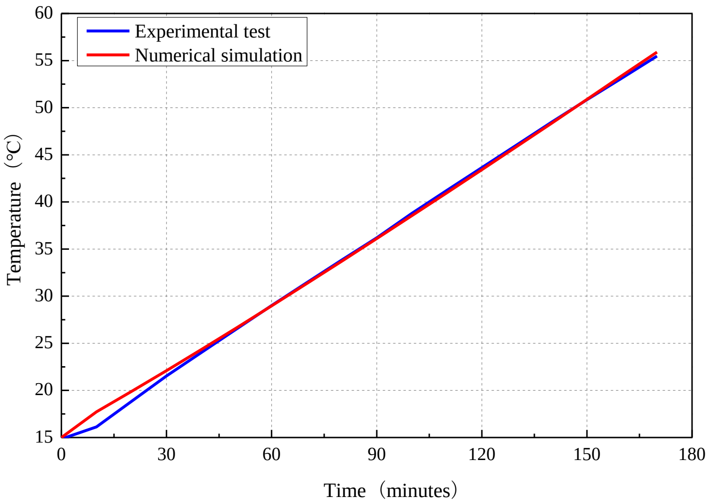


Fig. 3. Comparison of 2D numerical simulation and experimental measurement of water tank

According to the calculation results of Fluent, the heating power of the 2D model is 3282W, which is 2.4% higher than the experimental value (3207W), and the error falls in the allowable range proving the accuracy of the numerical simulation. The air source heat pump water heater was tested under the standard condition, and then the COP was calculated. The COP of benchmark water tank which we used for the test is 3.85. Based on the simulation results and test data, the COP which is estimated between 3.8 and 4.6 considering the other components of the air source heat pump water heater could meet the requirements.

Figure 4 is the temperature distribution and velocity distribution of the 2D model at different times. Compared with the two temperature distribution contours, we can see that during the heating process, the water in the upper part of the tank is gradually heated by the natural convection, the temperature gradient in the water tank is gradually reduced, and the biggest difference is about 2 °C. The water temperature in the lower part of the water tank is obviously higher than the upper part, and the high-temperature area is concentrated near the wall of the tank which is in contact with the copper coils. The water temperature field is coupled with the velocity field. The water temperature difference causes the natural convection in the water tank, which becomes the driving force of the velocity. It can be seen from the figure that the water movement in the tank is weak. With the increase of the heating time, the water movement intensity increases as well as the mixing degree. When the heating time reaches 167 minutes, the maximum velocity in the tank is only 0.035m/s.

60 minutes 120 minutes 60 minutes 120 minutes

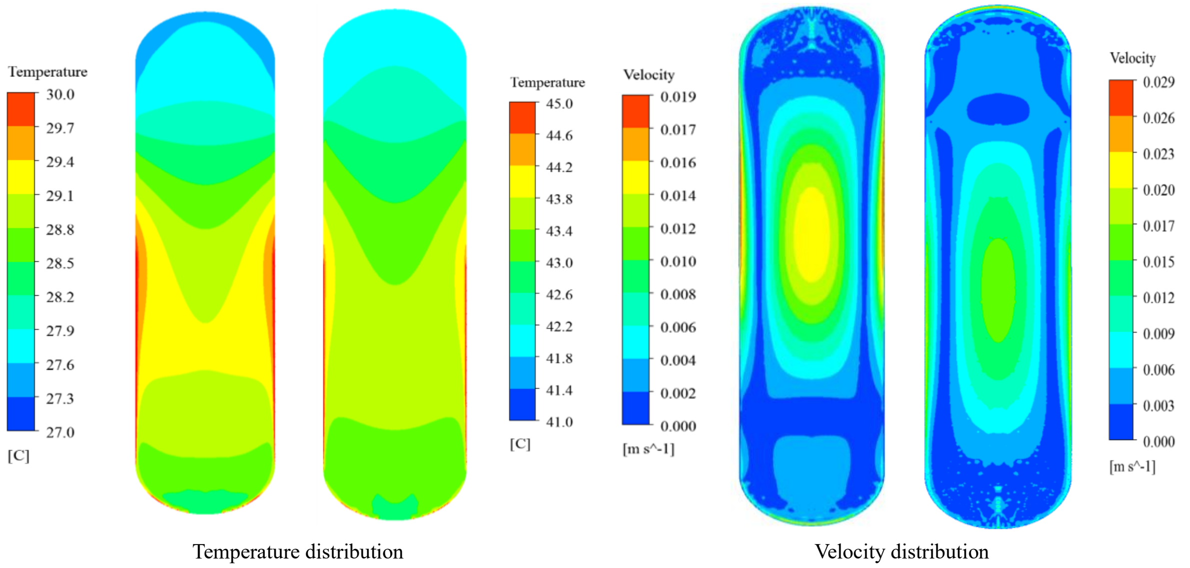


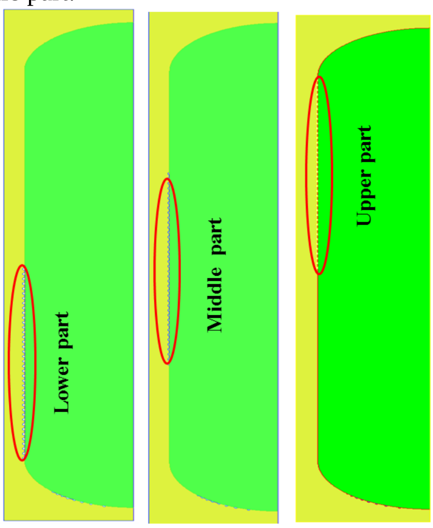
Fig. 4. Temperature and velocity distribution of 2D model at different time

4. Water tank optimum design

4.1. Location optimization of copper coils

In order to analyze and compare the positions of condensing copper coils on the heating effect of the water tank, the total heat transfer area and the other structural parameters are kept constant, and the condensing coils are placed in the lower, middle and upper parts respectively. Figure 5 shows the structure of the condenser coils at different positions.

Figure 6 shows the temporal evolution of water temperature in different locations. It can be seen that the water heating rate is the largest when the copper pipe is at the lower part of the tank, and the water is heated to 55 °C in 165 minutes. When the coils located in the upper part, the water heating time is the slowest, about 203 minutes. When the upper part of the water tank was heated, the lower part of the water cannot form natural convection with the upper part, and the water temperature of the lower part is very low. Therefore, when the copper pipe is located in the upper part of the tank, the heating time is significantly longer than in the lower and middle part.



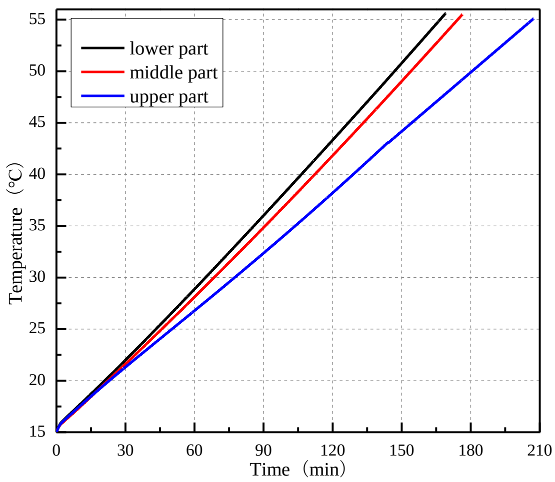


Fig. 5. Water tank with different coil position

Fig.6. Simulation results of different copper pipe positions

4.2. Spacing optimization of copper coils

In order to compare the pipe spacing on the heating effect of the water tank, the total heat transfer area and the other structural parameters are kept constant, the copper tubes pacing is set to 5mm, 10mm, 15mm and 20mm.

Table 1. Simulation results of different copper pipe spacing

Fixed-parameters	variable parameter (millimetres)	Heating time (minutes)
pipe diameter: φ7mm coils:39	5	179
	10	167
	15	152
	20	160

It can be seen from Table 1, when the copper tubes spacing is 5mm, the water heated to 55 °C for the longest time, about 180 minutes. The heating time is gradually shortened with the increase of the pipe spacing, and the heating time is 150 minutes when the pipe pitch is 15mm. But when the tube spacing increased to 20mm, the heating time is 160 minutes. The optimal pipe spacing can be derived in the optimization process of increasing the pipe spacing. This phenomenon occurs because when the pipe spacing changes, the position of the copper pipe has a corresponding change. The temperature field, the velocity field and the heat transfer effect in the water tank are affected by the pipe spacing and the pipe position. In addition, due to the addition of the bottom coil, the heat transfer effect is greatly improved by increasing the water heating rate and the natural convection rate.

4.3. Optimization of copper caliber

In order to compare the copper pipe diameter on the heating effect of the water tank, keeping the other structural parameters are kept constant, only to change the diameter of the condenser coils. With reference to the diameter parameters of the actual water tank products, the comparison of the three diameters of 5mm, 7mm and 9.52mm was made.

Table 2. Simulation results of different copper pipe spacing

Fixed-parameters	Diameter (mm)	Pipe turns	Gross weight (kg)	Heating time (minutes)
Pipe spacing: 10mm	9.52	39	9.06	155
	7	39	3.33	167
	5	39	1.89	179
	5	60	2.60	165
	5	80	3.28	152

Table 2 shows that when the turns of the copper coil are kept as 39, the 9.52mm-diameter coil has the largest heating rate which takes 155 minutes during the heating process. When the pipe diameter is 5mm (39 turns), the heating time is the longest, about 179 minutes. When the copper pipe diameter increases, the length of D-type tube will be increased accordingly, leading to an increase in the contact area between the copper pipe and the water tank and thus the heat transfer performance, which, on the other hand, will consume more cooper materials. When wrapping 60 turns copper pipe (5mm), the water heated from 15 °C to 55 °C requires 165 minutes. The heating time is similar to 7mm tube (39 turns), but copper consumption can be reduced by 0.73kg, and thus ¥ 29.2 deduction in cost (copper pipe price estimated as ¥40 Yuan/kg). When wrapping more turns (80 turns, 5mm), the heating time is 152 minutes, the copper consumption is 3.28 kg. The copper consumption is similar to that of 7mm copper tube (39 turns), while the heating time is reduced by about 9%, and the COP of the water heaters can be effectively enhanced. Moreover, the use of small diameter (about 5mm) copper pipe has predominant economic advantages.

4.4. Optimization of copper pipe turns

In addition, we also simulated the copper tubes with different turns of coils by keeping the structural parameters of condensing pipe coils constant. The total heat transfer increases with the increase of the number, the water heating rate and water flow rate is also increasing. While increasing the number of turns at the bottom of the coil, it shows the same variation.

5. Conclusions

In this paper, a 2D water tank model is established to simulate the heating charging process of water from 15 °C to 55 °C. An experimental validation is conducted to verify the reliability and accuracy of the numerical simulation method. In order to improve the COP of ASHPWH, pipe parameters such as location, spacing, diameter and turns were calculated and analyzed. The COP is estimated between 3.8 and 4.6 considering the other components of the air source heat pump water heater could meet the requirements. According to the results of simulation and experiment, the following conclusions can be drawn:

(1) The lower the coil is wrapped around, the faster the inside water will be heated. Under the cases where the coil is wrapped in the lowest part of the water tank, the heat transfer performance is shown as the best with excellent temperature uniformity of water.

(2) When the pipe spacing is 15mm (7mm-diameter), the heating rate is the largest. The small diameter copper tube (5mm) has a better heat transfer effect and economic advantages. The total heat transfer increases with the increase of the turns of pipe coils. Moreover, the water heating rate and water flow rate is also increasing.

The significant limitation of our study is that, we ignore the impact of other components, such as evaporators, compressors, etc. And the change of different structural parameters of the copper tube can cause the difference of refrigerant charge, the different heat transfer coefficient, and the heat transfer resistance of the copper tube is also different. From the perspective of the ASHPWH system, it may get a better result.

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