Concurrent Two-Phase Upward Flow of Air and Water Through an Open Vertical Tube and Through an Annulus[1]

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The concurrent vertical upward flow of air and water has been made at various rates and ratios of air to water in a 2⅛-in. x 20 ft. open transparent Tenite tube as well as in a 1 5/16-in. x 2⅛-in. annulus. Pressure drops and in-place ratios of gas to liquid have also been observed in order to correlate such data with corresponding flow types and patterns. Motion pictures taken at normal and especially those at high-speed have made it possible to see flow mechanisms indistinguishable to the naked eye.

There are many industrial operations in which gases and liquids flow vertically upward through open tubes as well as annuli. Although these operations have taken place for more than a century, it has been only within the past two decades that extensive laboratory studies have been made in iron pipe as well as clear plastic and glass tubing[1,2,3,4,5,6,7,8,9,10].

The visual studies which have been carried out in tubing ranging from ½-in. up to 2-in. in size have thrown much light on the various flow types which probably take place in deep wells, as well as in plant processing equipment.

A search of the literature revealed the fact that little, if any, visual studies had been made in annuli, hence the decision to compare the performance in an annulus with comparable flow rates and gas-liquid ratios in an open tube along with the added feature of taking slow-motion movies in both flow channels.

Description of Apparatus

In Figure 1, it can be seen that the apparatus is somewhat similar to the type of flow assembly which has been used by previous investigators with provisions to take such measurements as:

(1) Flow rates of both gas and liquid phases.
(2) Shut-in ratios of liquid to gas.
(3) Pressure drops over the flow section.

Discussion of Experimental Results

Open 2-in. Tube

In Figure 2, it is seen that the pressure drop decreases as the mass velocity of the air increases up to a rate of 5 lb./sec./ft.^{2} of open tubing for a low water rate of 10 lbs./sec./ft.^{2} For higher liquid rates, the pressure drops also decrease to minima at slightly higher air rates. To the left of these minima the flow type is primarily that of slugging. At very low air rates not shown on the graph, bubbles with occasional bullet-shaped pistons work their way slowly upward through the liquid. In this region of extremely low air flow rates, it was difficult to maintain steady-state conditions from the standpoint of pressure drop as well as flow rates of air and water. With no air or water flow the pressure drop would, of course, be the liquid head of water standing in the pipe, or 62.4 lbs./ft.^{2}/ft. of liquid height, or with air only 0.076 lbs./ft.^{2}/ft.

To the right of the minima, spray flow sets in with frothy annular rings of air-water bubbles and droplets moving at relatively slow rates along the walls of the pipe. In the central spray of water droplets, the velocity was much faster. These visual observations were clearly perceptible only through the showing of slow-motion movies resulting from high-photography at 800 frames/sec. When shown on the screen, the motion was slowed down to 24/800 or 1/33 of normal motion.

Flow through the 2⅛-in. x 1 5/16-in. Annulus

In Figure 3, it is easy to see that the pressure drop curves sweep through minima, however, at lower air mass velocities than those encountered in the open 2⅛-in. tube with slugging to the left and spray-annular flow to the right. With a larger wetted-wall area per unit area of cross-sectional flow, one would expect a lesser tendency for slugging in annuli. It is to be observed, however, that the minima for pressure drop drift toward the left with increasing water rates rather than to the

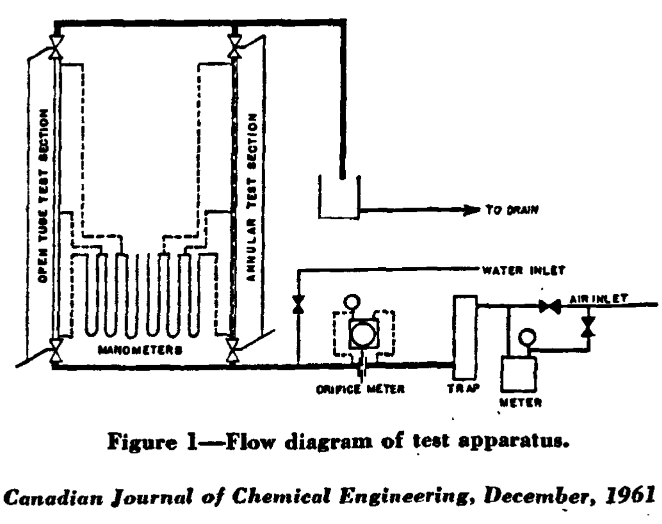

Figure 1—Flow diagram of test apparatus.

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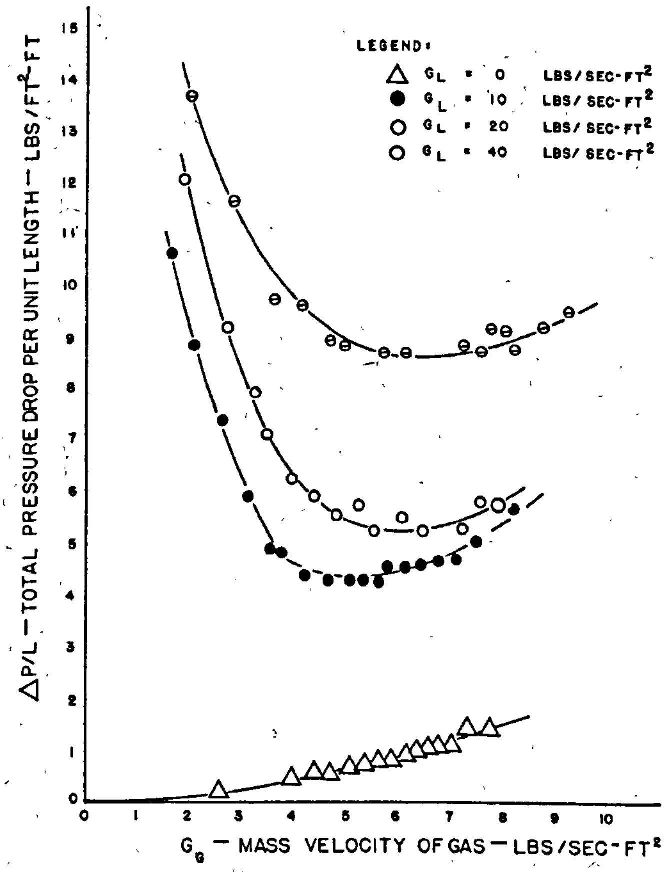

Figure 2—Flow of air and water through the 2⅛-in. open tube.

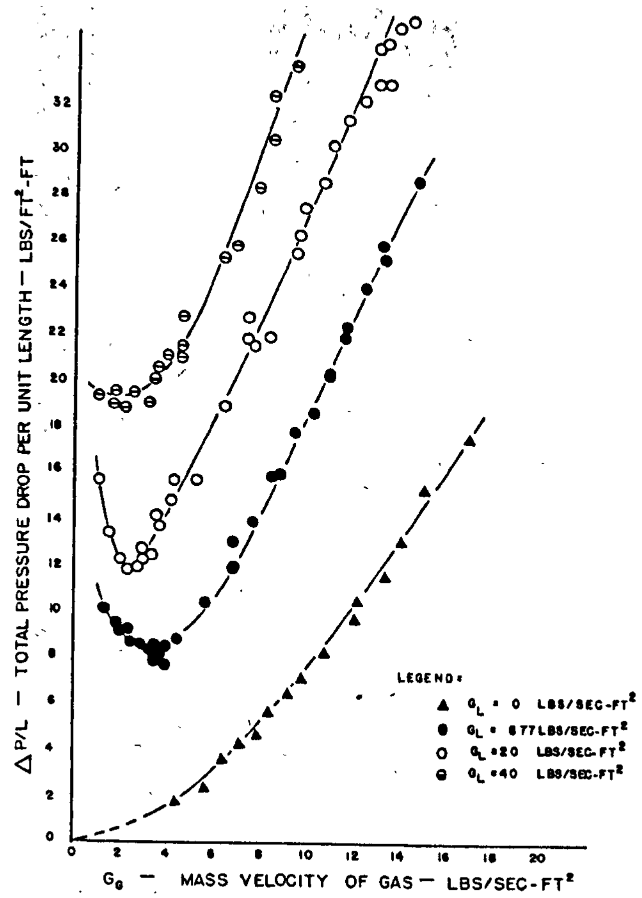

Figure 3—Flow of air and water through the 2⅛-in. x 1 5/16-in. annulus.

right as was the case with the open tube. No satisfactory explanation can be given as yet for this reversal in trend.

The higher pressure drops in the annulus over those in the open tube with the same cross-sectional area can be accounted for from the mean hydraulic radius, namely the cross-sectional area divided by the total wetted-wall perimeter of the inner and outer tubes.

"Sweep" and "Slippage" Studies

In the concurrent flow of gas and liquid through pipes in various positions, it has been found that the gas generally flows at a higher linear velocity than the liquid. This fact can be proved experimentally by shutting in the flow section during a run and measuring the amount of each phase *in place* or *in situ*. In Figures 4 and 5, graphs present a comparison of the *in place* vs the flowing ratios of liquid to gas by weight.

Petroleum engineers make these comparisons in order to obtain *slip velocity* or the velocity of gas compared to that of the liquid. Other investigators have termed these flow phenomena as sweep efficiency curves by stating that the fractional sweep efficiency is the flowing over the *in place* ratio of liquid to gas. For example in Figure 4 the sweep efficiency for water flowing at 10 lbs./sec./ft.^{2} has a fractional sweep efficiency of 0.05 when the flow ratio is 2.5 and the corresponding *in place* ratio is 50. At higher liquid flow rates, the sweep efficiency is considerably greater for the same flowing ratio.

In the case of the annulus (Figure 5), the sweep efficiency is considerably higher, especially at the higher water rate of 40 lbs./sec./ft.^{2} where the two ratios approach each other at the no-slippage line or equal linear velocities of gas and liquid.

"Lift" Efficiencies

The engineer is primarily interested in the conservation of energy in all industrial operations. For this reason Figures 6 and 7 were prepared in order to show the lift efficiency or the

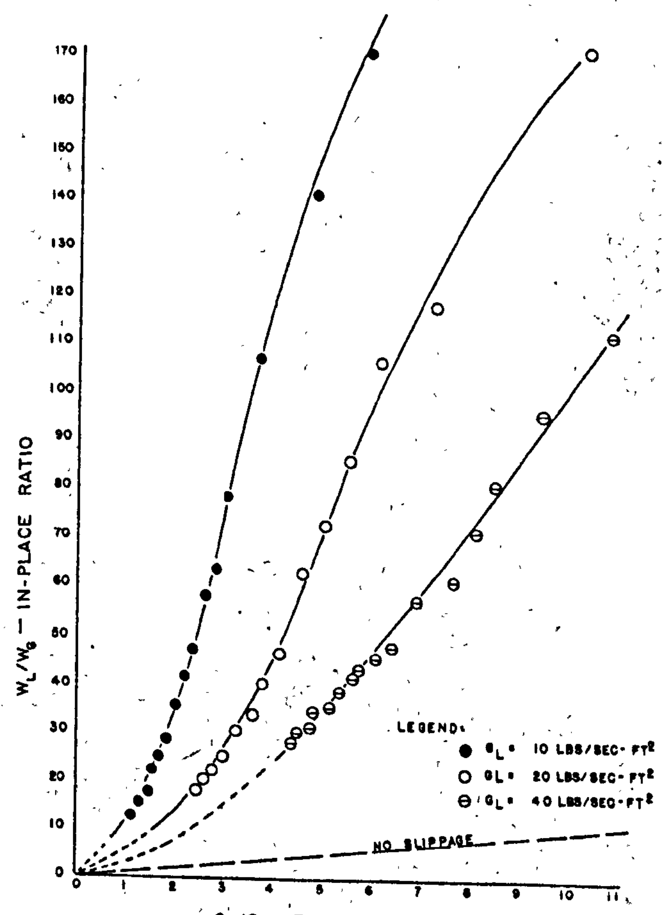

Figure 4—Flow of air and water through the 2⅛-in. open tube.

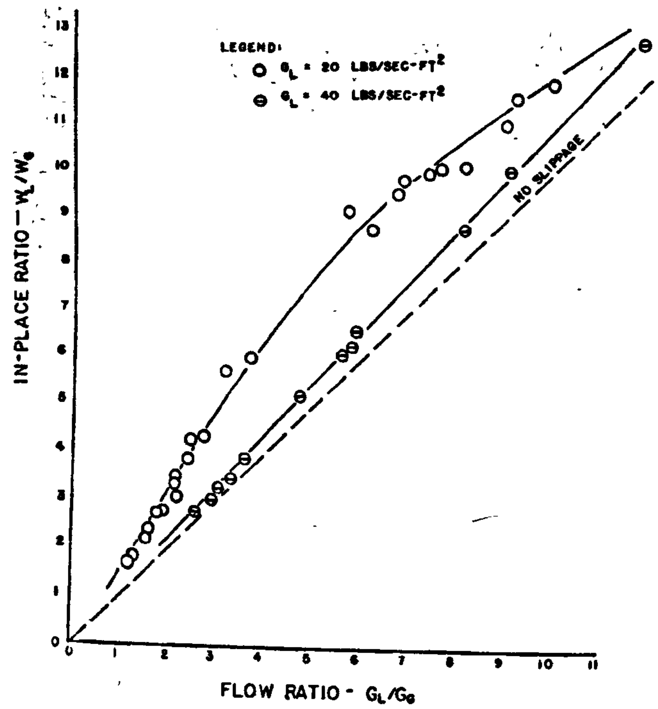

Figure 5—Flow of air and water through the 2⅛-in. x 1 5/16-in. annulus.

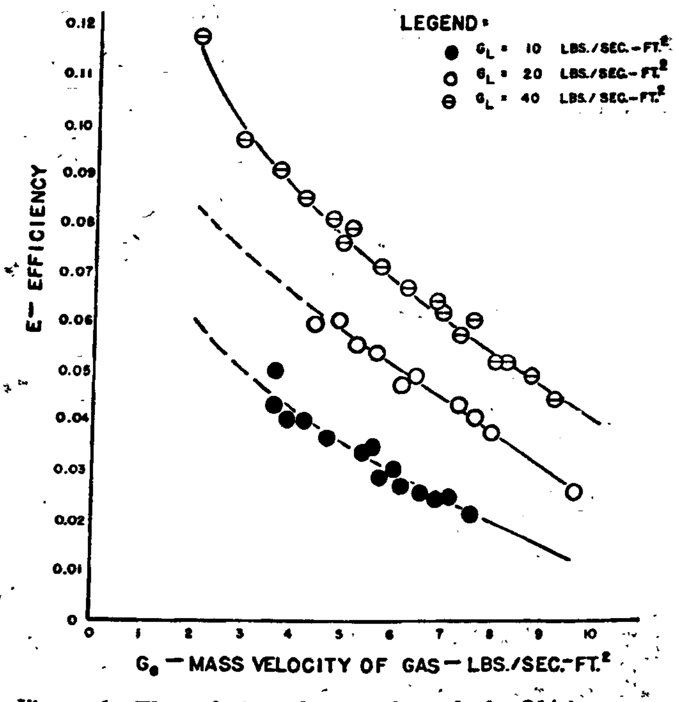

Figure 6—Flow of air and water through the 2⅛-in. open tube.

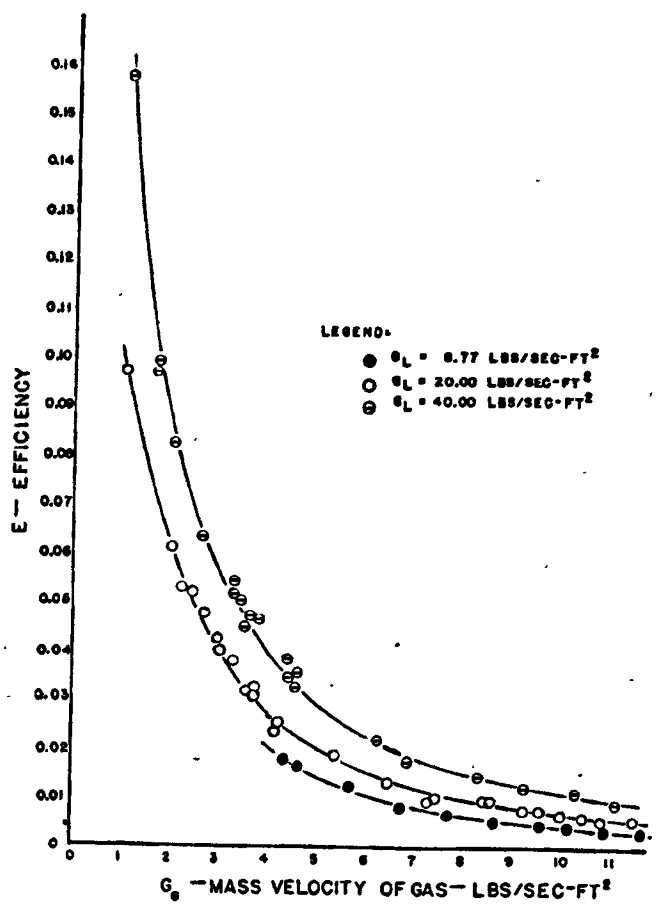

Figure 7—Flow of air and water through the 2⅛-in. x 1 5/16-in. annulus.

ratio of the actual work of lifting the liquid vertically compared to the work done by the air in expanding isothermally from the base to the top of the pipe section.

Over the range of ratios and flow rates which were studied in this experimental investigation, the efficiencies proved to be higher in the open tube than they were in the annulus. These efficiencies varied inversely with the gas-liquid ratios in these ranges; however, an earlier study[4] showed that the lift efficiency curve went through a maximum of 0.42 at a low ratio of gas to liquid and then fell off to zero with no flow of gas.

Strange as it may seem, the lift efficiency runs inversely proportional to the sweep efficiency values. In other words the lift efficiency was high when slugging was taking place and the liquid was making numerous trips up and down the tube; however, the air was being recompressed intermittently by the downward slippage of the water giving the air more than one chance to push upward against the water.

On the spray-annular side of the picture, better sweep-outs were being obtained; however, much of the air was flowing upward between the droplets in the spray without doing any actual lifting of the water, hence the lower lift efficiencies with the higher gas-liquid flowing ratios.

Motion-picture Studies

One of the principal objectives of these vertical flow studies has been that of obtaining a clear picture of the flow types or patterns which take place in the tube or annulus with various flow rates and ratios of gas to liquid. Unfortunately the written word or even a series of "still" photographs cannot convey adequately the visual story to the reader of the published page. Neither can the naked eye see what is taking place when rapid changes are taking place under certain flow regimes. For this reason during each "normal motion" flow, a second camera took a concurrent motion picture record of the flow at 800 frames/sec., thereby stretching out by time a factor of 33 when displayed to the viewer at the normal rate of 24 frames/sec. High-speed film and intensive lighting were required in order to give the required visibility on the movie screen.

Description of Flow Types in Open Tube

For the benefit of the reader who will not have the opportunity of seeing the film, an attempt will be made to present a

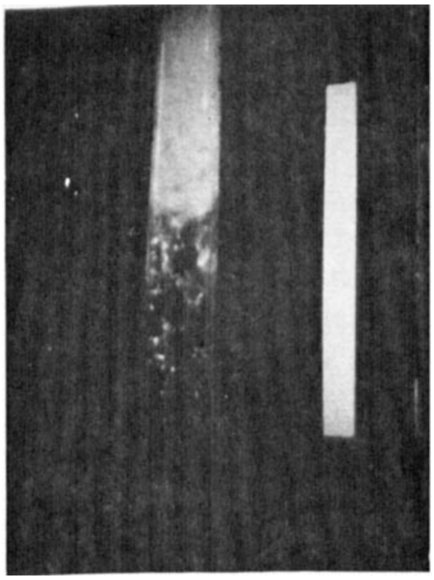

Figure 8a—(Air-Water) slug flow in open 2⅛-in. tube. Water rate — 20 lb./sec./ft.^{2}; Air rate 0.5 lb./sec./ft.^{2}. White strip is one foot in height.

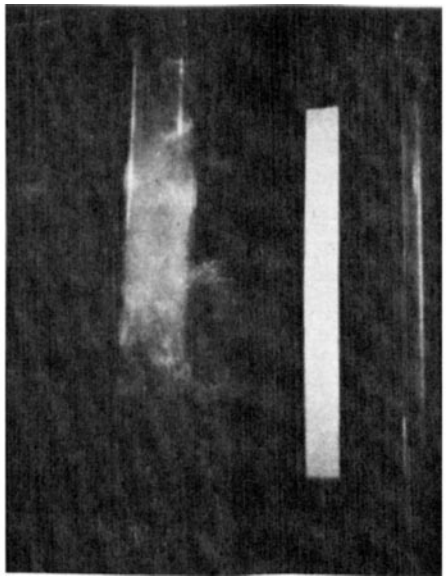

Figure 8b—(Air-Water) spray-annular flow is open in 2⅛-in. tube. Water rate 20 lb./sec./ft.^{2}; Air rate 10 lb./sec./ft.^{2}. White strip is one foot in height.

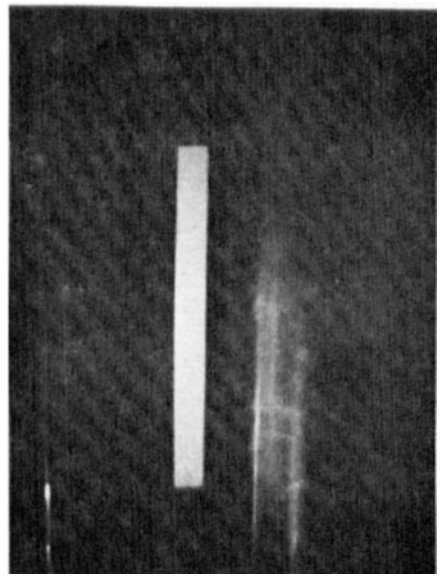

Figure 8c—(Air-Water) spray-annular flow through 1 5/16-in. x 2⅛-in. annulus. Water rate 20 lb./sec./ft.^{2}; Air rate 16.67 lb./sec./ft.^{2}. White strip is one foot in height.

word picture of the flow types which took place in an open 2⅛-in. I.D. tube, as water was moving vertically upward at 20 lbs./sec./ft.^{2} of open tubing. Air was first passed through the tube with the water, at a very slow rate, appearing as dispersed bubbles with an occasional bullet-shaped piston, the round nose being at the top of the slow-moving piston. A normal motion view with the naked eye gives one an adequate concept of this flow type.

Holding the water rate constant at 20 lbs./sec./ft.^{2}., the air rate was increased to 0.5 lbs./sec./ft.^{2} causing pronounced slugging as shown in Figure 8A. In the top half of the tube in the left-hand side of the photograph, the upward moving frothy slug can be seen, whereas the water in the bottom half of the section is slipping downward along the wall of the tube soon to meet a frothy slug moving upward in the center of the tube where the linear velocity is higher. Thus one can observe under slow motion, downward slippage of water along the inner tube wall and simultaneously upward movement of the frothy mixture of air and water in the center of the tube. The one-foot white strip has been placed to the right of the tube, so as to make it possible to time the period for the slug to move one foot under slow motion.

With the same water rate (20 lbs./sec./ft.^{2}), the air rate is again increased to 10 lbs./sec./ft.^{2} causing spray-annular flow as shown in Figure 8B. The water droplets in the spray are moving upward at an estimated velocity of 100 ft./sec. through the center of the tube, whereas a small fraction of the total water stream is moving along the inner wall of the pipe as annular frothy rings at linear velocities, ranging from 5-10 ft./sec.

Flow Types in Annular Flow

Let us maintain the same mass velocity of water in the annulus, namely 20 lbs./sec./ft.^{2}, as we did in the open tube. As air is flowed upward at a very slow rate, dispersed bubbles work their way upward through the water but the central inner tube (plugged at both ends) prevents the formation of bullet-shaped pistons. Referring to Figure 3, slugging takes place up to 2.5 lbs./sec./ft.^{2} for the air flow rate, with frothy air-water slugs moving upward in the center of the annulus, while downward slippage of water occurs simultaneously along the wetted walls of the inner and outer tubes, especially at the trailing end of each slug.

With the same fixed-mass velocity of water, the air rate is increased to 16.67 lbs./sec./ft.^{2} with the result that spray-annular flow takes place as it did with a high air rate in the open tube (Figure 8C).

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References

(1) Baxendell, P. B., Trans. Am. Inst. Mining, Met. Petrol. Engrs. T.P8027, 213 (1958).

(2) Bergelin, O. P., et al. Co-Current Gas-Liquid Flow in Vertical Tubes, Heat Transfer and Fluid Mechanics Inst., Berkeley, Calif. (1940).

(3) Brown, R. A. S., Sullivan, G. A., and Govier, G. W., Can. J. Chem. Eng. **38,** 62 (1960).

(4) Cromer, S., et al. Visual Studies of Air-Water Flow in a Vertical Pipe, AIME Tech. Pub. No. 1080, 136 (1940).

(5) Gosline, J. W., Expts on the Vertical Flow of Gas-Liquid Mixtures in Glass Pipes, ASME Trans. **118** (1936).

(6) Govier, G. W., Radford, B. A., and Dunn, J. S. C., Can. J. Chem. Eng. **35,** 58 (1957).

(7) Govier, G. W., and Short, W. Leigh, Can. J. Chem. Eng. **36,** 195 (1958).

(8) Poettman, F. H., et al. The Multiphase Flow of Gas, Oil and Water through Vertical Flow Strings, API Division of Production, March (1952).

(9) Uren, L. C., Flow Resistance of Gas-Oil Mixtures, etc. AIME Trans. (1930).

(10) Versluys, J., Math. Dev. in Theory of Flowing Oil Wells, AIME Trans. 118 (1930).

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