Design and experimental study of a new type of 45° overflow falling film distributor

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Abstract—A petrochemical acrylic fiber factory introduced a set of acrylic fiber devices in the 1980s. Among them, the evaporation device used for solvent recovery of acrylic fiber appeared to be difficult to heat exchange in the tube. In order to solve the problem, we designed a new 45° overflow falling film distributor device and an experimental system for single tube. The effects of flow rate, liquid level and orifice flow coefficient were investigated experimentally. The results show that the correlation between the orifice flow coefficient and the structure size of the fabric determines the film formation effect. When the flow rate of the single tube is constant, the absolute error of the orifice flow coefficient does not exceed 9%. Therefore, the orifice flow coefficient proposed in this experiment is a good guide to the optimal design of the fabric size.

1. INTRODUCTION

China's acrylic fiber industry was industrialized in 1969, but the energy waste caused by the backward technology of operating unit in the production process of acrylic fiber is becoming more and more serious, especially the equipment such as evaporator used for solvent recovery has problems such as low heat exchange efficiency and easy scaling[1]. At present, as one of the energy efficient utilization technologies, falling film evaporation technology in vertical pipe has the advantages of small temperature difference for heat-transfer, high heat transfer coefficient, simple installation structure and easy operation[2]. The key point of the falling film in the vertical pipe is the design of the film distributor. The structure of the film distributor determines whether the material can flow evenly in the pipe[3]. In the design of the film distributor, many scholars have done several relevant research, but there are few studies on the evaporator in the production process of acrylic fiber.

Therefore, this article aimed at the problems existing in the traditional acrylic production equipment. Considering the properties of working medium and the actual working condition, we designed a new type of 45° overflow film distributor and set up a single pipe experimental system to analysis the orifice flow coefficient of the film distributor and the structure size, and provided the best structure of the film distributor when the acrylic flow during 95~220 L/h.
2. DESIGN OF NEW FILM DISTRIBUTOR

In an acrylic fiber solvent recovery unit, the evaporator has some problems, such as material bias in the tubes, necessity to clean the equipment frequently, low life of equipment, etc. In order to solve the shortcomings of this type of evaporating equipment, it is necessary to improve the equipment structure. Therefore, combined with the commonly used heat transfer enhancement method, a new type of 45° overflow film distributor is designed in this paper to achieve uniform flow in the tube and improve the equipment heat transfer efficiency.

2.1. Existing equipment structure

In order to upgrade the original equipment, it is necessary to know the structure of the existing equipment in order to design the new film distributor. Table 1 and table 2 are the structure dimensions of the existing evaporator heat exchange tube and liquid distribution plate.

| TABLE 1. THE KEY DIMENSIONS OF HEAT TUBE |
|-----------------------------------------|
| Items | Inner diameter (mm) | Outside diameter (mm) | Tube wall thickness (mm) |
| Size   | 46.0               | 50.0                 | 2.0                     |

The falling-film evaporator tube plate consists of two liquid distribution plates, which are respectively called the upper distribution plate and the lower distribution plate. The liquid distribution plate exists to buffer the liquid and distribute the liquid in advance. The structure data of the liquid distribution plate are shown in table 2:

| TABLE 2. PARAMENTERS OF LIQUID TRAYS |
|--------------------------------------|
| Items | Upper distribution plate | Lower distribution plate |
| Large diameter of distribution tray (mm) | 1332 | 1335 |
| Number of holes                       | 324  | 676  |
| Hole margin (mm)                      | 54.00 | 56.00 |
| Hole diameter (mm)                    | 9.50  | 17.00 |
| Plate thickness (mm)                  | 3.00  | 3.00  |

2.2. Design of a new type film distributor

According to the size and structure of the existing equipment, a new type of 45° overflow film distributor is designed, as shown in figure 1 and figure 2. The overflow area shall be designed with 4 or 6 oblique cutting holes of the same diameter 45° from the axial direction. The lower end of the film distributor is placed on the tube plate. With the accumulation of working medium, the liquid level gradually overflows the oblique holes. The working medium flows down the wall of the tube at 45° along the oblique holes and in the vertical direction to form the evenly film in the tubes. The diversion effect of the film distributor is shown in figure 4. The structure of the film distributor is characterized by simple installation and high coaxiality with the heat exchange tubes. The installation part of the lower end of the film distributor has a 5° cone Angle with a height of 10mm, which has self-tightening effect. The liquid flow in the film distributor is close to the pipe wall to prevent flow interruption. Four 10mm steam holes were opened at the upper part of the overflow main section to balance the steam inside and outside the tubes.
As shown in figure 3, the lower part of the inserted heat exchange tube has a 15° bevel Angle, and the bottom end of the bevel Angle retains a straight edge section of 0.2~0.3mm. The bevel Angle is conducive to the smooth transition of materials in the pipe process from the film distributor to the inner wall of the pipe, which is more conducive to film formation.
2.3. Design of orifice flow coefficient

Many scholars have proved that there is a direct relationship between the liquid holding height and the flow rate, clarified that the liquid height in the form of static pressure determines the inlet velocity of the overflow hole and thus affects the flow state of the liquid in the pipe, and summarized this as the orifice flow coefficient[6]. The orifice flow coefficient $C_0$ can be calculated by the following formula:

$$C_0 = \frac{Q}{A_0 \sqrt{2gh}} \times 10^3$$

(1)

Where: $Q$ is the flow rate of a single pipe, L/s; $A_0$ is the total area of overflow hole of a single distributor, m$^2$; $H$ is the height of liquid level on the tube plate, m.

In the actual operation condition of the acrylic fiber evaporator, the single-tube flow rate is usually within the range of 95~220 L/h[7], and the orifice flow coefficient recommended in the domestic chemical industry manual is generally 0.6~0.85[8]. When the flow rate $Q$ of a single pipe is constant, the area of $A_0$ is first designed according to the orifice flow coefficient, and the value of $A_0$ is the initial value. And then substitute it into formula 2-1, and you get the height of $h$ on the tube plate. If $h$ is too high, the value of $A_0$ should increase correspondingly. If $h$ is too small, the value of $A_0$ should decrease accordingly. Otherwise, $A_0$ value cannot be determined. Finally, $A_0$ value can be determined according to the liquid level height on the tube plate. When the flow rate of a single tube is 95 L/h, the liquid level on the tube plate should reach the bottom of the overflow hole. When the flow rate of a single tube is 220 L/h, the liquid level on the tube plate should be about 20mm higher than the top end of the overflow hole.

If the orifice flow coefficient is 0.7 and the flow rate is 95 L/h, the minimum value of $h$ is 30mm to meet the requirement that the liquid level on the tube plate is higher than the overflow hole, then the area of $A_0$ at this time is 49mm$^2$. According to this area, three types of film distributor structures are designed, as shown in table III.

**TABLE 3. PARAMETER OF EXPERIMENTAL FILM DISTRIBUTORS**

| Section | Diameter (mm) | Number of holes | Suggested orifice flow coefficient |
|---------|---------------|-----------------|-----------------------------------|
| 1       | 3.95          | 4               | 0.80                              |
| 2       | 3.53          | 5               | 0.73                              |
| 3       | 3.22          | 6               | 0.68                              |

It must be pointed out that the experimental measurement to obtain the minimum film-forming flow related to the direction of flow regulating (flow from large to small or from small to large), because of the heat exchange tube inner surface and the existence of the adhesion between the liquid, when flow...
from large to small adjustment easier to form a evenly film in the tubes. Therefore, this paper suggested that the experiment flow should be start at low flow, and then constantly increasing experimental flow in order to obtain a more conservative experimental value.

3. SINGLE TUBE EXPERIMENT OF DESIGNED FILM DISTRIBUTOR

3.1. Single-tube cold mold experiment system
In order to better study the liquid film distribution under the actual working conditions, the experiment of multiple tube bundles was simplified to a single tube experiment. This experiment was carried out with water as the working medium at room temperature and pressure. The three specifications of film distributor were respectively used in the flow rates of 95 L/h, 125 L/h, 155 L/h, 190 L/h and 220 L/h. The experiment system is shown in figure 5.

The flowmeter in the experimental device adopts the rotor flowmeter with small pressure loss, convenient adjustment and strong operability, and the measuring range is 0~600ml. Choose transparent organic glass tube, and the size of the heat exchange tube is Φ50x6 mm, length is 1500mm. During the experiment, a little ink was added so as to better observe the liquid film flow in the tube.

During the experiment, a certain amount of working medium was first filled into the liquid storage tank, and then the circulating pump was opened. After passing the globe valve and the rotor flowmeter, the fluid reached the small cylinder of the distribution tray. The bottom of the small cylinder is slotted so that the fluid can settle on the tube plate under the large drum. The heat exchange tube with a film distributor mounted on the top has a certain height on the tube plate. With the accumulation of liquid on the tube plate, when the liquid level is higher than the bottom end of the hole on the film distributor, the liquid working medium will flow into the heat exchange tube along the hole in the form of spiral flow under the action of gravity and tangential velocity, and then fill the whole heat exchange tube. Finally, it flows into the reservoir and repeats in turn. According to the law of mass conservation of the fluid, when the head of the circulating pump remains unchanged, the liquid level on the small cylinder and tube plate of the distributing liquid remains stable after a period of time.

3.2. Processing and analysis of experimental data
Keep the flow rate of the working medium in each group of experiments the same, change the opening diameter of the film distributor, measure the actual height of the tube plate liquid level through experiments, then calculate the actual orifice flow coefficient of the film distributor, and finally
calculate the absolute error of the actual orifice flow coefficient and the theoretical orifice flow coefficient. The relationship between the flow of working medium and the height of liquid level on the tube plate is shown in figure 6.

Figure 6. Relationship between the liquid level and flow

Figure 6 intuitively illustrates the relationship between the flow of working medium and the height of liquid level on the tube plate. As can be seen from figure 3.2, in the interval of working medium flow of 100~350 L/h, the liquid level height on the tube plate increases with the increase of flow, and the theoretical calculation value and experimental value maintain an approximate upward trend. It can be seen from the relative error curve that the theoretical liquid level height and the actual liquid level height error of tube plate are mainly concentrated in 5~12.5%, and the average absolute error is 9%. The maximum error occurs when the working medium flow is 155 L/h, and the error is 12.5%.

Figure 7. The relationship between flow and flow coefficient

As can be seen from figure 7, the orifice flow coefficients of the three types of film distributor with different opening diameters were mainly concentrated between 0.68 and 0.87 at the flow rates of each group from 95 to 220 L/h, and the variation trend was generally downward, then upward, and finally downward. When the working medium flow rate is 125 L/h, the actual orifice flow coefficient of the three types of film distributor is at their respective low points. On the whole, the actual orifice flow coefficient of the film distributor with larger opening diameter is higher than that of the film distributor
with smaller opening diameter. Therefore, in the case of flow of 95~220 L/h, the film distributor with an opening diameter of 3.95mm should be selected.

Figure 8. The relationship between flow rate and relative error of flow coefficient

Figure 8 shows that the absolute error of orifice flow coefficient of the three types of film distributor is between 2.5% and 8% when the working medium flow is between 95~220 L/h. And with the increase of the flow, the absolute error curve shows a trend of decreasing. The maximum absolute error of the orifice flow coefficient occurs in the case of 125 L/h, 3.95 diameter of the opening of the film distributor, where the error is 9%. But after that, with the increase of the flow rate, the absolute error of the orifice flow coefficient of the distributor gradually decreases. At 220 L/h, it falls below 5%. However, for the other two types of film distributor, their orifice flow coefficient at 95~220 L/h did not exceed 7.5%. Therefore, the selected orifice flow coefficient can well guide the design and calculation of the structure size of the overflow hole for the three types, which is of great engineering significance.

4. CONCLUSION
In this paper, a new type of falling film distributor with 45° overflow is designed, and an experimental system of single-tube cold film is built for research. The effects of flow rate, liquid level height and orifice flow coefficient on film formation were studied experimentally. The main conclusions are:

(1) A new type of 45° overflow falling film distributor was designed. Under the action of tangential force and gravity, the working medium can quickly form a complete and uniform liquid film on the inner wall of the heat exchange tube, which can effectively enhance the heat exchange efficiency of the falling film inside the tube.

(2) Through a single pipe experiment system, it is found that under single-tube working medium flow of 95~220 L/h, the film distributor of Φ4x3.95 mm performs better than the Φ5x3.53 mm and Φ6x3.22 mm.

(3) When the single-tube flow rate of the working medium is 95~220 L/h, the maximum absolute error of the orifice flow coefficient proposed for the three types of film distributor is less than 9%, and the absolute error shows a decreasing trend with the gradual increase of the flow rate.

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