EFFECT OF RIPPLING AT THE SURFACE OF FALLING LAMINAR LIQUID FILMS ON FRICTIONAL PRESSURE DROP AND MASS TRANSFER RATE IN TURBULENT GAS STREAMS IN WETTED-WALL COLUMNS

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It is well known that when a liquid flows down a vertical surface under gravity, ripples appear on the surface of a falling liquid film and cause a certain amount of mixing of liquid near the surface. Numerous investigators^{1,2)} have shown that the rate of liquid-phase mass transfer in wetted-wall columns is enhanced owing to the rippling at the surface of the falling liquid film and is much larger than that predicted from the theory for smooth laminar liquid film. However, relatively little work has been done on the effect of rippling at the liquid surface upon the frictional pressure drop^{6,7)} and the rate of gas-phase mass transfer⁵⁾ in wetted-wall columns. In the present work, experiments were carried out on measurement of the pressure drops for the air-water and air-xylene systems and on the absorption of ammonia into aqueous sulfuric acid solution under the conditions of rippling film to examine the effect of rippling at the liquid surface on the momentum and mass transfer processes in turbulent gas streams in wetted-wall columns.

1. Frictional Pressure Drops for Gas Streams

1.1 Experimental

The apparatus and procedure were almost the same as those employed in the previous work³⁾. Air was used as the gas and water and xylene containing no surface-active agent were used as the liquids. The temperatures of gas and liquid were controlled and kept at 20°C. The gas-phase Reynolds number Re_G was varied from 2000 to 9000, while the liquid-phase Reynolds number Re_L ranged from 200 to 800. The densities and viscosities of the liquids are given in Table 1.

1.2 Results and discussion

The experimental results obtained with the air-water and air-xylene systems under cocurrent flow conditions are shown in Fig. 1, where the values of the

friction factor f_r calculated from the measured values of $\Delta P_f/Z$ are plotted as a function of the gas-phase Reynolds number Re_{Gr} based on the gas velocity relative to the liquid surface. Figure 2 is a similar plot of the friction factor data obtained under countercurrent flow conditions. In the calculation of f_r and Re_{Gr} ,

Table 1 Physical properties of liquids at 20°C

Liquid	Density [g/cm ³]	Viscosity [cP]
Water	0.998	1.01
Xylene	0.870	0.70

Fig. 1 Friction factor as a function of gas-phase Reynolds number based on gas velocity relative to liquid surface (cocurrent flow)

Fig. 2 Friction factor as a function of gas-phase Reynolds number based on gas velocity relative to liquid surface (countercurrent flow)

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the values of the interfacial velocity u_i and the thickness of the falling liquid film b were estimated from Eqs. (13), (16) and (17) given in the previous paper³⁾. The solid lines in Figs. 1 and 2 represent the theoretical equations, Eqs. (28) and (29) given in the previous paper³⁾, which were derived for the case of no rippling on the surface of the liquid film. The measured values of the friction factor f_r are in approximate agreement with the theoretical lines, although the data points lie slightly above the theoretical lines in the case of cocurrent flow and show some scatter in the case of countercurrent flow. The average deviations of the data points in the range of Re_{Gr} higher than 3000 are 5.3% and 2.9% for cocurrent flow and countercurrent flow, respectively. In the previous work³⁾, the frictional pressure drops for the air-water and air-glycerol solution systems were measured under the conditions of no rippling film and were found to be in good agreement with the theoretical predictions. Therefore, it may be concluded from the present and previous results that the effect of rippling on the frictional pressure drop for turbulent gas streams is negligibly small and that the theoretical equations, Eqs. (28) and (29) given in the previous paper³⁾, can be used for estimation of the friction factor for the case of rippling liquid film.

2. Rates of Gas-Phase Mass Transfer

2.1 Experimental

The apparatus and procedure were almost the same as those used in the previous work⁴⁾. A wetted-wall column, 2.0 cm I. D. and 80 cm long, was used. Experiments on the absorption of ammonia from air into an aqueous sulfuric acid solution were carried out. The sulfuric acid solution without surface-active agent which was recycled through the column was used as the absorbent and its concentration was about 1.5 g-mol/l. The ammonia content in the inlet air stream was about 2 vol%. The liquid-phase Reynolds number Re_L was kept at three constant values of 200, 400 and 600. The gas-phase Reynolds number Re_G was varied from 4000 to 20,000. The temperatures of gas and liquid were controlled and maintained at 25°C.

2.2 Results and discussion

The experimental results obtained for cases of both cocurrent flow and countercurrent flow are shown in Figs. 3 and 4, respectively, where the values of the gas-phase Sherwood number Sh_G calculated from the measured absorption rates are plotted against Re_{Gr} and compared with the theoretical lines for the case of no rippling liquid film. In calculating Sh_G and Re_{Gr} , the values of the interfacial velocity u_i and the thickness of the falling liquid film b were estimated from Eqs. (13), (16) and (17) given in the previous paper³⁾. The

Fig. 3 Average gas-phase Sherwood number as a function of gas-phase Reynolds number based on gas velocity relative to liquid surface (cocurrent flow)

Fig. 4 Average gas-phase Sherwood number as a function of gas-phase Reynolds number based on gas velocity relative to liquid surface (countercurrent flow)

solid lines in these figures represent the theoretical values of Sh_G in the limit of $Re_L = 0$ and $X \rightarrow \infty$, which were calculated numerically in the previous paper⁴⁾. As can be seen in these figures, the agreement between the experimental data and the theoretical line is fairly good, although the data points for countercurrent flow lie slightly below the theoretical lines. The average deviations of the data points are 2.6% and 2.2% for cocurrent flow and countercurrent flow conditions, respectively. In the previous work⁴⁾, absorption experiments were carried out with the ammonia-sulfuric acid solution system under the conditions of no rippling liquid film and the measured values of Sh_G were found to be in good agreement with the theoretical predictions. Thus, it may be concluded from the present and previous results that the effect of rippling on the surface of the falling liquid film upon the mass transfer rate in turbulent gas streams is negligibly small.

Conclusion

The frictional pressure drop for the turbulent gas stream was measured for the air-water and air-xylene systems under the conditions of rippling on the surface of the liquid film. The measured values of the fric-

tional pressure drop were in approximate agreement with the theoretical predictions for the case of no rippling liquid film.

Experiments on the absorption of ammonia from a turbulent air stream into aqueous sulfuric acid solution were carried out under the conditions of rippling on the surface of the liquid film. The agreement between the measured values of Sh_G and the theoretical predictions for the case of no rippling liquid film was fairly good.

From these results, it may be concluded that rippling on the surface of the falling liquid film does not affect appreciably either the frictional pressure drop or the rate of gas-phase mass transfer in the turbulent gas stream.

Nomenclature

b	= liquid film thickness	[cm]
D_G	= gas-phase diffusivity of solute gas	[cm ² /sec]
d	= column diameter, $2r_w$	[cm]
f_r	= friction factor based on relative gas velocity, $\Delta P_f r_i / \rho_G (u_m - u_i)^2 Z$	[—]
k_G	= average gas-phase mass transfer coefficient	[cm/sec]
Re_G	= gas-phase Reynolds number, $4W / \pi d \mu_G$	[—]
Re_{Gr}	= gas-phase Reynolds number based on gas velocity relative to liquid surface, $2r_i \rho_G (u_m - u_i) / \mu_G$	[—]
Re_L	= liquid-phase Reynolds number, $4\Gamma / \mu_L$	[—]

r_i	= radius of gas passage, $r_w - b$	[cm]
r_w	= column radius	[cm]
Sc_G	= gas-phase Schmidt number, $\mu_G / \rho_G D_G$	[—]
Sh_G	= average gas-phase Sherwood number, $k_G (2r_i) / D_G$	[—]
u_m	= average gas velocity	[cm/sec]
u_i	= interfacial velocity	[cm/sec]
W	= mass flow rate of gas	[g/sec]
X	= dimensionless column height, $Z / 2r_i$	[—]
Z	= column height	[cm]
Γ	= mass flow rate of liquid per unit perimeter	[g/cm·sec]
ΔP_f	= frictional pressure drop for gas stream through column	[g/cm·sec ²] or [Kg-force/m ²]
μ_G, μ_L	= viscosities of gas and liquid	[g/cm·sec] or [cP]
ρ_G	= density of gas	[g/cm ³]

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KINETICS OF ABSORPTION OF NITRIC OXIDE IN HYDROGEN PEROXIDE SOLUTIONS

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Introduction

Absorption is a useful technique for removal of nitric oxide from a gas mixture in many applications. A number of absorbents have been proposed for the removal of NO from gases. Adrian *et al.*⁽¹⁾ have reported on the development of a process for the reduction of NO content in flue gases using hydrogen peroxide solution as the absorbing liquid. Absorption with hydrogen peroxide solution has considerable advantages, such as high absorption rate, low capital

cost and formation of only water and nitric acid in the absorption process. This last factor makes it specially attractive for nitric acid plant tail-gas absorption, since the by-product from air pollution abatement can go directly into the main product of the plant.

There is practically no information in the literature on the kinetics of the reaction between H₂O₂ and NO in the liquid phase. As a first step, an attempt is made to elucidate the kinetics of absorption of NO in hydrogen peroxide solution and to determine the rate constant. The overall reaction with NO is

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