Liquid Flow and Gas Phase Mass Transfer in Wetted-Wall Towers

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New data have been obtained on vaporization of water from rippling and nonrippling films in a countercurrent wetted-wall tower. Other similar data in the literature have been analyzed, and an effect of liquid Reynolds number on gas phase mass transfer has been shown to exist. Discrepancies in much of the literature data can be explained on this basis.

The data on vaporization of water from rippling films have been correlated. The data on nonrippling films were correlated when the gas Reynolds number was calculated relative to the water surface.

Attempts to correlate data on vaporization of pure liquids in a wetted-wall tower brought to attention various discrepancies in the available literature. Data obtained in this laboratory on vaporization of water into air flowing countercurrently indicated that the gas phase mass transfer coefficient was affected by liquid flow rate. In most previous investigations (*1, 5, 6, 10, 12, 17, 21*) the liquid flow was not considered as a variable. Examination of the literature indicated that the observed discrepancies might possibly be explained by including liquid flow as a variable. Also recently published hydrodynamic studies (*15, 18, 25, 26*) indicated that liquid flow conditions affect surface area and gas phase pressure drop and therefore might be expected to influence the gas mass transfer process.

Hydrodynamic studies related to wetted-wall columns are well summarized in several recent articles (*2, 15, 25, 26*). The noteworthy conclusions are as follows: (a) the departure from true laminar flow in the liquid occurs at liquid Reynolds number of approximately 25, (b) liquid waves or ripples formed above this value of N_{Re_L} are of high amplitude and low frequency, gradually becoming high frequency, low amplitude waves as N_{Re_L} increases above 1,000, (c) at a value of $N_{Re_L} \sim 1{,}080$ the onset of turbulence is reached and the transition to turbulence is complete at $N_{Re_L} \sim 1{,}500$. Almost all the experimental work supporting the above conclusions were made with liquid flow only, the liquid being water. Only a few workers, notably Jackson (*15*), Thomas and Portalski (*26*), and Kamei and Oishi (*18*), actually used countercurrent flow with air.

Numerous reports are in conflict as to the effect of surface tension on rippling (*13, 15, 19, 25, 27*). The use of a surface-active agent has been common in eliminating rippling in liquid films. It should be noted however that McCarter and Stutzman (*21*) in their mass transfer studies obtained nonrippling films of various liquids at $N_{Re_L} > 25$, without the use of a surface-active agent.

Theoretical derivations (*7, 22*), predict a ratio of 1.5 for surface velocity to average velocity when the liquid film is in true laminar flow with no gas flow. Jackson, Johnson, and Ceaglske (*16*) presented considerable evidence that the ratio of surface velocity to average velocity increases from 1.5 to about 2.0 at $N_{Re_L} \sim 80$ and remains constant at about 2.0 ± 20% through the rippling range. Other workers (*11, 13*) have also indicated that rippling causes the surface velocity to exceed that predicted theoretically for true laminar flow. Friedman and Miller (*11*) showed that deviations of the wall from the true vertical by one part in 600 produced local velocities 200% in excess of those obtained on a true vertical wall.

The first comprehensive study of vaporization in a wetted-wall tower was made by Gilliland and Sherwood (*12*) who obtained data on both parallel and counterflow vaporization. Although the volumetric flow rate of the liquid was maintained approximately constant in all of this work and was well into the rippling range for the various liquids, the N_{Re_L} varied considerably owing to differences in viscosity and density. In correlating their data Gilliland and Sherwood found a dependence on the direction of gas flow when N'_{Re_g} was used. However when gas Reynolds number calculated relative to the pipe wall was used, both parallel and counterflow data could be represented by the same correlation. This was the basis for the use of N_{Re_g} by later workers correlating this type of data.

An allowance for liquid rate was made by Cairns and Roper in their studies of vaporization (*3*) and dehumidification (*4*) at high humidities. Their correlations are all made at a standard liquid rate of 77 lb./hr. Runs at other liquid rates were adjusted by a factor obtained from a linear plot (five points at low humidities) of Sherwood number, times p_{BM}/P vs. liquid rate. Scatter in the data at high humidities is considerable. Values of N_{Re_L} were in the transition and turbulent flow regions for the high-humidity runs.

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EXPERIMENTAL APPARATUS AND PROCEDURE

The apparatus used in this study is similar to that used in earlier work of this type. A viewing port was provided at the top of the column, which with a light source at the bottom allowed close observation of the liquid surface.

The wetted-wall section of the column, standard 1-in. stainless steel pipe, 40-in. long, was carefully aligned to the true vertical. Inlet and outlet calming sections were provided. Inlet and outlet gas and liquid temperatures were measured by fine wire copper-constantan thermocouples and a precision potentiometer. The humidity of the outlet air was determined from measured wet-and dry-bulb temperatures. Inlet air was supplied almost bone dry from a drying bed, and its humidity was measured before and after each run. Humidities were also measured occasionally with a dew-point instrument and agreed well with wet-and dry-bulb measurements. Liquid and gas flows were closely controlled and measured by calibrated rotameters. Further details of the apparatus and procedure are given elsewhere (*23*). Data were obtained on vaporization of distilled water over a wide range of liquid flow rates.* Another series of runs was made in which all observable rippling was eliminated by the addition of 0.3 wt. % Alconox (a commercial detergent). This was found to be the optimum concentration of this detergent by several other investigators (*9, 24*) who also indicated any additional resistance contributed by the detergent was small.

RESULTS

For convenience and clarity results on rippling and nonrippling films are discussed separately below. While the same quantity, N'_{Re_g}, is referred to in both sections, it should be noted that

* Tabular material has been deposited as document 6751 with the American Documentation Institute, Photoduplication Service, Library of Congress, Washington 25, D. C., and may be obtained for $1.25 for photoprints or for 35-mm. microfilm.

its calculation is dependent on the type of flow in the liquid film.

Rippling Films

Attempted correlation of data of the present authors by the method of Gilliland and Sherwood showed a definite trend with liquid rate. In runs at various liquid temperatures it was noted that the condition of rippling was strongly dependent on the liquid viscosity; this was also noted by Kamei, et al. (*19*). Therefore the N_{Re_L} was computed for the various data available because it includes the effect of both viscosity and liquid flow rate. The results are shown in Figure 1, where the straight lines represent data obtained at essentially constant N_{Re_L} (for example the data of Gilliland and Sherwood). The points (not shown) which each of these lines represent showed very little scatter about the lines. Investigations in which N_{Re_L} was not essentially constant show wide variation as indicated by the scatter of the points shown in Figure 1. Of the data of Cairns and Roper only the low-humidity runs were used.

The N_{Re_g} was used in Figure 1 rather than N'_{Re_g} in order to include all the available data. This could not be done with the N'_{Re_g}, since the necessary information for calculation was not included in some studies. The results of Jackson were originally presented with N'_{Re_g}. These data were adjusted by calculating N_{Re_g} allowing for the liquid surface velocities given by the author.

All data taken under rippling conditions for which N_{Re_L} could be estimated were plotted, as shown in the upper portion of Figure 2, to determine the dependence on N_{Re_L}. The dependence on gas rate was taken as $N_{Re_g}0.83$ as indicated by studies at constant N_{Re_L}. The scatter in this type of correlation is necessarily larger than it is in Figure 1 owing to division of the ordinates of Figure 1 by large numbers (for example $N_{Re_g}0.83$). The rippling data shown in Figure 2 show a slope of 0.15. The data of the present authors show about the same slope with a slightly smaller intercept.

Information on nonrippling films (see below) indicated that part of the dependence of the rippling data on N_{Re_L} could be eliminated by using N'_{Re_g} in place of N_{Re_g} in Figure 2. Accordingly, the data of Gilliland and Sherwood, Chilton and Colburn (*6*), and Flynn (*10*), were plotted using N'_{Re_g} calculated from Jackson's (*16*) experimentally determined ratio of 2.0 for surface velocity to average velocity of rippling films. When N_{Sh} (p_{BM}/P) was plotted vs. N'_{Re_g}, break points were noted at $N'_{Re_g} \sim 7,000$. The following equations were obtained from the data shown on Figure 3:

$$N_{Sh}(p_{BM}/P) = 6 \times 10^{-3}(N'_{Re_g})^{0.83}(N_{Re_L})^{0.15} \qquad N'_{Re_g} > 7{,}000 \qquad (1)$$

$$N_{Sh}(p_{BM}/P) = 9 \times 10^{-7}(N'_{Re_g})^{1.5}(N_{Re_L})^{0.24} \qquad N'_{Re_g} < 7{,}000 \qquad (2)$$

The above equations are approximate, since they are based on a meager amount of data. It should be noted that Colburn's results did not agree with Equation (2). Data obtained in the present work were in the $N'_{Re_g} <$ 7,000 range and agreed with Colburn's results.

NONRIPPLING FILMS

When the data on nonrippling films were plotted in the same manner as the rippling data in Figure 2, with N_{Re_g}, considerable scatter was evident about a line of approximately 0.06 slope. The nonrippling data are shown in Figure 2 (bottom), where N'_{Re_g} was used in obtaining the ordinate. The scatter is considerably less than when N_{Re_g} was used, and a least-square line for the present authors data had a zero slope. It is important to note that N'_{Re_g} for the nonrippling films was calculated with the theoretical value of 1.5 for the ratio of surface velocity to average velocity of a laminar film. The 0.83 exponent on N'_{Re_g} was indicated by the nonrippling data of McCarter and Stutzman and a number of nonrippling runs at constant N_{Re_L} made by the present authors.

DISCUSSION

The effects, mentioned above, of N_{Re_L} on gas phase mass transfer are further substantiated by considering the mass transfer-fluid flow analogy. Pressure-loss measurements reported in several articles (*18, 26*) have shown that friction losses are dependent on N_{Re_L}. This idea has been studied more thoroughly by Warner (*28*) in a disk column. He compared pressure-drop data with gas film mass transfer coefficients. Changes in the gas flow characteristics, as indicated by break points in graphs relating pressure drop and gas velocity, were found to be consistent with changes in the mass transfer data. The extensive pressure-loss data of Thomas and Portalski indicated a rise in pressure loss with liquid rate up to N_{Re_L} = 900 to 1,000, dropping to a minimum at N_{Re_L} = 1,300 to 1,500, and then rising again as the liquid goes through the transition to fully turbulent flow. The authors attributed this to the breakup of waves of high amplitude at $N_{Re_L} \sim$ 900 to low-amplitude, high-frequency ripples as the N_{Re_L} increases further. Mass transfer data at high N_{Re_L} is so limited that it is not possible to tell if the same trend is followed. The information available at high N_{Re_L} is that of Cairns and Roper in which p_{MB}/P was quite low and varied. Since the effect of this term is not definitely established, no conclusion could be drawn on this por-

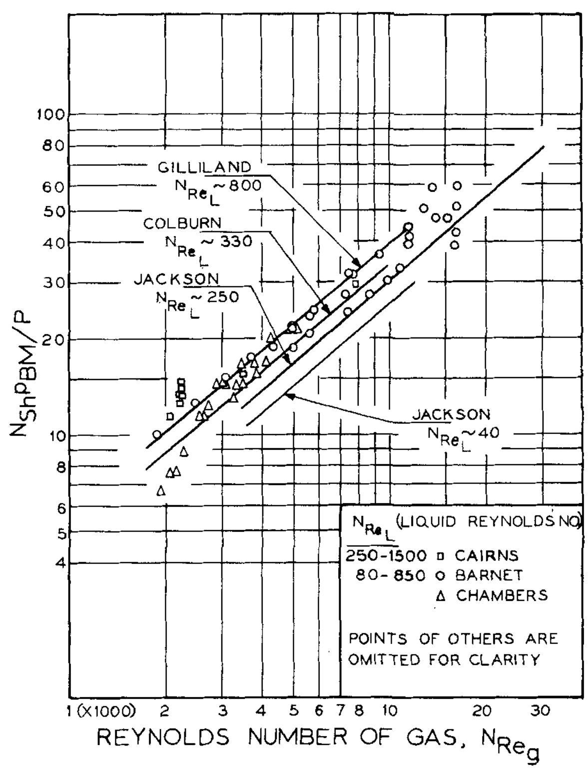

Fig. 1. Vaporization of water (rippling films) in wetted-wall columns showing trend with liquid Reynolds number.

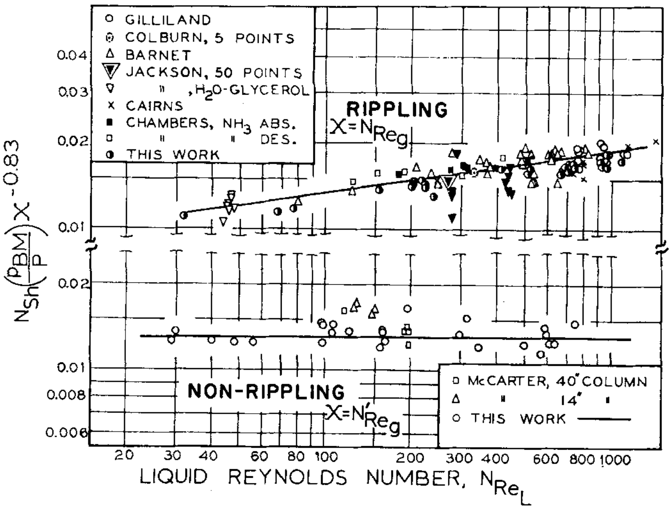

Fig. 2. Mass transfer data on rippling and nonrippling films showing effect of liquid Reynolds number.

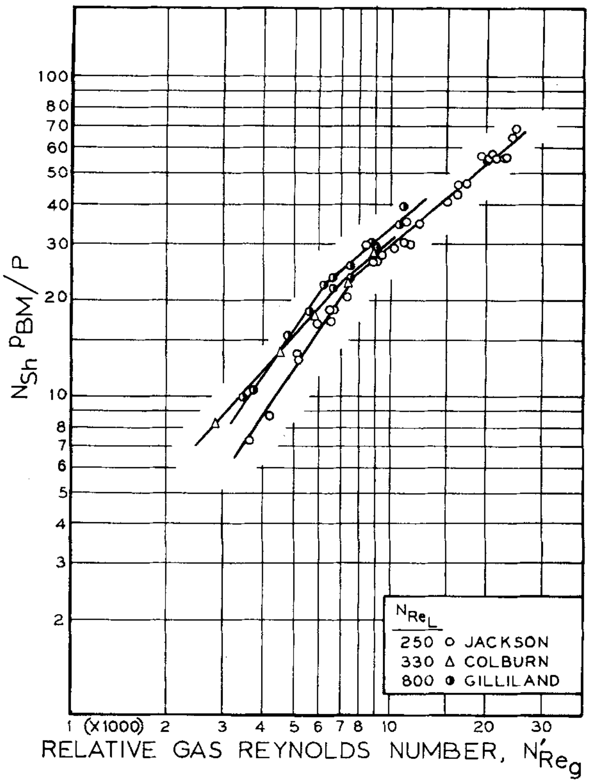

Fig. 3. Data on vaporization of water from rippling films show break points when correlated with relative gas Reynolds number.

tion of the mass transfer-fluid flow analogy.

Kamei and Oishi (*18*) correlated their wetted-wall pressure-drop measurements as

$$f_r/f_o = 1 + 3.97 \times 10^{-3} (N_{Re_L})^{0.476} (\mu_g/\mu_L)^{-0.271} \quad (3)$$

If nonrippling mass transfer is considered analogous to the friction loss on a dry wall and rippling mass transfer to friction loss due to a rippling liquid surface, Equation (3) can be compared with the following equation which is a reasonable representation of the mass transfer data presented in Figure 2:

$$(M.T.G.)_r/(M.T.G.)_o = 1 + 3 \times 10^{-3} (N_{Re_L})^{0.45}(\mu_g/\mu_L)^{-0.271} \quad (4)$$

The term (μ_g/μ_L) in Equation (4) was approximately constant in this work and was introduced only for comparison with Equation (3). In the numerator of the left side of Equation (4) N'_{Re_g} was used since it was used in obtaining the analogous quantity in Equation (3).

The use of the relative Reynolds number showed nonrippling vaporization to be independent of N_{Re_L}, while the rippling studies seemed to show a more complex dependence on N_{Re_L} and gas flow as evidenced by Figure 3. Some length of column is necessary before N'_{Re_g} can be said to characterize the gas flow. Schwarz and Hoelscher (*24*) have indicated that end effects are felt for about six pipe diameters from the gas inlet. Since various column sizes were involved in the results presented, the relative importance of end effects differed for each investigator. In the nonrippling studies the poor agreement of the data from the 3-in. diameter, 14-in. column with that from the longer columns could be due to end effects.

In the rippling studies a number of other factors are also important. As indicated previously the liquid surface velocity is not accurately known. This factor becomes very significant when N_{Re_g} is low and N_{Re_L} is high, resulting in values of N'_{Re_g} that may be 50% in error. Variation in the surface area due to rippling has been suggested by Dukler and Bergelin (*8*) as a cause for inconsistent results. Stirba and Hurt (*25*) have estimated the maximum increase in actual surface area due to ripples to be about 50%. The maximum increase in mass transfer, which may be attributed to surface area increase at N_{Re_L} of 1,000, is in the order of 20% if N'_{Re_g} is used.

One further factor might be considered in connection with surface area variation. The actual increase in surface area may not be the same as the effective increase in area for mass transfer. If the liquid wave height is such that disturbance and penetration of the laminar gas layer is not significant, then the total increase in surface area will not be felt in the mass transfer process. The maximum wave height has been estimated to be about two to three times the mean liquid-layer thickness (*8, 20*) depending somewhat on liquid rate. The situation is further complicated by variation of the effective gas laminar-layer thickness with gas flow rate. The order of magnitude of these factors indicates that the total increase in surface would not be effective in the mass transfer process. This is evident from Table 1, where mean liquid-layer thickness is given from Thomas and Portalski and effective gas film thickness for mass transfer is taken from the nonrippling data of McCarter and Stutzman. The latter authors also calculated various layer thicknesses for the gas flow from fluid mechanics information. These should be compared with the approximate maximum wave height in Table 1. It can be seen that both the gas flow condition and the mass transfer resistance can be affected by the liquid waves, depending on both gas and liquid Reynolds numbers. The complexity of the situation is apparent in the interaction studies of Hanratty and Engen (*14*).

The Schmidt group has not been included in this analysis, since it varies only a few percent over the conditions of all the data shown. When a Schmidt group exponent of − 1/3 to − 0.44 is used in the ordinate of Figure 2 the variation is even less, and only a few of the data points would be shifted as much as 1%. The ammonia data of Chambers and Sherwood have been included, since the Schmidt group is essentially the same as that for water in air.

Data on vaporization of organic liquids over a range of N_{Re_L} are very meager. McCarter and Stutzman and

TABLE 1. COMPARISON OF MAXIMUM LIQUID WAVE HEIGHT WITH GAS LAMINAR-LAYER THICKNESS AND EFFECTIVE FILM THICKNESS FOR MASS TRANSFER UNDER NONRIPPLING CONDITIONS

Liquid*			Gas†				
N_{Re_L}	m, (cm.)	Maximum wave height,** (cm.)	N'_{Re_g}	x, (cm.)	Rouse laminar layer, (cm.)	Laminar-layer thickness, (cm.)	Laminar plus buffer layer (cm.)
564	0.0348	0.105	4,000	0.618	0.308	0.133	0.745
860	0.0389	0.117	6,900	0.368	0.192	0.083	0.496
1,083	0.0409	0.123	19,000	0.131	0.079	0.034	0.204
1,320	0.0474	0.141	29,200	0.102	0.053	0.023	0.138
1,656	0.0623	0.186	38,200	0.083	0.042	0.018	0.109

* From Thomas and Portalski (*26*).
** Estimated as three times *m*.
† From McCarter and Stutzman (*21*).

Gilliland and Sherwood present data on *n*-butanol, ethyl acetate, and toluene. The data on each system show the same trend as does the water data with slopes of about 0.08 when plotted as in Figure 2 ($X = N_{Re_g}$).

CONCLUSIONS

The discrepancies in wetted wall vaporization data on rippling films of water can be explained by using N_{Re_L} to characterize liquid rippling and liquid surface velocity effects when N_{Re_g} is used. The surface velocity effect for the nonrippling case can be satisfactorily removed by using N'_{Re_g} as shown by the correlation of nonrippling data in Figure 2. Correlation of 220 data points of various investigators on vaporization of water from rippling films can be represented (see Figure 2) by

$$N_{Sh}\,(p_{BM}/P) = 0.0065\,(N_{Re_g})^{0.83}\,(N_{Re_L})^{0.15} \quad 25 < N_{Re_L} < 1{,}200 \quad (5)$$

The concurrent data of Gilliland and Sherwood can also be represented by Equation (5), since it does not involve N'_{Re_g}. Data of this work on nonrippling films can be represented by

$$N_{Sh}(p_{BM}/P) = 0.013\,(N'_{Re_g})^{0.83} \quad N_{Re_L} < 1{,}000 \quad (6)$$

when the N'_{Re_g} is computed with the theoretical equation for surface velocity of a laminar liquid layer.

The use of N'_{Re_g} with data on rippling films yielded no satisfactory correlation, and therefore Equation (5) is recommended for the rippling case. No conclusive evidence exists for the inclusion of the p_{BM}/P term. Data on ammonia absorption and desorption of Chambers and Sherwood are in agreement with Equation (5).

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NOTATION

D = diameter of tower
D_v = molecular diffusivity
f_r = Fanning friction factor when velocity relative to liquid surface is used
f_o = Fanning friction factor in dry pipe
k_g = gas phase mass transfer coefficient
m = mean liquid-layer thickness
$(M.T.G.)_r$ = mass transfer group for rippling case, $[N_{Sh}(N'_{Re_g})^{-0.83}(p_{BM}/P)]_r$
$(M.T.G.)_o$ = mass transfer group for nonrippling case, $[N_{Sh}(N'_{Re_g})^{-0.83}(p_{BM}/P)]_o$
N_{Re_g} = gas Reynolds number relative to pipe wall = $(Du\,\rho)/\mu_g$
N'_{Re_g} = gas Reynolds number relative to liquid surface = $(Du'\,\rho)/\mu_g$
N_{Re_L} = liquid Reynolds number = $(4\,\Gamma/\mu_L)$
N_{Sc} = Schmidt number = $(\mu_g/\rho\,D_v)$
N_{Sh} = Sherwood number = $(k_gRTD)/D_v$
P = total pressure
p_{BM} = logarithmic mean partial pressure of component B (the inert)
R = gas constant
T = absolute temperature
u = bulk average linear gas velocity
u′ = gas velocity relative to liquid surface = $u + V_s$ for counterflow
V = bulk average linear liquid velocity
V_s = liquid surface velocity, calculated as 2V for rippling flow and 1.5V for nonrippling flow
x = effective gas film thickness for mass transfer
Γ = mass flow rate of liquid per unit perimeter
ρ = gas density
μ_g = gas viscosity
μ_L = liquid viscosity

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