Height of a Liquid Film in a Horizontal Concurrent Gas-Liquid Flow

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Results of a study of the height of liquid films flowing concurrently with an air stream in a horizontal channel are presented. If three-dimensional waves exist at the interface, the dimensionless film height $h^+ = hu^*/\nu$, defined in terms of the friction velocity and the kinematic viscosity of the liquid, is primarily a function of the liquid Reynolds number.

The calculation of the thickness of a liquid film flowing along a wall in gas-liquid flows is complicated by the appearance of waves at the interface. The waves are accompanied by an increase in the rate of momentum transfer in the liquid film and the relation of this increase in the rate of momentum transfer to the wave structure is not known. Colburn and Carpenter (*3*) hypothesized that a liquid film under the influence of a high velocity air flow behaves as if it were the wall layer of a single-phase turbulent flow with the same thickness and wall shear stress. This suggestion has been developed by Kinney, Abramson, and Sloop (*6*), by Dukler (*4*), and by a number of other researchers. Dukler suggested that the eddy diffusivities of momentum for single-phase turbulent flow are applicable to the liquid film and found approximate agreement with data available in the literature.

Results of a study of the average height of liquid films flowing concurrently with an air stream in a horizontal channel are presented. It will be shown that if a three-dimensional wave pattern exists at the interface, the measurements of the average film height can be correlated by assuming that a universal velocity profile relation of the type used for turbulent flows can be applied to the liquid.

EXPERIMENTAL

The experimental system has been described in detail in previous publications (*2, 5, 7*). A liquid film flows on the bottom of an enclosed horizontal Plexiglas channel and a turbulent air stream flows over the liquid. The viscosity of the liquid was varied by using three glycerine-water solutions: (1) water, (2) G-I, 45-50 wt. % glycerine, (3) G-II, 70-75 wt. % glycerine. The aspect ratio of the channel (12 in. wide by 1.015 in. high) is large enough so that the flow in the center may be considered two-dimensional. Measurements were confined to the central regions of the channel. The channel is long enough (21 ft.) so that fetch effects can be eliminated. The pressure gradient and the gas velocity profile in the fully developed region are measured with pressure taps on the top of the channel and with an impact tube. If waves exist at the interface, the drag on the liquid will be greater than the stress at the top wall of the channel, and the velocity profile in the gas will be distorted. The effective shear stress at the gas-liquid interface can be calculated from the pressure drop and the distance of the maximum in the velocity profile from the interface by using a force balance (*5*). This calculation depends on the assumption that the shear stress is zero at the maximum in the velocity profile. Justification for this assumption is obtained from the measurements of Brighton and Jones (*1*) and from the good agreement between the correlation of velocity measurements in the top half of the channel and the correlation of velocity measurements in the dry channel (*2*).

A light absorption technique was used to measure the height of the liquid film. A detailed description of the technique and of measurements of the wave structure at the interface is presented in a previous paper (*7*) and in a thesis by one of the authors (*2*).

CORRELATION OF FILM HEIGHT DATA

Velocity data for turbulent flow have been correlated by an equation of the form

$$u^+ = f(y^+) \tag{1}$$

If this equation is assumed to describe the flow in a horizontal liquid film

$$u_a = \frac{u^*}{h} \int_0^{h^+} \frac{\mu}{\rho u^*} f(y^+) dy^+ \tag{2}$$

$$N_{Re} = \int_0^{h^+} f(y^+) dy^+ \tag{3}$$

It is seen that Equation (1) implies that h^+ is a unique function of the Reynolds number.

For gas-liquid flows on an inclined or vertical wall one would expect u^+ to be a function of the Froude number, as is suggested by the calculations of Dukler (*4*). In these cases it is not likely that h^+ is a unique function of the Reynolds number.

Turbulent velocity measurements in the channel when dry (*2*) show that the data can be correlated by the following equations:

$$u^+ = y^+ \qquad (0 \leq y^+ \leq y_L^+) \tag{4}$$

and

$$u^+ = y_L^+ + \frac{1}{K} \ln [1 + K(y^+ - y_L^+)] \qquad (y_L^+ \leq y^+ \leq h^+) \tag{5}$$

If Equations (4) and (5) are substituted into (3), there results

$$N_{Re} = \frac{1}{K^2} [\{1 + K(h^+ - y_L^+)\} \ln \{1 + K(h^+ - y_L^+)\}] - \frac{y_L^{+2}}{2} - \frac{(h^+ - y_L^+)}{K} + h^+ y_L^+ \tag{6}$$

The dry channel measurements give

$$K = 0.4 \text{ and } y_L^+ = 7.7.$$

for gas Reynolds numbers greater than 10,000. If the liquid film flowed in a channel as a single phase with the same conditions at the wall as prevails in the experiments,

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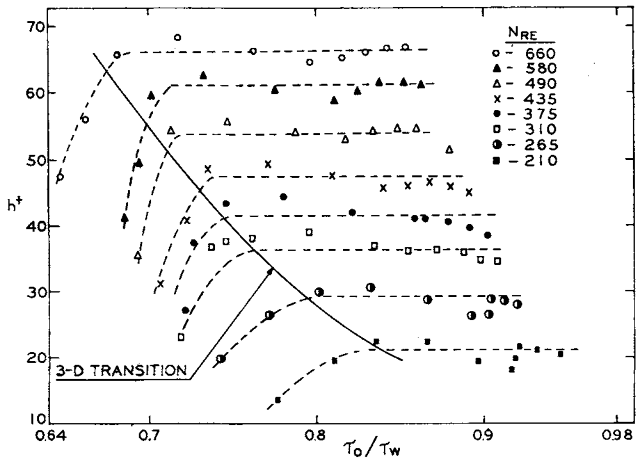

Fig. 1. Dimensionless film heights in air-water system.

it would have a Reynolds number greater than 10,000. It therefore seems appropriate to use the above constants to estimate film heights from (3), (4), (5), and (6).

RESULTS

Measurements h^+ as a function of the gas flow rate for different values of the liquid Reynolds number are shown in Figures 1 and 2. Increasing values of τ_o/τ_w correspond to increasing values of the gas Reynolds number. At low gas rates two-dimensional waves are present at the interface. At large enough gas flow rates such that three dimensional waves exist at the interface, h^+ is primarily a function of the liquid Reynolds number. This is a surprising result, since there is a considerable change in wave structure as the gas flow rate is increased.

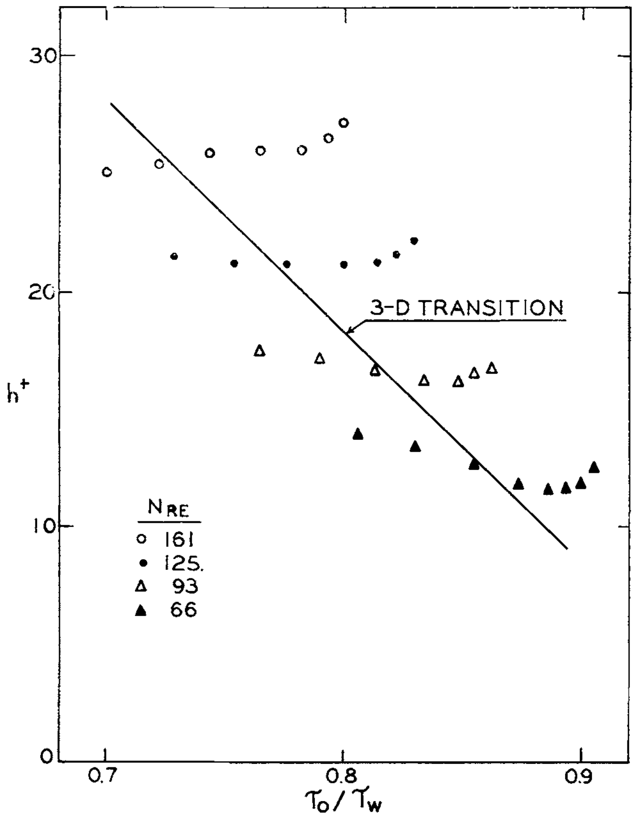

Fig. 2. Dimensionless film heights in glycerine (I)-air system.

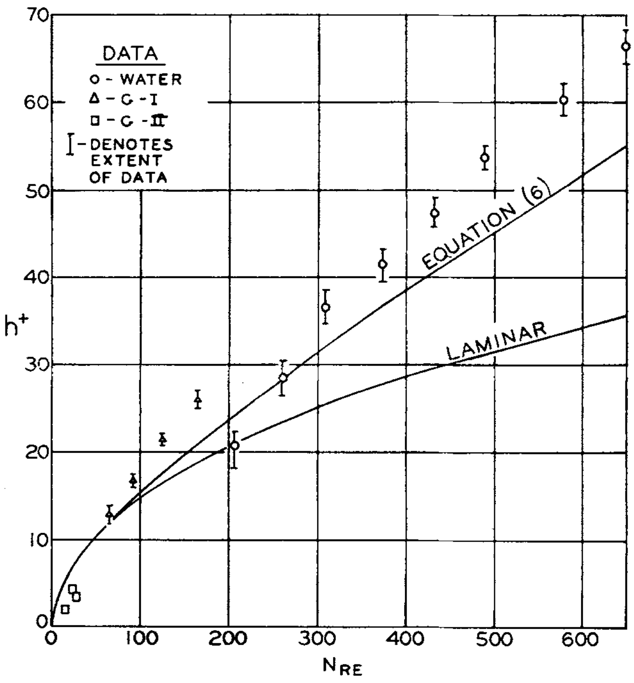

Fig. 3. Comparison of average film height data with predictions.

The average values of h^+ in the three-dimensional regime at each liquid Reynolds number are plotted in Figure 3. It is seen that at large liquid Reynolds numbers the film is much thicker than would be predicted by laminar flow relations.

Equation (6) is plotted in Figure 3 with $K = 0.4$ and $y_L^+ = 7.7$. It is seen that measured values of h^+ are somewhat larger than are predicted by single-phase turbulence measurements. However, considering the nature of the assumptions, the agreement between the predicted and measured film heights is as good as might be expected.

ACKNOWLEDGMENT

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NOTATION

h = height of the liquid film
h^* = $hu^*\rho/\mu$
K = von Karman's constant
N_{Re} = w/μ
u = gas velocity
u_a = mixed average gas velocity
u^* = friction velocity = $(\tau_w/\rho)^{1/2}$
w = mass flow rate of the liquid
y = distance from the wall
y^+ = $yu^*\rho/\mu$

Greek Letters

μ = liquid viscosity
ρ = liquid density
τ_o = shear stress at the gas-liquid interface
τ_w = shear stress at the wall

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Transmethylation Reactions of Monomethyl and Dimethylamine over Montmorillonite in a Flow System

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In this work the transmethylation reactions of monomethylamine and dimethylamine were investigated under steady state conditions in a flow system. A differential reactor was employed with montmorillonite as the catalyst and the initial rates of these reactions were measured isothermally. Mass velocities through the reactor were sufficiently high to eliminate bulk stream diffusion to the catalyst interface as a possible rate-controlling step of the reaction process. Pore diffusion was checked experimentally and shown to impose no limit on reaction rates.

The controlling phenomena of the reactions were determined by applying the Freundlich and Langmuir adsorption isotherms to the experimental results in the form of initial reaction rate vs. average partial pressure of reactant at constant temperature. Velocity constants and Arrhenius equations for these controlling processes were also determined.

REACTION SYSTEM AND CATALYST

The transmethylation reactions among the methylamines are (*1, 2*):

$$2\,CH_3NH_2 \rightleftharpoons (CH_3)_2NH + NH_3 \qquad (1)$$

$$CH_3NH_2 + (CH_3)_2NH \rightleftharpoons (CH_3)_3N + NH_3 \qquad (2)$$

$$2\,(CH_3)_2NH \rightleftharpoons (CH_3)_3N + CH_3NH_2 \qquad (3)$$

Since experimental temperatures did not exceed 372°C., thermal decomposition of the methylamines presented no problems (*3* to *6*).

Considering the transmethylation process as being analogous to alcohol dehydration, catalysts such as silica-aluminas, clays, or phosphates are each suitable for the reactions listed above, and it is found that active metals may also be used (*7, 8*).

Montmorillonite K-106 from Girdler catalysts was selected as the catalyst for the investigation of reactions (1) and (3). The basic structure of montmorillonite consists of a three-layer silica—alumina with hydroxyl groups —silica lattice (*9, 10*). The nature of the acidic sites of silica-alumina has been studied for amine base adsorption using infrared absorption analysis (*18*), indicating that these sites are initially Lewis sites, becoming apparent Bronsted sites when there is proton transfer to the adsorbed substrate from a surface hydroxyl ion. This description of the catalyst function is in accordance with earlier postulations and reviews (*11*).

RANGE OF VARIABLES COVERED IN THIS STUDY

Total pressure, 1.22 to 3.75 atm. Reactor mass velocities, 20 to 260 g./(hr.$^{-1}$) (cm.$^{-2}$). Monomethylamine transmethylation reaction, Temperatures: 320°, 336°, 344°, 356°, and 371°C. Reactant partial pressure: 0.26 to 1.33 atm. Dimethylamine transmethylation reaction, Temperatures: 249°, 262°, 277°, and 293°C. Reactant partial pressure: 0.14 to 1.06 atm.

The monomethyl and dimethylamine reactants were standard items purchased from The Matheson Company, Inc., and were found to be 98.0 and 99.5% pure, respectively, with the impurities being traces of other methylamines.

EQUIPMENT AND PROCEDURE

Batches of reactant methylamine (gaseous at room temperature) were diluted with helium and fed to the flow reaction system from a pressurized reservoir tank (4-cu.-ft. capacity at S.T.P.) through an ammonia regulator. The regulator was used to establish the system pressure, and a ⅛ in. stainless Hoke needle valve at the reactor exit was employed for flow control. Beyond this valve, the remaining system operated at essentially atmospheric pressure, with the gas stream passing through a rotameter (with a range up to 6 cu.ft./hr.), thence to a water scrubber for removal of the amines and ammonia. The pressurized portion of the reactor system was constructed of ¼ in. stainless steel tubing and corresponding fittings.