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Study on the performance of plate-fin heat exchanger for fresh air unit in hot summer and cold winter area

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Abstract: *In order to solve the problem of high energy consumption of fresh air in the operation of air-conditioning system, the heat and mass exchange efficiency of total heat exchange core is studied in this paper. By establishing the performance calculation mathematical model of the total heat exchanger, the effects of the change of the properties of thin film and fin, the shape of flow passage, the single layer height of heat exchanger core, the shape size of heat exchanger core and the face wind speed on the heat exchange efficiency and resistance of heat exchanger are studied theoretically.The results show that when the wing distance decreases from 8mm to 2.3mm, the total heat exchange efficiency increases by 5.1%; when the single layer height increases from 1.5mm to 2.5mm, the total heat exchange efficiency decreases by 13.3%; when the face-to-face wind speed of the core increases, the unit wind speed of the total heat exchange efficiency decreases by 12.88%.*

Keywords: plate-fin heat exchanger, total heat recovery, fresh air energy saving, heat and mass transfer performance

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I. INTRODUCTION

With the rapid development of economy, people have higher and higher requirements for indoor environment. In order to improve indoor air quality, it is necessary to ensure indoor fresh air exchange, but this will lead to an increase in air conditioning energy consumption. Data show that fresh air energy consumption usually accounts for 15% of air conditioning energy consumption. 24% [1]. In order to reduce the energy consumption of fresh air during air conditioning operation, it is of practical significance to study the new exhaust air heat recovery technology. There are many new exhaust heat recovery technologies, including plate sensible heat exchanger, heat pipe heat exchanger, intermediate cold medium sensible heat exchanger, plate-fin total heat exchanger, rotary wheel total heat exchanger, heat pump heat recovery and solution total heat recovery device [2]. This paper mainly studies the performance of full-hot plate-fin heat exchanger in small heat recovery fresh air unit which is more and more widely used.

In order to improve the heat transfer performance of plate-fin heat exchanger and reduce the energy consumption of fresh air, many scholars have done a lot of research on its calorific value exchange model and performance influencing factors. Liu Yanwen et al. [3] established a model of quasi-countercurrent total heat exchanger and studied the optimal performance of the total heat exchange core. LiZhiZhang [4] proposed a quasi-countercurrent parallel plate total heat recovery device to simulate the heat and mass transfer efficiency. Xu Baiping et al. [5] developed triangular wing fin and spiral spoiler, and experimentally studied their effects on fluid resistance and heat transfer enhancement. Wang Ying et al. [6] considered that the energy consumption of fan caused by the increase of secondary air flow should be comprehensively considered by studying the influence of secondary / primary air volume ratio on the heat transfer performance of plate-fin heat exchanger. Jin Yangfan et al. [7] compared the heat transfer performance of different water distribution modes of plate-fin indirect evaporative cooler, such as water distribution and lower water distribution, intermittence and continuity, and put forward a combination method of upper + part intermittent spray water distribution.

In this chapter, firstly, through the theoretical analysis of the heat and mass transfer mechanism of plate-fin heat exchanger, the calculation formula of sensible heat exchange efficiency is obtained by using heat transfer element method. then the formula for calculating the latent heat exchange efficiency is obtained from the dimensionless analogy of mass transfer and heat transfer. Plate-fin heat exchanger is a total heat exchanger, so the heat and moisture exchange of plate-fin heat exchanger is quantitatively coupled, and the calculation formula of total heat exchange efficiency is obtained. At the same time, the resistance of the heat exchanger core is also an important factor affecting the energy saving of the plate-fin heat exchanger. The calculation formula of the heat exchanger core resistance is obtained with reference to the relevant literature.

II. METHODS

2.1 Mathematical analysis of heat transfer process

Assuming that the convective heat transfer coefficient of the membrane surface and the fin surface is h, then the heat transfer to the fluid through the membrane is shown in the formula (2.1).

$$Q_1=hF_1(t_w-T) \quad (2.1)$$

H is theconvection heat transfer coefficient, W / (m^2 • ℃) ;F$_1$ is theprimary heat transfer area,;m^{2}is the average surface temperature of the membrane, ℃;Tis theAverage fluid temperature, ℃.

The mean temperature tm of the fin surface is lower than the root of the fin, which is below the membrane surface. In order to facilitate the heat transfer calculation, the heat transfer of the secondary heat transfer surface can be transformed as follows:

$$Q_2=h\eta_f F_2(t_w-T) \quad (2.2)$$

η_f is the fin efficiency.

The heat transfer of the two fluids arranged in the middle of the plate-fin total heat exchange core is the sum of the heat transfer on the primary surface and the secondary surface, in which there is only sensible heat transfer on the secondary heat transfer surface, while there is both sensible heat transfer and latent heat transfer on the primary heat transfer surface. then the sensible heat transfer of the core is shown in formulas (2.3) and (2.4).

$$Q_s=Q_1+Q_2=hF_1(t_w-T)+h\eta_f F_2(t_w-T)=hF_0\eta_0(t_w-T) \quad (2.3)$$

$$\eta_0=\frac{F_1+\eta_f F_2}{F_0} \quad (2.4)$$

Q_s is the heat transfer core shows heat exchange; η_0 is the surface efficiency ;F$_0$is the sum of primary heat transfer area and secondary heat exchange area, m^2.

When the primary heat exchange separates the hot, hot and cold fluid, and the convection heat transfer coefficient on both sides is considered equal, and the total heat transfer area is equal, there are:

The amount of heat transfer:

$$\begin{aligned} Q_s&=hF_0\eta_0(T_h-T_{w1})=hF_0\eta_0(T_{w2}-T_c)\\ &=\lambda_f F_1(T_{w1}-T_{w2})/\sigma_b-Q_L \quad (2.5)\end{aligned}$$

$$\begin{aligned} Q_s&=\frac{1}{\frac{2}{h\eta_0}+\frac{\sigma_b F_0}{\lambda_f F_1}}\left[1-\frac{Q_L\sigma_b}{\lambda_f F_1(T_h-T_c)}\right]F_0(T_h-T_c)\\ &=\frac{1}{\frac{2}{h\eta_0}+\frac{\sigma_b F_0}{\lambda_f F_1}}\left(1-\frac{m_w F_1 r_L\sigma_b}{\lambda_f F_1\Delta T_m}\right)F_0\Delta T_m \quad (2.6)\end{aligned}$$

The total apparent heat transfer coefficient is:

$$K=\frac{1}{\frac{2}{h\eta_0}+\frac{\sigma_b F_0}{\lambda_f F_1}}\left(1-\frac{m_w r_L\sigma_b}{\lambda_f\Delta T_m}\right) \quad (2.7)$$

The convective heat transfer coefficient can be obtained from the formula (2.8):

$$h=\frac{Nu\lambda}{D_e} \quad (2.8)$$

H is the convective heat transfer coefficient, W/(m^2℃); λ is the thermal conductivity of fluid, W/(m ℃);Nu is the nusselt number;De is the equivalent diameter of flow channel, m.

The expression of the heat transfer unit is expressed by the equation (2.9):

$$NTU=\frac{KF_0}{(mC_p)_{\min}} \quad (2.9)$$

For the straight cross flow in which neither of the two fluids is mixed, and the flow rate of the two streams is basically the same, the relationship between the sensible heat exchange efficiency and the number of heat transfer units is expressed as:

$$\varepsilon_x = 1 - \exp\left\{ (\frac{m_{\max}}{m_{\min}}) \cdot NTU^{0.22} \cdot \left[EXP\left(-\frac{m_{\min}}{m_{\max}} \cdot NTU^{0.78} \right) - 1 \right] \right\} \quad (2.10)$$

$m_{\min}$ is the minimum fluid mass in hot and cold fluids;$m_{\min}$ is the maximum fluid mass in kg/s- hot and cold fluids, kg/s.

2.2 Mathematical analysis of mass transfer process

Because heat transfer is similar to mass transfer, the expression of mass transfer is analogous to that of heat transfer:

$$m_w = K_d(d_1 - d_2) \quad (2.11)$$

The total mass transfer coefficient K_d is shown in formula (2.12):

$$K_d = \frac{1}{\frac{1}{h_{d_1}} + \gamma_m + \frac{1}{h_{d_2}}} \quad (2.12)$$

d_1 is the moisture content of fluid 1;d_2 is the moisture content of kg/kg dry air-fluid 2, kg/kg dry air;h_{d1} is the convective mass transfer coefficient between fluid 1 and film surface, kg/ (m^2 • s);h_{d2} is the convective mass transfer coefficient between fluid 2 and film surface, kg/ (m^2 • s).

The diffusion resistance of water molecules in heat transfer materials can be expressed by formulas (2.13) and (2.14):

$$\gamma_m = \frac{\delta}{D_{wm}} \Psi \quad (2.13)$$

$$\Psi = \frac{10^6 \left[(1-C)\phi_1 + C \right] \cdot \left[(1-C)\phi_2 + C \right]}{e^{(5294/T)} \omega_{\max} C} \quad (2.14)$$

δ isthe thickness of the heat exchange material, m; D_{wm} isthediffusion coefficient of moisture in the heat exchange material,,kg/(m • s); Ψ isthewet resistance coefficient, generally between 0.12-0.70; C istherepresents the adsorption types of different film materials; several commonly used film materials are：C for Si02 gel = 1; C=0.1 for molecular filter and C=10 for polymer; ϕ_1 istheRelative humidity of the fluid1,%; ϕ_2 istherelative humidity of the fluid 2，%; $\omega_{\max}$ isthefilm maximum water capacity，kg/kg;TistheThe Kelvin temperature of the film, K.

Due to the simultaneous existence of heat and mass transfer, the correlation between the plate flow and the flow in the tube can be obtained from (2.15):

$$\frac{h}{h_d} = c_p \rho \left(\frac{Sc}{\Pr} \right)^{2/3} = c_p \rho Le^{2/3} \quad (2.15)$$

ρ is the density of moist air ， kg/m3; Le is the Lewis number.

The latent heat exchange efficiency is shown in formula (2.16):

$$\varepsilon_d = 1 - \exp\left\{ \left(\frac{m_{\max}}{m_{\min}} \right) \cdot NTU_d^{0.22} \cdot \left[EXP\left(-\frac{m_{\min}}{m_{\max}} \cdot NTU_d^{0.78} \right) - 1 \right] \right\}^{[51]} \quad (2.16)$$

2.2 Total heat exchange efficiency and core resistance

Through the basic formulas of sensible heat efficiency, latent heat efficiency and total heat exchange efficiency, coupled with the calculation formula of enthalpy, the total heat exchange efficiency expressed by sensible heat efficiency and latent heat efficiency is deduced.

$$\varepsilon_h = \frac{A\varepsilon_x + B\varepsilon_d}{A+B} \quad (2.17)$$

$$A = \frac{1.005}{(d_1 - d_2)} \quad (2.18)$$

$$B = \frac{2500}{(t_1 - t_2)} \quad (2.19)$$

ε_h is the full heat exchange efficiency; A is the Show-up heat exchange efficiency weight coefficient; B is the

The latent heat exchange efficiency weight coefficient; t_1 is the Dry-bulb temperature of the fluid 1，℃;t_2 is the Dry-bulb temperature of the fluid 2，℃.

A fully developed laminar flow solution can be applied. Pressure loss is usually calculated by using the formula (2.20):

$$\Delta P = \left(\frac{4 f_I L}{R_e D_e} + K(\infty) \right) \frac{g_m^{\ 2}}{2\rho} \quad (2.20)$$

f_I is the stream resistance factor; L is the stream length，m; $K(\infty)$ is the coefficient of shock resistance; g_m is the free circulation section of air mass flow per unit area，kg/(m2 • s); R_e is the Reynolds number of the fluid in the flow channel.

III. RESULTS AND DISCUSSION

3.1 Effect of film and fin properties on the performance of heat exchanger

The changing trend of heat transfer efficiency is shown in the figure.

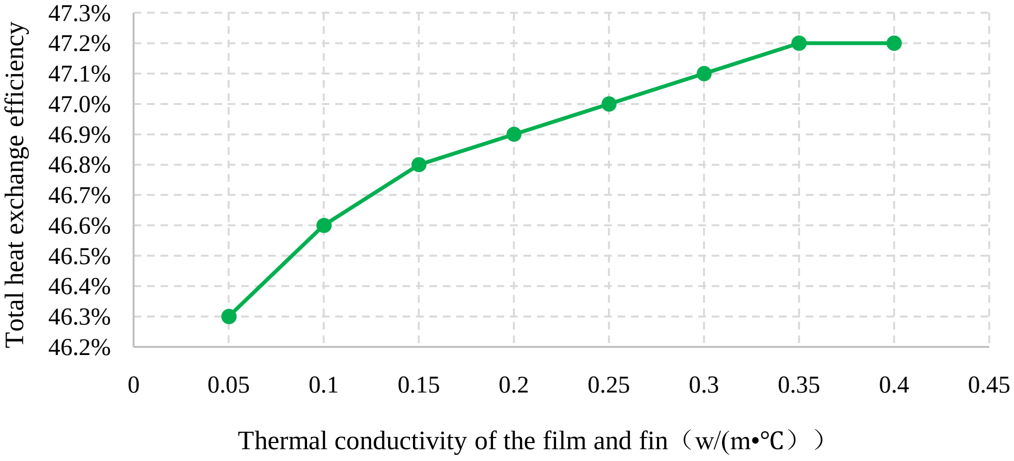

Figure 1:Effect of thermal conductivity of thin film and fin on total heat exchange efficiency of heat exchanger

It can be seen that with the increase of the thermal conductivity of the thin film and fins, the total heat exchange efficiency of the heat exchanger increases, but the increasing rate gradually slows down to a certain value, because the increase of the thermal conductivity increases the heat transfer coefficient, resulting in the increase of the number of heat transfer units, which increases the sensible heat transfer efficiency, but the efficiency can not increase all the time, and eventually tends to a certain value, if you need to continue to improve the efficiency. Other factors affecting the improvement of the exchange core should be considered.

The changing trend of heat transfer efficiency is shown in figure 2.

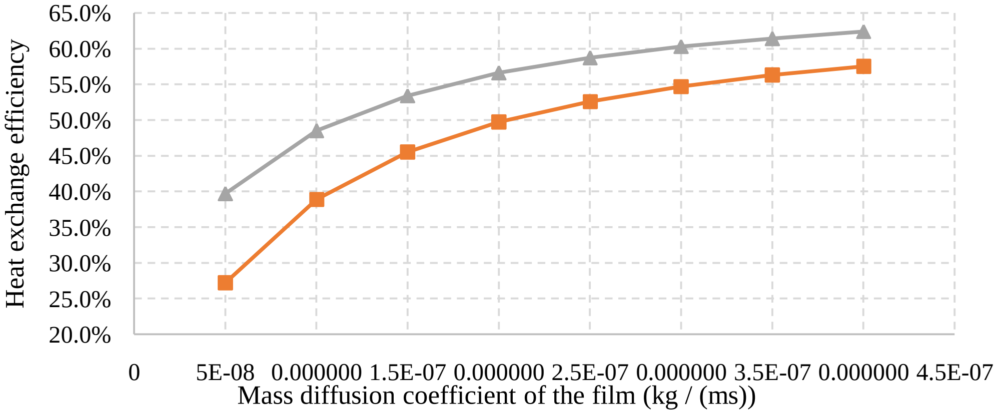

Figure 2 Effect of mass diffusion coefficient on full and latent heat transfer efficiency

The variation trend of latent heat and total heat exchange efficiency with the film mass diffusion coefficient is shown in figure 2. It can be seen that the latent heat efficiency and total heat efficiency of the heat exchanger increase with the increase of the film mass diffusion coefficient. The increase of mass diffusion coefficient increases the mass transfer coefficient, which leads to the increase of the number of mass transfer units (NTU), which increases the latent heat transfer efficiency, but the efficiency can not increase all the time, and eventually tends to a certain value.

3.2 Effect of flow Channel shape on the performance of Heat Exchanger

The channel shape selected in this study is square channel, rectangular channel with wing height ratio of 1 stroke 2, equilateral triangle channel, sinusoidal channel with wing height ratio of 0.866, and triangle channel with wing height ratio of 1 stroke 2. Under the same other operating conditions, the heat transfer efficiency is shown in figure 3.

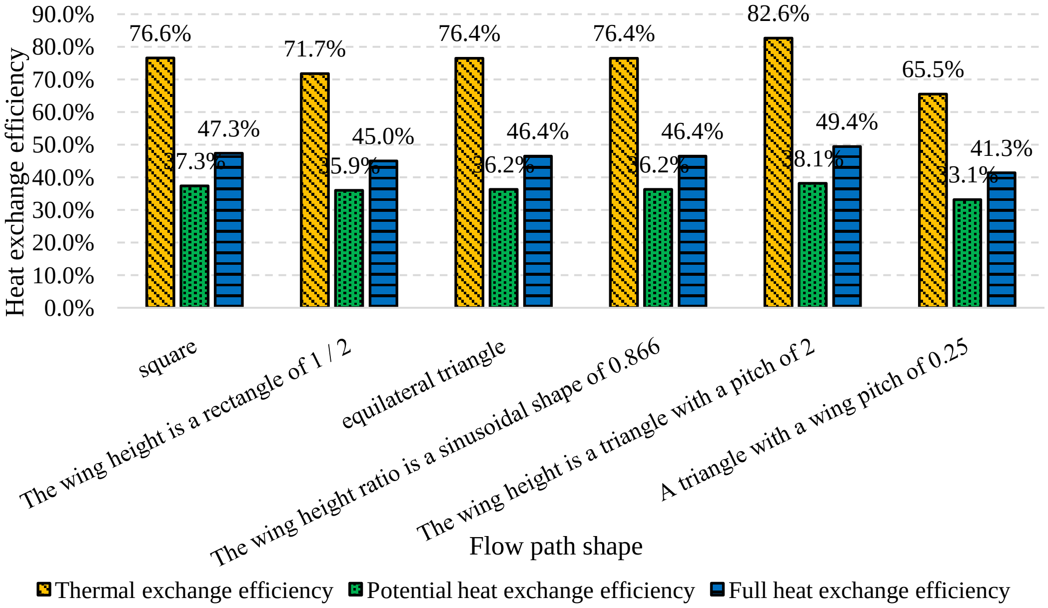

Figure 3:Effect of flow channel shape on heat exchange efficiency

In figure 3, the heat transfer efficiency of the triangular channel with the wing height ratio of 0.25 is the lowest, while the heat transfer efficiency of the triangle channel with the wing height ratio of 2 is the highest. Figure 3 also shows that the heat exchange efficiency of the equilateral triangular channel is equal to that of the sinusoidal channel with a fin height ratio of 0.866, because in the process of model calculation, the sinusoidal channel with a wing height ratio of 0.866 is approximately calculated as a triangle, so its heat transfer area is the same as that of an equilateral triangle.

3.3 Effect of single layer height on the performance of heat exchanger

In the case of a certain size of the heat exchanger core, the change of the height of the single layer may lead to the change of the number of channels, thus changing the total heat transfer area and heat exchange efficiency. Taking the equilateral triangular flow channel as the research object, the influence of single layer height on the performance of heat exchanger is discussed by changing its single layer height. Under the same other working conditions, the calculation results of different single-layer heights of triangular flow channels are shown in figure 4.

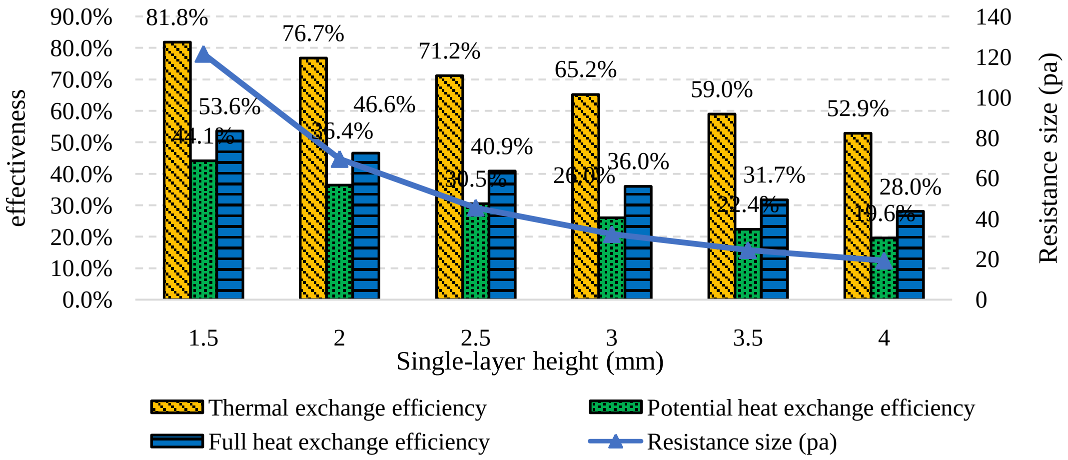

Figure 4:Effect of single layer height on the performance of heat exchanger

With the increase of single layer height, the heat exchange efficiency and core resistance decreased. When the single layer height increased from 1.5mm to 2.5mm, the sensible heat exchange efficiency decreased by 10.6%, the latent heat exchange efficiency decreased by 13.6%, the total heat exchange efficiency decreased by 13.3%, and the core resistance decreased to nearly three times. from the data analysis, the change of single layer height has a great influence on the latent heat exchange efficiency. This is because the increase of single layer height reduces the number of flow channels, the total heat transfer area, the fin efficiency, and the convective heat transfer coefficient and mass transfer, so the sensible heat transfer efficiency, latent heat exchange efficiency and total heat efficiency of the core decrease. When the layer height increases from 2.5mm to 4mm, the sensible heat exchange efficiency, latent heat exchange efficiency and total heat exchange efficiency decrease by 18.3%, 10.9% and 12.9%, respectively. The core resistance is reduced by 26.2pa. Compared with the data from single layer height from 1.5mm to 2.5mm, it is found that the change rate of sensible heat exchange efficiency increases by 1.6%, the change rate of latent heat exchange efficiency decreases by 7.3%, the change rate of total heat exchange efficiency decreases by 4.7%, and the resistance change rate decreases by 58.6%. It can be seen that with the increase of layer height, the sensible heat exchange efficiency increases gradually. While others are gradually affected by the height of the floor. To sum up, when designing the heat exchanger core, we should choose the appropriate single layer height as far as possible, so that the efficiency is higher and the core resistance is lower.

3.4 Effect of single layer height on the performance of heat exchanger

The increase of the frontal wind speed may increase the degree of turbulence in the flow channel, gradually destroy the laminar boundary layer, and increase the convective heat transfer coefficient, but the increase of the frontal wind speed leads to the decrease of the residence time of the fluid in the flow channel of the heat exchanger core, that is, the heat and mass exchange time of the hot and cold fluid is shortened, the heat exchange efficiency decreases, and the resistance of the heat exchanger core increases rapidly. In this section, under the condition that the size of the heat exchanger core remains unchanged, only the frontal wind speed is changed to discuss the change of heat exchange efficiency and resistance of the heat exchanger core. Under the same other working conditions, the model calculation results of different face-to-face wind speeds are shown in figure 5.

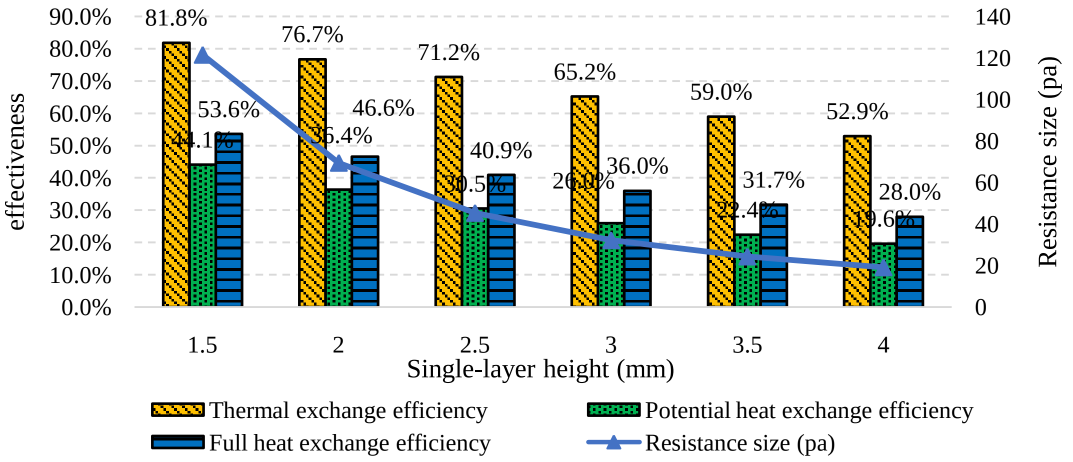

Figure 5:Effect of single layer height on the performance of heat exchanger

Figure 5 shows that with the increase of the face-to-face wind speed of the heat exchanger core, the heat transfer efficiency decreases gradually, and the resistance of the heat exchange core also increases. When the face-to-face wind speed changes from 0.25m/s to 1.5m/s, the sensible heat exchange efficiency decreases from 85.1% to 69%. At the same time, the change of sensible heat exchange efficiency is divided by the change of face wind speed. The unit wind speed decrease rate of sensible heat efficiency of core is 12.8%. Similarly, the unit wind speed decrease rate of latent heat exchange efficiency is 30.2%, the unit wind speed decrease rate of total heat exchange efficiency is 25.8%, and the unit wind speed growth rate of core resistance is 92.88pa/ (m). From this, it can be seen that the change of wind speed has the greatest influence on latent heat exchange efficiency, and the increase of wind speed also makes the resistance of core increase rapidly. This will reduce the heat recovery of the total heat exchanger and greatly increase the energy consumption of the fan, which may eventually become an energy-consuming equipment rather than an energy-saving equipment. This is because when the size of the heat exchanger core is fixed, the heat transfer area does not change, but the number of heat transfer units decreases, which leads to the decrease of heat transfer efficiency.

IV. CONCLUSIONS

The effects of the properties of thin film and fin, the shape of flow channel, the single layer height of heat exchanger core, the shape size of heat exchanger core and the face wind speed on the heat exchange efficiency and resistance of heat exchanger are studied theoretically. under the calculation condition, the following conclusions can be obtained:

(1) the sensible heat exchange efficiency and total heat exchange efficiency of the heat exchanger core increase with the increase of the thermal conductivity of thin film and fin. But the latent heat exchange efficiency has not changed. The increase of the mass diffusion coefficient of the film increases the latent heat exchange efficiency and total heat exchange efficiency of the heat exchanger core, but the sensible heat exchange efficiency does not change.

(2) Under the same single layer height, the total heat exchange efficiency of the triangular channel with the wing height ratio of 0.25 is the lowest of 41.3%, while the heat transfer efficiency of the triangle channel with the wing height ratio of 2 is the highest of 49.4%. The total heat exchange efficiency of the square channel and equilateral triangular channel with the same height of the single layer is 46.4% and 47.3% respectively, and the resistance of the corresponding core is 69.1pa and 69.3pa, respectively.

(3) Properly reducing the fin distance will increase the heat exchange efficiency and increase the core resistance less, but when the fin distance is too small, the heat exchange efficiency of the heat exchanger increases little, but the resistance increases greatly.

(4) The heat exchange efficiency and core resistance decrease with the increase of layer height. at the same time, the sensible heat exchange efficiency increases and the others decrease with the increase of layer height.

(5) The change of wind speed has the greatest influence on the latent heat exchange efficiency, and the increase of wind speed makes the resistance of the core increase rapidly, which will lead to the decrease of heat recovery of the total heat exchanger.

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