to 30 per cent over that obtained with film type condensation. Practically, however, the cost of the coating is bigger than the saving by the decreased heat-transfer surface area. If tetrafluoroethylene coatings promote the dropwise condensation of organic vapours, as Topper and Baer [4] found for ethylene glycol, nitrobenzene and aniline, the increase of the overall heat-transfer coefficient may be tremendous and the saving will overcome the cost.

The communicators have executed the experiments of condensation of water, carbon-tetrachloride and methanol vapour. The results verified the dropwise condensation characteristic of tetrafluoroethylene for steam, but did not for organic vapours. The experimental data are summarized in Table 1.

Three vertical tubes of aluminum, approximately 1 cm O.D., 50-cm long each were used. Tube A and B had tetrafluoroethylene films, approximately 0·0075-mm thickness, fused to their outer surfaces. Tube C had no resin film on it. Tetrafluoroethylene resin to A is produced by Daikin Industrial Co. and that to B is by E. I. DuPont Co.

REFERENCES

1. J. A. Edwards and J. S. Doolittle, Tetrafluoroethylene promoted dropwise condensation, *Int. J. Heat Mass Transfer* **8**, 663 (1965).
2. E. J. Le Fevre and J. W. Rose, Comments on the paper "Tetrafluorethylene promoted dropwise condensation", *Int. J. Heat Mass Transfer* **8**, 1179 (1965).
3. D. W. Butcher and C. W. Honour, Tetrafluoroethylene coatings on condenser tubes, *Int. J. Heat Mass Transfer* **9**, 835 (1966).
4. L. Topper and E. Baer, Dropwise condensation of vapors and heat-transfer rates, *J. Colloid Sci.* **10**, 225 (1955).

Int. J. Heat Mass Transfer. Vol. 10, pp. 1016–1018 Pergamon Press Ltd: 1967. Printed in Great Britain

PHOTOGRAPHIC STUDY OF THE INTERFACIAL DISTURBANCES OF LIQUID FILMS IN FALLING FILM FLOW, AND IN VERTICAL, DOWNWARD, ANNULAR TWO-PHASE FLOW

SZE-FOO CHIEN* and W. E. IBELE

University of Minnesota, Minneapolis, Minnesota, U.S.A.

(*Received* 20 *June* 1966 *and in revised form* 18 *January* 1967)

Liquid film flow is involved in many engineering processes and applications; from cooling and absorption towers to the protection of the nozzles of jet propulsion system, and the film cooling of high speed and re-entry vehicles. Knowledge of the nature and characteristics of the film interface is essential to the understanding of the film itself, the mechanism of flow and the transport phenomena of the flow. In this work, a series of photographs of the interface were taken to reveal typical interfacial disturbances and to explain some relationship between the interfacial disturbances and the flow characteristics.

EXPERIMENTAL EQUIPMENT

A diagram of the experimental equipment is shown in Fig. 1. The test section was made of 2-in I.D. acrylic clear plastic tubing, 126 in. in length. The gas phase flowed to the test section via a 2-in pipe, and had 57 in of straight run before contacting the liquid phase. Liquid was injected into the gas stream through an annular slot at an angle of 4° 38′ to the gas flow direction. The width of the injection slot was kept at 0·0808 in. Photographs were taken at two locations—one centred about 26 in from the liquid injection point, and the other about 74 in from the same point. The coverage of the photographs is about 8 in along the flow direction.

A high frequency Strobolight, used as the light source, was positioned about 45° from the direction of the camera, which was a 4 × 5 Graphic. Kodak Royal X Pan film was used. The exposure was adjusted such that the photographs show a sharp contrast of the interfacial disturbances. The background was kept dark so that only the disturbances on the front half of the tube were photographed.

Compressed air served as the gas phase and water served as the liquid phase. The flow rate of the gas phase varied from zero to 0·415 lb_m/s (corresponding to a velocity from zero to 250 ft/s) and the peripheral liquid flow rate

* Present address: Texaco Research Laboratories, Texaco Inc., Bellaire, Texas, U.S.A.

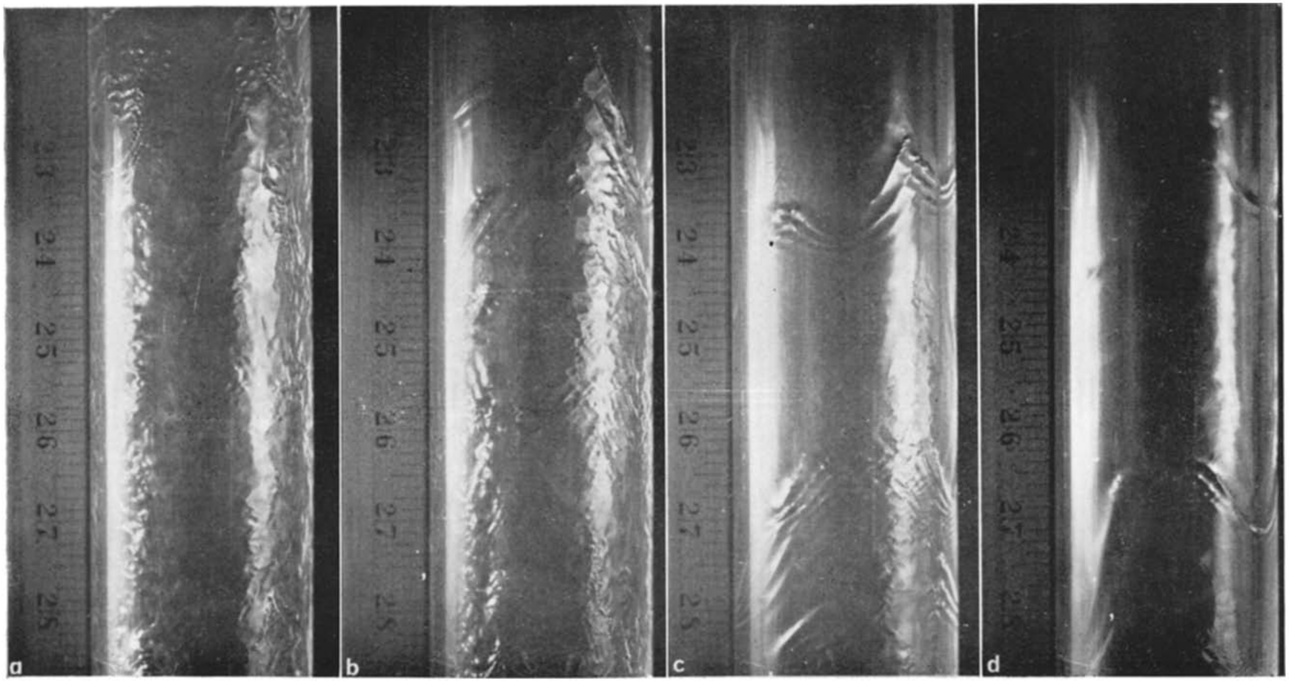

FIG. 2. Interfacial disturbances of the liquid film in falling film flow. Distance indicated in in. from the liquid injection point.
(a) $G_L = 0{\cdot}394$ lb_m/s-ft. (b) $G_L = 0{\cdot}467$ lb_m/s-ft.
(c) $G_L = 0{\cdot}566$ lb_m/s-ft. (d) $G_L = 0{\cdot}667$ lb_m/s-ft.

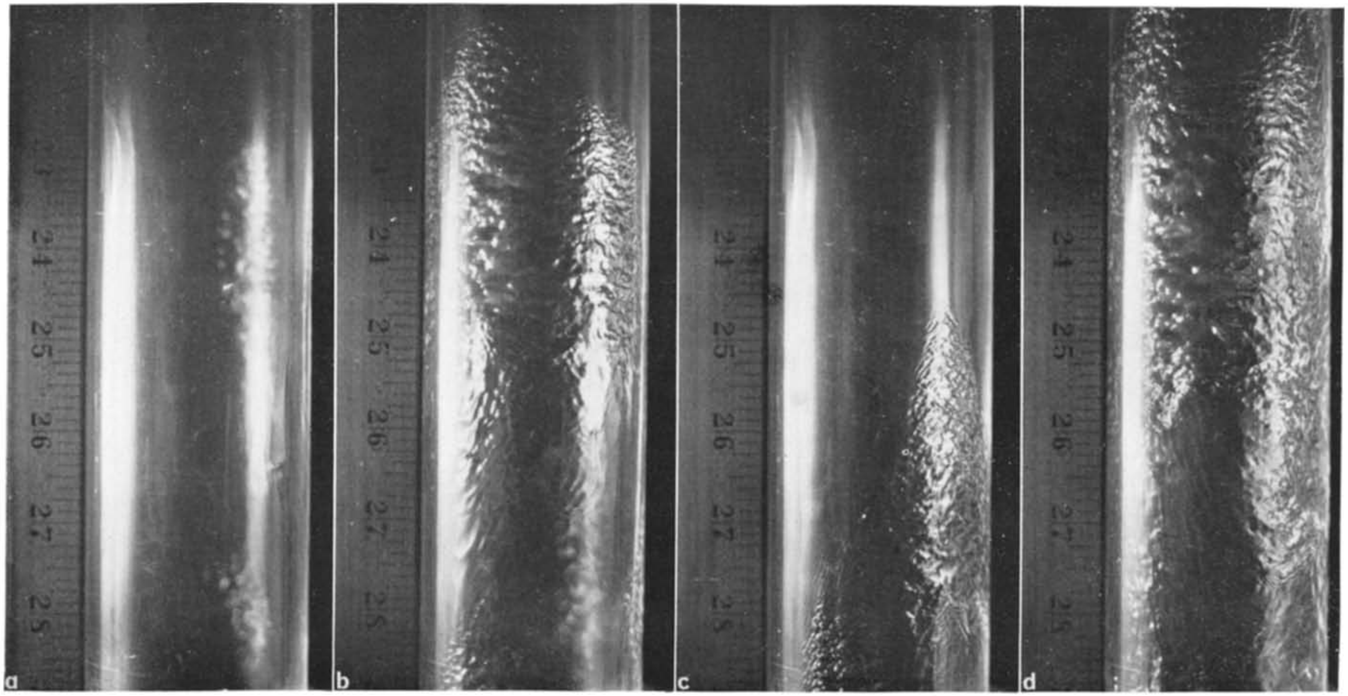

FIG. 3. Interfacial disturbances of the liquid film in falling film flow. Distance indicated in in. from the liquid injection point.
(a) $G_L = 1{\cdot}100$ lb$_m$/s-ft. (b) $G_L = 1{\cdot}380$ lb$_m$/s-ft.
(c) $G_L = 1{\cdot}452$ lb$_m$/s-ft. (d) $G_L = 1{\cdot}638$ lb$_m$/s-ft.

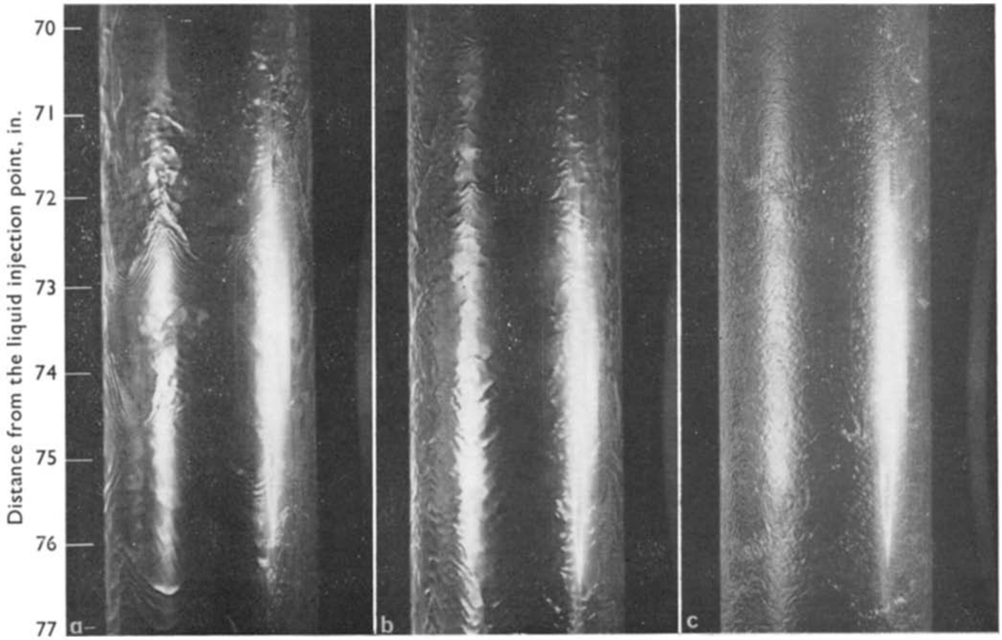

FIG. 5. Interfacial disturbances of the liquid film in two-phase flow. Liquid flow rate = 0·193 lb_m/s-ft.
(a) Falling film flow, $Re'_G = 0$. (b) Annular two-phase flow, $Re'_G = 72500$.
(c) Annular-mist two-phase flow, $Re'_G = 260000$.

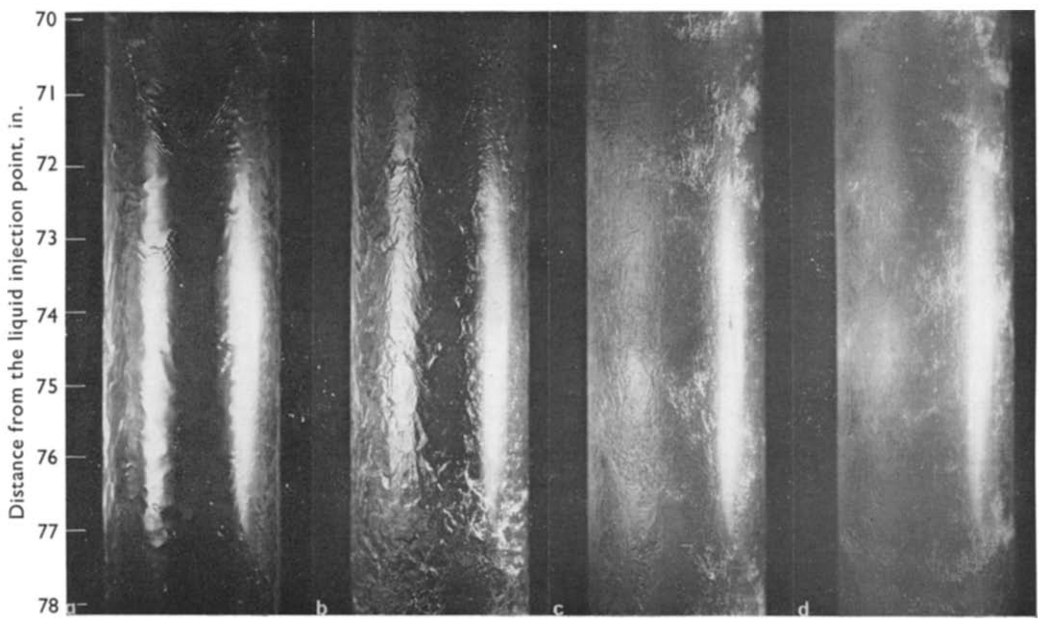

FIG. 6. Interfacial disturbances of the liquid film in two-phase flow. Liquid flow rate = 0·644 lb_m/s-ft.
(a) Falling film flow, $Re'_G = 0$. (b) Annular two-phase flow, $Re'_G = 50000$.
(c) Annular-mist two-phase flow, $Re'_G = 190000$. (d) Annular-mist two-phase flow, $Re'_G = 280000$.

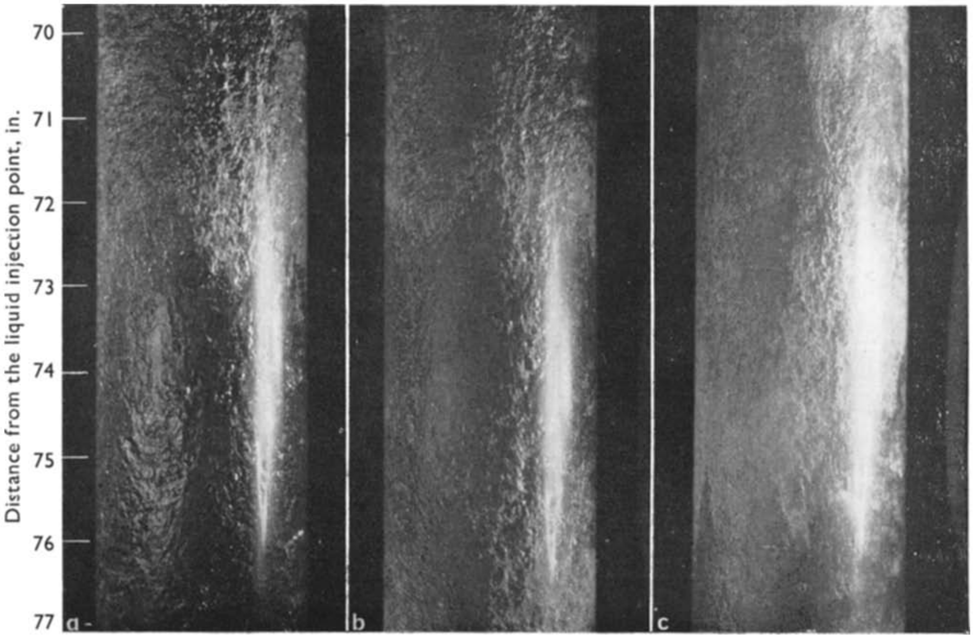

FIG. 7. Interfacial disturbances of the liquid film in two-phase flow. Liquid flow rate = 1·814 lb_m/s-ft.
(a) At transition from annular to annular-mist flow, Re'_G = 72500.
(b) Annular-mist flow, Re'_G = 130000.
(c) Annular-mist flow, Re'_G = 250000.

varied from 0·193 to 1·814 lb_m/ft-s. These flow rates can be converted to superficial Reynolds numbers:

$$Re'_L = \text{superficial liquid Reynolds number} = \frac{4G_L}{\eta_L}$$

$$Re'_G = \text{superficial gas Reynolds number} = \frac{4\dot{m}_g}{\pi D \eta_g}$$

where

G_L = peripheral flow rate of the liquid phase, lb_m/ft-s

$\dot{m}_g$ = flow rate of the gas phase, lb_m/s

D = diameter of the test section, ft

η_L and η_g = viscosity of liquid phase and gas phase, respectively, lb_m/ft-s.

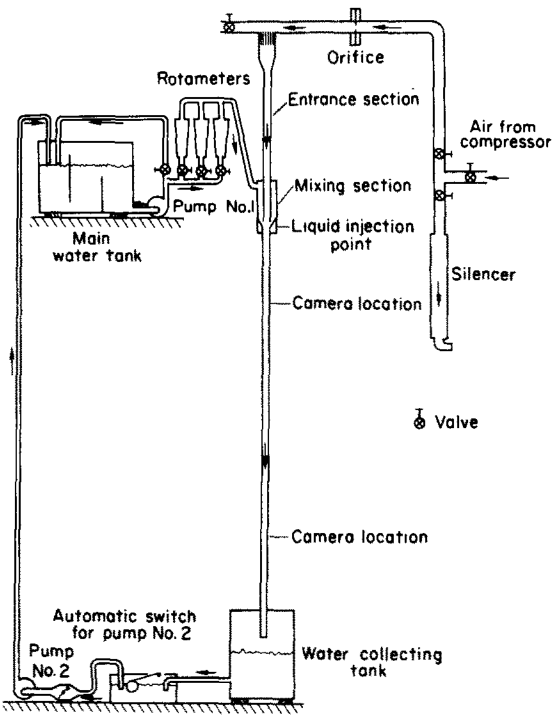

FIG. 1. Schematic set-up of the experimental equipment.

PHOTOGRAPHIC STUDY OF THE INTERFACIAL DISTURBANCES OF FALLING FILM FLOW

Falling film flow refers to downward film flow where the velocity of the gas phase is essentially zero. It is, therefore, a special case of two-phase flow. Photographs in Figs. 2 and 3 show the interfacial disturbances of the falling film flow at different liquid flow rates. These photographs are best viewed along with Fig. 4, which is the result of visual observation [1, 2] of the interfacial disturbances as a function of liquid flow rate and distance in the flow direction. At the location these photographs were taken, Fig. 4 shows that:

1. The interface will be disturbed when the liquid flow rate is less than 0·95 lb_m/ft-s.
2. When the liquid flow rate is beyond 0·95 lb_m/ft-s, patches of local ripple-like disturbances appear on the smooth interface.
3. The interface will be disturbed when the liquid flow rate is beyond 2·25 lb_m/ft-s.

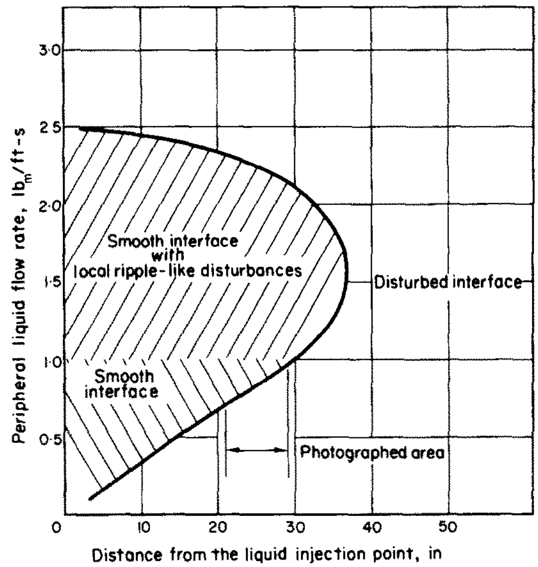

FIG. 4. Interfacial stability of falling film flow.

In Fig. 2, one may notice the trend of approaching a smooth interface as the liquid flow rate is increasing toward 0·95 lb_m/ft-s. Photographs in Fig. 3 show the patches of local disturbances appearing on the smooth interface. In Fig. 3(a), the liquid film on the front half of the tube has a smooth interface. However, on the back half of the tube there are two patches of local disturbances. These blurred shadows are barely noticeable. Figure 3(c) gives an excellent view of the local ripple-like disturbances. Figures 3(b) and 3(d) show the growing local disturbances washing downstream. A short time after Figs. 3(b) and 3(d) were taken the interface could be identical to that of Fig. 3(c).

When approaching the smooth interface flow condition by increasing the liquid flow rate, the interfacial disturbances take the form of a regular train of waves (Fig. 2); while on leaving the smooth interface flow condition by further increasing the liquid flow rate, the disturbances are in the form of local, ripple-like wave-groups (Fig. 3). The difference in the form of the disturbance suggests that different types of instability of the interface are involved. Jackson [4] proposed that turbulence can begin locally, the bulk of the film and sublayer beneath the disturbances remaining in streamline flow while the turbulent waves move at a velocity greater than that of the film. The disturbances shown on Fig. 3 seem in agreement with Jackson's proposal.

Two more photographs of the interfacial disturbances of the falling film flow are shown on Figs. 5(a) and 6(a). However, they were photographed at the downstream location (74 in from the liquid injection point). The interfacial disturbances there are random and complex.

PHOTOGRAPHIC STUDY OF THE INTERFACIAL DISTURBANCES OF TWO-PHASE FLOW

Figures 5–7 present the photographs of the interfacial disturbances of two-phase flow. These photographs are best viewed along with Fig. 8, which is the criterion for

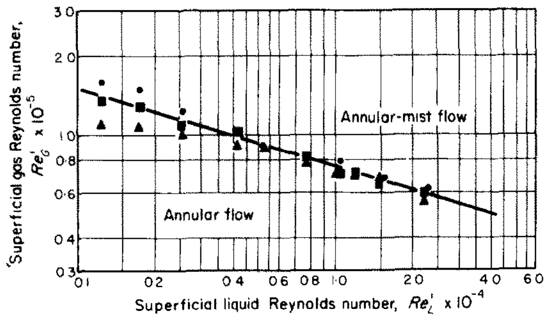

FIG. 8. Annular to annular-mist flow pattern transition of downward, cocurrent, two-phase flow.

Key
- ● Transition of flow pattern visually observed at 85–119 in from the liquid injection point.
- ■ Transition observed from pressure drop data at 42–85 in from the liquid injection point.
- ▲ Transition observed from pressure drop data at 85–119 in from the liquid injection point.

annular to annular-mist flow transition established by the visual observation and pressure measurements [2]. All of these photographs were taken with identical light and exposure conditions. The difference in the contrast is due to the effect of mist when it appears. On increasing the gas flow rate at a constant liquid flow rate, the mean film thickness decreases tremendously [2, 3] and the frequency of disturbances increases. In a steady state flow, the frequency of disturbances per unit time at a point can be approximated by the frequency of disturbances per unit distance along the flow direction in the neighborhood of the said point. All photographs show that the average distance between the successive disturbances decreases when the gas velocity increases which indicates the frequency of the disturbances has been increased.

The onset of liquid entrainment in the gas stream starts the transfer of the liquid droplets into the gas stream. In the same manner, small gas globules could be trapped in the liquid film. Indeed, small globules of gas are quite visible on Fig. 7(a).

The crest of the interface is the maximum height reached by the interface. At a given liquid flow rate the crest of the interface increases with an increase in the gas flow rate, until the transition from annular to annular-mist flow occurs. In the annular-mist flow region, the crest of the interface decreases with an increase in the gas flow rate [2]. It may be noted on Figs. 5 and 6 that the amplitude of the disturbances, or rather the appearance of the roughness of the interface, increases with gas flow rate when the flow is annular, but decreases with an increase in gas flow rate when the flow is of annular-mist type. Even without knowledge or measurement of the pressure drop of the flow, when the photographs in Fig. 7 are compared one could conclude that the roughness (and hence the friction) is greatest at the transition (Fig. 7a).

By judging the degree of mist in Figs. 5(c) and 7(c), which have approximately the same gas rate but different liquid rates, it reveals that the annular to annular-mist transition occurs earlier in the flow with the higher liquid rate. This phenomena suggests that there is a possible relationship between the film thickness and the stability of the flow.

In summary, these photographs have presented the typical interfacial disturbances of falling film flow and annular two-phase flow. Study of these photographs reveals some detail of the relationship between the interfacial disturbances and the character of the flow.

REFERENCES

1. S.-F. CHIEN and W. E. IBELE, Pressure drop and liquid film thickness of two-phase annular and annular-mist flows, *J. Heat Transfer* **86C**, 89 (1964).
2. S.-F. CHIEN, An experimental investigation of the liquid film structure and pressure drop of vertical, downward, annular two-phase flow, Ph.D. Thesis, University of Minnesota (1961).
3. D. A. CHARVONIA, An experimental investigation of the mean liquid film thickness and the characteristics of the interfacial surface in annular, two-phase flow, ASME Paper, 61-WA-243 Winter Annual Meeting, New York, N.Y. (1961).
4. M. L. JACKSON, Liquid film in viscous flow, *A.I.Ch.E. Jl* **1**, 231 (1955).