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Numerical Simulation and Optimization of a Mid-Temperature Heat Pipe Exchanger

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Abstract: In this paper, we take the mid-temperature gravity heat pipe exchanger as the research object, simulate the fluid flow field, temperature field and the working state of heat pipe in the heat exchanger by Fluent software. The effects of different operating parameters and fin parameters on the heat transfer performance of heat exchangers are studied. The results show that the heat transfer performance of the mid-temperature gravity heat pipe exchanger is the best when the fin spacing is between 5 mm and 6 mm, the height of the heat pipe is between 12 mm and 13 mm, and the inlet velocity of the fluid is between 2.5 m/s to 3 m/s.

Keywords: Gravity heat pipe heat exchanger, fluent, numerical simulation, heat transfer performance.

1 Introduction

Heat pipe exchanger has the advantages of high heat transfer efficiency, simple structure, stable performance and low cost [Jian and Luo (2018)], which is one of the best choices for waste heat recovery and utilization of flue gas [Cao (2011)]. Gravity heat pipe depends on gravity to realize the reflux of heat pipe working fluid [Zhang, Liu, Jin et al (2016)], which can work without liquid absorption core, so the gravity heat pipe exchanger has a better application prospect [Zhang and Song (2011)].

Noie-Baghban et al. applied heat pipe exchanger in the waste heat recovery of hospitail [Noie and majideian (2000)]. Bai et al. expounded the working principle of the heat pipe exchanger in double-effect lithium-bromide absorption-type cold and hot water unit, and analyzed the influencing factors on the performance of separate type heat pipe exchanger [Bai and Yang (2006)]. Noie pointed out that heat pipe has good heat transfer performance and has important application in the field of waste heat recovery [Noie (2006)]. Li carried out theoretical and experimental researches on heat-pipe heat recovery unit [Li (2007)]. Pan et al. described the application of heat pipe in the air conditioning system, studied the feasibility and effectiveness of the application of heat pipe technology in air conditioning heat recovery system, and analyzed the heat pipe air exchange equipment [Pan and Song (2007)]. Li used a kind of software which is Fluent to simulate the fluid flow and heat transfer process in the heat exchanger,and analyzed the simulation results by using the field synergy principle [Li (2010)].

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The researches of high-temperature heat pipe have achieved certain results, while the study in the application of the mid-temperature heat pipe is relatively limited [Targui and Kahalerras (2013)]. In this paper, the mid-temperature heat pipe is used to recover the waste heat of the flue gas. Simulating the fluid flow field, temperature field and the working state of heat pipe in the heat exchanger by Fluent software. The effects of different operating parameters and fin parameters on the heat transfer performance of heat exchangers are studied. Finally, the optimal operating parameters and the corresponding finned structure parameters are obtained.

In 2016, Ma et al. carried out an experimental study on heat pipe heat exchanger for industrial waste heat recovery. The experimental results show that the on-line cleaning device had an obvious effect on the heat transfer [Ma, Yin, Shen et al (2016)].

2 The design of mid-temperature gravity heat pipe exchanger

A waste heat recovery device is designed for an industrial kiln in a certain factory. The exhaust gas temperature of the kiln is 470℃ and the mass flux of flue gas is 5 000 kg/h. According to the requirements to design the heat pipe exchanger, in the evaporation section, the flue gas mass flow (M_1) is 5 000 kg/h, the inlet temperature (T_1') is 470℃, and the selected exit temperature (T_1'') is 230℃. And the cooling fluid in the condensing section is air, the mass flow (M_2) and inlet temperature (T_2'') of which are 5500 kg/h and 20℃ respectively.

According to the parameters and the whole design method above, the mid temperature heat pipe exchanger is designed. There are 8 rows of heat pipe which are made of carbon steel in the middle temperature section, and the heat conduction- A is chosen as the working fluid in the heat pipe. There are 5 rows of heat pipe which are also made of carbon steel in the normal temperature section, and the working mid of is water. So the heat exchanger has 13 rows of heat pipe, which are arranged in a positive triangular cross row, that is, 13/12. The evaporating section of the heat pipe has the same length as the condensing section, which are both 1000 mm. Thus the original parameters of the heat pipe exchanger are determined.

3 The numerical simulation study of the mid-temperature heat pipe exchanger

3.1 Physical model

Heat pipe exchanger can be regarded as a heat exchange device, and the evaporation section and condensation section of it are independent of each other. Therefore, the evaporation section and the condensation section are numerically simulated and analyzed respectively. And a reasonable physical model of fluid operation and heat transfer must be established before the numerical simulation. Tab. 1 gives the design and structure parameters of the mid-temperature heat pipe exchanger.

Due to the symmetry of the inner structure of the heat exchanger and the heat pipe itself, the minimum element which is shown in Fig. 1 can be selected for calculation and analysis.

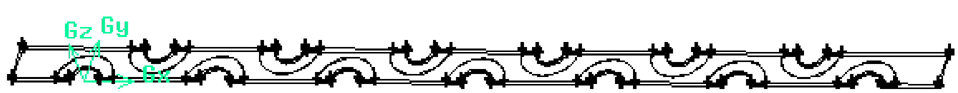

Figure 1: The calculation area of the pipe exchanger

Table 1: The structure parameters and design parameters of the pipe exchanges

Structure parameters				Design parameters			
Internal diameter of pipe (mm)	20	Length of the evaporator (mm)	1000	Evaporation		Condensation	
External diameter of pipe (mm)	25	Length of the condenser (mm)	1000	Inlet temperature (℃)	470	Inlet temperature (℃)	20
External diameter of the fin (mm)	50	Length of pipes at the windward side (mm)	65	Outlet temperature (℃)	230	Mass flow (kg/h)	5500
Thickness of the fin (mm)	0.8	Arrangement of the HP	13/12	Mass flow (kg/h)	5000		
Spacing of the fin (mm)	4	Number of the depth pipes	13				

3.1.1 Govering equations

Due to the complexity of the structure and the flow field in the mid-temperature heat pipe exchanger, it is assumed that the fluid flow and heat transfer are in a stable state, the fluid is an incompressible fluid and the physical property is constant in numerical simulation. The heat transfer process of fluid flow is restricted by the law of conservation of mass, the law of conservation of momentum and the law of conservation of energy.

The fluid flow is simulated by solving the local average Navier-Stokes equation. And the time-related three-dimensional mass and momentum conservation equations are as follows:

$$\frac{\partial \rho}{\partial t}+\nabla\cdot(\rho \mathrm{u})=0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}[\rho u_i u_j + p\delta_{ij} - \tau_{ji}]=0, i=1,2,3 \tag{2}$$

$$\frac{\partial(\rho T)}{\partial t}+div(\rho u T)=div(\frac{k}{c_p}gradT)+S_T \tag{3}$$

where C_P, T and k are the specific heat capacity, temperature, heat transfer coefficient of the fluid; S_T is the internal heat source of a fluid and the part of fluid mechanical energy that is converted to heat by viscous action.

3.1.2 Boundary conditions

In the simulation calculation of the heat pipe exchanger in this paper, the boundary conditions of the heat pipe exchanger are selected as follows:

(1) The fluid and solid regions in the heat pipe exchanger are solved by the separate

solver.

(2) The inlet boundary condition is set to the mass flow boundary condition.

(3) The outlet boundary condition is set to the flow boundary condition.

(4) The two sides of the fluid flow area are set as symmetrical boundary conditions.

(5) The base tube of the heat pipe and the wall of the fins in contact with the flue gas are set to fixed, non-slip boundary conditions.

(6) The wall of heat pipe is set to the constant heat flux boundary condition according to the model.

4 Results and analysis of numerical simulation

The average heat flux density of the single heat pipe is calculated according to the energy conservation of the evaporation section and the condensing section in the heat pipe. The boundary condition of heat pipe is set to constant heat flux by FLUENT, and the heat exchanger is numerically simulated. In order to investigate the effect of inlet temperature of cold fluid on the heat transfer performance, the following condition is adopted: the inlet speed of hot fluid is 2.5 m/s, the inlet temperature of cold fluid is 293 K and the inlet velocity of cold fluid is 2 m/s. Fig. 2 shows the variation of the average Nu with the number of tube rows in evaporation and condensation section.

Nu is a standard number indicating the intensity of convection heat transfer. And the formula is as follows：

$$Nu = \frac{hd_0}{\lambda} \tag{4}$$

where h represents the heat transfer coefficient of the outer surface of the heat pipe and λ represents the coefficient of thermal conductivity of fluid respectively.

$$h = \frac{Q_i}{A_0 \cdot \Delta T} \tag{5}$$

where Q_i, A_0 and ΔT represents the heat exchange of a single heat pipe, surface area of the heat pipe without fins and logarithmic mean temperature difference.

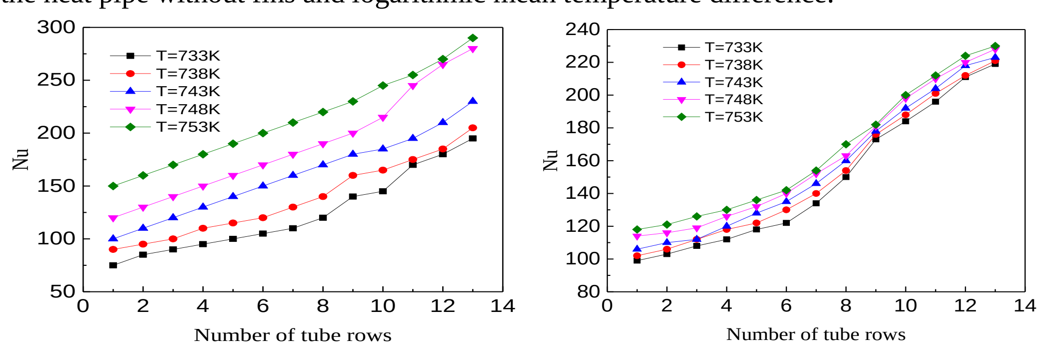

Figure 2: Variation of the average Nu with the rows in evaporation and condensation at different inlet temperatures of the hot fluid (a) Variation of the average Nu with the rows

in evaporation (b) Variation of the average Nu with the rows in condensation

In Fig. 2, We can see that the average Nu of the wall in heat pipe increased with the number of tube rows at different inlet temperatures of the hot fluid in evaporation and condensation. Meanwhile, the average Nu of the wall in heat pipe increased with the inlet temperature in the same rows.

In order to investigate the effect of inlet velocity of cold fluid on the heat transfer performance, the following condition is adopted: the inlet temperature of hot fluid is 743 K, the inlet temperature of cold fluid is 293 K and the inlet speed of it is 2 m/s. Fig. 3 depicts that the average Nu of the wall in heat pipe changes with the number of tube rows when the inlet speed of the flue gas is different.

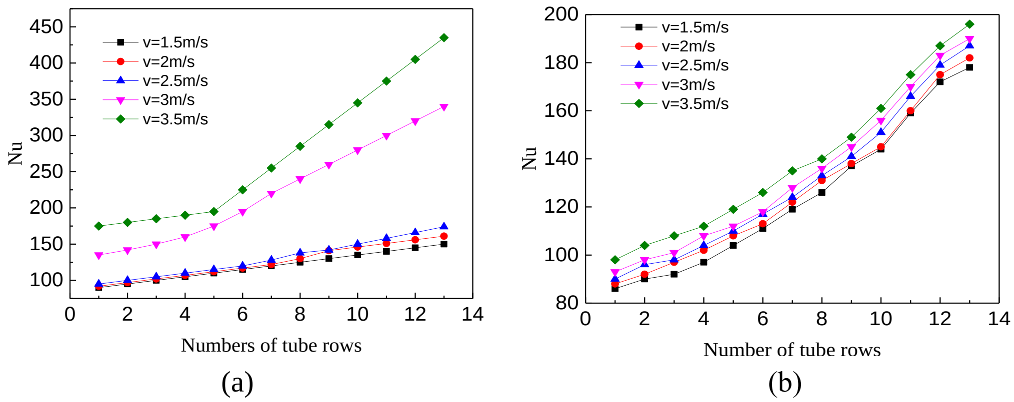

Figure 3: Variation of the average Nu with the rows in evaporation and condensation at different inlet velocities of the hot fluid (a) Variation of the average Nu with the rows in evaporation (b)Variation of the average Nu with the rows in condensation

As can be seen from Fig. 3, the average Nu of the wall in heat pipe increased with the number of tube rows at different inlet velocities in evaporation and condensation. Meanwhile, the average Nu of the wall in heat pipe increased with the inlet velocity in the same rows. And the effect of inlet velocity of the hot fluid tends to be stronger than the inlet temperature on heat transfer performance of the heat pipe.

5 An optimization of mid-temperature HP heat exchanger

5.1 The selection of optimization parameters

When the type of heat pipe and fin are selected, the fin parameters can be divided into three types: fin spacing, height and thickness. The finned parameters determine the finning ratio and fin efficiency of the heat pipe, and have a great influence on the flow resistance and heat transfer characteristics of the heat pipe.

In the computational model of this paper, the outer diameter of the heat pipe is 25 mm, the fin spacing is 4 mm, the fin height is 12.5 mm, and the fin thickness is 0.8 mm. When determining the finned parameters, the sum of the outer diameter of the heat pipe and the height of the fin should be smaller than the distance between the heat pipes; In engineering practice, the finned height is usually about half of the outer diameter of the heat pipe [Mao (2011)]. The fin thickness can be generally taken as 0.3~3 mm, and the fin spacing should not be too large or too small, 4~8 mm can be taken generally, because the heat pipe in this paper is high fin heat pipe, the influence of fin thickness on heat transfer is not taken into account, and the fin thickness is taken as 0.8 mm to keep constant. To sum up, five calculated values were selected for each factor, so the fin spacing shall be 3 mm, 4 mm, 5 mm, 6 mm and 7 mm, and the height of the fin shall be 9.5 mm, 11 mm, 12.5 mm, 14 mm and 16.5 mm.

5.1.1 Influence of fin parameters and heat pipe spacing on heat exchanger performance

The heat transfer of heat pipe is mainly evaluated by some technical indexes: total heat transfer Q, average convection heat transfer coefficient h_f and the fin efficiency η.

$$h_f = \frac{Q_i}{A \cdot \Delta T} \tag{6}$$

$$A = A_b + A_f \tag{7}$$

Where A_b, A_f represents the area of heat pipe where has no fin and fin surface area of the heat pipe.

(1) Fin spacing

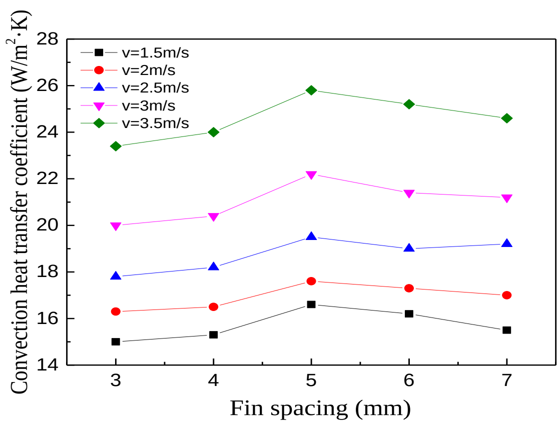

Figure 4: Average convection heat transfer coefficient of the heat exchanger with the change of fin spacing

Under the condition that the inlet temperature of the hot fluid in the evaporation section of the heat exchanger is constant, and the inlet temperature and velocity of the cold fluid in the condensing section keeps invariant, the variation curve of average convection heat transfer coefficient with fin spacing at different inlet velocity of heat flow was shown in Fig. 4. It can be seen from the diagram that the average convection heat transfer coefficient of the heat exchanger increases first with the increase of fin spacing and then decreases gradually at different inlet velocity of heat flow. This is because when the fin spacing is less than the sum of the boundary layer of the fluid flow between adjacent fins, the flue gas cannot flow into the wing root region and cause the flow to stagnate, which results in the deterioration of the heat transfer in the region and the decrease of the average convection heat transfer coefficient of the heat exchanger. Therefore, the fin spacing should not be too small; With the increase of fin spacing, the velocity of flue gas at the wing root increases and the heat transfer effect is enhanced, so the average convection heat transfer coefficient increases. With the increase of fin spacing, the number of fins decreases and the flue gas disturbance decreases, which results in the decrease of average convection heat transfer coefficient.

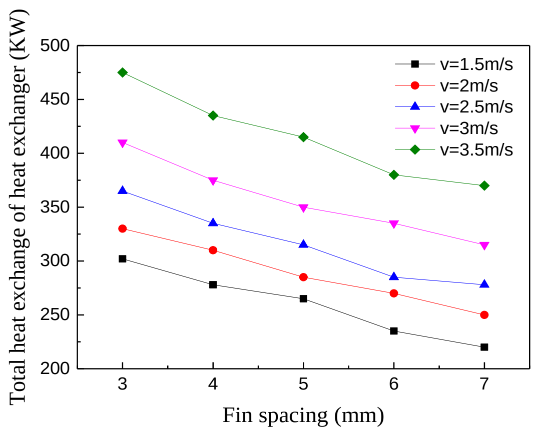

Figure 5: Total heat transfer of the heat exchanger along with the change of fin spacing

As shown in Fig. 5 that the total heat transfer rate of heat exchanger decreases with the increase of fin spacing, and the rate of decline is very large. Therefore, the total heat transfer of heat exchanger is closely related to fin spacing. With the increase of fin spacing, the heat transfer area of heat pipe is greatly reduced, the heat transfer resistance of convection is greatly increased, and the total heat transfer of heat exchanger is greatly reduced. When the fin spacing range from 3 mm to 5 mm, the average convection heat transfer coefficient increases gradually, while the total heat transfer decreases gradually. This is because the change of the effective heat transfer area of the heat pipe has more influence on the total heat transfer of the heat exchanger than the change of the average convection heat transfer coefficient on the total heat transfer of the heat exchanger. When the fin spacing range from 5 mm to 7 mm, the average convection heat transfer coefficient and the effective heat transfer area of the heat exchanger decrease gradually, so the total heat transfer of the heat exchanger decreases gradually.

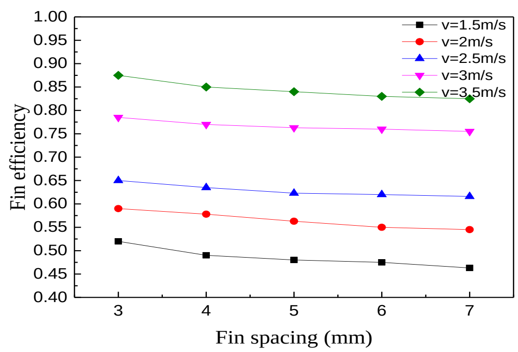

Figure 6: The fin efficiency changing along with the change of fin spacing

The relationship between fin efficiency of the heat pipe and the fin spacing at different inlet velocities was shown in Fig. 6, in which the inlet velocity and temperature of the cold fluid are invariant, and the inlet temperature of the hot fluid is 743 K. It can be seen from the diagram that the fin efficiency of the heat pipe decreases gradually with the increase of wing spacing when the inlet velocity of the thermal fluid in the evaporation section remains constant. It can be seen from Fig. 4 that the average convection heat transfer coefficient increases greatly with the increase of fin spacing when the fin spacing is taken as 3~5 mm, so the heat transfer resistance decreases significantly, and the temperature difference between the fin and the heat fluid decreases, which increases the temperature difference between the base tube and the fin. Therefore, the fin efficiency decreased gradually; When the wing spacing changes in 5~7 mm, the average flue gas temperature in the evaporation section increases and the average surface temperature of the fin increases, so the fin efficiency does not change obviously. Which indicate that compared with the average convection heat transfer coefficient, the influence of flue gas temperature on fin surface temperature is more significant.

According to the relationship between the average convection heat transfer coefficient, the total heat transfer efficiency and the fin spacing, and considering the economy and safety of the heat pipe exchanger, the optimum value of fin spacing is between 5 mm and 6 mm. In addition, the requirements of flue gas cleanliness and manufacturing process should also be taken into account in the selection of fin spacing.

(2) Fin height

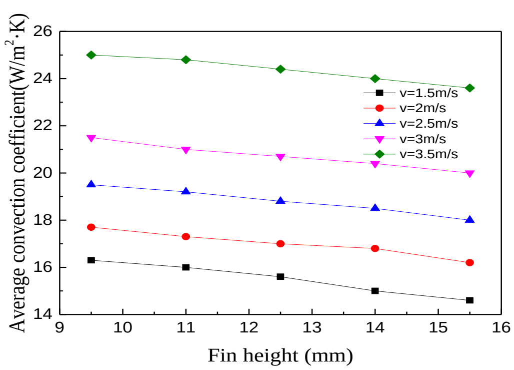

Figure 7: Average convection heat transfer coefficient of the heat exchanger with the change of fin height

The relationship between average convection heat transfer coefficient and fin height at different inlet velocities of hot fluid was shown in Fig. 7, in which the inlet temperature of the hot fluid is 743 K,the inlet temperature of the cold fluid is 293 K, and the inlet velocity is 2 m/s.It can be seen from the figure that the average convection heat transfer coefficient of the heat exchanger decreases gradually with the increase of fin height, which is because the increase of fin height weakens the fluidity of flue gas in the fin root region, and the heat transfer capacity also weakens, and the convection heat transfer coefficient decreases. Therefore, the height of fin should not be too large in the structural design of heat exchanger.

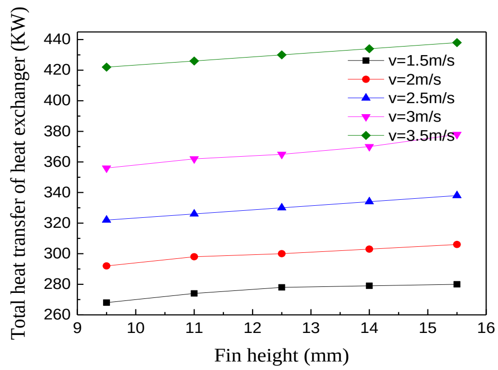

Figure 8: Total heat transfer of the heat exchange along with the change of fin height

The relationship between total heat transfer and finned height of heat pipe heat exchanger at different inlet velocities of hot fluid was given in Fig. 8. It can be seen from the figure that the total heat transfer increases with the increase of fin height at different inlet velocities, and the increase showed a decreasing trend, which is because the total heat transfer area increases and the heat transfer resistance decreases with the increase of fin height, showing that the effect of the increase of heat transfer area on heat transfer is greater than that on heat transfer by decreasing convection heat transfer coefficient. However, when the fin height increases, the average surface temperature of the fin increases and the fin efficiency decreases. In addition, the thermal resistance of the fin increases with the increase of the fin height, so the increase range of the total heat transfer of the heat pipe heat exchanger decreases gradually.

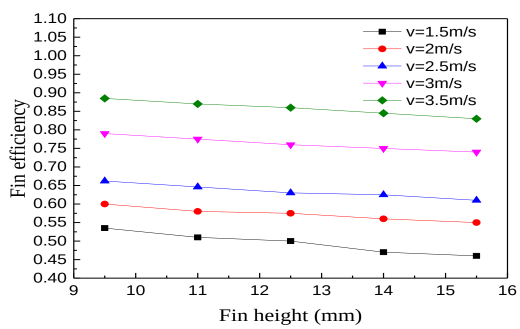

Figure 9: The fin efficiency changing along with the change of fin height

The relationship between fin efficiency and fin height of heat pipe at different inlet velocities of hot fluid was shown in Fig. 9. It can be seen from the figure that the fin efficiency decreases with the increase of fin height, and the drop remains unchanged. Which is because the thermal resistance of the fin increases with the increase of the fin height, and the mean surface temperature of the fin increases, resulting in the decrease of the fin efficiency.

According to the previous experience, the fin height of heat pipe is usually chosen to be about half of the outer diameter of heat pipe in the design of heat pipe heat exchanger

[Wang (2013)]. Considering the influence of fin height on convection heat transfer coefficient, heat transfer and fin efficiency, the fin height of heat pipe in this paper can be chose between 12 mm and 13 mm.

6 Conclusions

Based on the numerical simulation of mid temperature heat pipe exchanger, the effects of different inlet temperature and velocity of heat fluid on the flow, heat transfer performance and working state of heat pipe exchanger are analyzed. The heat transfer performance of the heat exchanger is also related to the fin parameters of the heat pipe. According to the simulation results and analysis above, the conclusions are as follows:

(1) when the inlet velocity of flue gas in evaporation section increases from 1.5 m/s to 3.5m/s, the steam temperature in heat pipe decreases gradually; If the inlet velocity of the hot fluid is too small, the steam temperature in the water heat pipe will exceed the working limit temperature of the working mid in the middle and low temperature transition zone, which will lead to the phenomenon of pipe burst.

(2) when the spacing of fins of the heat pipe changes in 3~7 mm, the average convection heat transfer coefficient of heat exchanger increases first and then decreases with the increase of fin spacing, and there is an optimum value in the middle. However the total heat exchange and fin efficiency of heat pipe decrease with the increase of fin spacing. The spacing of fins should not be too small because smaller spacing will easily lead to the stagnation of flue gas flow and make the local heat transfer deteriorate. Therefore, the optimal fin spacing in this paper is in the range of 5~6 mm.

(3) When the fin height of heat pipe changes in 9.5~15.5 mm, the average convection heat transfer coefficient and fin efficiency of heat exchanger decrease with the increase of fin height, while the total heat transfer of heat pipe exchanger increases with the increase of fin height, and the total heat transfer of heat exchanger decreases with the increase of fin spacing. The heat transfer increased with the increase of fin height, and the increasing amplitude showed a decreasing trend. So the optimum range of fin height in this paper is 12~13 mm.

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