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Fundamental Investigation of the Flow in an Agitated
Thin Film Evaporator (1st Report, The Flow in a
Horizontal Agitated Thin Film Evaporator)*

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In this report, we observe the flow pattern in a horizontal agitated thin film evaporator under the condition that thermal effects are excluded. The test model is a horizontal cylinder which has the wiping blades inside. The working fluid is water.

We researched the liquid volumetric flow rate and the revolution of the wiping blades which affect the profile of the wiped liquid fillet, the state of the thin liquid film, the residence time in the apparatus and the axial dispersion. We also researched the profile of the fillet in a two-dimensional shallow water tunnel.

1. Introduction

The agitated thin film evaporator which has wiping blades keeping a constant clearance from the cylinder is a kind of heat exchanger. It is suitable for evaporating and condensing the high viscous as well as the heat sensitive substances. Schneider⁽¹⁾, Kern and Karakas⁽²⁾, Fisher⁽³⁾ and Mutzenberg⁽⁴⁾ have investigated the flow pattern in a vertical agitated thin film evaporator to get a high over-all heat transfer coefficient and to determine the various parameters on which the unit efficiently operates without causing a hot spot or passing through of the working liquid.

In the vertical evaporator, the residence time is seriously affected by gravity but almost independent of the revolution of the blades⁽¹⁾, while, in the horizontal one, it is only affected by the axial thrust that is caused by the centrifugal force acting on the liquid fillets built up in front of the wiping blades. The horizontal one, therefore, is suitable to control the residence time freely, but its flow pattern is scarcely known⁽⁵⁾.

The purpose of our work is to resolve such problems as passing through and a hot spot which frequently arise in the horizontal agitated thin film evaporator. In the actual evaporator, since the thermal and the hydrodynamic effects are closely coupled, it is very difficult to resolve

these effect simultaneously.

Then, as the first step, we investigated the flow pattern in an evaporator without the thermal effects experimentally using water of the room temperature as the working liquid, and clarified the state of the thin liquid film, the residence time in the apparatus and the axial dispersion, for various liquid volumetric flow rates and revolutions of the wiping blades which affect the profile of the wiped liquid fillet.

Moreover, we observed the profile of the fillet in a two-dimensional shallow water tunnel and found that the theory of hydraulic jump is applicable to the relation between the height of the liquid fillet and that of the liquid film.

We used the electric probe of Dukler and Bergelin⁽⁶⁾ to measure the liquid film thickness. The average residence time measured by the tracer-pulse method was compared with the time calculated from measured values of the hold up volume and the volumetric flow rate. It is reconfirmed in the horizontal evaporator that the revolution of the wiping blades much affects the average residence time.

2. Nomenclature

D : inner diameter of the cylinder
g : gravitational acceleration
 h_1 : liquid film thickness
 h_2 : height of the liquid fillet close to the blade
 h_m : time-average thickness of the liquid film measured by the electric probe
 h_{tm} : average thickness of the liquid film including the liquid fillets $=W/\pi DL$

L : distance from inlet of a cylinder to outlet

$L_{\theta I}$, $L_{\theta II}$: circumferential lengths of the liquid fillet at the positions

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- I, II, respectively (see Fig.1)
 N : revolution of the wiping blade (rpm)
 Q : volumetric flow rate
 R : radius of the wiping blade
 T : average residence time $=W/Q$
 t_1^*, t_2^* : time of the first and the second output, respectively
 u : average axial velocity $=L/T$
 V : translation velocity of the liquid fillet
 W : hold up
 δ : clearance between the inner cylinder wall and the tip of the wiping blade $=(D/2)-R$
 μ_{21}, μ_{22} : variances of the first and the second output, respectively
 ν : kinetic viscosity
 π : pi
 φ_1, φ_2 : occurrence frequencies which are defined as a fraction of time duration when the liquid film thickness is less than δ at the position I, II, respectively
 ω : angular velocity of the wiping blade
 D : axial dispersion coefficient
 Fr : Froude number $=V/(gh_1)^{1/2}$
 M : degree of mixing
 PeB : Bodenstein number $=uL/D$
 ReI : film Reynolds number $=(4Q/\pi D)/\nu$
 ReN : rotational Reynolds number $=(4\delta\pi DN/60)/\nu$
 T^* : non-dimensional average residence time $=T/L(g\nu)^{-1/3}$

3. Experimental apparatus

We made a horizontal straight cylindrical model as shown in Fig.1, to resolve the problems of the agitated thin film evaporator hydrodynamically. Fig.2 shows a schematic diagram of experimental apparatus.

The cylinder and the wiping blades are made of transparent vinyl chloride for inside observation. The cylinder length between the inlet and the outlet is $L=380$ mm, and the inner diameter is $D=100$ mm, respectively. In the cylinder, four wiping blades are attached on the rotor driven

Fig.1 Horizontal straight cylinder model

by a 2 HP DC electric motor through the V belt.

The clearance between the inner cylinder wall and the blade tip is kept 1 mm along the axis.

When the revolution of the wiping blades measured by means of the stroboscope is in the range of 400 rpm to 1000 rpm, the centrifugal acceleration is sufficiently greater than the gravitational one. The working liquid are fed from a Westco pump of 80 watts. A rotary piston type flowmeter and a cock are provided at the inlet, and a measuring tank at the outlet. For distributing the working liquid in the cylinder regularly, a vinyl chloride disk of 70 mm diameter is set 50 mm downstream from the inlet.

In the cylinder, Dukler-Bergelin's electric probe⁽⁶⁾ shown in Fig.6, which consist of a pair of platinum rods of 1 mm diameter with a 3 mm distance, are mounted

A: Tank	J: Strain meter
B: Pump	K: Magnetic oscillograph
C: Tank	L: Belt
D: Flow meter	M: DC motor
E: Cock	N: Measuring tank
F: Evaporator	O: Photo transistor
G: Probe	P: Amplifier
H: Shallow tank for calibration of probes	Q: Stroboscope
I: Wheatstone's bridge	R: Lamp
	S: Bypass
	T: Manometer

Fig.2 Schematic diagram of experimental apparatus

Fig.3 Photograph of a liquid fillet

$$ReI=1.27 \times 10^3, ReN=1.58 \times 10^4$$

for measuring the liquid film thickness and the residence time, at the positions I, II, III shown in Fig.1. The probe end was polished by sand paper and was made flush with the inner cylinder surface.

Two peepholes were provided at the outlet side flange for looking at the cross section of fillets.

4. Experimental method

We photographed the liquid fillet through the transparent cylinder (see Fig.3) and also through the peephole (see Fig.4) under the stroboscopic illumination synchronized with the rotor revolution. In the latter case, we illuminated the cross section of the liquid fillet through a slit at the positions I, II, III to observe how the form of the liquid fillet varied with the axial position.

We used two methods for evaluating the film thickness. In one method, the average thickness of the liquid film including the liquid fillets is calculated by using the results on the hold up. In the other method, the thickness is measured using Dukler-Bergelin's probes, a dynamic strain meter (DPM-3CT6, Kyowa Electric Instrument Co., LTD.) and a magnetic oscillograph.

The measuring procedure on the hold up is as follows. We shut the cock at the exit of the measuring tank shown in Fig.2. When the liquid level in the tank reaches a prescribed level, we shut the cock E. The hold up is defined to be the volume of liquid flowing into the tank after closing the cock. And the values of several experiments were averaged.

The time-average film thickness h_m was measured by the electric probe. The occurrence frequency φ , which is defined as the fraction of time duration when the film thickness is less than δ , was also measured by the electric probe, see Fig.5.

The relation between the film thickness and the electric current on the dynamic strain meter is calibrated in a two-dimensional horizontal shallow tunnel.

The average residence time is evaluated by dividing the hold up volume by the volumetric flow rate, and also from the time duration when any one-shot tracer traverses the distance between two or three probes. The probes are also used for measuring the film thickness, because the electric resistance of the liquid is more affected by the change of the tracer concentration than by that of the film thickness. The calibration between the tracer concentration and the electric current of the strain meter is also carried out in the two-dimensional tunnel only when the film thickness is equal to the clearance δ .

Since the residence time is essentially defined as the time when the liquid passes from the inlet to the outlet, it is related not only to the flow mechanism in the apparatus but also to the end effects at the inlet and the outlet⁽²⁾. Here, to separate the flow mechanism, we defined the residence time as the reduced time when the liquid passes from the inlet to the outlet. The reduced time is calculated from the measured one, when the liquid passes from the first probe to the second one, by the following Eq.(1),

$$t_2^* - t_1^* = \frac{\int_0^{t_2} c_2 dt}{\int_0^{t_2} c_2 dt} - \frac{\int_0^{t_1} c_1 dt}{\int_0^{t_1} c_1 dt} \quad (1)$$

Here, the concentration curve is replaced by a smooth one as shown in Fig.6. c_1 and c_2 are concentrations of the first and the second output of the tracer, respectively. We could also detect the difference in the axial velocity along the axis, because we measured the concentration at three positions.

To explain the axial dispersion we used the concept of degree of mixing, proposed by Inoue and Tonooka⁽⁸⁾ as follow:

$$M = (\mu_{22} - \mu_{21})^{1/2} / (t_2^* - t_1^*) \quad (2)$$

where the values are normalized. To compare with the Bishoff Equation⁽⁹⁾, M is also shown as follows,

$$M = (2\delta/\mu L^*)^{1/2} = (2/PeB)^{1/2} \quad (3)$$

Rel=6.36×10², Ren=1.38×10⁴
Fig.4 Cross sections of a fillet

where L^* is the distance between the probes. When $M=0$, the flow is called "piston flow", and M increases with the degree of mixing.

5. Experimental result and discussion

5.1 Profile of the liquid fillet

From the photographs as shown in Fig.3, we deduced the circumferential length L_θ of the fillets at the positions I and II, and found that L_θ increases with an increase in the film Reynolds number and a decrease in the rotational Reynolds number, see Fig.7. It was also observed from the photographs of the cross section of the liquid fillets that about 9 mm height of the liquid fillets close to the blade didn't change with the volumetric flow rate, the revolution of the blades and the axial position.

5.2 Liquid film

The time-average film thickness measured by the electric probe increases with an increase in Re_l and a decrease in Re_n , and the value approaches ultimately to that of the clearance δ , see Fig.8.

When Re_l was larger than 800, h_m did not differ in the axial direction. The axial flow of the film seems to be affected not only by the axial difference in the film thickness, but also by the axial flow component of the fillets. Since the latter effects are not necessarily clear in the present experiments, we are planning to make the effects clear.

Since the liquid flows through the film, and when Re_l is small, the fillet little appears in the cylinder, the film

thickness is expected to decrease gradually in the axial direction. Nevertheless a rather small thickness was measured at the upstream position shown in Fig.8, because of the measurement error involved in the small bubbles in the film. As in the case of h_m , the average thickness h_{tm} of the film included the fillet increases with an increase in Re_l and a decrease in Re_n . In accordance with the definition, the value of $(h_{tm} - h_m)$ is proportional to the hold up volume occupied by the fillets.

The occurrence frequencies φ are shown in Fig.9 with respect to Re_l and Re_n , where the data symbols related to Re_n shown in Fig.9 are the same as those in Fig.7, and they also appear in the following figures. φ decreases with a decrease in Re_n and an increase in Re_l . The downstream values in φ are less than the upstream ones. It is desirable in the actual evaporator that the liquid film be distributed uniformly on the heated surface in order to get good heat transfer and to prevent the occurrence of a hot spot. accordingly, the liquid film is expected to work favorably when φ is small.

Small bubbles appear in the liquid film at small volumetric flow rate and at high revolution. With our electric probes, however, we couldn't distinguish these bubbles from the variation of the liquid film thickness, in the effects on the electric resistance.

5.3 Average residence time

The tracer-pulse experiments showed that the axial velocity increased from the upstream to the downstream as shown in Fig.10.

The average residence time measured directly between the positions I and II

Fig.5 Representative example of observed liquid film thickness

Fig.7 Circumferential length of liquid fillets

$Re_l = 8.52 \times 10^2$, $Re_n = 1.18 \times 10^4$
Fig.6 Representative example of observed residence time

was shorter than that calculated from the hold up volume as well as the volumetric flow rate by several per cent. This is considered to be the reason why the latter includes the afore mentioned end effects. These experimental results are arranged as (see Fig.11),

$$T^* = 2.14 \times 10^3 Re_L^{-0.78} Re_N^{-0.45} \quad (4)$$

In the present horizontal evaporator, the residence time is more closely related to Re_L than in the vertical one, and it also depends on Re . In the horizontal one, therefore, the residence time is more controllable than in the vertical one. T^* in the former is larger than that in the latter by nearly three times.

5.4 Degree of mixing

Figure 12 shows the degree of mixing defined by Eq.(2) with Re_L and Re_N as parameters. Since M decreases with Re_N , with a decrease in Re_N the flow approaches to the piston flow and a large axial difference in the concentration is obtained, thus such performances as evaporation and condensation are improved.

When Re_L is small, M decreases with an increase in Re_L as in the vertical one⁽⁴⁾. For $Re_L \geq 300$, however, M is independent of Re_L and 0.32 or 0.22, at the measuring point of 100 mm and 200 mm, respectively. The latter value is less than the vertical ones.

For $Re_L \geq 300$, the fillets grow sufficiently and the film becomes more stable as shown in Figs.8 and 9. This is why the degree of mixing is leveled. And the

Fig.8 Average liquid film thickness

Fig.9 Occurrence frequency

reason why M varies with the distance L^* proportionally to $(L^*)^{-1/2}$ as shown in Eq. (3) is that D/u for a distance L_{II} is larger than that for the over-all distance L_{III} , since the axial dispersion coefficient D decreases toward downstream, and simultaneously the axial flow is accelerated.

5.5 Experiments in a two-dimensional shallow water tunnel

As mentioned above, the height of the fillet close to the blade is almost independent of the volumetric flow rate, the revolution and the axial position. We conducted experiments in a two-dimensional shallow water tunnel shown in Fig.13, for the purpose of finding out clearly how to determine the height of the fillet, and the mixing pattern between the fillet and the film.

The over-all length of the tunnel is 4000 mm, the width 500 mm and the height 150 mm. In the middle of it, a test section of 1000 mm long is set. In the

Fig.10 Accelerated flow

Fig.11 Average residence time

Fig.12 Degree of mixing

tunnel the film thickness is measurable at any point by means of a precision hydrobarometer. The accuracy of the measurement is within 1/20 mm in a range of the film thickness from 0 mm to 25 mm. The bottom plate of the tunnel is adjustable precisely in the vertical direction. A wiping blade is towed on two rails above the tunnel parallel to the bottom by a DC motor through the change gear as well as the chains. The speed range of the blade is from 0.32 m/s. The clearance between the blade tip and the bottom has a constant value of 2.55 mm, see Fig.13.

The height of the fillet close to the blade, h_2 , was measured on the photograph, see Fig.14. The translation velocity of the liquid fillet was detected by photoelectric instruments.

Figure 15 showing the ratio of the height h_2 to the film thickness h_1 with the Froude number, $Fr = V/(gh_1)^{1/2}$, indicates that the theory of the hydraulic jump holds even in the present case, as

$$h_2/h_1 = \{(1 + 8 Fr^2)^{1/2} - 1\} / 2 \quad (5)$$

Assuming that h_1 is nearly equal to δ , in our horizontal straight model, we have

$$Fr = R\omega / (R\omega^2 \delta)^{1/2} = (R/\delta)^{1/2} \quad (6)$$

Thus, the height, h_2 , has to be independent of the volumetric flow rate, the revolution of the blade as well as the axial position, and is very close to the experimental value ($h_2 = 9$ mm), since h_2 is 9.4 mm when the experimental conditions $R = 49$ mm and $\delta = 1$ mm are put into Eqs.(5) and (6). We also tried the flow visualization by the aid of the hydrogen bubble method, and observed a violent mixing between the fillet and the film.

5.6 Modelling of the liquid fillet and the axial thrust

According to the observation, we con-

Fig.13 Two-dimensional shallow water tunnel

Fig.14 Representative example of observed liquid fillet

sider a model of the liquid fillet as shown in Fig.16. Here, the observer is moving with the blade.

The circumferential length of the fillet, L_θ , decreases along the axis. In the circumferential direction, the height changes at the portion of the jump, while the height close to the blade, h_2 , scarcely changes. It is emphasized in the fillet model as shown in Fig.16. Let us consider the force balance which acts on the fillet, in three directions, as shown in Fig.16:

1) Circumferential direction

The relation between the film thickness h_1 and the height close to the blade h_2 is determined by the theory of the hydraulic jump represented in Eqs.(5) and (6).

2) Radial direction

A force caused by the static pressure in the fillet balances with the centrifugal force normal to the casing surface.

3) Axial direction

Referring to the triangular abc - $a'b'c'$ shown in Fig.16, the force caused by the static pressure acts in the axial direction. The axial thrust is considered to be balanced with the shearing force which occurs between the surface abc and the wall when the fillet flows in the axial direction.

Fig.15 Height of liquid fillet

Fig.16 Liquid fillet model and axial thrust

Using the fillet model shown in Fig. 16 and the average residence time shown in Eq.(4), we can get the circumferential length of the fillet averaged in the axial direction. Namely, putting the non-dimensional numbers, T^* and Re_L , into Eq.(4), the hold up is written as

$$W = 5.35 \times 10^2 g^{-1/3} Re_L^{0.22} Re_N^{-0.45} \pi D L \quad (7)$$

On the other hand, using the fillet model, the hold up is given by

$$W = (\pi D h_1 + n h_2 L_{0m}) L \quad (8)$$

From Eq.(7) with Eq.(8),

$$L_{0m} = \pi D (5.35 \times 10^2 g^{-1/3} Re_L^{0.22} Re_N^{-0.45} - h_1) / n h_2 \quad (9)$$

Given experimental conditions as n , D and h_1 , Eq.(9) results in L_{0m} shown in Fig.17. Here h_2 is obtained by using Eq.(5) under an assumption of $h_1 = \delta$.

The curves show quantitatively the effects of the volumetric flow rate and the revolution on the average circumferential fillet length. These values seem to be nearly equal to half of the experimental values, L_{01} , shown in Fig.7.

It is therefore concluded that we can approximately predict L_{0m} from Eq.(9) based on the presented fillet model.

7. Conclusions

Through observations in the horizontal straight model of a thin film evaporator, using water of the room temperature as the working liquid, we have the following conclusions for the flow pattern excluding the thermal effects.

1) The liquid fillet grows and flows with rotation under effect of the centrifugal force, when the film Reynolds number is large than the critical one. Its circumferential length increases with an increase in the volumetric flow rate and with a decrease in the revolution.

Fig.17 Effects of Re_L and Re_N on L_{0m}

2) The height of the liquid fillet close to the blade is independent of the volumetric flow rate, the revolution and the axial position. It agrees with one given by the theory of the hydraulic jump, see Eqs.(5) and (6).

3) The film thickness asymptotically approaches to the value of the clearance between the inner cylinder wall and the tip of the wiping blade, when the volumetric flow rate is larger enough for the liquid fillet to grow. The character of the film comes to be improved with higher volumetric flow rate and lower revolution.

4) The average residence time directly measured by the tracer-pulse method is smaller than the one calculated from the measured values of the hold up and the volumetric flow rates and higher revolutions, and are given by Eq.(4).

5) The mixing character in the axial direction is better than that of a vertical evaporator and comes to be improved with lower revolutions. The degree of mixing diminishes with higher volumetric flow rates. But when the film Reynolds number is larger than the critical one, it is independent of the volumetric flow rate and almost constant.

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