Performances of gas-water direct-contact heat transfer

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Abstract. Compared with indirect-contact heat exchanger, gas-water direct-contact heat exchanger has superiority of decreasing metal heat-exchange surface, small temperature difference and volume, less investment and good antiseptic effect. This paper studies the droplets movement characteristics and performance of gas-water heat and mass transfer. The gas-water direct-contact heat transfer differential equation has been set up to obtain temperature distribution of flue gas and water. The main factors are also analyzed. In this paper, a direct-contact heat transfer model is established for a project, and the results of theoretical calculation and engineering operation are compared. The model has been verified.

Keywords: direct-contact, flue-gas condensation, motion characteristics, heat and mass exchange, heat transfer model, test verification.

1 Introduction

Nowadays the increasing attention has been paid to energy conservation and environmental protection. As a clean energy, the natural-gas consumption has increased rapidly. As a heating source, gas-fired boilers have been widely promoted in northern cities. However, due to the high exhaust temperature, the condensing heat in the flue gas is difficult to be recovered. Scholars have studied the flue-gas waste heat recovery of the gas-fired boiler[1-5]. It has been proposed to recover the condensing heat of flue gas by the absorption heat pump[6], which has solved the problem that the return-water temperature is higher, and the condensing heat of the flue gas can not be recovered.

The atomized low-temperature water directly contacts the flue gas. The flue gas is cooled below dew point and water vapor in the flue gas releases condensation heat, which has achieved the purpose of recovering waste heat and condensed water. Direct contact heat exchangers are generally combined with absorption heat pumps. The flue gas is cooled by low-temperature water produced from the absorption heat pump in the direct contact heat exchanger, the heated low-temperature water enters the absorption heat pump to be cooled and then is pumped to the direct contact heat exchanger. An automatic alkali adding device is arranged in the direct contact heat exchanger for the low-temperature water, and the key parts of equipment are protected against corrosion, which has solved the corrosion problem of equipment.

Theoretical analysis of direct contact heat transfer is carried out in the literature [7-9], and the analytical solution for the flue-gas water heat transfer efficiency is obtained. However, it is assumed that the particle size of droplets and physical properties of flue gas are constant during the heat transfer, which simplifies the calculation and also affects the calculation accuracy. The above factors are considered in this paper, a micro model of heat and mass exchange between flue gas and water droplets is established, and the numerical solution of heat transfer between flue gas and water droplets is obtained.

2 Analysis of motion characteristics of water droplets

To study the heat and mass exchange characteristics of flue gas and water, the motion characteristics of water droplets should be firstly studied and the velocity distribution of water droplets can be obtained. The relative motion of water droplets and flue gas is not all downstream or upstream. The velocity of water droplets relative to flue gas can be decomposed into vertical and horizontal directions

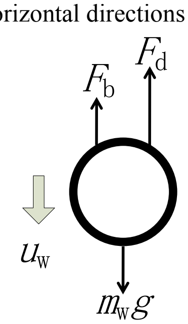

Fig. 1. This figure describes the force analysis of water droplet in the vertical direction.

For example, in the vertical direction, water droplets move in the initial velocity of u0 relative to the flue gas. Water droplets are affected by three forces(m_wg), downward gravity(F_b), upward buoyancy, and upward frictional resistance(F_d). Buoyancy is negligible compared to gravity, and the force analysis of water drops is as follows:

$$m_w \frac{du_{w,v}}{d\tau} = m_w g - F_d \tag{1}$$

Where, m_w is weight of a single drop, kg; $u_{w,v}$ is droplet velocity in the vertical direction, m/s; τ is time, s; and g is gravitational acceleration(9.8m/s^2).

The calculation formula for gravity:

$$m_w g = \frac{1}{6}\pi d_w^3 \rho_w g \tag{2}$$

where, d_w is droplet size, m; ρ_w is droplet density, kg/m^3.

The calculation formula for resistance [11]:

$$F_d = \frac{1}{4}\pi d_w^2 C_d \times \frac{1}{2}\rho_f u_{w,v}^2 \tag{3}$$

where, C_d is resistance coefficient.

At low Reynolds number(Re<1000), optimum resistance coefficient expression[10-11] is as follows:

$$C_d = 24(1 + 0.197\mathrm{Re}^{0.63} + 2.6\times10^{-4}\mathrm{Re}^{1.38})/\mathrm{Re} \tag{4}$$

$$\mathrm{Re} = d_w u_{w,v} / \mu \tag{5}$$

where, μ is coefficient of dynamic viscosity, Pa.s.

Therefore, it is as below:

$$\frac{du_{w,v}}{d\tau} = g - \frac{F_d}{m_w} = g - \frac{3}{4}C_d\rho_f u_{w,v}^2 / (\rho_w d_w) \tag{6}$$

Assume that:

$$f(u_{w,v}) = g - \frac{3}{4}C_d\rho_f u_{w,v}^2 / (\rho_w d_w) \tag{7}$$

That is:

$$\frac{du_{w,v}}{f(u_{w,v})} = d\tau \tag{8}$$

Since the calculation formula in C_d contains u_w, C_d cannot be considered as a constant. Therefore, it is difficult to obtain analytic solutions by integration, and numerical analysis would be used.

In order to calculate the velocity distribution of water droplets, the motion time of water droplets is divided into several motion ranges at $d\tau$ intervals. The initial velocity of water droplet is $u_{w,v}(0)$, and the exit velocity of droplets at the n-th motion interval is $u_{w,v}(n)$. When $d\tau$ is small enough, higher calculation accuracy can be guaranteed. Iterative method is used. According to formula (1) - (8) and initial velocity $u_{w,v}(0)$, the $u_{w,v}(1)_1$ can be calculated, in which subscript denotes iteration times. Assume that $u_{w,v}(0)_2=(u_0+ u_w(1)_1)/2$, so the $u_{w,v}(1)_2$ can be calculated. It is by analogy until "$u_{w,v}(1)_{n+1}- u_{w,v}(1)_n$" is within the acceptable accuracy range. Taking "$u_{w,v}(1) = u_{w,v}(1)_{n+1}$" as the initial value of the relative velocity for the next period of time, so that the velocity distribution over the entire time period can be calculated.

In the calculation, as the droplet velocity decreases, "$f(u_w)=0$" will appear. At this point, the vertical relative velocity of the water droplet will no longer change, and this velocity is defined as the settling velocity relative to the flue gas. Fig.2 illustrates the settling velocity of water droplet with different sizes in flue gas (50°C). With the increasing of droplet size, the settling velocity increases approximately linearly.

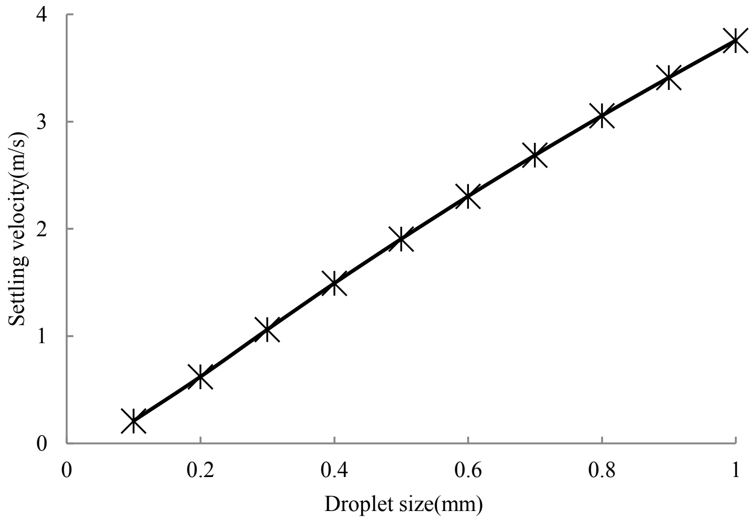

Fig. 2. It illustrates the settling velocity of water droplet with different sizes in flue gas (50℃).

The horizontal velocity distribution is similar to the above method. In the horizontal direction, it is only affected by resistance, so the force analysis of water drops is as follows:

$$\frac{du_{w,h}}{d\tau} = -\frac{3}{4} C_d \rho_f u_{w,h}^2 / \rho_w \qquad (9)$$

Where, $u_{w,h}$ is droplet velocity in the horizontal direction, m/s The numerical method is also used to solve the problem.

A gas boiler flue-gas waste heat recovery project in Beijing is taken for example. The water droplets are ejected vertically at 15m/s. the flue gas with 2m/s flow across the water droplets. The height of direct contact heat exchanger is 1.5m. The physical parameters of water droplets and flue gas change little in the heat transfer, which are calculated as the constant values. The flue-gas density is 1.09kg/m^3, the droplet density is 1000kg/m^3, and the dynamic viscosity coefficient of flue gas is 1.86×10^{-5}Pa.s. In order to ensure the calculation accuracy, $d\tau$ is taken as 0.01s. The trajectories and relative velocities of water droplets with different sizes are shown in Fig.3 and Fig.4. As can be seen from the figures, the larger the droplet size, the slower the vertical velocity decreases and the shorter in the horizontal direction water droplets moves, which is more easier to avoid the phenomenon that water droplets are taken away by flue gas.

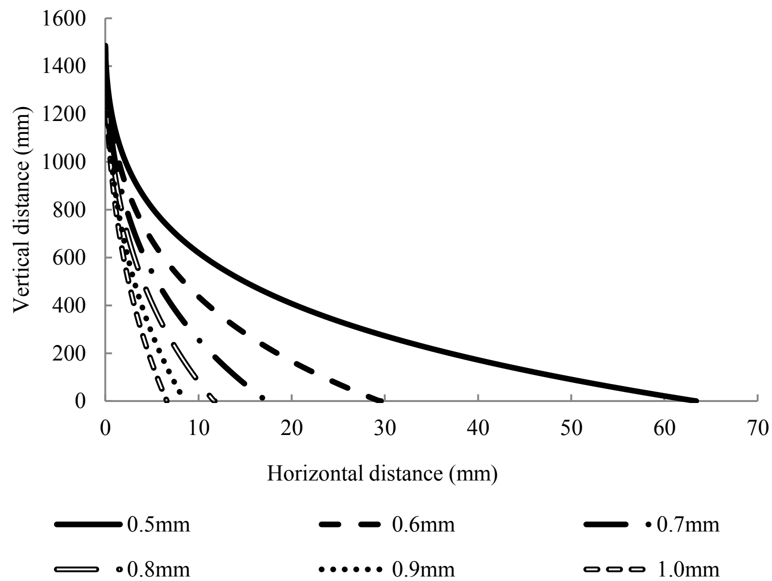

Fig. 3. Trajectories of droplets with different sizes are shown in the figure.

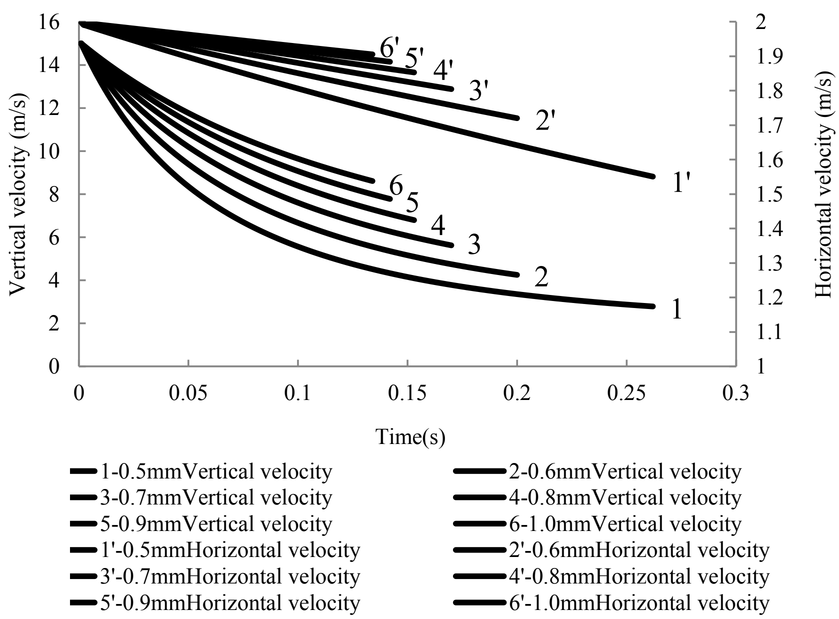

Fig. 4. Relative velocity of droplets with different sizes are shown in the figure.

In the above calculations, all values of Re are less than 1000, so the applicable conditions of C_d formula are satisfied.

3 Analysis of heat and mass transfer between water droplets and flue gas

The heat and mass transfer process of water droplets with flue gas containing water vapor is a complex physical phenomenon. In order to facilitate the analysis, the following assumptions are made:

（1）The droplet is spherically symmetric and the temperature is uniform distribution, so the lumped parameter method can be used；

（2）The radiative heat transfer between droplets and flue gas is ignored；

（3）The flue gas and water vapor are ideal gases；

（4）The influence of mass transfer on heat transfer is ignored [7];

（5）The Lewis criterion is established [7].

In the flue gas waste heat recovery system of gas boiler, the heat and mass transfer characteristics of direct contact heat transfer between water droplets and flue gas are different from those of conventional spray chambers:

（1）The main component of natural gas is CH_4, and flue gas is rich in water vapor. In the mass transfer process, the water vapor pressure in the flue gas is generally higher than the saturated vapor pressure in the boundary layer of the water droplet. Therefore, the direction of mass transfer is generally opposite to the direction of the water air mass transfer in the spray chamber.

（2）In the gas-water heat and mass transfer process, when the flue-gas temperature is below the dew point temperature, condensed water vapor in the flue gas includes not only the vapor mass transfer, but also the condensation of water vapor caused by the temperature drop of the flue gas, which is different from the conventional surface heat transfer and water-air mass transfer.

According to Fick mass diffusion law, the mass diffusion equation of spherically symmetric model in the radial direction is as follow:

$$\dot{m} = -D\rho_{\mathrm{f}}\frac{dY}{dr} + Y\dot{m} \qquad (10)$$

Where, $\dot{m}$ is mass diffusion rate per unit area, kg/m^2/s; D is mass diffusion coefficient, m^2/s; ρ_{f} is flue-gas density, kg/m^3; Y is water vapor mass ratio; r is radial coordinate, which is 0 at the center of the droplet and expressed as subscript s on the surface of the droplet, m.

Y can be calculated by the following formula[12]:

$$Y = \frac{P_{\mathrm{w}}M_{\mathrm{w}}}{P_{\mathrm{w}}M_{\mathrm{w}} + (P - P_{\mathrm{w}})M_{\mathrm{f}}} \qquad (11)$$

Where, P_{w} is water vapor pressure, Pa; M_{w} is molecular weight of water(18); P is flue-gas pressure, Pa; M_{f} is molecular weight of flue gas(29).

According to the literature[12], the mass transfer formula per unit time through the water droplet surface is as follows:

$$m_{\mathrm{z}} = 2\pi d_{\mathrm{w}} \frac{\lambda_{\alpha}}{c_{\mathrm{p},\alpha}} \ln(1 + B_{\mathrm{M}}) \tag{12}$$

Where, m_z is total mass diffusion rate of water droplet surface, kg/s; λ_α is thermal conductivity of flue gas, W/m/K; $c_{p,\alpha}$ is specific heat capacity of flue gas, J/kg/K.

Defining mass transfer number B_M:

$$B_{\mathrm{M}} = \frac{Y_{\mathrm{s}} - Y_{\infty}}{1 - Y_{\mathrm{s}}} \tag{13}$$

where, subscript s represents the parameters of water droplets surface, and subscript ∞ is the parameter of flue gas.

The heat transfered by flue gas to droplets is:

$$Q_{\mathrm{h}} = \pi d_{\mathrm{w}}^{2} h (T_{\infty} - T_{\mathrm{s}}) \tag{14}$$

Where, h is the convective heat transfer coefficient of droplets and flue gas, which can be calculated by following formula[13-14]:

$$Nu = \frac{h d_{\mathrm{w}}}{\lambda_{\alpha}} = 2 + 0.6\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3} \tag{15}$$

Therefore, it can be deduced:

$$Q_{\mathrm{h}} = \pi d_{\mathrm{w}} \lambda_{\alpha} (T_{\infty} - T_{\mathrm{s}})(2 + 0.6\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}) \tag{16}$$

The condensation heat of water vapor is:

$$Q_{\mathrm{c}} = m_{\mathrm{c}} L \tag{17}$$

Where, m_c is condensate water flow, kg/s; L is latent heat of water vapor, kJ/kg.

In the process of heat and mass transfer, the mass and temperature of water droplets are increased, so that heating capacity of droplets is as follows:

$$Q = Q_{\mathrm{h}} + Q_{\mathrm{c}} = \pi d_{\mathrm{w}} \lambda_{\alpha} (T_{\infty} - T_{\mathrm{s}})(2 + 0.6\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}) + m_{\mathrm{c}} L \tag{18}$$

The change rate of droplet temperature is as follows:

$$\frac{dT_{\mathrm{s}}}{d\tau} = \frac{Q}{c_{\mathrm{p}} m_{\mathrm{w}}} \tag{19}$$

Where, c_p is specific heat of water at constant pressure, kJ/（kg.℃）.

According to the conservation of energy, the amount of heat obtained by water droplets and released by the flue gas should be equal. The heat released by flue gas includes sensible heat and condensation heat of the water vapor. The condensation heat of water vapor is Q_c, and the sensible heat Q_h is as follows:

$$Q_{\mathrm{h}} = \pi d_{\mathrm{w}} \lambda_{\alpha} (T_{\infty} - T_{\mathrm{s}})(2 + 0.6\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}) = \frac{c_{\mathrm{p},\alpha} m_{\mathrm{f}} dt_{\infty}}{d\tau} \tag{20}$$

$$m_{\mathrm{f}} = \frac{m_{\mathrm{w}}}{k} \tag{21}$$

Where, m_f is flue-gas mass flow, kg/s; k is water-gas ratio, which is mass flow ratio of water to flue gas.

The relationship between m_c and m_z should be paid attention to. When "T_∞-dt_∞" is above the dew point temperature of flue gas, the mass transfer can be considered as diffusive mass transfer, and m_c is m_z. When "T_∞-dt_∞" is below the dew point temperature of flue gas, mass transfer not only includes diffusive mass transfer, but may also mass transfer due to the condensation of water vapor. So the amount of water vapor remaining in the flue gas (residual water vapor) should be calculated according to the accumulated diffusive mass transfer. Then, according to the flue-gas temperature of "T_∞-dt_∞", the amount of saturated water vapor in the flue gas is determined. When the amount of residual water vapor is greater than saturated water vapor, the condensation of water vapor will occur, and the amount of condensed water vapor will be added to the calculation.

In the process of heat and mass transfer, various physical properties and droplets sizes are changing, which are correlated with the nonlinear flue-gas temperature or droplets temperature. If they are regarded as variables, it is difficult to get a theoretical solution. And if they are regarded as fixed values, the calculation results will be inaccurate. In order to ensure the accuracy of calculation, numerical analysis method is used.

According to motion characteristics of water droplets, movement time of water droplets is divided into several sections at $\triangle\tau$ intervals. The infinitesimal equations are established for each section. For a section, as initial parameters of water droplets and flue gas are known, the heat transfer and mass transfer in the section can be calculated, and the parameters of calculated water droplets and flue gas are taken as the initial conditions of next section. Water droplets and flue gas can flow downstream, upstream, and across.

It is assumed that size of the water droplet is 0.5mm, initial flue-gas temperature is 70℃, inlet temperature of low temperature is 20℃, water-gas ratio is 5, heat exchanger height is 1.5m, and water droplets fall perpendicular to flue gas at a speed of 15m/s.， Based on these, the variation of exhaust temperature after heat exchanger with the change of parameters is studied.

（1）Droplet size

Droplet size ranges from 0.3mm to 1.0mm. As shown in Fig.5, the flue-gas temperature decreases with decreasing droplet size. This is because in the case of constant mass flow of water, reducing droplet size is equivalent to increasing the contact area. Moreover, the droplet size decreases, causing water droplets to slow down more quickly. The contact time between water droplets and flue gas increases when the heat exchanger height is constant. When droplet size decreases to a certain extent (0.3mm), the exhaust temperature can even be reduced to the water inlet temperature of 20℃. At this point, it is meaningless to reduce the droplet size to recover the waste heat.

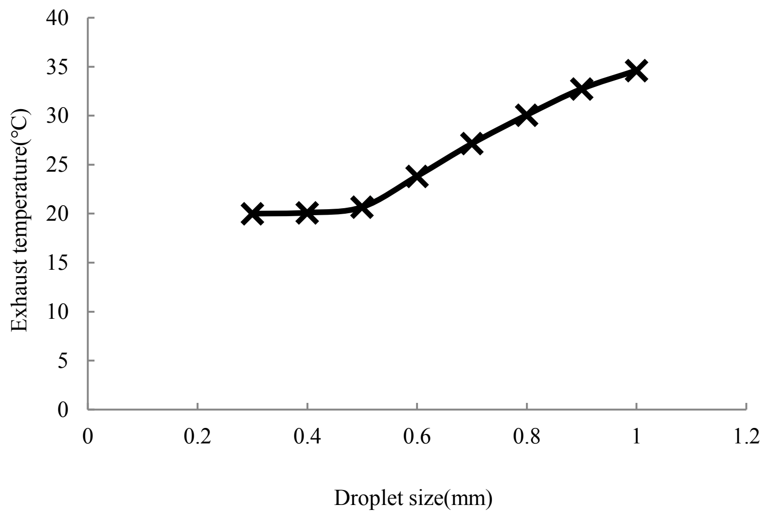

Fig. 5. The figure shows relationship between droplet size and exhaust gas temperature.

（2）Water-gas ratio

Water-gas ratio ranges from 1 to 10. As shown in Fig.6, the exhaust temperature decreases with the increase of water-gas ratio, that is because increasing water-gas ratio is equivalent to increasing heat exchange contact area. When water-gas ratio increases to 8, exhaust temperature is reduced to 20℃, and increasing water-gas ratio will not improve heat transfer effect.

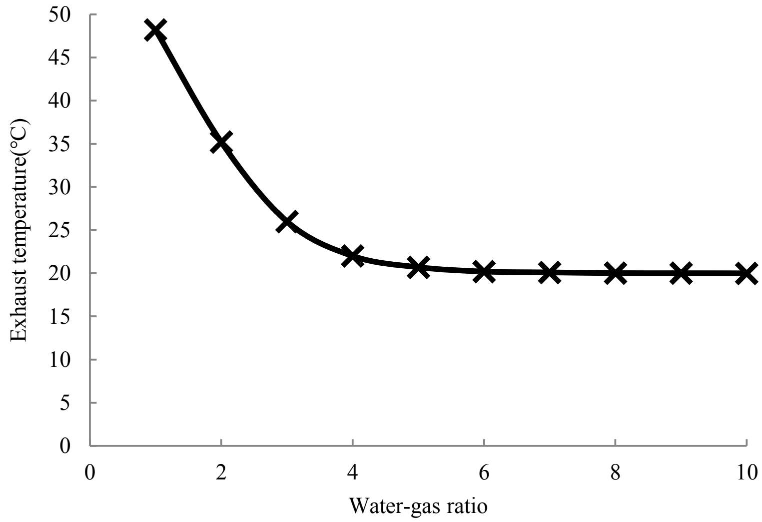

Fig. 6. The figure shows the relationship between water-gas ratio and exhaust temperature.

（3）Heat exchanger height

The height of the heat exchanger ranges from 0.5m to 2.0m. As shown in Figure 7, increasing the height of the heat exchanger equals to increasing the contact time between the flue gas and water droplets. When the height of the heat exchanger is increased to 2m, the exhaust gas temperature is about 20°C.

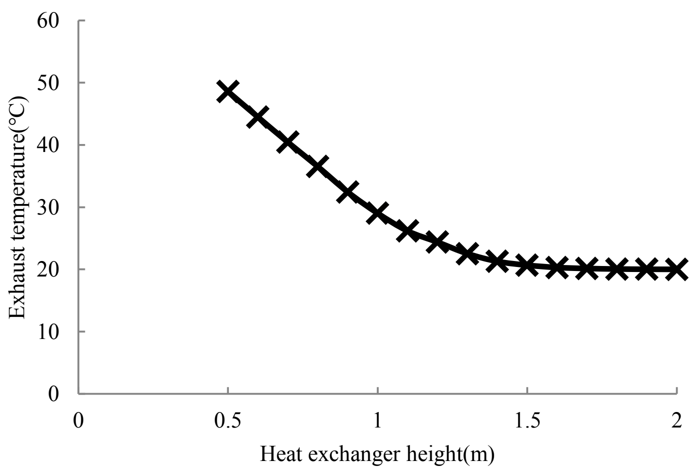

Fig. 7. The figure shows the relationship between height of heat exchanger and exhaust temperature.

（4）Initial water droplet velocity

Initial water droplet velocity ranges from 5m/s to 30m/s. As shown in Fig.8, the exhaust temperature increases with the initial velocity of water droplets. Initial water droplet velocity will increase convective heat transfer coefficient of flue gas and water, but will decrease the contact time.

The higher the initial water droplet velocity is, the worse the heat transfer effect is, and the initial kinetic energy of droplet is increased, which can increase the power consumption of water pump. Therefore, the initial water droplet velocity should not be too high, but increasing initial water droplet velocity can prevent low-size droplets from being removed by high velocity flue gas.

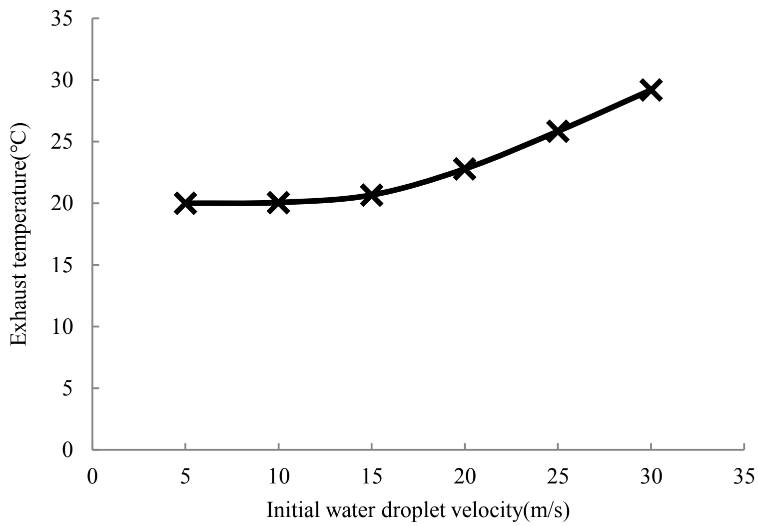

Fig. 8. The figure shows the relationship between initial water droplet velocity and exhaust temperature.

（5）Initial flue-gas temperature

Initial flue-gas temperature ranges from 50℃ to 100℃. As shown in Fig.9, exhaust temperature varies little with increasing initial flue-gas temperature. When initial flue-gas temperature increases from 50℃ to 100℃, the exhaust temperature increases less than 1℃. This is because increasing flue-gas temperature does not reduce the contact time and area between flue gas and water droplets.

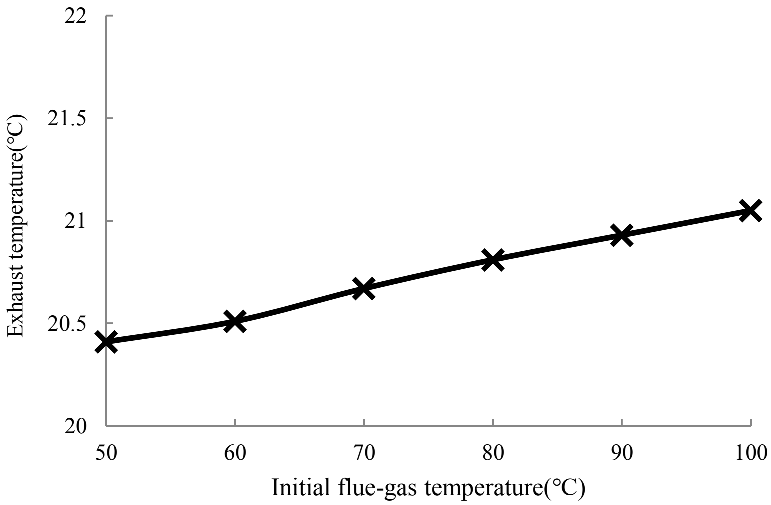

Fig. 9. The figure shows the relationship between initial flue-gas temperature and exhaust temperature.

（6）Initial water temperature

Initial water temperature ranges from 10°C to 40°C. As shown in Fig.10, exhaust temperature increases approximately linearly with initial water temperature, and initial water temperature is the limiting temperature that flue gas can be cooled to.

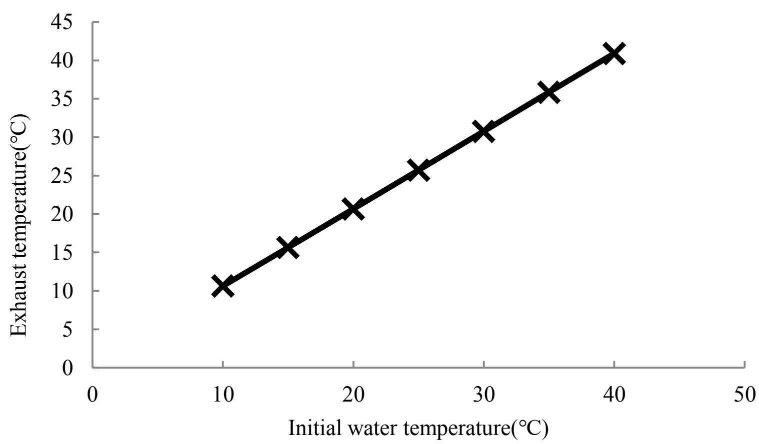

Fig. 10. The figure shows the relationship between initial water temperature and exhaust temperature.

The contact area and contact time of flue gas and water droplets have greater influence on heat transfer effect. Therefore, the size, water-gas ratio and height of heat exchanger are the main factors affecting the heat transfer. The initial water temperature is the limiting factor affecting the exhaust temperature, which determines the cooling limit of the exhaust temperature.

4 Experimental analysis of direct contact heat transfer

There are three 29MW hot-water boilers and a 14MW hot-water boiler in a gas-fired boiler room in Beijing. The temperature of flue gas entering the chimney is generally 60-80℃.

In this project, an absorption heat pump and direct contact heat exchangers are added, which is used to recover flue-gas waste heat of a 29MW boiler. The absorption heat pump generates low-temperature water by using gas for driving to recover flue-gas waste heat and heats the return water of heat supply network. In heat exchangers, flue gas exchanges heat with low-temperature water to release sensible heat and latent heat, and is discharged to the atmosphere through the chimney. The low-temperature water is pumped into absorption heat pump after heating in direct contact heat exchangers.

There are three direct contact heat exchangers, in which the size of a single heat exchanger (length × width × height) is 2m×2.45m×1.5m. Water droplets can be regarded as free fall motion with initial velocity 15m/s. According to the heat exchanger height 1.5m, it can be calculated that time of water droplets from the outlet of the nozzle to the surface of the water is 0.28s. The flue gas moves along the length direction of the heat exchanger with 2m/s, and the time is 3s through the heat exchanger.

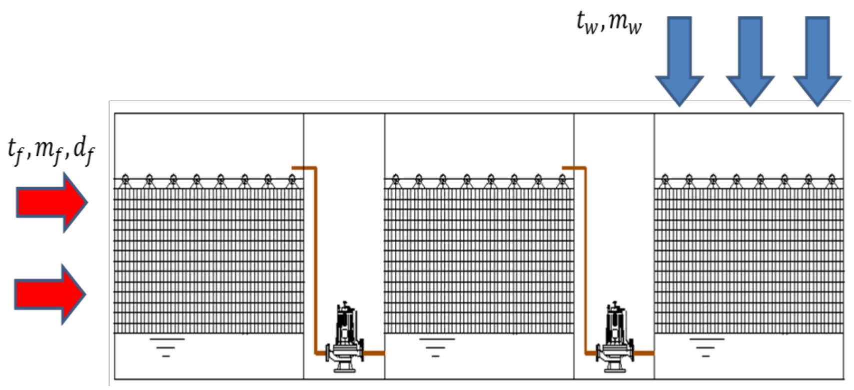

Fig. 11. The figure shows the model of direct contact heat exchanger.

The mesh is divided according to the movement time, and the time interval is 0.02s. In the vertical direction, it can be divided into 14 sections, where the outlet temperature of water in the first section is equal to the inlet temperature of water in the second section, and so on. It can be divided into 150 sections in the length direction, where the outlet temperature of flue gas in the first section is equal to the inlet temperature of flue gas in the second section, and so on. The mesh is shown in Fig.11.

After the flue gas passes through the left heat exchanger, the flue-gas temperature of each micro segment is mixed as the initial temperature of the middle heat exchanger, and so on. The water drop passes along the right heat exchanger and flows into the pool, and mixing temperature is used as the initial temperature of the middle heat exchanger, and so on.

Fig.12- Fig.13 compares simulation results with experimental results:

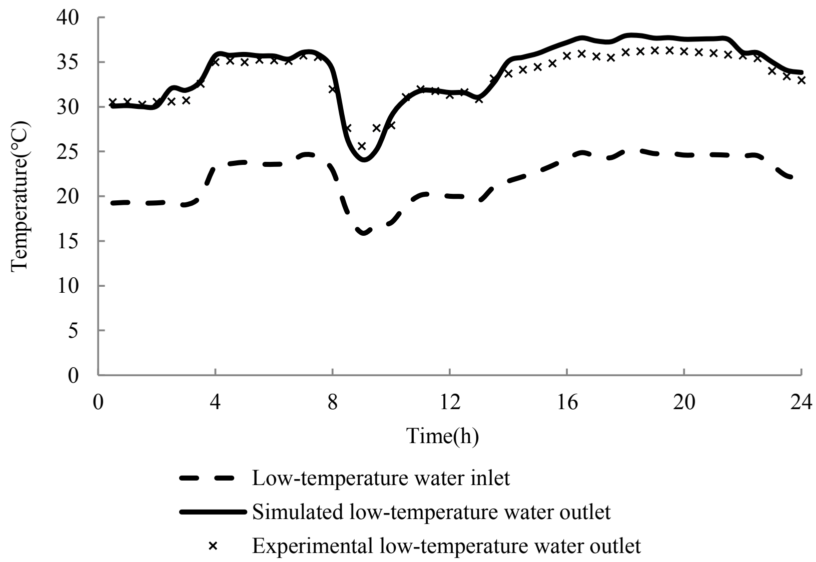

Fig. 12. The figure shows the comparison between simulation and experimental of water outlet.

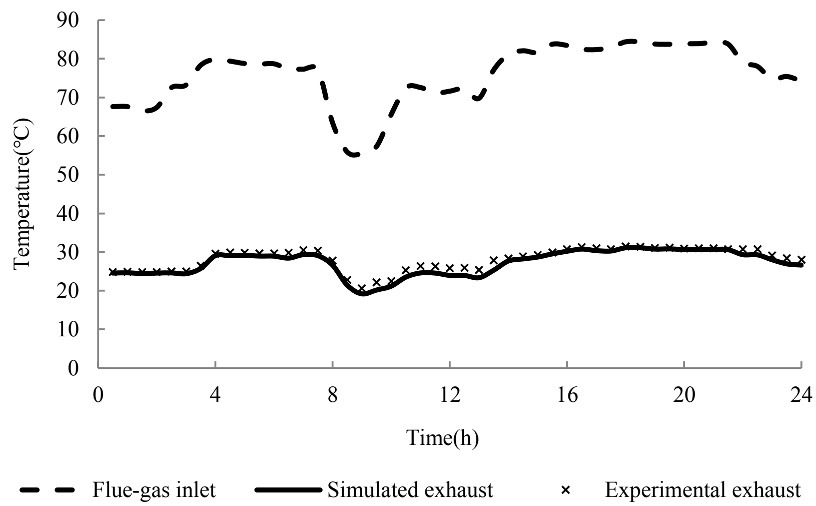

Fig. 13. The figure shows the comparison between simulation and experimental of flue-gas outlet.

By comparison, the error of water side and flue-gas side is within 2°C, and the average error is 0.98°C and 0.95°C, respectively. The main reasons for the errors are that：

1. The sizes of water droplets are in normal distribution, not a constant；
2. The water droplets do not drop completely vertically, but fall at a certain angle；
3. In the process of water droping, collision is inevitable.

All the above problems are simplified in this model, and further research is needed.

5 Conclusion and discussion

In this paper, the direct contact heat transfer of flue gas and water has been analyzed and validated by experiments. The following conclusions are obtained:

（1）The motion characteristics of water droplets are analyzed theoretically, and the numerical solutions of velocity distribution of water droplets are obtained. The larger the droplet size, the higher the settling velocity.

（2）Heat-exchange characteristics of flue gas and water droplets have been analyzed, and the main factors have been studied. The results show that the water droplet size, water-gas ratio and heat exchanger height are the main factors influencing heat transfer.

（3）The direct contact heat exchangers of flue-gas waste heat recovery project in a gas-fired boiler were measured and the accuracy of theoretical calculation results has been verified.

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