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Thermodynamic Performance Analysis of New Paper Machine Air Hood Heat Recovery System

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ABSTRACT

In this paper, a new heat recovery system of hot air hood of paper machine is proposed, the thermodynamic model of the system is established, and the effect of different thermal parameters on the heat recovery efficiency of the system is studied. The results indicate that both the recovered energy and the proportion of exhaust air passing through the latent heat exchanger attenuate as fresh air temperature increase and fresh air moisture content decrease. The system heat recovery increasing with rising of exhaust temperature. Exhaust temperature and exhaust relative humidity have different effects on sensible and latent heat recovery. The maximum value of proportion of exhaust air passing through latent heat exchanger appears when the exhaust relative humidity is 35.8%. Overall, the fresh air temperature and the exhaust relative humidity have great influence on the heat recovery efficiency.

Keywords: *Dryer section, heat recovery, latent heat exchanger, numerical simulation*

1. Introduction

The paper industry is one of the important basic raw material industries of the national economy,[1] but also the fourth largest energy-consuming industry in the world. As the production of paper and cardboard continues to increase, the energy consumption of the paper industry will also increase, and it is expected that by 2050, the total energy consumption of the paper industry will increase to 386-434 million tons of standard coal.[2] In the entire paper-making process, the drying department is the largest energy-consuming process, and its energy consumption accounts for

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about 65% of the entire paper-making process.[3,4] Therefore, how to reduce the energy consumption of the drying department is not only the key to energy saving of the paper machine, but also the key to reducing the energy consumption of the whole paper mill.

For the sheet drying section, the steam entering the drying cylinder condenses and exerts heat inside the cylinder, and the released heat is transferred to the wet paper web covering the outer surface of the drying cylinder, causing the moisture in it to evaporate. The heat quality of the steam evaporated from the wet paper web is still high, and if it is discharged directly, it will cause a large energy loss.[5-7] Therefore, a hot air hood is installed outside the dryer set of the paper machine.[8] The hot air hood encloses the entire drying section, and the high-quality steam evaporated from the wet paper web is used to preheat the air subsequently fed into the hood through the heat exchange system, while the lower quality steam is used to heat the process water required for the operation of the paper machine.[9,10] The external drying process undergoes two heat exchanges to recover the large amount of steam generated by the internal drying, thus reducing the energy consumption of the entire drying section. The hot air hoods include open hoods, semi-closed hoods and hermetic gas hoods. Among them, the high-humidity closed gas hood can form a relatively closed space outside the drying cylinder, so that the temperature and humidity therein remain relatively stable, reducing the ineffective heat loss on the surface of the drying cylinder and saving steam consumption, while the temperature and moisture content of the exhaust air is higher, creating favorable conditions for exhaust air heat recovery.[11,12]

The existing literature on the hermetic gas hood is relatively small, mainly focusing on hood temperature and humidity measurement,[13] hood zero control,[14] hood ventilation system control[15] and the influence of hood air supply temperature,[16] and less research on the thermodynamic analysis of hood heat recovery system and heat recovery energy efficiency. The hot air in the enclosed hot air hood is mainly obtained from the fresh air through the heat recovery system, which absorbs the heat released from the exhaust air of the hood. Therefore, the thermodynamic parameters of the fresh air and the exhaust air of the hood will have a certain influence on the heat recovery system of the hot air hood. Therefore, this paper proposes a new hot air hood heat recovery process, establishes a corresponding mathematical model, and investigates the influence of the temperature and humidity of fresh air and hood exhaust air on the heat recovery energy efficiency of the hot air hood.

2. Heat Recovery System of Hermetic Gas Hood

2.1 System processes

Fig. 1 shows the new hot air hood heat recovery process designed in this paper. As shown in Fig. 1, the high-temperature and high-humidity gas hood exhaust air first pass through the primary sensible heat recycler to release heat, at which time the enthalpy contained in the exhaust air is still high; then, a certain percentage of the exhaust air enters

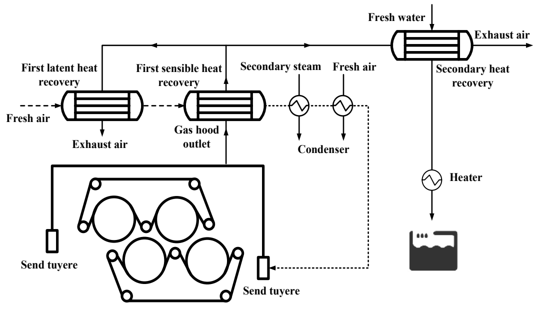

Fig. 1. New hot air hood heat recovery system.

the primary latent heat recycler, and the remaining exhaust air is used for secondary heat recovery. In this process, the new air from the environment with lower temperature is firstly exchanged with the exhaust air of the gas hood in the latent heat recovery, because the flow rate of the exhaust air is small, so the latent heat in it is gradually released to heat the new air, without causing a sharp increase in the temperature of the new air. Subsequently, the fresh air enters the sensible heat exchanger and is further heated by the high-temperature hood exhaust, which is close to the hood exhaust temperature. In this process, the gas hood exhaust is utilized step by step according to the quality, and the temperature of the gas hood exhaust will not cause significant fluctuations in the fresh air temperature, and the heat exchange temperature difference between latent heat and sensible heat exchanger is small, which not only reduces the heat exchange loss significantly, but also improves the system stability.

2.2 Thermal modeling

To simplify the calculations, the following assumptions are made for the model :

1) The system is well sealed, with no leakage.

2) Except for the heat exchanger, the work mass does not generate heat loss in the rest of the equipment and piping.

3) The temperature of the fresh air at the outlet of the sensible heat recycler is 5℃ lower than the air hood exhaust air temperature.

4) The gas hood exhaust air temperature at the outlet of the latent heat recycler is 10℃ higher than the fresh air temperature.

Based on the above assumptions, the corresponding mathematical model is established as follows.

2.2.1 Calculation process of fresh air side

The mass flow rate($F_{m,1}$)of dry air in fresh air is:

$$F_{m,1} = \frac{F_{v,1}\rho_1}{1+\omega_1} \quad [1]$$

where $F_{v,1}$ is the volume flow of fresh air, m^3/h; ρ_1 is the density of fresh air, kg/m^3; ω_1 is the moisture content of fresh air, g/kg (dry air).

The fresh air has a constant mass flow rate of dry air throughout the calculation of the model, there is:

$$F_{m,1} = F_{m,2} = F_{m,3} = F_{m,4} = F_{m,5} \quad [2]$$

For assumption 3), the relationship between the temperature of fresh air at the outlet of the sensible heat recycler and the exhaust air temperature of the gas hood can be obtained as:

$$T_3 = T_6 - 5 \quad [3]$$

When the fresh air passes through the latent heat exchanger and sensible heat exchanger, the water content before and after passing through the heat exchanger remains the same because only sensible heat is exchanged, so there is:

$$\omega_1 = \omega_2 = \omega_3 \quad [4]$$

The fresh air passes through the latent heat exchanger and from the equation of energy conservation it is obtained that:

$$F_{m,2}h_2 = F_{m,3}h_3 + Q_{latent} \quad [5]$$

The fresh air passes through the sensible heat recycler and from the equation of energy conservation it is obtained that:

$$F_{m,3}h_3 = F_{m,2}h_2 + Q_{sensible} \quad [6]$$

2.2.2 Air hood exhaust side calculation process

The mass flow rate of dry air in the air hood exhaust, $F_{m,6}$ is:

$$F_{m,6} = \frac{F_{v,6}\rho_6}{1+\omega_6} \quad [7]$$

The heat load of the latent heat recycler is:

$$Q_{latent} = F_{m,6}(h_7 - h_8) \quad [8]$$

The heat load of the sensible heat recycler is:

$$Q_{sensible} = F_{m,6}(h_6 - h_7) \quad [9]$$

3. Influence of Various Factors on the Thermal Performance of Hot Air Hood

3.1 The influence of fresh air temperature and humidity

Fig. 2 shows the influence of fresh air temperature on the total heat recovered by the system. From the figure, it can be seen that the total heat recovered by the system gradually decreases with the increase in fresh air temperature. When the fresh air temperature is 15℃, the total heat recovered by the system is 1864.1 kW, while when the fresh air temperature is 35℃, the total heat recovered is 1243.3 kW, which is 33.3% lower than before. This is because the lower the fresh air temperature is, the greater the heat exchanger temperature difference is, and the more energy can be recovered. Therefore, the energy-saving potential of the system is higher in winter than in summer.

Fig. 3 shows the influence of fresh air temperature on the proportion of exhaust air passing through the latent heat exchanger. It can be seen from the figure that, like the trend of total heat recovery, the proportion of gas hood exhaust air passing the latent heat exchanger gradually decreases with the increase of fresh air temperature. When the fresh air temperature is 15℃, the proportion of gas hood exhaust air passing through the latent heat exchanger is 6.2%, while when the fresh air temperature is 35℃, the proportion becomes 2.6%, which is 58.1% lower compared with the previous one. Therefore, for the new hot air gas hood heat recovery system, attention needs to be paid to adjusting the ratio of exhaust air passing through the latent heat exchanger in different seasons, and the ratio needs to be increased in winter, otherwise it will cause the thermal imbalance of the heat recovery system.

Fig. 4 shows the influence of fresh air moisture content on the total heat recovered by the system. From the figure, it can be seen that the total heat recovered by the system increases gradually with the increase of fresh air moisture content. When

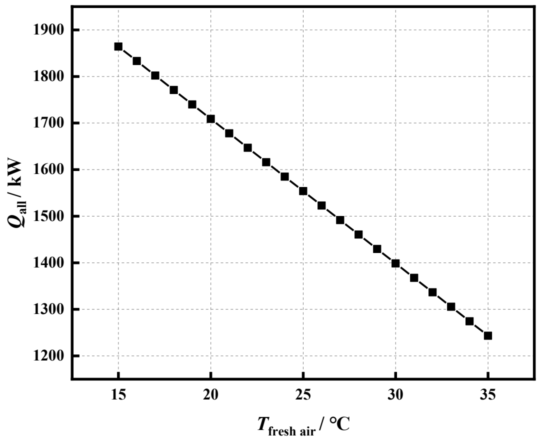

Fig. 2. Influence of fresh air temperature on total heat recovery.

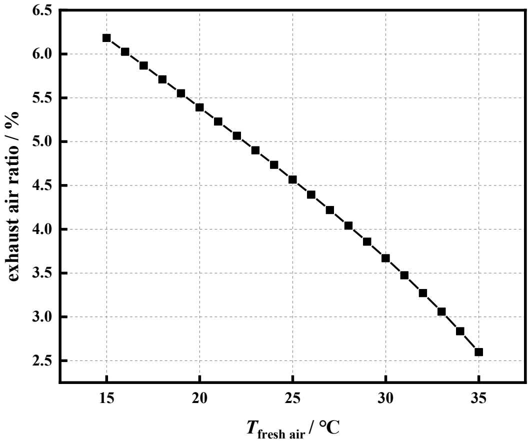

Fig. 3. Influence of fresh air temperature on the ratio of exhaust air.

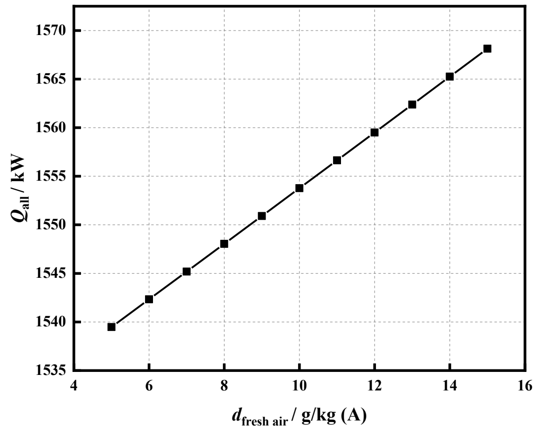

Fig. 4. Influence of fresh air moisture content on total heat recovery.

the moisture content of fresh air is 5 g/kg, the total heat recovered by the system is 1539.5 kW, while when the fresh air temperature is 15 g/kg, the total heat recovered is 1568.1 kW, which is only 1.9% higher than before. As the fresh air warms up, the water vapor in the fresh air does not undergo a phase change, so the fresh air humidity has less effect on the total recovered heat.

Fig. 5 shows the influence of fresh air moisture content on the proportion of exhaust air passing through the latent heat exchanger. It can be seen from the figure that, like the trend of total heat recovery, the proportion of air hood exhaust air passing the latent heat exchanger increases gradually with the increase of fresh air moisture content. When the moisture content of fresh air is 5 g/kg, the proportion of gas hood exhaust air passing through the latent heat exchanger is 4.4%, while when the moisture content of fresh air is 15 g/kg, the proportion becomes 4.7%, which is only 6.8% more than before.

3.2 The Influence of air hood exhaust air temperature and humidity

Fig. 6 shows the influence of gas hood exhaust air temperature on the proportion of exhaust air passing through the latent heat exchanger. It can be seen from the figure that, unlike the trend of total heat recovery, the proportion of gas hood exhaust air passing through the latent heat exchanger gradually decreases with the increase of gas hood exhaust air temperature. When the hood exhaust air temperature is 70℃, the proportion of hood exhaust air passing through the latent heat exchanger is 6.4%, while when the hood exhaust air temperature is 90℃, the proportion becomes 3.0%, which is 53.1% lower compared to before.

Fig. 7 shows the influence of air hood exhaust air

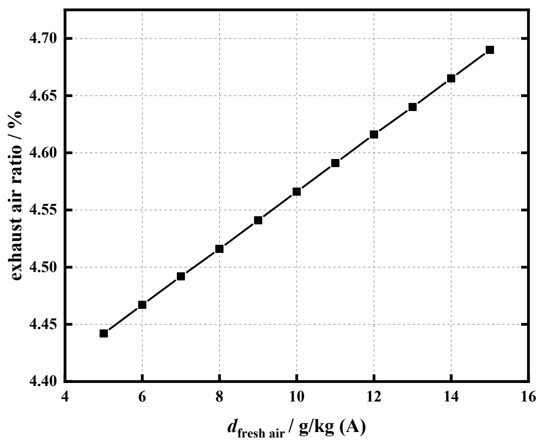

Fig. 5. Influence of fresh air moisture content on the ratio of exhaust air.

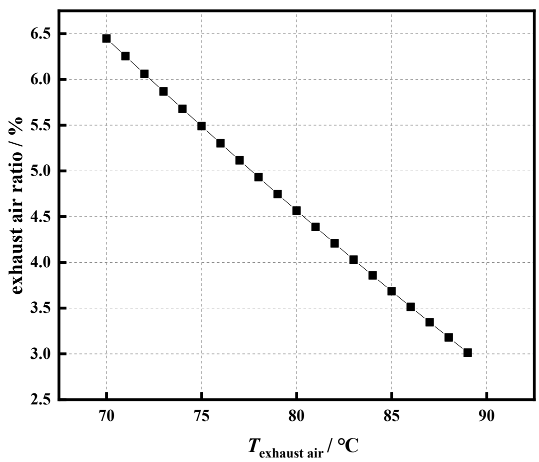

Fig. 6. Influence of exhaust air temperature on the ratio of exhaust air.

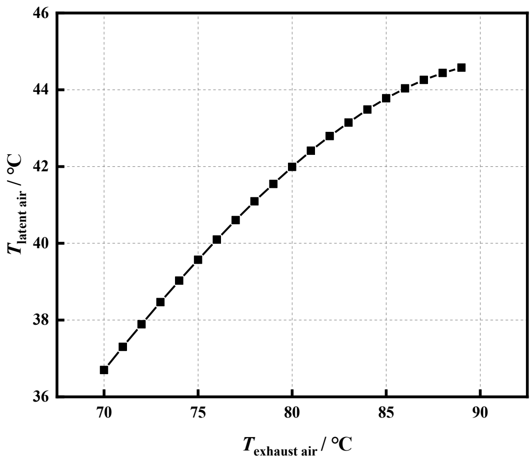

Fig. 7. Influence of exhaust air temperature on latent air temperature.

temperature on the fresh air temperature at the outlet of the latent heat exchanger. From the figure, it can be seen that as the exhaust air temperature of the gas hood increases, the temperature of fresh air at the outlet of the latent heat exchanger increases, and the increasing trend tends to level off gradually. When the exhaust air temperature is 70℃, the outlet temperature of fresh air in the latent heat exchanger is 36.8℃, while when the exhaust air temperature rises to 90℃, the outlet temperature of fresh air in the latent heat exchanger is 44.6℃, an increase of 21.2%.

Fig. 8 shows the effect of gas hood exhaust air temperature on the latent heat, sensible heat exchanger and total heat recovery respectively. It reflects the total heat recovered by the system increases gradually with the increase of the gas hood exhaust air temperature. When the gas hood exhaust air temperature is 70℃, the total heat recovered by the system is 1242.7 kW, while the gas hood exhaust air temperature is 90℃, the total heat recovered is 1833.9 kW, which is 47.6% more than before. It can also be seen from the figure that the heat recovered by both latent and sensible heat recyclers increases with the increase of the hood exhaust air temperature, but the increase of latent heat recycler tends to level off gradually, while the increase of sensible heat recycler tends to increase gradually. Meanwhile, the heat recovered by the sensible heat recycler is more than that by the latent heat recycler.

Fig. 9 shows the influence of the relative humid-ity of the exhaust air from the gas hood on the proportion of exhaust air passing through the latent heat exchanger. From the figure, it can be seen that the proportion of exhaust air passing through the latent heat exchanger tends to

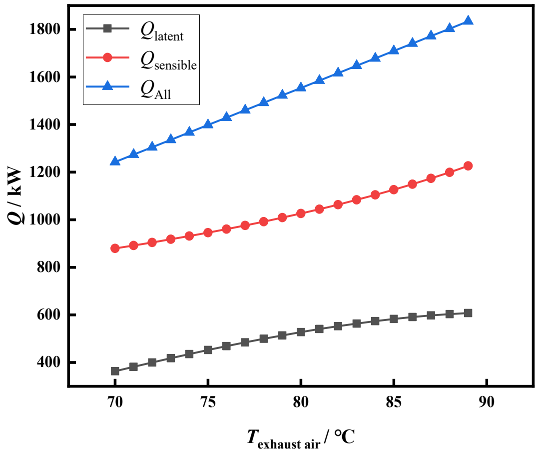

Fig. 8. Influence of exhaust air temperature on total heat recovery.

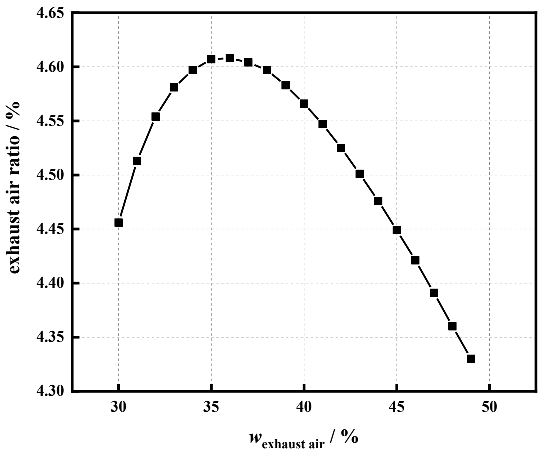

Fig. 9. Influence of relative humidity of exhaust air on the ratio of exhaust air.

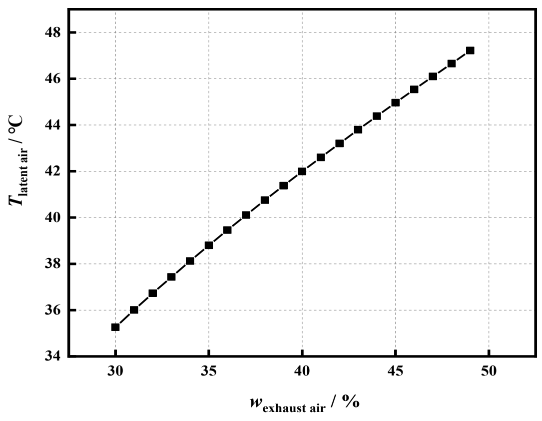

Fig. 10. Influence of relative humidity of exhaust air on latent air temperature.

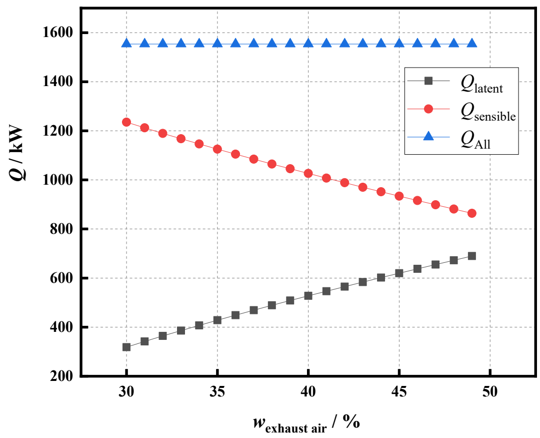

Fig. 11. Influence of relative humidity of exhaust air on total heat recovery.

increase and then decrease with the increase of the relative humidity of the exhaust air increases.

Fig. 10 shows the influence of the relative humidity of the exhaust air from the gas hood on the temperature of the fresh air at the outlet of the latent heat exchanger. It reflects the temperature of fresh air at the outlet of the latent heat exchanger increases linearly with the increase of the relative humidity of exhaust air. When the relative humidity of exhaust air is 30%, the outlet temperature of fresh air in the latent heat exchanger is 35.2℃, while when the relative humidity of exhaust air is 50%, the outlet temperature of fresh air in the latent heat exchanger is 47.3℃, an increase of 34.4%.

Fig. 11 shows the influence of the relative humidity of the gas hood exhaust air on the latent heat and sensible heat recyclers and the total recovered heat, respectively. It can be seen from the figure that the total recovered heat of the system remains the same as the relative humidity of the gas hood exhaust air increases, but the heat recovered by the latent heat recycler gradually increases, while the heat recovered by the sensible heat recycler gradually decreases.

4. Conclusions

In this paper, a thermodynamic model of a new hot air hood heat recovery system is established and the effect of different thermal parameters on the system heat recovery efficiency is studied, with the following conclusions.

1) The total heat recovery of the hot air hood heat recovery system and the proportion of exhaust air passing through the latent heat exchanger decreases with the increase of fresh air temperature and increases with the increase of fresh air moisture content.
2) As the exhaust air temperature of the hood increases, the total heat recovery of the system increases, among which the increasing trend of latent heat recovery gradually decreases, while the increasing trend of sensible heat recovery gradually increases.
3) As the relative humidity of the exhaust air from the gas hood increases, the total heat recovery of the system remains the same, but the latent heat recovery gradually increases, while the sensible heat recovery gradually decreases. And the proportion of exhaust air passing through the latent heat exchanger

shows a trend of increasing first and then decreasing.

4) For the whole recovery system, the fresh air temperature and the relative humidity of the air hood exhaust air have a greater impact on the heat recovery efficiency.

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