Numerical Analysis of Water Temperature Distribution in the Tank of ASHPWH with a Cylindrical Condenser

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Abstract: Air source heat pump water heaters (ASHPWH) are becoming increasingly popular for saving energy, protecting the environment and security purposes. The water temperature distribution in the tank is an important parameter for an ASHPWH. This paper presented a mathematic model for a cylindrical water tank with a cylindrical condenser as its heat source. The computational fluid dynamics (CFD) software package, FLUENT, was used to study hot water temperature distribution in the tank of the ASHPWH. In addition, the effects of tank dimension and the type of condenser coil on water temperature distribution were discussed. The work of this paper could be used for the optimization of tank and condenser coil designs.

Key words: air source heat pump water heater; water temperature distribution; numerical analysis; tank dimension; condenser coil

NOMENCLATURE

D_1	diameter of water tank
H	height of water tank
D_2	diameter of condenser coil
L	length of condenser coil
T_C	condenser coil temperature
T	water temperature
t	time
P	pressure
$\vec{u}$	velocity vector

Greek Symbols

ν	kinematic viscosity
ρ	density
β	thermal expansion coefficient

1. INTRODUCTION

There are three popular types of residential water heater used in China market: electric resistance, direct gas fired and solar water heater. They have their own advantages and disadvantages. For example, energy efficiency of electric resistance water heater is low. Gas fired water heater has safety incipient fault. Solar water heater is mainly confined by terrene, climate, building level[1].

ASHPWH composed of heat pump circulation system and water tank, is a type of heater utilizing air as heat source and its structure is shown as Fig.1[2].It makes use of refrigerant in evaporator absorbing the air heat, and the condenser is directly inserted into the tank for heating water. Its heating coefficient is 3 to 4 times greater than conventional electrical resistance heater’s. The condenser coil water heating can achieve water-electricity separation which makes it good electrical security. Therefore, ASHPWH has such advantages as pollution-free, high- efficiency, energy saving, safe-reliability and perfect self-control, etc. The common design is to insert the condenser coil of ASHPWH into the water tank. This design could be less expensive than others and more efficient because of the elimination of the water circulating pump and a heat exchange. Comparing with general air conditioning, it is in dynamic environment. Evaporating pressure, condensing pressure and heating capacity increase with hot water temperature rising. For using the water heater in daily life, hot water is drawn off the top of the water tank and replaced by cold water entering at the bottom. When the outlet temperature is constant, if the longitudinal temperature difference in a water tank gives rise , the average hot water temperature will reduce, the value of COP will increase. Therefore, according to the hot water temperature distribution, design the rational water tank and the type of condenser coils, and thus greatly increase the heating coefficient [3].

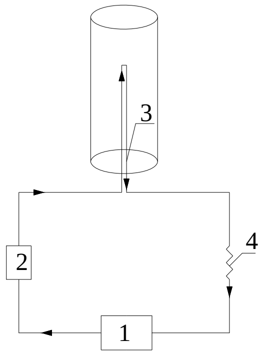

Fig1. Schematic diagram of ASHPWH

1—Evaporator 2—Compressor 3—Condenser 4—Capillary tube

In this paper, the impact that the tank dimension and the type of condenser coil of an ASHPWH with cylindrical condenser on the water temperature longitudinal stratification was investigated by using FLUENT computational fluid dynamics software package.

2. MATHEMATIC MODEL

Fig.2 showed the geometry of the water tank with the condenser coil. The model was assumed as natural convection in three dimensional enclosed spaces. The parameters of water tank and condenser coil were shown in Fig3.

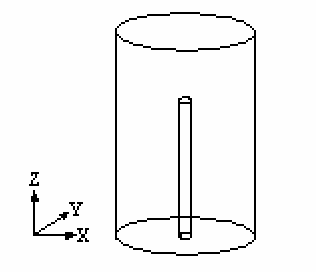

Fig2. Schematic of water tank structure

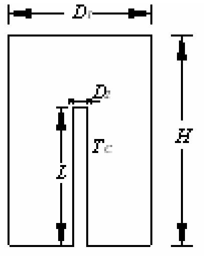

Fig3. Physical model

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

(1)The water tank sidewall was assumed adiabatic.

(2)The condenser coil immersed in tank was cylindrical.

(3)The condenser coil was regarded as the fixed temperature wall boundary, the temperature was the average value of results of testing.

(4)The water flow was turbulence[4],[5].

(5)Natural convection flow was modeled with Boussinesq approximation[2].

For many natural-convection flows, you can get faster convergence with the Boussinesq model than you can get by setting up the problem with fluid density as a function of temperature. This model treats density as a constant value in all solved equations, except for the buoyancy term in the momentum equation[6]:

$$(\rho - \rho_0)g \approx -\rho_0 \beta (T - T_0) g \qquad (1)$$

where ρ_0 is the (constant) density of the flow, T_0 is the operating temperature, and β is the thermal expansion coefficient. Equation (1) is obtained by using the Boussinesq approximation $\rho = \rho_0(1 - \beta \Delta T)$ to eliminate ρ from the buoyancy term. This approximation is accurate as long as changes in actual density are small; specifically, the Boussinesq approximation is valid when $\beta(T - T_0) << 1$.

Governing equations for fluid were written as following equation.

Continuity :

$$\nabla \cdot (\rho \vec{u}) = \rho \nabla \cdot \vec{u} = \nabla \cdot \vec{u} = 0 \qquad (2)$$

The Navier-Stocks:

$$\frac{D\vec{u}}{Dt} = -\frac{\nabla P}{\rho_0} + \nu \nabla^2 \vec{u} - \frac{\Delta \rho g}{\rho_0} \qquad (3)$$

After submitting Eq.(1) into the foregoing equation, it then became

$$\frac{D\vec{u}}{Dt} = -\frac{\nabla P}{\rho_0} + \nu \nabla^2 \vec{u} - g\beta(T - T_0) \qquad (4)$$

Energy:

$$\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T = \alpha \nabla^2 T \qquad (5)$$

Boundary condition: At all walls either the no-slip or the shear-free velocity boundary condition was prescribed. The surface temperature of condenser coil was the first boundary condition. The rest of sidewalls were assumed adiabatic.

Initial condition: The initial temperature was natural temperature of water.

3. CALCULATION AND RESULTS

3.1 Numerical Method

Grids were generated by the GAMBIT program. For calculation accuracy, some grids were refined in which the temperature changed violently, some grids were loosened in which the temperature changed slowly in order to reduce a total of mesh volumes and calculated capacity[7]. The grids of fluid in horizontal plane were shown as Fig.4. The grids were locally refined near the condenser coil. Away from the coil, the grids were more and more loosened.

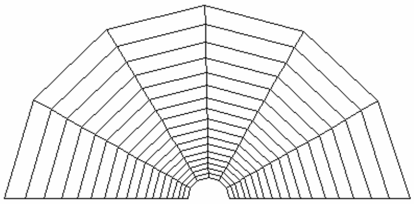

Fig.4 Grids of fluid in horizontal plane

There are many methods of generating grid. The types of grid are complicated and various. For three dimensional flow, GAMBIT creates hexahedral, pyramidal, and wedge elements[8]. Mesh type used in this study was hexahedral structure mesh. Firstly, meshed the bottom surface. When it was finished, specified the volume which included the bottom surface, then GAMIBIT automatically meshed the entire volume. After repeated calculation, the interval size was 0.04m.

After meshing the water tank, the grid file was imported directly into FLUENT for next step calculation. The segregated solver was used to drive the model to convergence. The standard k-epsilon turbulence model was utilized to compute water flow. For velocity-pressure coupling, Simplec algorithm was selected and first order upwind scheme was chosen. The implicit scheme was used for time discretization.

3.2 Calculation Condition

Tab.1 Calculation condition

Condition	Condition Parameter
Ⅰ	D_1=0.38m H =1.5m D_2 = 0.04m L=1.0m T_C = 328+5×i (i = 0,1,2,3.4.5) Heating Time: 1h
Ⅱ	D_1=0.38m H=1.5m D_2=0.04m T_C = 333K L= 0.6+0.2×i（i = 0,1,2,3,4） Heating Time: 1h
Ⅲ	D_2=0.04m T_C = 333K L= 2/3×H D_1/H= 0.118,0.165,0.253,0.465,1.316 (The volume of tank was constant.) Heating Time: 1h
Ⅳ	D_1=0.465m H =1m D_2 = 0.04m L= 0.67m T_C =333 K Heating time: 1h,1.5h,2h,2.5h,3h

3.3 Results

3.3.1 Effects of the Condenser Temperature on Water Temperature Distribution

When the dimension of tank, the length of condenser coil and heating time were constant, the condenser temperature was gradually up to 353K from 328K, the temperature interval was 5K. The impact of boundary condition change on water temperature was very great. With the increase of condenser temperature, the average temperature, the maximum temperature and the minimum temperature were growing linearly in Fig.5. The maximum temperature difference in the tank altitude direction was up to 9.6K from 5.6K, and the temperature stratification was remarkable. With the increase of condenser temperature, the temperature of water surrounding the condenser increased, which eliminated water natural convection in the tank, aggravated the temperature uniformity. The temperature difference rose up[9].

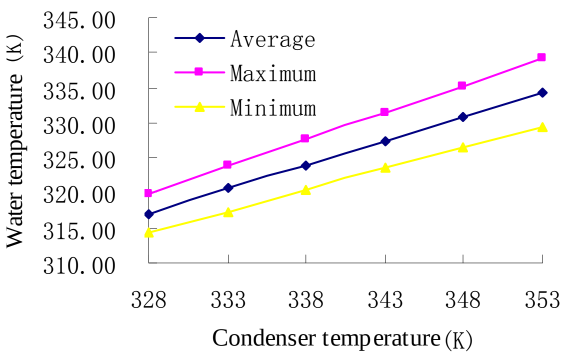

Fig.5 Results of condition Ⅰ

3.3.2 Effects of the Length of Condenser on Water Temperature Distribution

As the tank dimension, the temperature of condenser coil and heating time were constant, the length of condenser was gradually up to 1.4m from 0.6m, and the length interval is 0.5m. In **Fig.6**, with the length of condenser coil increasing, the average temperature, the maximum temperature and the minimum temperature changed unobviously. Therefore, when the length of condenser coil was greater than 2/5 of the tank height, water temperature changed little.

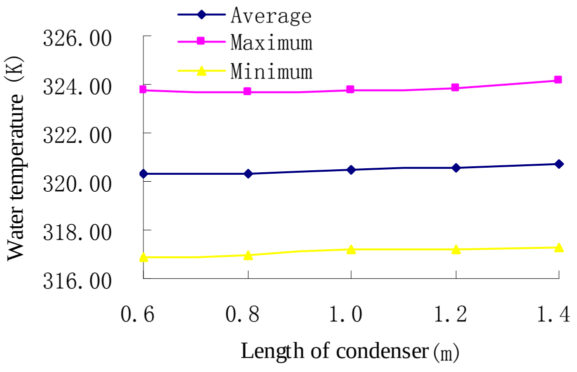

Fig.6 Results of condition Ⅱ

3.3.3 Effects of the Tank Dimension on Water Temperature Distribution

With the condenser temperature, heating time and the tank volume fixed, the height of tank was gradually up to 2.5m from 0.5m, and its diameter reduced to 0.294m from 0.658m gradually. Preliminary analysis showed that water temperature changed little when the length of condenser coil was greater than 2/5 of the tank height. So the length of condenser coil was taken as 2/3 height of the tank. In Fig.7, with the ratio of the tank's diameter to height increasing, the average temperature, the maximum temperature and the minimum temperature increased firstly, then reduced, the maximum average temperature was 322.6K at 0.465 ratio of the tank's diameter to height. The maximum temperature difference in the tank altitude direction was up to 9.4K from 1.5K, the temperature stratification was remarkable. Fig.8 (a), (b) gave the water temperature

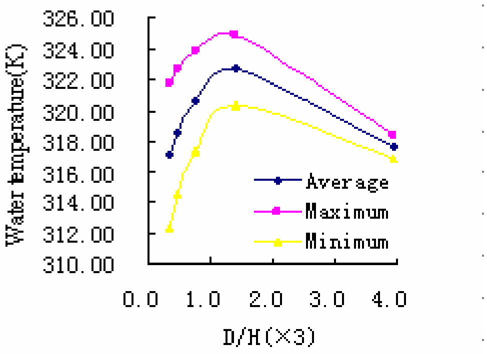

Fig.7 Results of condition Ⅲ

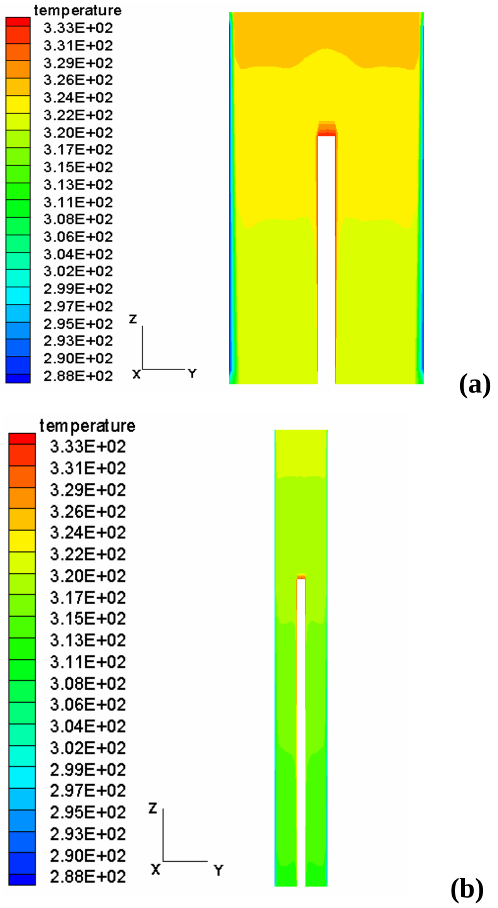

Fig.8 The temperature contour of flow along asymmetric cutplane; (a) The ratio of tank's diameter to height is 0.465. (b) The ratio of tank's diameter to height is 0.118.

distribution in two tanks whose ratio of diameter to height were 0.465 and 0.118. Because of the increase of the tank height, the water velocity was reduced, which eliminated water natural convection, aggravated the temperature uniformity.

3.3.4 Effects of Heating Time on Water Temperature Distribution

In Fig.7, other conditions were constant, the maximum average temperature was 322.6K at 0.465 ratio of the tank diameter to height. Although the average temperature was the maximum value in this tank, the temperature difference was not the minimum value. Therefore, the heating time was extended to observe the variation of temperature difference. Fig.8 illustrated the temperature difference in the tank altitude direction changed unobviously with the increase of heating time. The temperature grew 1K after 1.5h of heating, and then there wasn't remarkable change.

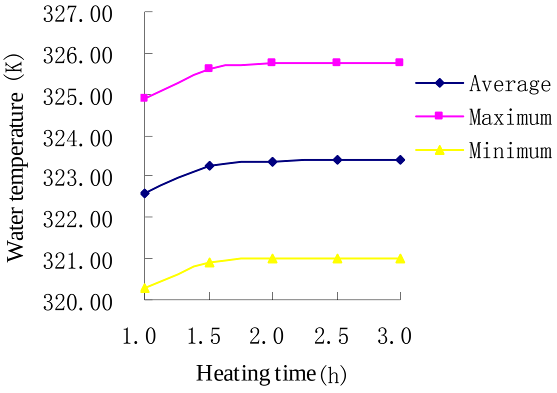

Fig.8 Results of condition Ⅳ

4. CONCLUSION

This paper presented a mathematic model for a cylindrical water tank with a cylindrical condenser as its heat source. FLUENT software was used to study water temperature distribution inside a water tank that was heated by a heat pump, and discussed the influences of the condenser temperature, the length of condenser coil, the ratio of the tank's diameter to height upon water temperature distribution. This paper showed that the average temperature, the maximum temperature and the minimum temperature were growing linearly with the increase of condenser temperature. Meanwhile, the temperature stratification was remarkable. When the length of condenser coil was greater than 2/5 of the tank height, water temperature changed little. With the ratio of the tank's diameter to height increasing, the average temperature, the maximum temperature and the minimum temperature increased firstly, then reduced, the maximum average temperature was 322.6K at 0.465 ratio of the tank diameter to its height. The water tank was optimized according to the above influencing factors.

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