# Film Inversion of Cocurrent Two-Phase Flow in Helical Coils

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The use of cocurrent tubular flow reactors for carrying out gas-liquid reactions has been a subject of investigation only in recent years. A particularly useful form would seem to be a helical coil, and indeed interest in such applications has been shown recently by some process industries (*1, 2*). However, Carter (*2*), in discussing some of the problems encountered in attempting to produce 6.6 nylon by a continuous cocurrent polymerization process, pointed out that there is so little published information on two-phase flow in helical tubes that it is not possible to specify such a reactor, particularly for high velocity flows. He did outline an approximate empirical approach to the problem.

Additional basic information on flow behavior, and on heat and mass transport in two-phase flow in helical tubes would obviously be desirable as an aid in reactor design. Such knowledge would also be useful in the design of heat transfer coils and furnace coils (*3*). Low-pressure distillation in such coils has also been studied (*4*).

In a preliminary investigation into the pressure drop and holdup characteristics of cocurrent gas liquid flow in helically coiled tubes, we have noticed an interesting phenomenon, which is described below. As the liquid density is usually considerably larger than that of the gas, it is reasonable to suppose that liquid would be forced to the outer wall of the coiled tube by centrifugal forces. However, it was observed that for certain ranges of liquid and gas flow rates the liquid travelled on the inner wall of the tube (by inner wall is meant that portion of the wall nearest the axis of the coil; see Figure 1). This rather striking phenomenon is called *film inversion* in this paper. Film inversion was found to occur at low liquid but high gas flow rates. At a constant (fairly low) water rate and low gas rates the liquid film in upward helical cocurrent flow was located mainly on the outside of the tube wall, but as the gas velocity was increased the liquid film moved from this position, first into the neutral position shown in Figure 1 (right side) and then into the inverted position shown in the same figure (on the left side). As the gas velocity continued to increase, the film moved further and further up the inner wall of the tube.

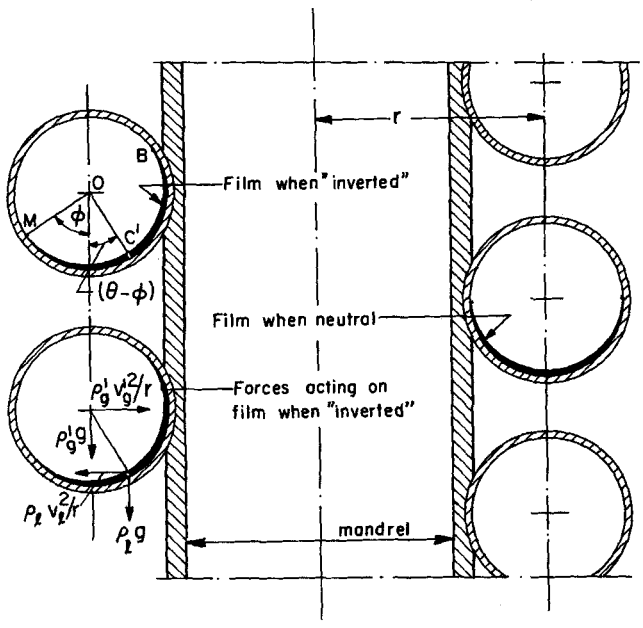


Fig. 1. Diagram of helical coil showing inverted and neutral film positions and the system of forces acting on the inverted film. Diagram not to scale.

The physical explanation for the occurrence of film inversion is that the magnitude of the slip velocity between the gas and liquid phases is at times so large that greater centrifugal forces act on the gas phase in spite of its much lower density, and cause it to flow on the outer wall. For example, if the gas is a thousand times lighter than the liquid, it should only be necessary that the gas travel at about thirty-two times the velocity of the liquid for the centrifugal forces acting on both phases to become equal.

In the following sections some measurements of the gas and liquid flows at which inversion occurs are reported, and a simple theoretical analysis is presented and compared with experimental results.

## EXPERIMENTAL STUDIES

The test section of the apparatus consisted of three parts. A 12-ft. horizontal length of transparent ⅝-in. I.D. plastic tubing led to a helical coil, which in turn was followed by a 10-ft. vertical section. Three helical coils were used (dimensions are given in Table 1), and observations and high-speed movies could be made easily for all three sections at the same gas and water mass flow rates. Flows were metered with rotameters, and gas and liquid were introduced into the first section through an air nozzle surrounded by a concentric water inlet tube. The helical coils were made by grooving lengths of acrylic tubing to make mandrels and by solvent welding the semiflexible plastic tubing into the grooves.

The film inversion point was observed in the following way. An arbitrary mark $M$ (see Figure 1) was made on the underside of the coiled tube. The measured angle $\phi$ subtended by this mark with the vertical at the center point 0 of the tube was 14 ± 1 deg. When the air-water tube-wall boundary line corresponded to the mark $M$ on the tube, the film was called *inverted*. This position on the tube was selected for the mark because the boundary marking the limit of the liquid and gas interface was observed to respond much more sensitively at this point to a change in flow rates than when the fluid was in the neutral or symmetrical position.

Obviously, the criterion used to define inversion was arbitrary, and the angle $\phi$ (see Figure 1) could have been chosen equally well at any other convenient value. The angle $2\theta$ subtended by the liquid film at the tube center was estimated by measurement of the arc $MB$, and was remarkably constant for quite different air and water flow rates, $\theta$ having a value of 27 ± 3 deg. The inversion point was approached from both directions with the liquid flow being held constant and the

Table 1. Specifications of the Helical Coils Made of ⅝ In. I.D. Tubing

| Coil No. | Mandrel diameter, in. | Tube length, ft. |
|---|---|---|
| 1 | 12 | 17.5 |
| 2 | 9 | 20.0 |
| 3 | 6 | 23.0 |

Angle of elevation of all coils 5 deg.

gas flow rate adjusted. Good reproducibility was obtained in all cases, and no dependence upon the direction of approach to the mark $M$ by the liquid film boundary seemed evident. Bromophenol red was used as an aid in making the visual observations (concentration 1 g./14 imp. gal. water).

Liquid velocities in the tube were estimated by injecting a small pulse of concentrated dye into the liquid film at the bottom of the helical coil, and timing the travel of this pulse to the top of the coil by a stop watch. By means of this technique velocities of the order of 4 ft./sec. could be measured with an accuracy of ± 0.15 ft./sec. The averages of four velocity readings were taken.

## THEORY

A simple force balance can be applied to this system, which will, however, neglect the effects of the angle of elevation of the helical tubes (in this work about 5 deg. from the horizontal), ellipticity of the tube and of secondary flow.

It is also assumed in the analysis that the distance between the center of mass of the liquid and a vertical line through the center of the tube is small compared with the radius of the mandrel. The amount of liquid in the tube is usually small enough to justify the further assumption that the center of mass of the gas corresponds to the center of the tube.

When the liquid is in the neutral position it is assumed that the centrifugal forces acting on equal volumes of gas and liquid are equal, that is

$$\frac{\rho_l v_l^2}{r} = \frac{\rho_g v_g^2}{r} \qquad (1)$$

When the liquid film is in the inverted position and flowing at a velocity $v_l$, the forces acting on the film are as shown in Figure 1. For equilibrium to exist the resultant force must act along the line $OC'$, that is, along the line connecting the centroids of the gas and liquid phases. Hence, if $\rho_l g >> \rho_g' g$ (which is usually true) then

$$\tan(\theta - \phi) = \frac{\left(\frac{\rho'_g v'^2_g}{r} - \frac{\rho_l v_l^2}{r}\right)}{\rho_l g} \qquad (2)$$

where the primed symbols refer to gas phase quantities in the inverted case. Introducing Equation (1), we can rewrite Equation (2) as

$$\rho_l v_l^2 = \rho_g' v_g'^2 - \tan(\theta - \phi)\, rg\rho_l = \rho_g v_g^2 \qquad (3)$$

Equation (3) relates the gas and liquid velocities at which a liquid film will move around the wall of a tube for a given system, and gives the change in gas velocity necessary at constant liquid velocity to cause an angular displacement of $\phi$ in the flow position of liquid film.

It is not implied in this analysis that only certain values of the angle $(\theta - \phi)$ are permissible. Obviously, this angle may assume any value, depending upon the relative magnitude of the square of the liquid and gas velocities. However, for experimental purposes $\phi$ was fixed at 14 ± 1 deg. and $\theta$ was observed to be quite constant (about 28 deg.).

## RESULTS AND DISCUSSIONS

In each of the three coils, at a number of constant liquid rates, data were obtained for the gas velocity at which film inversion was observed, with inversion defined in terms of an arbitrary radial movement of 14 deg. of the film. These data are plotted in Figure 2 according to Equation (3), with $v_l\rho_l^{1/2}$ as abscissa against $(\rho'_g v_g'^2 - \tan(\theta - \phi)\, rg\rho_l)^{1/2}$ as ordinate.

Nine of the twelve experimental points lie close to the theoretical curve with a scatter among these nine points

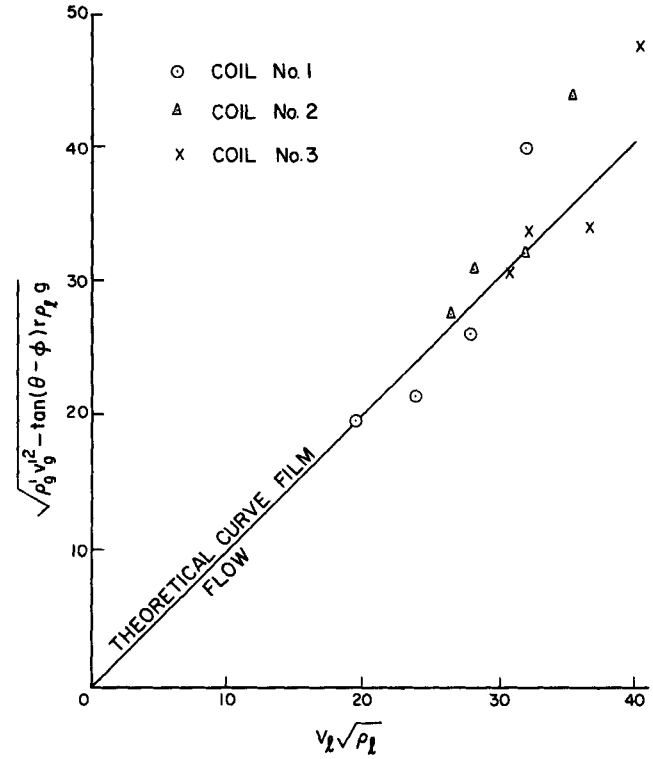


**Fig. 2. Predicted and experimental film inversion conditions in the helical coil.**

of about ± 9%. The three points which obviously do not agree with the theory are those representing experiments made at the highest air and liquid flow rates. In these experiments, large amounts of the liquid phase were being transported as droplets, and the liquid film formed mainly as a result of droplet deposition. Hence, film flow as implied by the model would not really exist in these cases and so the above mathematical analysis would not apply. These tests in the mist flow region either gave no apparent film inversion or an inversion point difficult to observe, because the water film appeared to be continually broken and replenished at random positions and with high frequencies. However, at lower liquid rates when true film flow of liquid exists the phenomenon of liquid film inversion can occur. Intuitively, one expects liquid to be thrown to the outer wall in gas-liquid flow in a coiled tube, but the magnitude of the slip velocity in film flow makes film inversion possible.

Observations of the types of flow patterns in the horizontal entrance and vertical exit tubes were made at the same air and water flow rates as those in the helical tube. The flow pattern in the horizontal tube was of the stratified type with annular flow occurring at the higher gas flow rates. In the vertical tube, the flow pattern was always of the annular type, but in the helical tube under the same conditions the behavior seemed to be a compromise between the two simpler flow pattern types. In a comparative study of the vertical, helical, and horizontal two-phase sections, it has been found also in this work that the pressure drop in the helical coils is about the same as in equivalent horizontal sections. Secondary liquid flow is therefore probably unimportant in increasing the pressure drop in helical coil two-phase cocurrent flow. We plan to publish comprehensive data on these measurements in the near future.


## ACKNOWLEDGMENT

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## NOTATION

$g$ = acceleration due to gravity
$r$ = radius from center of mandrel to center of tube
$v$ = mean velocity in neutral position
$\rho$ = density in neutral position
$\theta$ = angle subtended by liquid film at tube center
$\phi$ = angle subtended with the vertical by mark $M$ at tube center

**Subscripts**

$g$ = gas phase
$l$ = liquid phase

**Superscript**

= inverted position

## LITERATURE CITED


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# Uranium Chlorination in Fused Salts


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In a recent publication (*1*), the kinetics of the chlorination of uranium tetrachloride in the fused lithium chloride–potassium chloride eutectic were analyzed by a model based upon diffusion of U(IV) in a falling liquid film with a chemical equilibrium restriction at the interface. The results of this model are incorporated in the following expression:†

$$\frac{\overline{C_4}}{C_0} = \frac{C_{40}}{C_0} - S\left[\frac{C_{40}}{C_0} - \left(\frac{C_4}{C_0}\right)_{eq}\right]\frac{1}{Q^{2/3}} \qquad (1)$$

where the theoretical value of the parameter S is

$$S = 12.4\,\frac{\sqrt{D_l L}\,a^{2/3}}{\nu^{1/6}} \qquad (2)$$

Equation (1) predicts that a plot of the outlet U(IV) fraction against $1/Q^{2/3}$ should be a straight line with a slope equal to the parameter S times the driving force for diffusion and an intercept equal to the U(IV) fraction in the feed salt. In reference *1*, however, the data were analyzed by plotting the dimensionless concentration $\overline{C}^*$ against $1/Q^{2/3}$, which effectively forces $\overline{C_4}/C_0$ to pass through the value $C_{40}/C_0$ at $1/Q^{2/3}$ equal to zero. If the data are plotted according to Equation (1), on the other hand, it is found that the intercepts do not in general coincide with the measured value of $C_{40}/C_0$, but range from 0.93 at low temperatures to 1.02 at high temperatures. The deviations of the intercepts from the predicted value are probably not significant, since the data were obtained in the range $3 < 1/Q^{2/3} < 6$ and extrapolation to $1/Q^{2/3} = 0$ is of dubious validity.

A more reliable interpretation of the data is obtained by focusing on the slopes of plots of $\overline{C_4}/C_0$ vs. $1/Q^{2/3}$ in the flow rate range in which the data were obtained. According to Equation (1), division of the measured slopes by the driving force $[C_{40}/C_0 - (C_4/C_0)_{eq}]$ should yield the geometry and property dependent parameter S, the theoretical value of which is given by Equation (2). This has been done for the data obtained with pure chlorine reactant gases, taking $C_{40}/C_0 = 0.942$ and $(C_4/C_0)_{eq}$ directly from the equilibrium measurements. The results of this method of data analysis are shown in Figure 1 and are compared to the theoretical values of S computed from Equation (2) (these are given in the second column of Table 1 in reference *1*). For temperatures between 400° and 600°C., the agreement is good; the activation energy of the experimentally determined parameter S is 6.2 kcal./mole, compared to the theoretical value of 5.0 kcal./mole. The absolute values of S are also quite close to those predicted by Equation (2). This agreement further substantiates the original conclusion that the chlorination of uranium tetrachloride in this system is controlled by U(IV) diffusion in the salt phase, and that the measured equilibrium U(IV) fractions provide the correct driving force for mass transfer.

At 650° and 700°C., however, the experimental values fall considerably below both the theoretical and low temperature lines. In addition to the possible reasons discussed in reference *1*, this discrepancy may also be due to the fact that the equilibrium U(IV) fractions were not

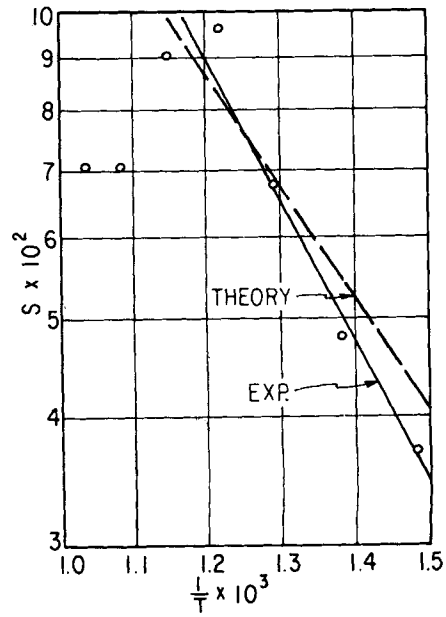


**Fig. 1. Comparison of experimental results with diffusion-equilibrium model.**

† Equation (1) is a combination of Equations (3) and (4) of reference *1*.