FLOW AND MIXING CHARACTERISTICS IN AN AGITATED THIN-FILM EVAPORATOR WITH VERTICALLY ALIGNED BLADES

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The flow structure and mixing characteristics of a high-viscosity fluid in an agitated thin-film evaporator with vertically aligned multiple blades were investigated by measuring the material exchange rate between the fillet and film using an electro-conductivity method. The optimum design of an agitated thin-film evaporator with multiple blades was studied. The results show that vertically aligned multiple blades can strongly promote the material exchange between the fillet and film compared with a conventional single blade. Furthermore, it is shown that the optimum distance between the vertically aligned blades can be determined by the mixing Reynolds number and the number of blades required can be estimated from the material exchange rate.

Introduction

Agitated thin-film evaporators are operated in a vaccum, and the residence time of a solution in the evaporator can be reduced to less than a few seconds. Therefore, agitated thin-film evaporators are more widely used than any other type of evaporator for many applications in the food, polymer, pharmaceutical and petrochemical industries which involve the operations of concentration, deodorization, devolatilization of unreacted residues and refining. In particular, such processes often treat solutions of high-viscosity or heat-sensitive materials, and therefore an agitated thin-film evaporator becomes much more useful. The agitated thin-film evaporator and its applications are described in detail by Leonald[4] and

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Mutzenburg *et al.*[5] This type of equipment has been called "scraped-surface heat exchanger." In this study, however, it is called "agitated thin-film evaporator", because it has a fixed gap between the blade tip and the cylindrical wall.

Figure 1 shows a schematic diagram of the flow field in an agitated thin-film evaporator with high-viscosity fluid. The supplied high-viscosity fluid flows down along the cylindrical shell-wall and is agitated by a rotating blade. The agitation forms both a falling thin film behind the blade and a falling fillet in front of the blade. The thin film consists of both a radial drag flow due to the rotating blade and a downward flow due to gravity. The film over the cylindrical wall may contribute both to heat transfer through the cylindrical wall to the film fluid and to evaporation from the film surface to the atmosphere. The fillet consists of a falling spiral flow and may contribute to material exchange between fillet and film.

Flow and mixing in an agitated thin-film evaporator with a single blade have been studied by many investigators (Kern *et al.*,[2] Godau,[1] Nakamura *et al.*,[7] and Schweizer *et al.*[8]). However, most works have not given the details of flow structure and mixing mechanism in the apparatus. Therefore, they failed to indicate the fault point which dominates the performance of this apparatus and could not suggest how an optimum apparatus should be designed. On the other hand, Komori, Takata and Murakami[3] recently investigated the flow structure and mixing mechanism of a high-viscosity fluid in an agitated thin-film evaporator with a single blade. They showed that the most of the fluid (more than 70% of the supplied fluid) flows down in the fillet and that the material exchange between fillet and film is extremely low. They also indicated that the flow structure reduces the performance of a conventional evaporator with a single blade. Furthermore, Komori *et al.*[3] suggested that the apparatus could be improved by use of vertically aligned multiple blades to promote material exchange between fillet and film.

The purpose of the present study is both to investigate the flow and mixing characteristics in an agitated thin-film evaporator with vertically aligned multiple blades, and to show how the blades should be designed to greatly promote material exchange between fillet and film. An agitated thin-film evaporator with vertically aligned multiple blades is shown in **Fig. 2**. In the appratus, the fillet and film are first formed in the upper-blade region and then are mixed in the region (gap) between the upper and lower blades. The mixed fluid is again distributed by the lower blade to make the fillet and film, and this process is repeated at each stage between the vertically aligned blades. Therefore, material exchange between fillet and film is expected to be promoted by the

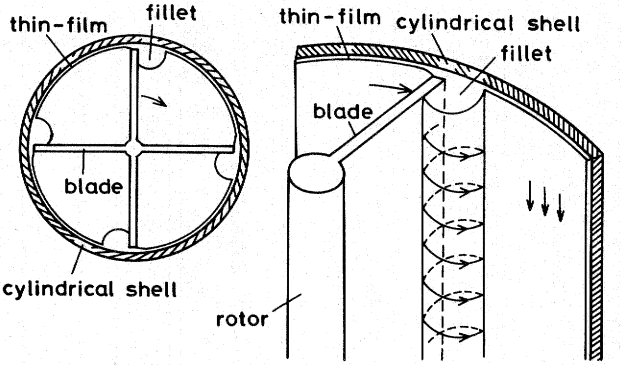

Fig. 1. Schematic diagram of flow field in an agitated thin-film evaporator with high viscosity fluid

repeated agitation. In the present study, an apparatus with vertically aligned double blades was used since the flow structure and mixing mechanism in the region between the two blades are the same as those in any region between the blades of an multiple-blade evaporator, as shown in **Fig. 2**. Experiments were conducted under the isothermal flow condition without evaporation (as in the previous work[3]). The material exchange rate between fillet and film in the region between the upper and lower blades was measured by an electro-conductance method and the material exchange rate of the double-blade apparatus was studied by comparing it with that of a conventional single-blade apparatus. Also, the optimum distance between the upper and lower blades was determined and a method for determining the number of blades required was proposed.

1. Experiments

Figure 3 shows a schematic diagram of the experimental apparatus used here: an agitated thin-film evaporator with vertically aligned double blades and a measuring system. Experiments were conducted under the isothermal flow condition without evaporation. The model apparatus was made of a stainless steel cylinder of 0.5 m length, 0.25 m inner diameter and 50 μm out-of-roundness. Two rotating blades were arranged in line along the axis of the cylinder and were connected to a shaft. The shaft was driven by a motor with a variable speed-driver, and its rotational speed was measured with a tachometer. The distance between the upper and lower blades could be adjusted arbitrarily and was changed from 0 m to 0.03 m. The blades, made of stainless steel plate, were 0.1 m long and 0.003 m in thickness. As the Newtonian high-viscosity fluid, a corn syrup was used. It was fed from the top of the cylinder vessel by using a gear pump operating at a constant flow rate.

The clearance between blade-tip and cylindrical wall was measured with an eddy-current-type gap detector (PU-05, Applied Electronics Co., Ltd.) which was

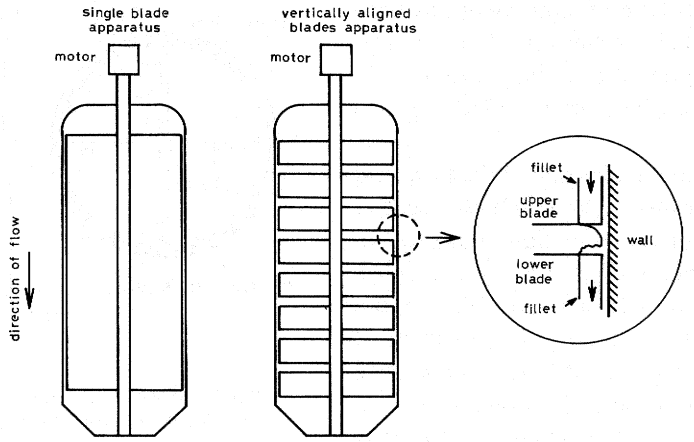

Fig. 2. Schematic diagrams of blade geometries in conventional single-blade apparatus and vertically aligned multiple-blade apparatus

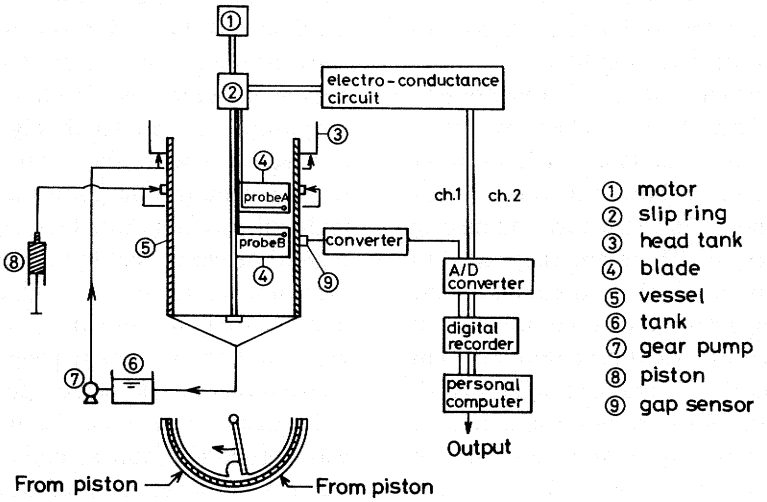

Fig. 3. Experimental double-blade apparatus and measuring system

mounted on the cylinder vessel. The surface of the detector mounted on the cylinder was adjusted to the same level as the inner surface of the cylinder, and therefore the blocking effect of the detector on the flow was negligibly small.

The concentration of the fillet was measured by an electro-conductance method and the material exchange rate between fillet and film in the region between the upper and lower blades was evaluated from concentration measurements. The conductivity probe used here was made of a platinum wire of 0.2 mm outer diameter and 3 mm length. The two probes were mounted respectively on the upper and lower blades where the fillets were formed, and concentration fluctuations of the two fillets formed in the upper- and lower-blade regions were simultaneously measured. The probes were operated at different frequencies (0.5 kHz and 5 kHz) to avoid interference between them.[6] The dimensions of the probe were very small compared to those of the fillet, so that the free surface of the fillet was not deformed by the probe. A KCl solution of the same viscosity as the feeding fluid was used as a tracer and was fed to the film in the upper-blade region at a constant flow rate by a piston injector (a step response method). The ratio of the flow rate of the tracer to that of the feeding fluid was 0.67%, and therefore the effect of the tracer on the flow field could be neglected.

The output signals from probes A and B were filtered respectively by a low-pass filter of 1 kHz and a high-pass filter of 2 kHz to detect the right signal, and then were amplified and rectified. Finally, the signals were transmitted to a digital recorder through and A/D converter and processed by a personal computer. The signals detected by the probes include such small concentration deviations, less than $\pm 4\%$ of the ensemble-averaged concentration, that the ensemble-averaged concentration is almost the same at any point of the fillet. This suggests that the tracer of KCl solution is uniformly dispersed in the fillet. Thus the concentration of the fillet was represented by

the concentration measured at one point in the fillet.

The experiments were conducted by changing the clearance between blade tip and cylinder wall, h_0, the blade-tip speed, u_b, the flow rate per unit peripheral length, Γ, the viscosity, μ, and the distance between upper and lower blades, L. Here h_0 ranged from 1.0 to 1.5 mm, u_b from 5.24 to 9.17 $m \cdot s^{-1}$, Γ from 0.01 to 0.03 $kg \cdot m^{-1} \cdot s^{-1}$, μ from 2 to 7 $Pa \cdot s$ and L from 0 to 0.03 m. The range of blade-tip speed was almost the same as that of an industrial evaporator.

2. Results and Discussion

2.1 Material exchange-rate

To evaluate the material exchange-rate between fillet and film in the region between the upper and lower blades, the material exchange rate, M, was defined by

$$M=(C_{f,B2}-C_{f,A2})/(\bar{C}-C_{f,A2}) \qquad (1)$$

The material exchange rate can quantitatively indicate how much film fluid in the upper-blade region is mixed into the fillet in the lower-blade region.

Figure 4 shows a comparison of the measured material exchange rate, M, of the vertically aligned double-blade apparatus (hereafter DBA) with that of the single-blade apparatus (hereafter SBA). Here the distance between the two blades was 0.02 m for DBA and 0.0 m for SBA. It is found that the material exchange rate of SBA is extremely small compared with that of DBA and that it does not depend on the flow rate per unit length or the blade tip-speed. The small material exchange rate of SBA can easily be explained from the numerical predictions based on a Lagrangian random-walk model used by Komori *et al.*[3] This also means that in a conventional single-blade evaporator most of the fluid flows down in the fillet without effective mixing with the film. In the case of DBA, the material exchange rate is rather high and increases with increasing u_b. This shows that the fillet and film in the upper-blade region are well mixed in the region between the vertically aligned blades. This also suggests that the use of vertically aligned multiple blades may be most effective in substantially promoting material exchange between fillet and film, and that most of the supplied fluid may be effectively evaporated in the film region of a multiple-blade evaporator.

2.2 Optimum distance between the vertically aligned blades

The distance (gap) between the upper and lower blades in DBA was changed from 0 m to 0.025 m by moving the lower blade and the material exchange rate was evaluated by measuring the concentrations of the tracer in the fillets in both the upper- and lower-blade regions. **Figure 5** shows the measured values of the material exchange rate, M, against the

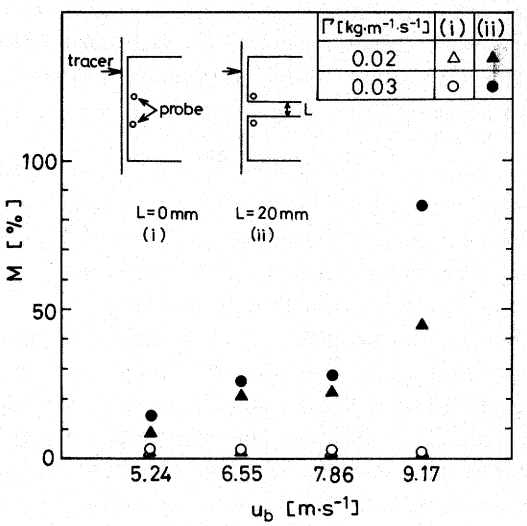

Fig. 4. Comparisons of material exchange rate, M, of a single-blade apparatus with that of a double-blade apparatus

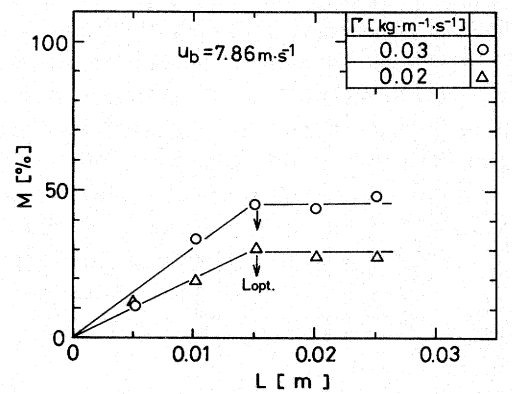

Fig. 5. Influence of distance between upper and lower blades, L, on material exchange rate, M

distance between the upper and lower blades, L. It is found that the material exchange rate increases with increasing L and reaches a constant value. Here, the smaller distance between the vertically aligned blades is better in both developing compact axial-size equipment and reducing the initial cost of the apparatus. In this sense, the optimum distance between the upper and lower blades $L_{opt.}$, should be defined as the minimum distance where the material exchange rate reaches a constant value. From **Fig. 5**, it is found that the optimum distance is about 0.015 m. The same behavior of the material exchange rate was observed under all experimental conditions. **Figure 6** shows the values of the optimum distance between the vertically aligned blades, $L_{opt.}$, against the mixing Reynolds number, Re_M. Here the conventional mixing Reynolds number, Re_M, was used, because the optimum length, $L_{opt.}$, can be better correlated by the conventional mixing Reynolds number than by the film Reynolds number or the mixing Reynolds number with clearance. The optimum distance, $L_{opt.}$, slightly

increases with increasing mixing Reynolds number, Re_M, but it does not depend on the clearance, h_0. It is also found that the optimum distance is correlated with the solid line in **Fig. 6**:

$$L_{opt.} = 0.005 \cdot Re_M^{1/4} \text{ [m]} . \quad (2)$$

These results well show how the distance between the blades of a multiple-blade evaporator should be determined from the mixing characteristics.

2.3. Calculation of number of blades

The second problem in the design of a multiple-blade evaporator is how the number of vertically aligned blades to attain complete mixing between fillet and film. To address this problem, a numerical simulation was adopted. The simulation used the assumption that the material exchange-rate M is always the same at every stage. This assumption is based on the fact that the flow structure and mixing mechanism are the same at every stage. When the material exchange rate in the region between the vertically aligned blades and the ratio of the flow rate in the thin film to the total flow rate are denoted by M and ϕ_m, respectively, the concentration of the fillet in the n-th blade region, $C_{f,n}$, can be given by the concentration of the thin film in the $n-1$ th blade region, $C_{m,n-1}$, as shown in **Fig. 7(a)**. From the expression, together with the initial conditions of $C_{m,1}=1$ and $C_{f,1}=0$, the concentration of the fillet at each blade can easily be calculated by use of the procedure shown in **Fig. 7(b)**. If the concentration of the fillet, $C_{f,n}$, reaches the cross-sectionally averaged concentration over the horizontal plane of the fillet and film, $\bar{C}$, it shows that all of the fluid initially fed into the apparatus has passed the film region. **Figure 8** shows the distributions of the concentration of the fillet normalized by $\bar{C}$, C_f^*, against the number of blades, N. It is found that the normalized concentration of the fillet, C_f^*, depends on the material exchange rate M. For the smaller material exchange rate of $M<0.3$, C_f^* cannot reach unity for fewer than 10 blades. On the other hand, for values of $M>0.5$, C_f^* rapidly increases in the range of $N<7$ and reaches unity at $N=7$. These results show that the number of blades can easily be determined from **Fig. 8** against an arbitrary value of M. Also, an actual multiple blade evaporator should be operated under the condition of $M>0.5$, and in that sense a number of blades fewer

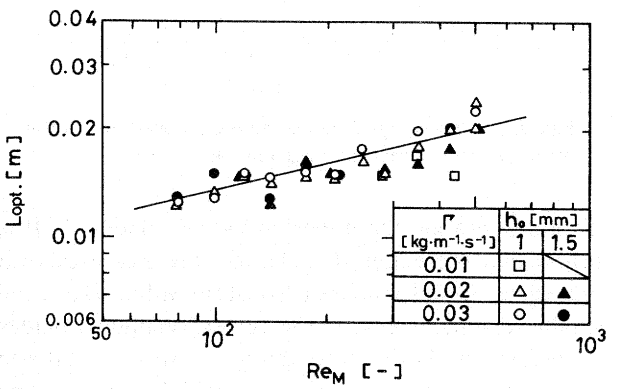

Fig. 6. Correlation between optimum distance, $L_{opt.}$, and mixing Reynolds number, Re_M

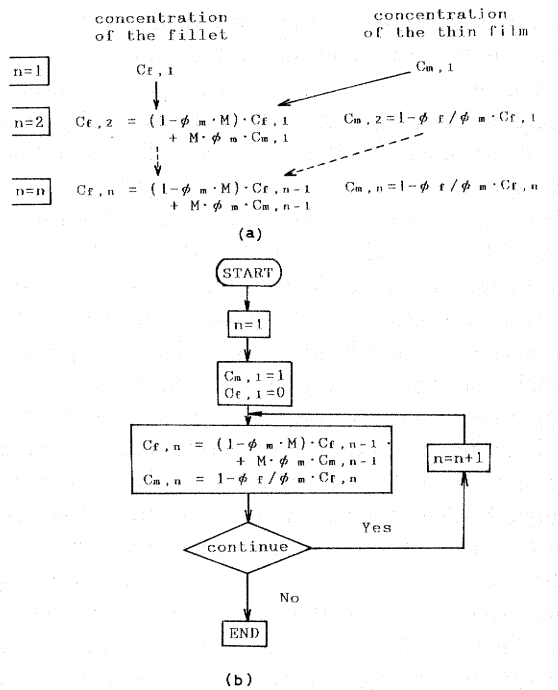

Fig. 7. Calculation procedure for number of blades

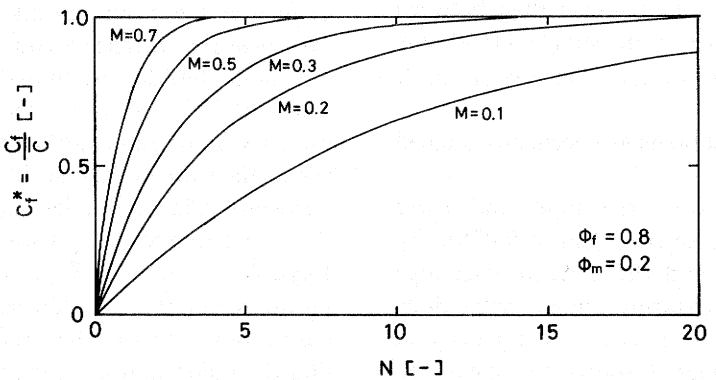

Fig. 8. Relationship between normalized concentration of fillet, C_f^*, and number of blades, N

than seven is recommended.

Conclusions

The flow structure and mixing characteristics of a high-viscosity fluid in an agitated thin-film evaporator with vertically aligned multiple blades were investigated under the isothermal flow condition without evaporation and the optimum design of the evaporator was studied. The main results of this study can be summarized as follows.

(1) Vertically aligned multiple blades can strongly promote material exchange between fillet and film, thus increasing the efficiency of the equipment.

(2) The optimum distance between the vertically aligned blades can be determined by the mixing Reynolds number. The number of blades depends on the material exchange rate, but it can be numerically calculated by use of the material exchange rate and the ratio of the flow rate in the film to the total flow rate.

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Nomenclature

C_f	=	concentration of fillet	[mol/l]
$C_{f,A2}$	=	concentration of fillet detected by probe A after releasing tracer	[mol/l]
$C_{f,B2}$	=	concentration of fillet detected by probe B after releasing tracer	[mol/l]
C_f^*	=	normalized concentration of fillet, $C_f^*=C_f/\bar{C}$	[—]
C_m	=	concentration of thin film	[mol/l]
$\bar{C}$	=	cross-sectionally averaged concentration over the horizontal plane of fillet and film	[mol/l]
d	=	inner diameter of cylindrical vessel	[m]
h_0	=	clearance between blade tip and cylinder wall	[m]
L	=	distance between upper and lower blades	[m]
$L_{opt.}$	=	optimum distance between upper and lower blades	[m]
M	=	material exchange rate defined by Eq. (1)	[—]
N	=	number of blades	[—]
n	=	rotation number	[s^{-1}]
Re_M	=	mixing Reynolds number, $Re_M=n\cdot d^2/\nu$	[—]
u_b	=	blade-tip speed	[$m\cdot s^{-1}$]
Γ	=	flow rate per unit peripheral length	[$kg\cdot m^{-1}\cdot s^{-1}$]
μ	=	fluid viscosity	[Pa·s]
ν	=	kinematic viscosity	[$m^2\cdot s^{-1}$]
ϕ_f	=	ratio of flow rate in fillet to total flow rate	[—]
ϕ_m	=	ratio of flow rate in thin film to total flow rate	[—]

〈Subscript〉

n	=	n-th blade

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