THE EFFECTS OF MULTIPLE INCLINED BLADES ON FLOW AND MIXING CHARACTERISTICS IN AN AGITATED THIN-FILM EVAPORATOR

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The effects of multiple inclined blades on the flow and mixing characteristics of a high-viscosity fluid were investigated in an agitated thin-film evaporator under isothermal conditions. The residence time distribution, mean residence time, material exchange-rate and power consumption were measured, and the effects of the inclined blades on the measured quantities were examined by comparison with the measurements in a vertical-blade evaporator. The results show that the flow and mixing characteristics in the axial direction are almost the same in the inclined-blade evaporator as in the vertical-blade evaporator, and that the mean residence time can be controlled by using inclined blades. Multiple inclined blades can provide almost the same material exchange rate as multiple vertical blades, even when the distance between upper and lower inclined blades is reduced to about half that between vertical blades. The results further show that the power consumption of inclined blades can be reduced to about half that of vertical blades.

Introduction

Agitated thin-film evaporators are widely used in food, petrochemical and pharmaceutical processes which require efficient concentration, deodorization and refining of materials of high viscosity or those subject to thermal decomposition.

The flow structure in an agitated thin-film evaporator consists of fillet flow and film flow.³⁾ Komori *et al.*³⁾ investigated the flow structure and mixing mechanism of high-viscosity fluid in an agitated thin-film evaporator in detail. They showed that the most of the fluid (more than 70% of the total flow-rate) flows down in the fillet with a downward velocity corresponding to 20 times the film fluid velocity. Therefore, fluid mixing between fillet and film is extremely suppressed in a conventional evaporator with a single vertical blade. Furthermore, they suggested that the equipment should be improved to promote fluid mixing or material exchange between fillet and film. More recently, Komori *et al.*⁴⁾ showed that vertically aligned multiple blades can promote better material exchange between fillet and film than can the conventional evaporator with a single vertical blade. The fluid-dynamical results based on the usage of conventional vertical blades also suggest that inclined blades as shown in Fig. 1-(b) more effectively promote the transportation of a high-viscosity fluid

in the axial (downstream) direction than the vertical blade as shown in Fig. 1-(a) and that they can be considered to contribute well to the material exchange of a high-viscosity fluid between fillet and film. Most published studies¹⁻⁶⁾ have been conducted using vertical blades. However, no studies on the effects of

Fig. 1. Schematic diagrams of vertical double blades and inclined double blades

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inclined blades have been reported.

The purpose of this paper is to investigate the ability of inclined blades in an agitated thin-film evaporator with a high-viscosity fluid, and to show experimentally whether the apparatus with inclined blades is really superior to that with vertical blades used in the previous studies.

1. Experiments

Figure 2 shows the experimental apparatus, consisting of an agitated thin-film evaporator and a measuring system. Experiments were conducted under the isothermal flow conditions without evaporation. The apparatus was made of a stainless steel cylinder of 0.5 m length, 0.25 m inner diameter and 50 μ m out of round. **Figure 3** shows the geometries of the inclined blade used here. The blade had an adjustable mechanism and the angle of inclination of the blade, β , could be adjusted to 0, 15, 30 and 45 degrees. The blades were made of stainless steel plate, and were of 0.05 m axial length and 0.003 m thickness. The blades were arranged along the axis of the cylinder and were rotated by a connecting shaft. As a Newtonian high-viscosity fluid, corn syrup was used and was fed from the top of the cylinder vessel by a gear pump at a constant flow rate. The clearance between the blade tip and the cylinder wall was measured by means of an eddy current-type non-contact gap detector (PU-05, Applied Electronics Co., Ltd.) mounted on the cylindrical vessel.

The residence time distribution of the high-viscosity fluid was measured in the apparatus shown in Fig. 2-(a). It was measured by means of an electro-conductivity method. A distributor was mounted on a shaft to uniformly disperse the supplied high-viscosity fluid. A KCl solution of the same viscosity as the supplied fluid was used as a tracer and was fed into the supplied fluid by a piston injector in a moment (a pulse response method). The ratio of the volume of injected tracer to that of supplied fluid held in the apparatus (holdup) was so small (3%) that the effect of the tracer on the flow field could be neglected. The residence time distributions were found to be almost the same at any point just under the blade, so that the measurements were conducted at only one point, just under the blade.

Figure 2-(b) shows the experimental apparatus, consisting of an agitated thin-film evaporator with vertically aligned double blades. It was used for measurements of holdup, material exchange rate and power consumption. Two rotating blades were arranged in line along the axis of the cylinder and were connected to a shaft. The measuring system is also shown in the figure.

The holdup defined by the fluid mass being held in the equipment was measured by simultaneously

Fig. 2. Experimental apparatuses and measuring systems

Fig. 3. Inclined-blade geometry

shutting off the flow at the top and at the bottom of the cylinder.

The concentrations of KCl tracer in the two fillets formed in the upper and lower blade regions were measured by means of an electroconductivity method and the material exchange rate between fillet and film was evaluated from these tracer concentrations. The conductivity probe was made of a platinum wire, and

Table 1. Experimental conditions

Measured quantities	Mean residence time	Residence time distribution	Material exchange rate	Power consumption
Conditions				
μ [Pa·s]	4–99	3	2–104	4–69.8
Γ [kg·m ⁻¹ ·s ⁻¹]	0.015–0.03	0.02–0.03	0.01–0.03	0.01–0.03
u_b [m·s ⁻¹]	5.24–9.17	5.24–9.17	5.24–9.17	5.24–9.17
h_0 [mm]	1.0–1.5	1.0	1.0–1.5	0.5–1.5
β [deg]	–30–45	0–45	0–30	0–45

wire of 0.2 mm outer diameter and 3 mm length was used for fluid with a viscosity of 2–7 Pa·s. For fluid with a much high viscosity of 100 Pa·s, wire of 1 mm outer diameter and 1 mm length was used. The measuring technique is the same as used by Komori *et al.*⁴⁾

Power consumption was measured by a straingage torque transducer attached to a shaft. The net torque was obtained by subtracting the no-load torque from the total torque.

The experimental conditions of the above experiments are listed in **Table 1**.

2. Results and Discussion

2.1 Mean residence time

The mean residence time of the high-viscosity fluid in the apparatus, T_R , is calculated by

$$T_R = H_0 / F_0 \quad (1)$$

where H_0 is the holdup of the fluid being held in the apparatus and F_0 the mass flow rate of the fluid in the apparatus. **Figure 4** shows the measured values of T_R per unit axial length against the inclination angle of the blade β . It is found that the mean residence time, T_R , decreases with increasing β . This suggests that the mean residence time can be controlled by changing the inclination angle β in the range of $-45^\circ < \beta < 45^\circ$. In addition to the above measurements in the viscosity range of 4–7 Pa·s, the mean residence time was measured for the high viscosity of 70 and 99 Pa·s, and its values are shown in Fig. 4 by the closed symbols. The mean residence time for the very high viscosity almost obeys the same relation for the viscosity of 4–7 Pa·s. This suggests that the mean residence time can be controlled over the wide viscosity range of 2–100 Pa·s by using the inclined blade.

2.2 Residence time distribution

Figure 5(a) compares the residence time distribution measured in the vertical-blade apparatus with that measured in the inclined-blade one. It is found that the residence time distribution becomes sharp compared with that in the vertical-blade apparatus. This shows that the axial transporation of the fluid is promoted by the inclined blade. It also means that

Fig. 4. Effect of the inclination angle of the blade, β , on mean residence time, T_R

Fig. 5. Comparisons of measured and normalized residence time distributions for the inclined-blade apparatus with that for the vertical-blade one

the inclined blade effectively acts to transport the high-viscosity fluid in the axial direction, in which it could not be quickly transported by the vertical blade. Figure 5-(b) shows the residence time distribution normalized by $E(\theta) = (C/m) \cdot F_0 \cdot T_R$ against dimensionless time $\theta = t/T_R$. Here m is the quantity of tracer injected into the apparatus, F_0 the mass flow rate in the apparatus and T_R the mean residence time. It is found that the normalized distributions of the residence time are almost the same for the vertical-blade apparatus as for the inclined-blade one. This means that the flow structure and mixing mechanism in the axial direction are similar for the two apparatuses. It also suggests that the inclined blade should be designed to promote fluid exchange between the fillet and film as well as in the case of the vertical blade.⁴⁾

2.3 Material exchange rate

To evaluate the material exchange rate between fillet and film in the inclined-blade apparatus, the material exchange rate, M , was defined by the following equation as in the previous work.⁴⁾

$$M = (C_B - C_A) / (\bar{C} - C_A) \quad (4)$$

Figure 6 shows the material exchange rate, M , measured for the vertically aligned double inclined blades and for a single inclined blade. Here the distance between the double inclined blades, L , was 0.0 m and 0.02 m. It is found that the material exchange rate for the single inclined blade is extremely small compared with that for double inclined blades. The small material exchange rate is attributed to the fact that most of the fluid flows in the fillet without being effectively mixed with the film fluid. In the case of the double inclined blades with a gap distance of $L = 20$ mm the material exchange rate is rather higher than in the cases of the single inclined blade with $L = 0$ mm, and M increases with increasing blade-tip speed, u_b . This shows that the fillet and film formed in the upper blade region are well mixed in the gap region between the vertically aligned inclined blades. It also suggests that the use of vertically aligned multiple inclined blades with a gap may best promote the material exchange between the fillet and film. Figure 7 shows measured values of the material exchange rate, M , against the gap distance between the upper and lower blades, L . The material exchange rate, M , increases with increasing L and reaches a constant value. Hence the optimum distance between the upper and lower inclined blades, L_{opt} , which makes compact axial-size equipment possible, should be defined as the minimum distance where the material exchange rate reaches a constant value. Then the optimum distance, L_{opt} , is 0.016 m for $\beta = 0^\circ$, 0.012 m for $\beta = 15^\circ$ and 0.011 m for $\beta = 30^\circ$, and the material exchange rate, M_{end} (hereafter the final material

Fig. 6. Comparisons of material exchange rate, M , for a single inclined-blade apparatus with that for a double inclined-blade one

Fig. 7. Effect of the distance between the upper and lower blades, L , on the material exchange-rate, M

exchange rate), does not vary so much with the three values of L_{opt} . The results become clearer when L_{opt} is plotted against mixing Reynolds number Re_{M1} and when the final material exchange rate, M_{end} , is plotted against $\Gamma \cdot \mu \cdot u_b^2 / (\rho \cdot g)$. Figure 8 shows that L_{opt} increases with Re_{M1} and can be reduced to about half compared with that of the double vertical blades. Figure 9 shows that the final material exchange rate, M_{end} , for the double inclined blades is almost the same as for the double vertical blades.

2.4 Power consumption

Figure 10 shows the power consumption measured in the apparatus with the inclined blade. Here dimensionless numbers appearing in the ordinate axis mean the best-fit parameters obtained by the apparatus equipped with vertical blade. In this study, these parameters are used to directly compare the power consumption of a vertical blade with that of an inclined blade. The inclination angle of the blade, β , ranged from 15 to 45 degrees. It is found that the

Fig. 8. Correlation between the optimum distance, L_{opt} , and the mixing Reynolds-number, Re_{M1}

Fig. 9. Correlation between the final material exchange rate, M_{end} , for double vertical and double inclined blades, and parameter $(u_b^2 \cdot \mu \cdot \Gamma / (\rho \cdot g))$

Fig. 10. Correlation of the measured power consumption on the mixing Reynolds number, Re_{M2}

power consumption is independent of the inclination angle, but it does depend on the clearance between blade tip and vessel wall, h_0 . The power consumption is well correlated by the dotted lines within $\pm 10\%$ deviation for each clearance:

$$N_p = 195 \cdot R_{eM2}^{-1.2} \cdot R_{eL}^{0.3} \quad (h_0 = 1 \text{ mm}) \quad (5)$$

$$N_p = 180 \cdot R_{eM2}^{-1.2} \cdot R_{eL}^{0.3} \quad (h_0 = 1.5 \text{ mm}) \quad (6)$$

where N_p is the power number, R_{eM2} the mixing Reynolds number, R_{eL} the film Reynolds number. The measurements of power consumption in a wide range of fluid viscosity clearly show that the power consumption in an agitated thin-film evaporator with an inclined blade can be reduced to about half that³⁾ with a vertical blade, shown by a solid line in Fig. 10. It also means that the inclined blade is effective in reducing the energy cost for an actual evaporator. For reference, measurements of power consumption for the very high-viscosity fluid are also plotted in Fig. 10, since they were not shown in the previous paper.³⁾

Conclusions

The effects of the inclined blade on flow and mixing characteristics have been investigated in an agitated thin-film evaporator under isothermal flow conditions without evaporation, and the operating performance of inclined blades were examined by comparing them with that of vertical blades. The main results of this study can be summarized as follows.

- 1) The mean residence time can be controlled by changing the inclination angle of the blade. According to the normalized residence time distribution, the flow structure and mixing mechanism in the inclined-blade apparatus are almost the same as in the vertical-blade one.
- 2) Vertically aligned multiple inclined-blades can more effectively promote material exchange between fillet and film than a single inclined-blade. Even when the distance between the inclined blades is reduced to half the distance between the vertical blades, the final material exchange rate for the multiple inclined blades can almost equal that for the multiple vertical blades.
- 3) The power consumption of the inclined blades can be reduced to about half that of the vertical blades.
- 4) Vertically aligned multiple inclined blades will be more useful both in developing an evaporator of compact axial size and in reducing the energy cost of the evaporator.

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Nomenclature

C_A	= concentration of fillet in upper blade	[mol/l]
C_B	= concentration of fillet in lower blade	[mol/l]
$\bar{C}$	= cross-sectionally averaged concentration in fillet and film	[mol/l]
d	= inner diameter of vessel	[m]
E	= normalized concentration, $E=(C/m) \cdot F_0 \cdot T_R$	[—]
F_0	= volumetric flow-rate in apparatus	[m ³ · s ⁻¹]
H	= axial length of apparatus	[m]
H_0	= holdup	[kg]
h_0	= clearance between blade tip and cylindrical vessel	[m]
L	= distance between upper and lower blades	[m]
L_b	= axial length of blade	[m]
L_{opt}	= optimum distance between upper and lower blades	[m]
M	= material exchange rate between fillet and film	[—]
M_{end}	= final material exchange rate	[—]
m	= quantity of tracer thrown into the apparatus	[mol]
N_P	= power number, $N_P = P/(\rho \cdot (n \cdot d)^3 \cdot h_0 \cdot L_b)$	[—]
n	= rotation number	[s ⁻¹]
P	= power consumption	[J]
R_{eL}	= film Reynolds number, $R_{eL} = 4 \cdot \Gamma / \mu$	[—]
R_{eM1}	= mixing Reynolds number, $R_{eM1} = \rho \cdot n \cdot d^2 / \mu$	[—]

R_{eM2}	= mixing Reynolds number, $R_{eM2} = \rho \cdot n \cdot d \cdot h_0 / \mu$	[—]
t	= time	[s]
T_R	= mean residence time	[s]
u_b	= blade tip speed	[m · s ⁻¹]
Γ	= mass flow-rate per unit peripheral length	[kg · m ⁻¹ · s ⁻¹]
β	= inclination angle of blade	[deg]
θ	= normalized time, $\theta = t / T_R$	[—]
μ	= fluid viscosity	[Pa · s]
ρ	= fluid density	[kg · m ⁻³]

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