

THE FILM CONDENSATION OF MIXED VAPOUR IN A VERTICAL COLUMN

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Abstract—In the film condensation of mixed vapour, the heat-transfer coefficient for the liquid film is given by the same equation as previously presented for the condensation of pure vapour. The dependence of the mass-transfer coefficient in vapour phase upon the rate of condensation is explained by the film theory, but for the mass transfer in liquid film, the agreement of the experimental values of the mass-transfer coefficients with the values calculated on the basis of the penetration theory is excellent.

NOMENCLATURE

<p>C, molar concentration [kg-mole/m³];</p> <p>C_p, specific heat [kcal/kg-mole °C];</p> <p>D, diffusion coefficient [kg-mole/m h];</p> <p>g, gravitational acceleration [m/h²];</p> <p>h, heat-transfer coefficient in liquid film [kcal/m² h °C];</p> <p>h_g, heat-transfer coefficient in gas phase [kcal/m² h °C];</p> <p>k, thermal conductivity [kcal/m h °C];</p> <p>K_y, total mass-transfer coefficient based on vapour mole fraction [kg-mole/m² h Δy];</p> <p>k_x^*, mass-transfer coefficient in liquid phase defined by equation (10) [kg-mole/m² h Δx];</p> <p>k_y, mass-transfer coefficient in vapour phase [kg-mole/m² h Δy];</p> <p>k_y^*, mass-transfer coefficient in vapour phase defined by equation (6) [kg-mole/m² h Δy];</p> <p>L, length of wetted wall [m];</p> <p>l, distance in vertical direction [m];</p> <p>M, molecular weight;</p> <p>N, rate of mass transfer [kg-mole/m² h];</p> <p>N_{cond}, condensation number, $h(\mu_l^2/k_l^3\rho_l^2g)^{1/4}$;</p> <p>$N_{\text{ReL}}$, liquid film Reynolds number, $4\bar{\Gamma}/\mu_l$;</p> <p>N_{ReV}, vapour Reynolds number, Gd/μ_v;</p> <p>N_{Sh}, Sherwood number, $k_y d/D_v$;</p>	<p>q, heat flux per unit area [kcal/m² h];</p> <p>T, temperature [°C];</p> <p>ΔT_v, temperature difference in vapour phase [°C];</p> <p>t, time [h];</p> <p>x, mole fraction in liquid phase;</p> <p>y, mole fraction in vapour phase;</p> <p>Γ, liquid flow rate per unit perimeter [kg/m h];</p> <p>Γ_0, liquid flow rate per unit perimeter at the top of test section [kg/m h];</p> <p>λ, heat of vaporization [kcal/kg-mole];</p> <p>Φ, N_l/k_y;</p> <p>μ, viscosity [kg/m h];</p> <p>ρ, density [kg/m³];</p> <p>θ, k_y^*/k_y.</p> <p>Subscripts</p> <p>A, component under consideration;</p> <p>i, vapour-liquid interface;</p> <p>l, liquid phase;</p> <p>loc, local;</p> <p>t, total;</p> <p>v, vapour phase;</p> <p>w, wall;</p> <p>*, equilibrium.</p>
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1. INTRODUCTION

CONDENSATION of mixed vapour composed

of condensable component has been practically used in the industry as a fractional condenser in the distillation column. The process of the film condensation of mixed vapour on a cooling surface involves the mass transfer as well as the heat transfer.

The problem was treated by Colburn and Drew [1] who first analysed it theoretically on the basis of the film theory. Kent and Pigford [2] adapted the concept of transfer unit to the partial condensation process, and related the number of transfer units to the liquid-phase and vapour-phase resistances, the surface area, and the amount of condensation. Kirshbaum and Tröster [3, 4] observed that the degree of distillation in partial condensation is affected by the vapour velocity and the amount of condensation. Van Es and Heerjes [5, 6] developed the theory of mass transfer in the condensed film, and obtained the qualitative agreement between the experimental and the theoretical results. Mirkovich and Missen [7] showed that the heat-transfer coefficients for the filmwise condensation of mixed vapour are smaller than those of pure vapour. The effects of the molecular weight difference of diffusing components and the Ackermann factor upon the mass-transfer coefficient for condensation of mixed vapours were considered by Estrin *et al.* [8].

Since the rate of condensation of vapour composed of only condensable components is comparatively large, the influence of bulk flow to the mass flux in the direction normal to the cooling surface should be considered. The condensation of mixed vapour may be considered as a high mass transfer phenomenon. The transfer coefficients for the high mass transfer rates were derived on the basis of the film, the penetration, and the boundary-layer theories described as in the textbook by Bird *et al.* [9]. The experimental work on the condensation of mixed vapour in the light of the high mass-transfer rates was carried out by Drew *et al.* [8].

This paper refers to the experiments on con-

densation of mixed vapour on a wetted wall column. The rate of condensation, the vapour velocity, and the length of column were varied. The concentration at the vapour-liquid interface was estimated by the interfacial temperature, and the over-all mass-transfer operation during condensation was divided into the mass transfer in the vapour phase and the liquid phase. The mass-transfer coefficients in the vapour phase and the liquid phase were investigated in the light of high mass transfer phenomenon.

2. EXPERIMENTAL APPARATUS AND METHOD

The apparatus used in this investigation is shown schematically in Fig. 1. It consisted

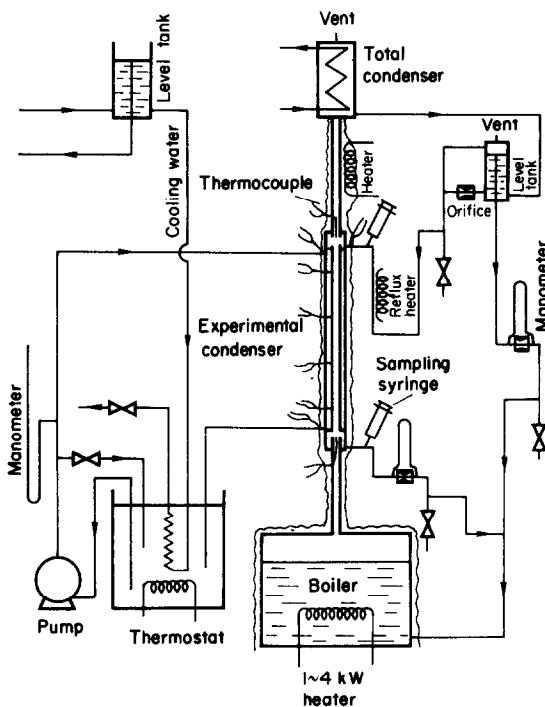


FIG. 1. Experimental apparatus.

essentially of a boiler, an experimental condenser, and a total condenser. A wetted wall column equipped with an annular jacket was used as the experimental condenser described above. The cooling water with a fixed tempera-

ture controlled by a thermostat was circulated through the jacket, and the wall of the column was maintained at a constant temperature to obtain the uniform condensation over the test section. The four wetted wall columns of 330, 830, 1330 and 1830 mm in length of the test section with i.d. 21 mm were used. The column was made from copper pipe around which copper wire was wound in spiral with 30 mm pitch. Chromel–alumel thermocouples were imbedded in the outside of the pipe to measure the temperature of the wall.

Mixed vapour of methanol–water was generated in the boiler by electrical heating, and the generated vapour velocity was controlled electrically. Passing through the test section counter-currently to the liquid film flowing down along the column wall, the vapour was partially condensed on the surface of the liquid film. The vapour which did not condense in the test section was perfectly liquefied in the total condenser.

A part of the condensate from the total condenser was returned to the test section as a reflux. A constant flow rate of the reflux liquid was ensured by using a constant level tank and a orifice flow meter. The temperature of the reflux liquid was kept constantly close to the boiling point by an electric heater.

It was found that an approximate equilibrium state was established in about 3 h after the vapour began to flow through the test section. After an equilibrium state had been established, it was maintained for more than an hour; and then the temperatures of vapour at the inlet and the outlet of the test section, the reflux, the wall of the column, and the cooling water at the inlet and the outlet of the test section, were measured by thermocouples. Liquid samples were taken from the top and the bottom of the test section. Further, the flow rates of the reflux, the liquid from the bottom of the test section, and the liquid returned from the level tank to the boiler were measured by weighing the liquid samples which were collected for a fixed time. It was also checked with the orifice flow meters

at the same time. Analysis of the composition of the samples from the top and the bottom of the test section were carried out by determining the refractive index of each sample by means of the Abbe refractometer.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Heat transfer in liquid film

In this experiment, liquid was returned to the top of the test section as the reflux, and flowed down as a thin film along the column wall. Mixed vapour was condensed on the surface of the liquid film. In the case of the ordinary film condensation on a vertical wall, there is considerable change in the flow rate of the condensate from zero at the top to some value at the bottom of the wall. On the other hand, in the present case with the reflux, the flow rate of liquid on the wall does not change so much over the length of the test column.

For the film condensation of mixed vapour on a vertical wall in steady state, the profiles of the temperature and the concentration in the liquid film and the vapour phase are shown schematically in Fig. 2. It is allowable to assume

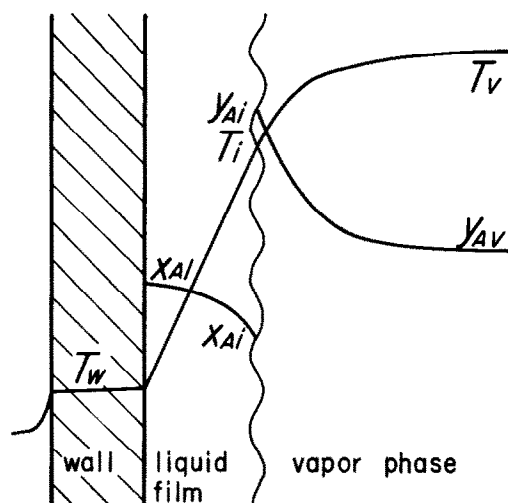


FIG. 2. Temperature and concentration profiles in the vapour phase and in the liquid film.

that the sensible heat transferred by the fluid flow is negligible as compared with the heat flux through the wall. The heat flux through a unit area of the wall q_w is given as the sum of the latent heat q_λ which is evolved by the condensation of vapour at the vapour-liquid interface, and the heat flux q_v which is transferred by conduction from the vapour phase to the interface. It can be written as follows [1]:

$$q_w = q_\lambda + q_v = N_t \lambda + h_g (T_v - T_i) \frac{a}{1 - e^{-a}} \quad (1)$$

where $a = N_t C_p / h_g$ and N_t is the rate of condensation. The heat transfer coefficient h_g in the vapour phase was calculated by the conventional experimental equation described in [10]. The value of q_v calculated by the value of h_g is that of order of 10 kcal/m²h. On the other hand, q_λ is that of order of 10³ kcal/m²h in this experiment. Thus almost all of the heat flux through the wall will be ascribed to the latent heat evolved at the vapour-liquid interface of the liquid film. It seems, therefore, that the resistance of the liquid film is controlling the heat transfer between vapour and the wall. In Fig. 3, q_λ is plotted against $T_v - T_w$ which is the temperature difference between the bulk of vapour and the wall.

The rate of the condensation, that is the liquid flow rate on the wall was changed by varying the temperature difference $T_v - T_w$. The thickness of the liquid film is proportional to the cubic root of the liquid flow rate in the laminar flow. Thus, the larger the flow rate is, the smaller the variation of the thickness of the film. The resistance of the liquid film to heat transfer is considered to be proportional to the film thickness. As the reflux liquid was fed at the top of the test section, the thickness of the liquid film did not change so much with the change of the temperature difference $T_v - T_w$. The resistance to the heat transfer did not vary with the change of $T_v - T_w$. In Fig. 3, therefore, the heat flux q_λ increases linearly with the increase of $T_v - T_w$ for each vapour Reynolds number N_{ReV} . For each N_{ReV} , the straight line

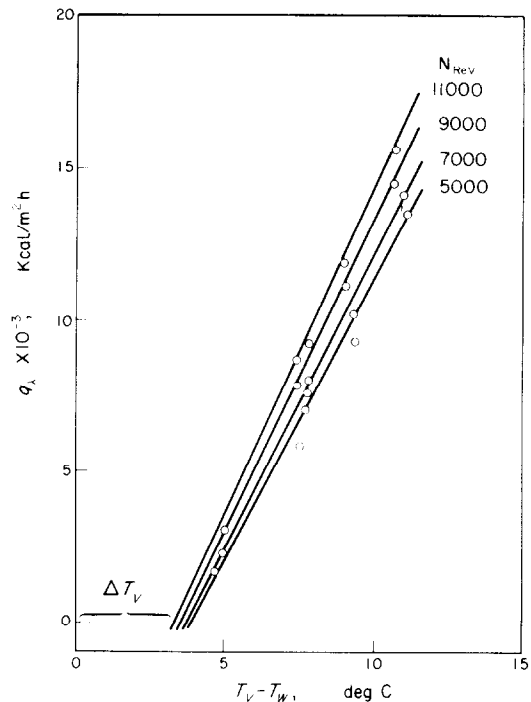


FIG. 3. Variation of the latent heat evolved at the vapour-liquid interface with temperature difference between vapour and wall.

was extended to the point where the heat flux q_v was zero, and the temperature difference ΔT_v between the bulk of vapour and the wall was determined at this point. This value ΔT_v represented the temperature difference existing in the vapour phase. The heat flux q_v was calculated by the temperature difference ΔT_v . However, it seems that ΔT_v has little contribution to the total heat transfer, as q_v is very small as compared with q_λ — q_v is the order of 10 kcal/m²h and q_λ is the order of 10³ kcal/m²h as described above. In the condensation of mixed vapours, q_v is neglected, and the heat transfer coefficient of the liquid film is given as follows:

$$h = \frac{q_v}{(T_v - T_w) - \Delta T_v} \quad (2)$$

With this heat-transfer coefficient, the condensation number

$$N_{cond} = h(\mu_l^2 / k_l^3 \rho_l^2 g)^{\frac{1}{4}} \quad (3)$$

is calculated with the physical properties of the liquid in the film, and plotted against the liquid Reynolds number $N_{ReL}(=4\bar{\Gamma}/\mu_l)$, in Fig. 4.

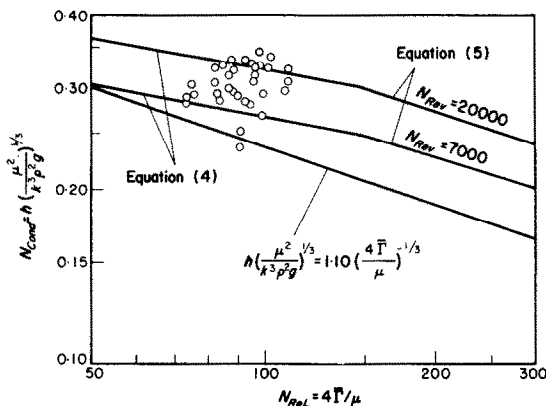


FIG. 4. Correlation of the condensation number with the vapour Reynolds number.

In the case of the condensation of saturated pure vapour, it is considered that there is no temperature difference in the vapour phase, and the temperature difference between vapour and the cooling wall is that of the liquid film of condensate. The condensation number was given as the empirical functions of the liquid Reynolds number and the vapour Reynolds number [11] and was correlated as follows:

$$N_{\text{cond}} = 0.147 (N_{ReL})^{-0.2} (N_{ReV})^{0.17} \quad (4)$$

for $20 < N_{ReL} < 150$, $7000 < N_{ReV} < 20000$

$$N_{\text{cond}} = 0.298 (N_{ReL})^{-1/3} (N_{ReV})^{0.17} \quad (5)$$

for $150 < N_{ReL} < 400$, $7000 < N_{ReV} < 20000$

where N_{ReL} was calculated with the mean flow rate of liquid at the top and the bottom of the cooling wall. In that paper [11] it was found that N_{cond} varied very little in the range $N_{ReV} < 7000$.

Equations (4) and (5) are shown with the solid lines in Fig. 4. The results of the condensation of the mixed vapour agree with that of the vapour of one component.

Thus, it will be concluded that the heat transfer in the liquid film in the case of the film condensation of the mixed vapour in a vertical column can be treated in the same way that of the condensation of the vapour of one component.

3.2 Mass transfer coefficients in vapour phase

In the case of the film condensation of mixed vapour on the vertical wall, concentration profiles of the more volatile component in the vapour phase and the liquid film are shown in Fig. 2.

Since the rate of the condensation of the mixed vapour composed of only condensable components is comparatively large, it will cause a bulk flow from the vapour phase to the interface. A number of moles of the more volatile component are transferred from the vapour phase into the interface by bulk flow. Since the bulk flow has considerable effect on the vapour velocity profile and the concentration profile in the vapour phase, the problem must be treated as the high mass-transfer phenomenon.

The mass-transfer coefficient k_y^* for the high mass-transfer rates in the vapour phase is defined as

$$N_{Ai} = -k_y^* (y_{Ai} - y_{Av}) + y_{Ai} N_i \quad (6)$$

where N_{Ai} is a molar flux of the more volatile component transferred from the bulk of the vapour phase into the liquid film through the vapor-liquid interface. The mole fraction of the more volatile component y_{Ai} in the vapour phase at the interface was estimated on the assumption that the mixed vapour at the vapour-liquid interface is saturated at the temperature $T_i (=T_v - \Delta T_v)$. The mass-transfer coefficient k_y^* is plotted against the total rate of condensation N_i in Fig. 5.

The values of k_y^* depend upon the total rate of the condensation N_i , and increase with the increase of N_i for each vapour Reynolds number N_{ReV} , as shown in Fig. 5. To examine the effect of the total rate of condensation N_i on the mass-

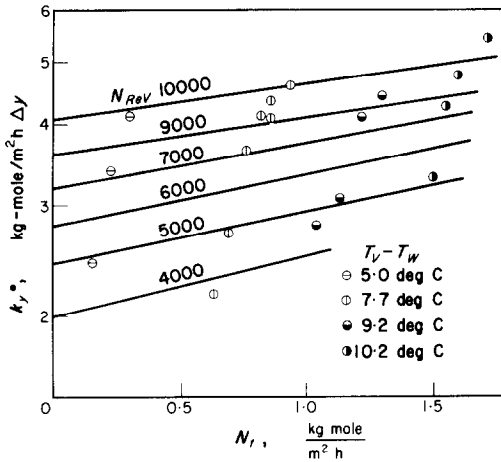


FIG. 5. Mass-transfer coefficients in vapour phase plotted against the total condensation rate.

transfer coefficients, the following relation is introduced.

$$k_y = \lim_{N_t \rightarrow 0} k_y^* \quad (7)$$

The mass-transfer coefficient k_y obtained from equation (7) is one for the limiting condition in which the effect of bulk flow on the velocity profile and the concentration profile is neglected. The ratio θ of the mass-transfer coefficients ($=k_y^*/k_y$) is calculated from the experimental data, and plotted against Φ ($=N_t/k_y$) in Fig. 6.

The relation between θ and Φ is derived on the basis of the film theory as follows [9]

$$\theta = \frac{\Phi}{e^{\Phi} - 1} \quad (8)$$

This relation is shown by a solid line in Fig. 6. The agreement of the data with the theory is satisfactory. Therefore, it will be concluded that for this case of the condensation of mixed vapour, the effect of the rate of the condensation on the mass-transfer coefficient of the vapour phase can be evaluated on the basis of the film theory.

On the basis of the film theory, the mass-transfer coefficient k_y for the condensation of

mixed vapour is defined by Colburn-Drew [1], as follows:

$$N_t = k_y \ln \frac{z - y_{Ai}}{z - y_{Av}} \quad (9)$$

where $z = N_{Ai}/N_t$.

The mass-transfer coefficient k_y in the vapour phase at various temperature differences was calculated by equation (9) with experimental data, and plotted against the vapour Reynolds

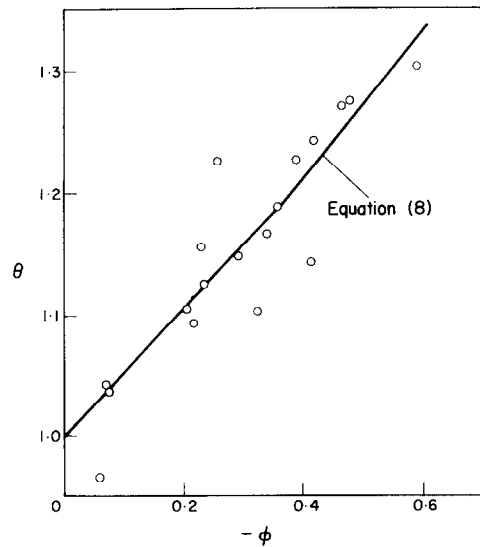


FIG. 6. Relation between θ and Φ for the mass transfer in vapour phase.

number N_{ReV} in Fig. 7. For all the temperature differences $T_v - T_w$, the plotted data lie on a straight line, and it also shows that the transfer coefficient k_y calculated by equation (9) has no dependence on the total rate of the condensation N_t . It will be adequate, therefore, to calculate the vapour phase mass-transfer coefficient k_y for the condensation of mixed vapour in a vertical column by equation (9).

3.3 Mass-transfer coefficient in liquid film

In the liquid film, the bulk flow from the vapour-liquid interface into the liquid phase is

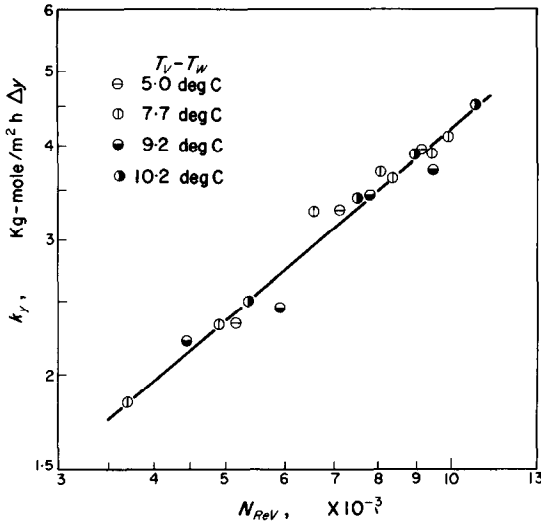


FIG. 7. Mass-transfer coefficients in vapour phase calculated with equation (9).

caused by the condensation, and affects the concentration profile and the velocity profile in the liquid film. For the condensation of mixed vapour, the mass-transfer coefficient of the liquid phase depends on the rate of condensation. The liquid phase mass-transfer coefficient k_x^* for the high mass-transfer rate is defined in the same way as the vapour phase mass-transfer coefficient k_v^* by

$$N_{Ai} = k_x^* (x_{Ai} - x_{Al}) + N_t x_{Ai} \quad (10)$$

The mole fraction x_{Ai} at the vapour-liquid interface is estimated from the temperature T_i at the interface under the assumption that the liquid at the interface is in equilibrium with vapour. The mass transfer coefficients k_x^* are calculated by equation (10) from the experimental data, and plotted against the total rate of condensation N_t in Fig. 8. These experiments were carried out in the range of the laminar film flow.

The local mass-transfer coefficient $k_{x,loc}^*$ for the high mass-transfer rate is given on the basis of the penetration theory, as follows:

$$k_{x,loc}^* = \frac{N_t}{(\sqrt{\pi}) \varphi e^{\varphi^2} (1 + \text{erf } \varphi)} \quad (11)$$

where

$$\varphi = (N_t/C) \sqrt{(t/D_l)} \quad (12)$$

In the case of the condensation of vapour in the wetted wall column, the time of contact of liquid with vapour is given on the assumption that the

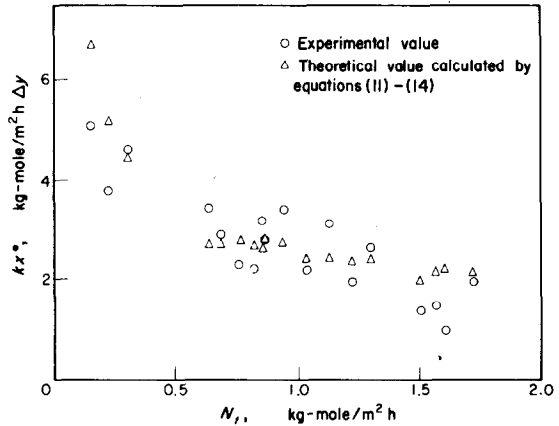


FIG. 8. Comparison of the experimental mass-transfer coefficients in the liquid film with theoretical values.

total rate of condensation N_t is nearly uniform at any point in the liquid-vapour interface, as follows:

$$t = \left\{ \frac{24 \rho_l \mu_l}{g(N_t M)^3} \right\}^{\frac{1}{3}} \{ (\Gamma_0 + N_t M l)^{\frac{1}{3}} - \Gamma_0^{\frac{1}{3}} \} \quad (13)$$

where Γ_0 is the liquid flow rate per unit perimeter at the top of the wetted wall. For each experimental condition the theoretical values of the local mass-transfer coefficient $k_{x,loc}^*$ is calculated from equations (11)-(13); and averaged over the total length of the wetted wall column to obtain the mean transfer coefficient in the liquid phase by equation (14)

$$k_x^* = \frac{1}{L} \int_0^L k_{x,loc}^* dl \quad (14)$$

The theoretical value of k_x^* depends on the total rate of condensation N_t , the liquid flow rate at

the top of the wetted wall, the length of the column L , and the physical properties of the liquid mixture. The mass-transfer coefficient k_x^* calculated by equations (11)–(14) is shown in Fig. 8. As the liquid flow rate and the length of the column were fixed, the scattered calculated values may be due to the differences of the physical properties (mainly molecular weights) of each component. The agreement of the experimental values of the mass-transfer coefficient k_x^* with the calculated values is almost satisfactory.

The mass-transfer coefficients k_y in the vapour phase increases with the increase of the total rate of condensation as shown in Fig. 5. On the other hand, the mass-transfer coefficients k_x^* in the liquid phase decrease with the increase of the total rate of condensation as shown in Fig. 8. Therefore, the larger the total rate of condensation of mixed vapour is, the more important the role of the liquid resistance to the mass transfer is.

3.4 Dependence of mass-transfer coefficient on column length

The overall vapour mass-transfer coefficient K_y are calculated from the experimental data for the four different columns length, and from equation (9) using y_A^* in the place of y_{A^b} , where y_A^* is the mole fraction of methanol in the vapour phase in equilibrium with the corresponding liquid composition x_{A^l} in the liquid film. These are plotted against the vapour Reynolds number N_{ReV} in Fig. 9. The longer the column length is, the smaller the value of the overall vapour mass-transfer coefficient K_y is. The mass-transfer coefficient k_x^* in the liquid phase is calculated with equations (11)–(14), and with this k_x^* the mole fraction x_{A^l} in the liquid phase at the vapour–liquid interface is determined by equation (10) for each experimental data. The mass-transfer coefficient k_y in the vapour phase is calculated by equation (9) with y_{A^l} in equilibrium with x_{A^b} and is plotted against the vapour Reynolds number N_{ReV} in Fig. 10. Although in $L = 33$ cm, the values of k_y are a

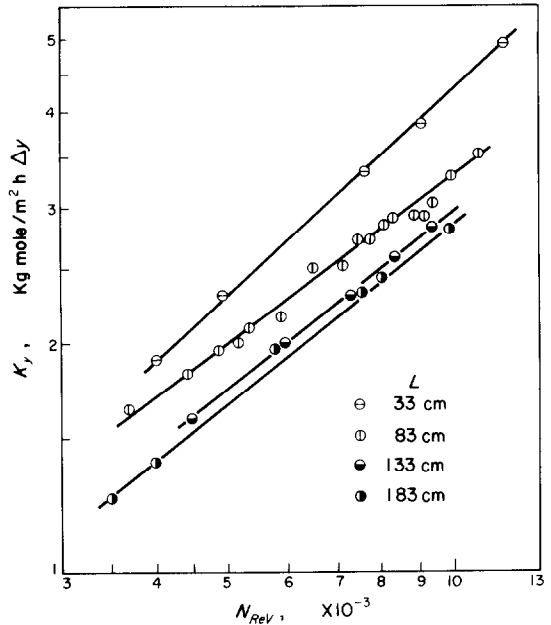


FIG. 9. Overall vapour mass-transfer coefficients for the four different column lengths.

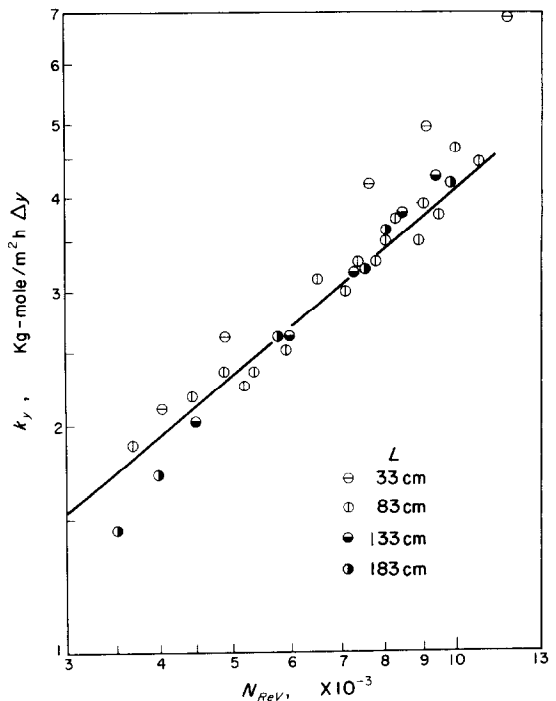


FIG. 10. Mass-transfer coefficients in vapour phase for the four different column lengths.

little larger than those in other lengths, the values of k_y do not change so much with the variation of the column length. The variation of k_y with the column length can be considered to be negligible, taking into account the accuracy of the experimental data. The following equation is obtained from the data shown in Fig. 10

$$N_{Sh} = 0.0069 (N_{ReV})^{0.92}. \quad (15)$$

In the case of the condensation of mixed vapour on the vertical wall, the mass-transfer coefficient k_y in the vapour phase does not change with the variation of the column length, but the mass-transfer coefficient k_x^* in the liquid phase changes with the column length. As a result, the overall vapour mass-transfer coefficient K_y shown in Fig. 9, changes with the variation of the column length.

3.5 Comparison of vapour phase mass-transfer coefficients in various operations

j_D -factors for the mass transfer in vapour phase in the mixed vapour condensation are calculated from the corresponding mass transfer coefficients, and compared with those for the vaporization and the distillation in the wetted wall columns, they are plotted against N_{ReV} in Fig. 11.

Many experimental results, for the vaporization and the distillation in the wetted wall columns summarized by Sasai [12], are shown

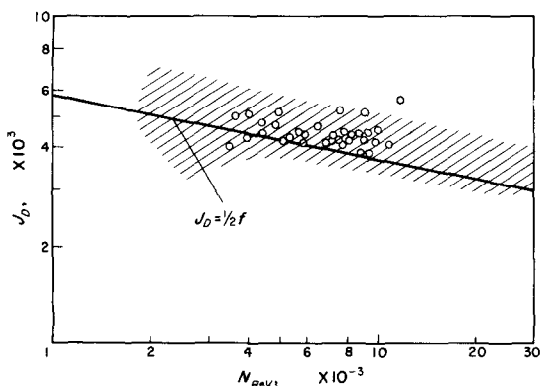


FIG. 11. j_D -factor for the mass transfer in vapour phase.

by the shaded portion in Fig. 11. The results in this paper agree with those of the vaporization and the distillation, and the values of j_D -factor are larger by about 10 per cent than those derived from Chilton-Colburn's analogy [13] shown by a solid line in Fig. 11.

4. CONCLUSIONS

1. In the filmwise condensation of mixed vapour on a vertical column, the heat-transfer coefficient in the liquid film will be calculated by the same equations for the condensation of pure vapour, that is

$$N_{cond} = 0.147 (N_{ReL})^{-0.2} (N_{ReV})^{0.17}$$

$$\text{for } 20 < N_{ReL} < 150,$$

$$7000 < N_{ReV} < 20000$$

$$N_{cond} = 0.298 (N_{ReL})^{-1/4} (N_{ReV})^{0.17}$$

$$\text{for } 150 < N_{ReL} < 400,$$

$$7000 < N_{ReV} < 20000.$$

2. The dependence of the mass-transfer coefficients k_y^* in the vapour phase for high mass-transfer rate, upon the bulk flow caused by the condensation, will be explained by the film theory for the high mass-transfer rate as shown in Fig. 6.

3. For the laminar flow of liquid film, the agreement between the experimental mass-transfer coefficients k_x^* in the liquid phase and the calculated values by equations (11)–(14), is almost satisfactory as shown in Fig. 8.

4. For the mass transfer in vapour phase, the experimental equation (15) is derived, and j_D -factor for the mixed vapour condensation agrees with those of the vaporization and the distillation in the wetted wall column.

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CONDENSATION PAR FILM D'UNE VAPEUR DE MÉLANGE DANS UNE COLONNE VERTICALE

Résumé—Dans la condensation d'une vapeur de mélange, le coefficient de transport de chaleur pour le film liquide est donnée par la même équation que celle présentée auparavant pour la condensation de la vapeur pure. La dépendance du coefficient de transport de masse dans la phase vapeur en fonction de la vitesse de condensation est expliquée par la théorie du film, mais, pour le transport de masse dans le film liquide, l'accord des valeurs expérimentales des coefficients de transport de masse avec les valeurs calculées sur la base de la théorie de la pénétration est excellent.

FILMKONDENSATION VON MISCHDAMPF IN EINER VERTIKALKOLONNE

Zusammenfassung—Bei der Filmkondensation von Mischdampf wird der Wärmeübergangskoeffizient für den Flüssigkeitsfilm durch dieselbe Gleichung beschrieben, die früher für die Kondensation von reinem Dampf vorgelegt wurde. Die Abhängigkeit des Stofftransportkoeffizienten in der Dampfphase von der Kondensationsgeschwindigkeit wird durch die Filmtheorie erklärt. Doch für den Stofftransport im Flüssigkeitsfilm ist die Übereinstimmung der gemessenen Werte für den Stofftransportkoeffizienten mit den auf der Basis der Eindringtheorie berechneten Werten ausgezeichnet.

ПЛЁНОЧНАЯ КОНДЕНСАЦИЯ СМЕШАННОГО ПАРА В ВЕРТИКАЛЬНОЙ КОЛОННЕ

Аннотация—Для случая плёночной конденсации смешанного пара коэффициент теплообмена жидкой плёнки даётся тем же уравнением, которое приводилось ранее для конденсации чистого пара. Зависимость коэффициента массообмена в паровой фазе от скорости конденсации объясняется плёночной теорией. Для случая массообмена в жидкой плёнке получено отличное соответствие между экспериментальными значениями коэффициента массообмена и значениями, рассчитанными на основе теории проницаемости.