Research on Flow and Condensation Heat Transfer Coefficient of multi-channel cylinder dryer in U-shaped Section

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Abstract. The cylinder dryer is the most energy-consuming part of the papermaking drying section. Whether the drying cylinder can effectively drain the drying cylinder affects the drying efficiency of the drying cylinder. The design of the multi-channel drying cylinder effectively improves the problem of the difficulty of the water accumulation discharge. In order to obtain a channel cross-sectional shape with better drainage and better heat transfer, two channels with different cross-sectional shapes are selected to study the flow and heat transfer of steam in this experiment. The changes of the channel heat transfer coefficient under different working conditions are studied and compared. The result show that the U-shaped channel heat transfer effect is better than that of other shape channels in the multi-channel dryer.

1. Introduction

The paper industry is one of the important pillars of a country’s national economy. Paper and cardboard have become an indispensable part of our daily lives[1], which highlighting the importance of the paper industry. In the entire paper industry process, the dryer section occupies the most resources and energy consumption. Therefore, the dryer section is the part to explore the energy-saving[2]. It is shown that the main reason for the high energy consumption during the operation of the dryer in the studies is that the condensate cannot be discharged in time, which leads to an increase in thermal resistance[3].

The multi-channel drying cylinder is an improved drying cylinder designed to solve the problem above[4], and the design of the multi-channel drying cylinder can effectively discharge the condensed water in time and avoid the retention of the condensed water to affect the heat transfer. As shown in Figure 1, the design idea of this drying cylinder is to cancel the drainage device of the original drying cylinder, and the drainage design is transferred to the drying cylinder wall. The uniformly arranged axial channels are processed on the drying cylinder wall, and small openings on the channels are opened. The mechanism is as follows: steam from the inlet channel, and it is restricted to flow in the channels due to the design, and condenses and release heat in the channels. Then the condensed water is formed the wall of the dryer channels. With the increase of the subsequent steam, a pressure difference is generated inside the dryer, and the condensed water produced by condensation heat transfer is discharged from the channels by the pressure difference. The whole process is limited in the designed channel, and almost no condensation water will be remained in the channel. Based on the design of Argonne National Laboratory, Dong Jixian [5] improved and designed a new type of siphonless multi-channel dryer. The schematic diagram of the structure is shown in Figure 2. Its design is the same as that of ANL, in which small channels are also provided on the inner wall of the dryer. The difference from ANL is that the
steam enters the channel from the steam inlet to condense and release heat, and the condensed water produced after condensation heat exchange is subjected to the subsequent steam. After the water is discharged from the channel, there is basically no water accumulation. At the same time, considering more convenient drainage technology, the opening method of the channels is no longer arranged along the axial direction as before, but forming with an angle oblique distribution along the axial direction. The rotating inertia force also causes the condensed water accumulation. Therefore, the further exploration and improvement of papermaking industry equipment, is necessary to save papermaking energy consumption.

In order to have a deeper understanding of the mechanism of the multi-channel dryer, and the condensation heat transfer dissipation of steam in the channels, a single channel of the dryer is selected in the experiment. Recent years, the research on channel heat transfer is particularly extensive. The main research is divided into three types: micro channels, small channels, and large channel. Many researchers have conducted specific studies on each type. However, there is no accepted conclusion for the definition of the three channels. At present, many division principles are adopted by KANDLIKAR which are divided by the calculation of hydraulic diameter. The channels with the hydraulic diameter $d_h$ in the range of 10–200μm are micro channel, and the channels with the $d_h$ is in the range of 200μm–200mm are small channel, and the rest are large channels.

In order to grasp the influence of different cross-sectional shapes on the heat transfer of the multi-channel dryer, the channels with different rectangular and U-shaped cross-sectional shapes under the same hydraulic diameter are selected in the experiment. At present, in the channel heat transfer research, many researches focus on micro channel, but these studies are only applicable to micro scale. As for large-scale equipment, a further research is needed. Therefore, the condensation heat transfer of the channels should be further studied, and whether the excellent progress made in the research of microchannels can be applied to other types of channels should be considered, so as to provide more adequate guidance for the theoretical research of multi-channel dryers.
2. Experimental Study

2.1. Experimental Equipment

As shown in Figure 3, the experiment is divided into three parts: steam circuit, cooling water circuit and test section. Considering that it is difficult to directly use pulp for research, the paper web is simulated with cooling water and a thermocouple is installed to measure the temperature, condensation heat transfer coefficient. In order to observe the condensed flow pattern of vapor in the channel, a high-speed camera is used to observe the test section. The test section is the core part of the experimental system. The vapor passes through and condenses and release heat to the cooling water on the other side of the channel. The cooling water is recycled to cool the steam in the test section.

![Figure 3 Flow chart of experimental equipment of multi-channel condensation](image)

2.2. Experimental data processing

The energy conversion of steam in the multi-channel dryer complies with the conservation of energy. After the steam is condensed, part of the heat is transferred to the cooling water through the channel wall, and the rest is lost to the environment during the heat transfer process. The heat balance satisfies the formula (1)

\[ Q_{s,i} = Q_{c,i} + Q_{l,i} \]  \hspace{1cm} (1)

Where \( Q_{s,i} \), \( Q_{c,i} \) and \( Q_{l,i} \) represent the condensation heat transfer, cooling water heat absorption and heat loss of the \( i \)-th section of the steam channel, respectively. However, considering the small channel wall thickness of the experimental device and the thermal insulation treatment, the heat loss of each section is much smaller than the total heat transfer, so in the calculation, the formula is considered that as \( Q_{s,i} = Q_{c,i} \).

The heat absorbed by the cooling water channel can be obtained by formula (2):

\[ Q_{c,i} = M_c \cdot C_p \cdot (t_{c,i+1} - t_{c,i}) \]  \hspace{1cm} (2)

Where \( M_c \) is the mass flow rate of cooling water, \( k_g/h \), \( C_p \) is the specific heat capacity at constant pressure, \( (K_g \cdot K) / (K_g \cdot K) \); \( t_{c,i+1} \), \( t_{c,i} \) represent the inlet and outlet temperature of cooling water in section \( i \), respectively, K.

Because the length of the entire experimental channel is short, the density of the cooling water changes very little during the experiment, and the evaporation of the cooling water can be ignored. Therefore, it is considered that the mass flow of the cooling water in the entire cooling water channel is in a conservation state, as formula (3) shows:

\[ M_c = M_{c,in} = M_{c,out} \]  \hspace{1cm} (3)

The calculation of \( C_p \) at standard atmospheric pressure is calculated according to formula (4) [6]:

\[ C_p = 4224.0 - 4.1861t_{c,i} + 0.1308t_{c,i}^{-2} - 0.0014t_{c,i}^{-3} \]  \hspace{1cm} (4)
Where $\bar{t}_{cl}$ is the average temperature of the test section, which is calculated by $\bar{t}_{cl} = \frac{t_{c,i} + t_{c,i+1}}{2}$. And the unit is K.

Using the average temperature of steam measured in section $i$ and the average temperature between the walls, the local condensation heat transfer coefficient of this section can be calculated, and the condensation heat transfer coefficient of the entire channel can be obtained by formula (5):

$$\overline{h_i} = \frac{q_{xi}}{A_i (t_{wi} - t_{ui})} \quad (5)$$

Where $\bar{t}_{si}$, $\bar{t}_{wi}$ are the average steam temperature and the average wall temperature corresponding to the section; $A_i$ is the heat exchange area of the $i$-th channel. $h_i$ is the local condensation heat transfer coefficient of the section.

3. Results and discussion

3.1. The influence of steam inlet mass flow rate
As shown in Figure 4, the relationship between the steam condensation heat transfer coefficient and the steam mass flow rate at the entrance is revealed. Under the same mass flow of cooling water, the steam condensation heat transfer coefficient increases with the increase of the steam inlet mass flow rate, and the U-shaped condensation heat transfer coefficient is larger than the rectangular condensation heat transfer coefficient.

![Figure 4 The influence of different steam mass flow rates on the heat transfer coefficient](image)

**Figure 4** The influence of different steam mass flow rates on the heat transfer coefficient

![Figure a Bubbly flow](image)

![Figure b Slug flow](image)

**Figure 5** Flow rates
According to Figure 4, when the cooling water mass flow rate is 140.4 kg/h, the condensation heat transfer coefficient with the U-shaped channel is significantly higher than the condensation heat transfer coefficient with the rectangular channel. Under the U-shaped channel, the condensation heat transfer coefficient reaches the peak and then shows a slow increasing trend. The reason is that there are few edges and corners in the U-shaped channel, and the steam condensate is not easily to be disturbed. In the experiment, the local heat accumulation caused by the appearance of liquid bridges is observed, and the heat transfer coefficient increases sharply. When the steam flow rate is high, the liquid bridge is not easy to form under the push of steam. Therefore, the heat transfer coefficient tends to increase steadily.

When the steam mass flow rate $G$ is $30 \text{kg/(m}^2 \cdot \text{s)}$, the growth rate of the condensation heat transfer coefficient slows down significantly. The reason is that when the steam mass flow rate in the channel is less than $30 \text{kg/(m}^2 \cdot \text{s)}$, the two-phase flow patterns in the two channels are mainly bubbly flow and wavy flow, as shown in Figure 5. The relative velocity of the two-phase flow is relatively large, which causes the change of the flow pattern and the continuous increase of the condensation heat transfer coefficient. When the steam mass flow rate is higher than $30 \text{kg/(m}^2 \cdot \text{s)}$, the two-phase flow pattern in the channel is annular flow, and the existence of annular flow causes the relative velocity between gas and liquid increase. The annular flow occupies most part of the channel, and the annular flow forms a uniform liquid film covering the surface of the channel and forms the thermal resistance. However, due to the large steam mass flow rate, the thickness of the liquid film is thin under the impact. The heat transfer enhancement caused by the turbulence of the liquid film exceeds the resistance of the liquid film which hinder the heat transfer. Therefore, the overall heat transfer coefficient of the channel is still increase.

### 3.2. The influence of cooling water mass flow rate

As shown in Figure 6, the scatter showing the change of the condensation heat transfer coefficient with the change of the cooling water mass flow rate. With the increase of the cooling water mass flow rate, there is no significant change in the two channels, but the condensation heat transfer of the U-shaped channel reveals the relationship between the steam condensation heat transfer coefficient and the steam mass flow rate at the inlet. Under the same mass flow of cooling water, the steam condensation heat transfer coefficient increases with the increase of the steam inlet mass flow rate, and the U-shaped channel’s condensation heat transfer coefficient is larger than that of the rectangular channel.
4. Conclusions
As a necessity of human life, paper measures the level of modernization and civilization of a country. Therefore, the improvement of the paper industry is particularly important, especially in the modern era where resources are scarce. The design of the multi-channel dryer is an exploration of the improvement of the paper industry. By studying the heat transfer of the channels under the two cross-sections, it is concluded that the heat transfer effect of the U-shaped channel is better than that of the rectangular channel under the same conditions, which is more suitable for the application of industrial design.

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