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Heat and Mass Transfer Model for an Internally-circulating Falling-liquid-film Type Multi-stage Evaporator/Distiller

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A novel continuous, multi-staged falling-liquid-film type evaporator/distiller has been developed making use of the advantageous surface-renewal effect of the Wall-Wetter device. By using the heat transfer correlations useful for evaluating the evaporative heat transfer coefficient, this study constructed a heat and mass transfer simulation model of the depressurized distillation for concentration of high-boiling-point mixtures.

1. Introduction

The Wall-Wetter device (Noda et al. 2006) developed for a batch evaporation process has the characteristics that the process liquid pooled in a tank is pumped up due to the centrifugal effect of the rotating Wall-Wetter wings and forms an internally-circulating stream of falling-liquid-film inside the evaporator vessel. This batch evaporator has an excellent advantage of energy saving and reduction of evaporation time due to the fact that the evaporating rate can be kept at a high constant rate during the whole process time by maintaining the whole heat transfer surface always wet with the internally circulating process liquid. In addition, the surface-renewal effect results in an evaporative heat transfer augmented due to the periodically impinging liquid jet issuing from the upper edges of the rotating Wall-Wetter wings (Mukaida et al. 2018). By making use of these advantageous effects, a new multi-staged evaporator has been developed for continuous evaporation processes. This study proposes a heat and mass transfer model appropriate for process simulation analysis on purification of high-boiling-point fatty acid esters.

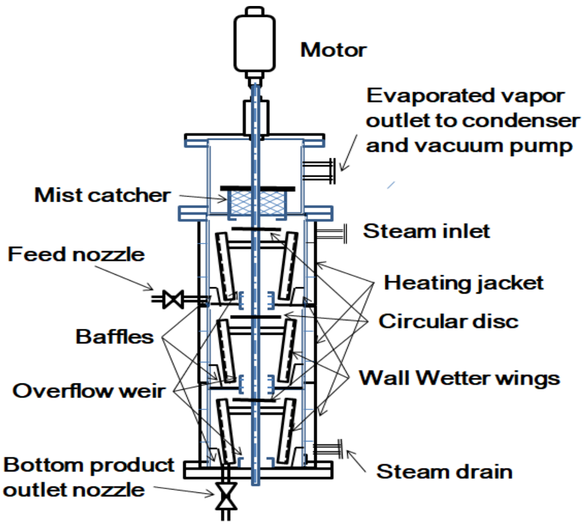


Figure 1: Standard type test equipment

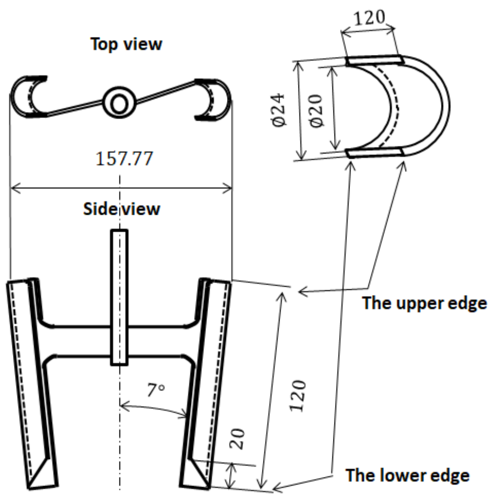


Figure 2: Structure of a Wall-Wetter wing

2. Equipment: structure and its characteristic functions

Figure 1 shows a standard-type three-staged evaporator/distiller. A liquid mixture to be distilled is fed onto the first stage tray. A Wall-Wetter wing, shown in Figure 2, equipped in each stage pumps up the liquid pooled on the tray due to centrifugal effect and its liquid jet issuing from the upper edges of the Wall-Wetter wing forms a periodically-disturbed falling liquid film on the inside cylindrical heat transfer surface, where heat and mass transfer takes place. A certain rate of the liquid pooled in each stage is overflowed beyond the central hole weir and flows down onto the next stage rotating circular disk, and due to its centrifugal effect, another falling liquid film is formed in the stage. In such a manner, the liquid pooled in the third stage bottom is withdrawn as the bottom product. On the other hand, the vapor generated by evaporation from the falling liquid film of each stage flows upward through the central hole, and then is condensed as the overhead product in the overhead condenser, where the operating pressure is controlled by a vacuum pump. The heat input is given from each stage steam jacket as a side-heater.

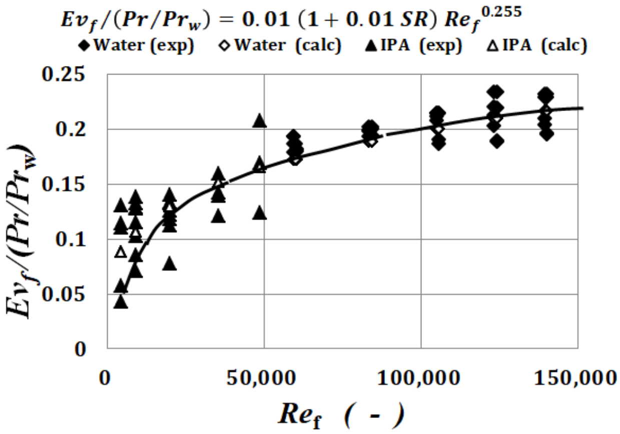


Figure 3: Experimental correlations of evaporative heat transfer coefficient against film Reynolds number (Mukaida et al. 2018)

Figure 3 shows the heat transfer correlation obtained by the previous evaporation experiment (Mukaida et al., 2018). The correlation equation is given by

$$Ev_f = 0.01(1+0.01SR)\,Re_f^{\,0.255}\,(Pr/\;Pr_W) \tag{1}$$

where the dimensionless evaporative heat transfer group is given by the following defining equation:

$$Ev_f = h_{EV}\left(\frac{\mu^2}{\rho_L{}^2 g \kappa_f{}^3}\right)^{1/3} \tag{2}$$

Here the evaporative heat transfer coefficient is defined as $h_{EV} = \kappa_f / \delta$ by using the film thickness.

The Pr and Pr_w are the Prandtl numbers for test fluid and water, respectively, and $Re_f = 4\Gamma/\mu$ the film Reynolds number.

The surface renewal factor is defined in a form of the Strouhal number

$$SR = n_{ww} f_{SR} D_i / \; v_{av} \tag{3}$$

where n_{ww} is the number of Wall-Wetter wings, f_{SR} the frequency of surface-renewal motion, D_i the inside diameter of evaporator vessel, and v_{av} the average velocity of falling liquid film.

The liquid flow rate pumped up by the Wall-Wetter wings can be calculated by using the following correlation obtained by the previous experiment (Yamaji, 2002, Mukaida et al. 2018)

$$V_{cir} = 1.309\left(D_t/2\right)^{0.613}\left[g^2+\left(r\omega^2\right)^2\right]^{-0.69}\left[g\left(h-h_0\right)\right]^{1.89} \tag{4}$$

Here as shown in Figure 4, h is the height of liquid pool, h_0 the critical liquid height, r the radial distance from the rotation axis at h_0, D_t the inside diameter of Wall-Wetter gutter, ω the angular velocity of Wall-Wetter wings. Therefore the film Reynolds number is obtained by

$$Re_f = \frac{4\Gamma}{\mu} = \frac{4\rho_L V_{cir} / (\pi D_i)}{\mu} \quad (5)$$

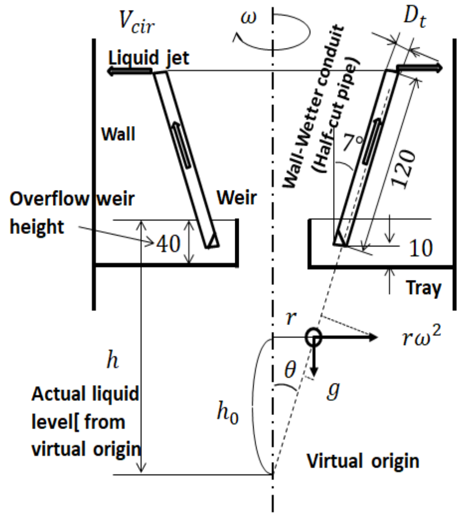


Figure 4: Calculation of flow rate of liquid pumped up by a Wall-Wetter conduit (Mukaida et al. 2018)

3. Modelling and specified problem for process simulation analysis

This distiller system can be regarded as a kind of stripping columns: the feed to be distilled is supplied on the first (top) stage tray, the vapor issuing from the top stage is directed to the overhead condenser, and usually the reflux flow is not used. Each stage steam jacket can be considered as a side heater. The purified product is obtained as the product withdrawn from the bottom stage. This bottom stage has a side heater but does not have a reboiler.

In a manner similar to McCabe-Thiele stage-by-stage calculation based on the equilibrium stage model, process simulation analysis was performed by adding a side-heater to each stage. The heat input to the falling liquid film from the steam jacket is given at *i*th stage by

$$Q_i = U_i A_i (T_{ji} - T_{fi}) \quad (6)$$

Since the steam-jacket-side heat transfer resistance h_j^{-1} at each stage is sufficiently small owing to the condensation heat transfer. The overall heat transfer coefficient at *i* stage is obtained from the relation:

$$U_i = \left[\frac{1}{h_{EVi}} + \frac{\delta_{ti}}{\kappa_t} + \frac{1}{h_{ji}} \right]^{-1} \quad (7)$$

Assuming each stage to be in equilibrium, the model is constituted by the following set of mass and enthalpy balance equations:

(top stage)

$$\begin{aligned} M_{1k} &= V_{1k} y_{1k} + L_{1k} x_{1k} - V_{2k} y_{2k} - F x_F = 0 \\ E_1 &= V_1 H_{V1} + L_1 H_{L1} - V_2 H_{V2} - F H_{LF} - Q_1 = 0 \end{aligned} \quad (8)$$

(second stage)

$$\begin{aligned} M_{2k} &= V_2 y_{2k} + L_2 x_{2k} - V_3 y_{3k} - L_1 x_{1k} = 0 \\ E_2 &= V_2 H_{V2} + L_2 H_{L2} - V_3 H_{V3} - L_1 H_{L1} - Q_2 = 0 \end{aligned} \quad (9)$$

(bottom stage)

$$\begin{aligned} M_{3k} &= V_3 y_{3k} + W x_W - L_2 x_{2k} = 0 \\ E_3 &= V_3 H_{V3} + W H_{LW} - Q_3 = 0 \end{aligned} \quad (10)$$

where the bottom stage has a side heater input Q_3 but does not have a reboiler.

As an example of high-boiling-point mixtures, a binary mixture of methyl-oleate (NBT = 343.85℃) and ethylene-glycol (NBT = 197.3℃) is tested by the following depressurised continuous distillation.. The evaporative heat transfer coefficient is estimated using the heat transfer correlations shown in Figure 3.

[Problem] The process simulation problem adopted is how a high purity methyl-oleate can be obtained from the feed of 3 kmol/h binary mixture (methyl-oleate 96.667 mole % and ethylene-glycol 3.333 mol%). Owing to the non-disclosure agreement, these substances were adopted as the imitated test mixture instead of the real high-boiling-point substances. The operation pressure is kept at 1 mmHg for lowering the bubble point of the mixture. When Re_f = 58,530 (rotation number N = 220 rpm), the evaporative heat transfer coefficient is evaluated as h_{EV} = 2063.7 W/m^{2}K within the overall transfer coefficient U = 1417.7 W/m^{2}K.

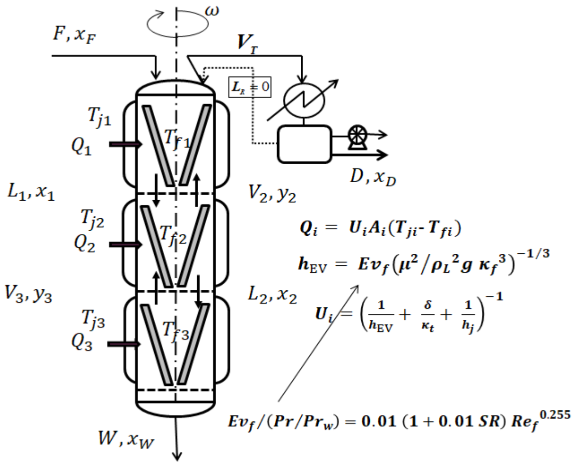


Figure 5: Schematic 3-stage evaporator, showing variables for process simulation

The composition of the feed supplied at 90℃ is a mixture of 2.9 kmol/h of methyl-oleate and 0.1 kmol/h of ethylene glycol. The drawing rate W kmol/h of the bottom product is a control parameter which influences the purity of the bottom product. In this operating condition, the heat input is given to each stage steam jacket: $Q_1 = 101.0$ MJ/h, $Q_2 = 29.3$ MJ/h, $Q_3 = 20.9$ MJ/h, respectively.

4. Process simulation analysis

4.1 Calculation results

Figure 6 shows a schematic picture of the calculation result obtained when the drawing rate of the bottom product $W = 2.775$ kmol/h. In this condition, the purity of the product 99.999 mol% of methyl-oleate has successfully been obtained. The recovery factor of methyl-oleate is 95.7%. The remaining methyl-oleate 0.125 kmol/h is discharged in the overhead product $D = 0.225$ kmol/h.

The temperature of the falling liquid film becomes 146.8℃ at the top stage, 156.3℃ at the second stage, and 156.8℃ at the bottom stage.

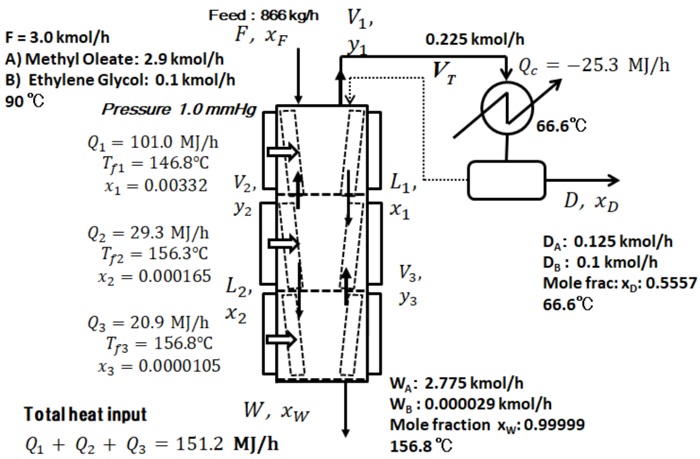


Figure 6: Result of process simulation analysis obtained when the drawing rate of bottom product is controlled at 2.775 kmol/h

The total heat duty amounts to

$$Q_{total} = Q_1 + Q_2 + Q_3 = 151.2 \text{ MJ/h} \tag{11}$$

4.2 Effect of bottom product drawing rate on product purity

Figure 7 indicates that the impurity of the bottom product clearly decreases with the decreasing drawing rate of the bottom product. This suggests that the purity of methyl-oleate product can be improved greatly if the drawing rate is decreased with the lowering recovery factor. To elevate the purity of the methyl-oleate product implies that some portion of methyl-oleate is discharged from the overhead product.

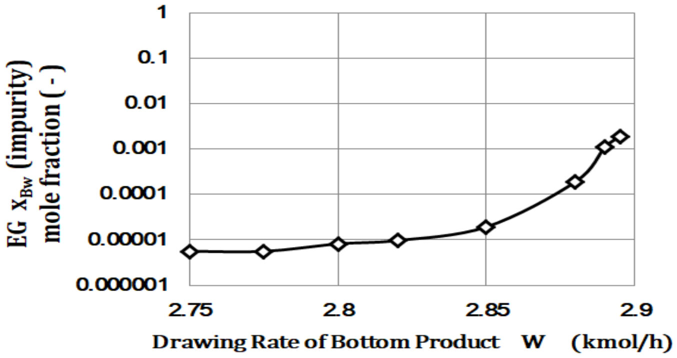


Figure 7: Variation of product impurity with bottom product drawing rate

4.3 Effect of bottom product drawing rate on total heat duty

As shown in Figure 8, it is natural that the total heat duty decreases gradually with the decreasing drawing rate. This is due to the fact that the reflux ratio is always kept zero in the operating condition.

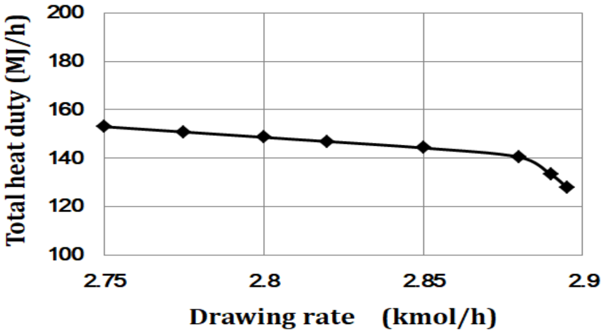


Figure 8: Variation of total heat duty with bottom product drawing rate

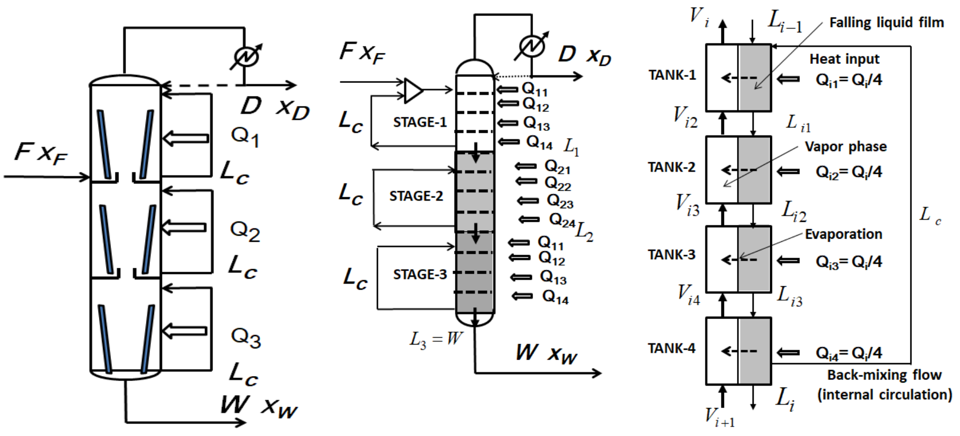
5 Back-mixing effect due to internally circulating flow

5.1 Simulation analysis by tank-in-series model

This flow system has the following two characteristic effects: (1) elongation of the residence time or the contact time for evaporation and (2) back mixing effect due to the internally-circulating flow caused by the Wall-Wetter device installed in each stage. It is necessary to examine the back mixing effect in the falling liquid film since a portion of the liquid reaching the bottom is pumped up again to the top of the same stage.

Figure 9 shows a schematic configuration of modelling for examining the effect of back-mixing. The flow rate of internally circulating flow L_c kmol/h is caused by the rotating Wall-Wetter.

In order to take into consideration the vertical variation in flow rate of the falling liquid film within each stage, as shown in Figure 9(b), the tank-in-series model was applied by dividing each stage into four tanks in series. The liquid pooled in each tank is assumed to be well-mixed. In a manner similar to the above process simulation analysis, the effect of back-mixing was examined by means of the tank-in-series mode using the ratio of the back mixing rate to the feed rate L_c/F as a control parameter.



(a) (b) overall column STAGE - i

Figure 9: Schematic configuration of internally circulating flow
(a) Standard basic flow *(b) Tank-in-series model accompanied with feedback lines*

5.2 Influence of circulating flow on product purity

The effect of back mixing was evaluated by the product purity. Figure 10 gives the calculation result.

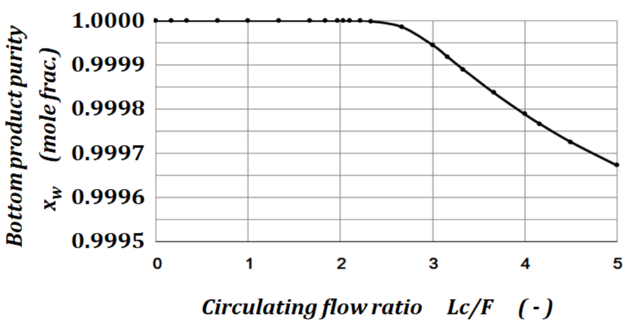


Figure 10: Effect of internally-circulating flow on purity of bottom product

It has been confirmed that the purification process may go down when the back-mixing parameter goes beyond 2.5. This suggests that the liquid flow rate pumped up by the Wall-Wetter wings should not exceed a certain critical value such as $L_c / F = 2.5$.

6 Conclusions

By utilizing the experimental flow and heat transfer correlations, the heat and mass transfer model proposed has successfully demonstrated to give an appropriate process simulation analysis to a newly developed continuous Wall-Wetter evaporator/distiller for purification process of methyl-oleate from a binary mixture of methyl-oleate and ethylene glycol. The calculation results suggest that desirable purity of the methyl-oleate product can be achieved depending on the drawing rate of the bottom product. However the tank-in-series model talking into account the back-mixing effect also suggests that the circulating flow-rate parameter has a certain critical value and that the product purity goes down if going beyond it. Much still remains in the simulation model to be examined by the experimental investigation.

References

Mukaida T., Kataoka K., Yamaji H., Noda H. and Ohmura N., 2018, Evaporative Heat Transfer Characteristics of a Novel Continuous, Multi-Staged Evaporator/Distiller with Unsteady Falling Liquid Film Flow (in Japanese), Kagaku Kogaku Ronbunshu, 44, 107 – 112.

Noda H., Mukaida T., Kaneda M., Yamaji H. and Kataoka K., 2006, A High-Efficiency Distillatiopn System for Batch or Semi-batch Chemical Reactors, Distillation & Absorption 2006, IChemE, 745 – 753.

Yamaji H., 2002, Fundamental study on Development and Design of Wall Wetter Evaporator, Doctor Dissertation (in Japanese), Kobe University, Kobe, Japan.