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EFFECT OF PIPE LENGTH ON THE TRANSITION BOUNDARIES FOR HIGH-VISCOSITY LIQUIDS

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Abstract—This paper analyzes the hydrodynamics near the discharge of a pipe carrying gas and liquid in horizontal stratified flow. It is shown that for high-viscosity liquids, pipe length may have a considerable effect on the transition from the stratified to nonstratified (annular or intermittent) flow pattern. This leads to a flow-pattern map which contains the pipe length as a parameter for this transition boundary.

INTRODUCTION

The present work was undertaken in an attempt to resolve a controversy as to the effect of viscosity on flow-pattern transitions. Weisman *et al.* (1979) reported a study on the effect of viscosity on the flow-pattern boundaries using water–glycerine solutions of 75 and 150 cP with air as the gas phase. Their data indicated that the transitions showed "relatively little change from the map obtained with a water–air system". This result is particularly interesting with respect to the stratified–nonstratified transition boundary since it is in clear contradiction to the prediction of the Taitel & Dukler (1976) model.

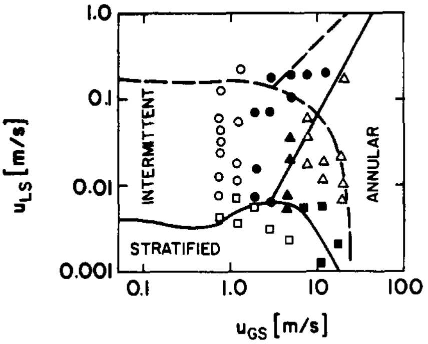
As a result we carried out experiments with high-viscosity liquids using a glycerine/water–air system in a horizontal 3.8 cm dia pipe, 15 m long; the results of the experiments are shown in figures 1 and 2. The lines in the figures show the results of our theoretical model (Taitel & Dukler 1976). As seen, the theory is in reasonable agreement with the experimental results. The dashed lines represent the theory for the case of a water–air system (which also shows good agreement with the experiments). It is quite clear that the effect of viscosity is indeed substantial and that the theoretical model predicts the effect of viscosity reasonably well.

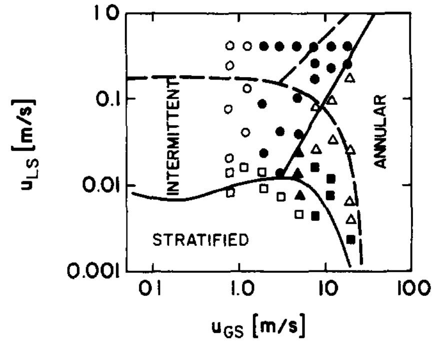
It is suggested that the main reason for the contradiction stems from the different test-section lengths used in the two studies. It may also be partly due to the criterion used by Weisman for the existence of slug flow. For high-viscosity liquids and relatively short pipes an open exit will affect the liquid level at the entrance of the pipe. Since this level controls the transition to slug flow, this transition can be influenced by the pipe length. In the Weisman *et al.* (1979) study, the pipe length was 120 dia whereas in our experiment it was approx. 360. This difference will be shown to partly explain the discrepancy between the two sets of experimental results. In the following analysis the effect of pipe length on the stratified–nonstratified boundary is studied.

ANALYSIS

Figure 3 shows a typical profile of the liquid level with distance that occurs for highly viscous liquids. The liquid drains at the exit and as a result the liquid level is at a minimum at this location, increasing in the upstream direction. One can identify three heights:

(1) H_E—the equilibrium level. This level is obtained for stratified equilibrium flow in an infinitely long tube. This is also the liquid level far away from the exit for a pipe of finite length.





□ smooth-stratified (SS)
■ wavy-stratified (SW) } stratified (S)
○ elongated bubble (EB)
● slug (SL) } intermittent (I)
△ annular, ann./disp. (AD)
▲ wavy-annular (AW) } annular (A).

Figure 1. Flow patterns for 165 cP glycerine/water–air in a horizontal 3.8 cm dia pipe: ——, theory for 165 cP; – – –, theory for 1.0 cP;

Figure 2. Flow patterns for 90 cP glycerine/water–air in a horizontal 3.8 cm dia pipe: ——, theory for 90 cP; – – –, theory for 1.0 cP.

(2) H_S—the stability level. The stability level is the level above which waves will be unstable. If the liquid level is higher than the stability level then transition to intermittent or annular flow will take place as a result of the exponential increase in amplitude of the surface waves (Taitel & Dukler 1976).

(3) H_C—the critical level. The flow is supercritical if the liquid level is lower than H_C and subcritical if it is above H_C. The theory of channel flow (Henderson 1966) shows that for free fall the liquid level at the pipe exit is approximately the critical level.

Figure 3 shows a typical exit configuration for a high-viscosity liquid. As seen in this particular example, $H_E > H_S > H_C$. Since $H_E > H_S$, large waves will grow on the equilibrium level and transition to intermittent or annular flow will take place (Taitel & Dukler 1976). However, for this to occur the pipe length has to be longer than the distance x (see figure 3), the length needed for the liquid level to reach the stability level. If the pipe length is shorter than x, transition to intermittent or annular flow will not take place even for gas and liquid rates at which it would be expected to occur in long pipes. Thus, it is seen that the transition from stratified to intermittent or annular flow will depend not only on the pipe diameter, fluid properties and flow rates but also on the length of the pipe.

However, the typical case demonstrated by figure 3 only shows the case where $H_E > H_S > H_C$. There are six possible relations among H_E, H_S and H_C. The most important relations that bear direct influence on the flow pattern are as follows:

(I) $H_S > H_E$. When this is the case the flow will always be stratified, regardless of pipe length. When $H_E < H_S$ we distinguish between the two possibilities.

(II) $H_C > H_S$. In this case the stratified flow is unstable at the exit and transition from stratified flow will occur, regardless of pipe length. This is often the case for low-viscosity liquids (such as water) therefore, in this case, the flow-pattern transition will be independent of pipe length.

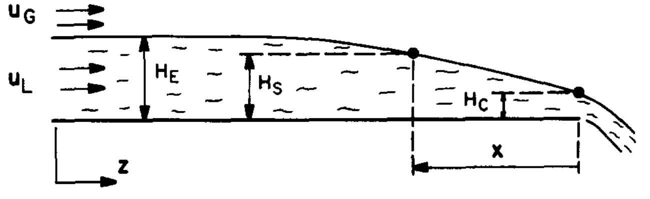


Figure 3. Film level at pipe exit.

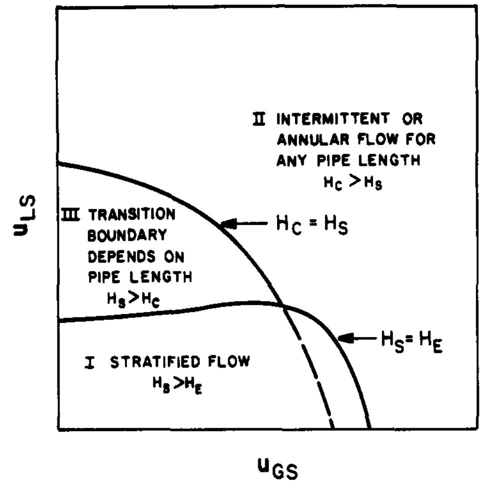


Figure 4. Schematic diagram for flow-pattern zones.

(III) $H_S > H_C$. This is the situation shown in figure 3, in which case transition to intermittent or annular flow will also depend on the pipe length.

Figure 4 schematically shows these three zones on a flow-pattern map with the superficial velocities of the gas and the liquid u_{GS} and u_{LS} as coordinates. The lines $H_E = H_S$ and $H_C = H_S$ separate the flow map into three zones: in zone I only stratified flow can be observed; zone II is the region where flow cannot be stratified, regardless of pipe length; zone III is the region where the transition from stratified flow depends on pipe length as well as the other variables. The quantitative determination of the location of these three zones requires a solution for the three levels H_E, H_S and H_C. In zone III, transition lines which depend on the pipe length can be calculated by solving for the distance x (see figure 3) needed for the liquid level to rise from the critical level, H_C, to the stability level H_S.

A steady-state momentum balance on a liquid cross-sectional area A_L yields

$$\rho_L \frac{d(u_L^2 A_L)}{dz} = -\tau_L S_L + \tau_i S_i - A_L \rho_L g \frac{dh}{dz} - A_L \frac{dp}{dz}. \qquad [1]$$

In [1], u_L is the average liquid velocity in a cross-sectional area A_L, S_L is the wetted solid–liquid perimeter and S_i is the liquid–gas perimeter, τ_L and τ_i are the shear stresses acting on S_L and S_i, respectively, p is the pressure and h is the local liquid level; z is an axial coordinate in the downstream direction.

A similar expression is obtained for the gas layer overriding the liquid stream,

$$\rho_G \frac{d(u_G^2 A_G)}{dz} = -\tau_G S_G - \tau_i S_i - A_G \frac{dp}{dz} \qquad [2]$$

where the subscript G refers to the gas zone.

Using [2] to eliminate dp/dz from [1] and taking into account continuity of the liquid and gas ($U_L A_L = U_{LS} A$ and $U_G A_G = U_{GS} A$), yields

$$\frac{dh}{dz} = -\frac{dh}{dx} = \frac{-\frac{\tau_L S_L}{\rho_L A_L} + \frac{\tau_i S_i}{\rho_L}\left(\frac{1}{A_L} + \frac{1}{A_G}\right) + \frac{\tau_G S_G}{\rho_L A_G}}{g - \frac{\rho_G}{\rho_L} u_{GS}^2 \frac{A^2 A_L'}{A_G^3} - u_{LS}^2 \frac{A^2 A_L'}{A_L^3}} \qquad [3]$$

where u_{LS} and u_{GS} are the superficial velocities of the liquid and gas, respectively; A_L' is the derivative of A_L with respect to h ($= dA_L/dh$).

Equation [3] can be integrated with respect to x to obtain the liquid level profile. The shear stresses τ_i, τ_L and τ_G are obtained from conventional correlations, as detailed in Taitel & Dukler (1976). The critical level H_C is obtained by solving for the level which will make the denominator equal to zero, while the equilibrium level H_E is the one which will make the numerator zero.

Solution for the stability level is not directly connected to [3] and is obtained through the solution of the equation (Taitel & Dukler 1976, 1977)

$$g - \frac{\rho_G}{\rho_L - \rho_G} u_{GS}^2 \frac{A^2 A_L'}{A_G^3 \left(1 - \frac{h}{D}\right)^2} = 0. \quad [4]$$

RESULTS AND DISCUSSION

Figure 5 represent the results for a 90% glycerine/water–air system at atmospheric pressure and 25°C for a pipe diameter of 3.8 cm. The calculated stratified–nonstratified (intermittent or annular) transition boundaries are plotted as a function of pipe length x/D. The line $H_S = H_E$ corresponds to our previous theory (Taitel & Dukler 1976) and it is the special case of an infinitely long tube. The line $H_S = H_C$ corresponds to the negligible effect of the pipe length. Note that for $x/D > 300$ the results in figure 5 shows that the transition is very close to the $x/D \to \infty$ boundary. This explains nicely the experimental results in figure 1, which agree with the theory for $x/D \to \infty$.

Note that the nonstratified region is subdivided by the line $H_E = 0.5$ into the annular and intermittent subregions. $H_E/D = 0.5$ was suggested (Taitel & Dukler, 1976) as thc criteria for the boundary between the annular and intermittent flow.

The dashed lines represent the transition boundaries for an infinitely long pipe for the water–air system. The curve $H_S = H_C$ can also be considered valid for the water–air system since both H_S and H_C do not depend on the liquid viscosity (the slight difference in density can be neglected). Zone III, which ranges between the $H_S = H_E$ and $H_S = H_C$ lines, is much smaller for the water–air system, suggesting that the exit effect for the water–air system, namely for low-viscosity liquids, is less important.

Figure 6 compares this theory with the data of Weisman *et al.* (1979). A discrepancy is still in evidence when comparing the theory for $h/D = 120$ with the data. However, the agreement is now significantly better and an examination of the data gives some additional clues. In particular, note that both stratified and slug flow patterns were reported to exist over a range of identical gas and liquid flow rates. In this overlapping region we suspect slug flow actually existed. Weisman (1986) indicated that in these experiments occasional slugs appearing at over 5-min intervals were ignored. However, our data show that near the transition conditions the period between slugs could be at least as large as 5 min. Between these widely separated slugs the system appears to display the stratified pattern as the liquid level slowly builds to a value high enought to initiate a slug (Taitel & Dukler 1977). In light of this observation, the agreement of the Weisman data with our earlier theory seems acceptable.

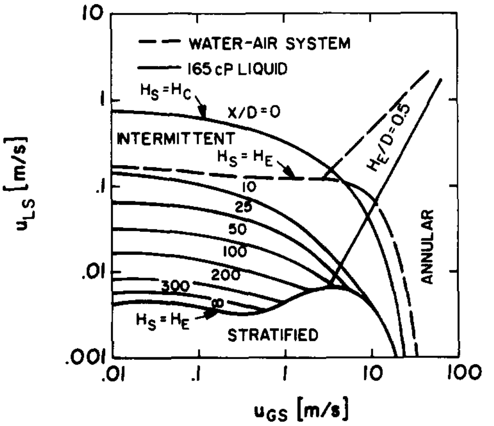


Figure 5. Effect of pipe length on the stratified–nonstratified transition; $D = 3.8$ cm, $\mu_L = 165$ cP, $\rho_L = 1.23$ g/cm^3.

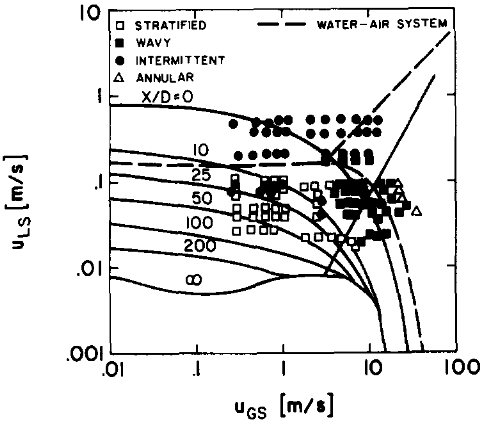


Figure 6. Effect of pipe length, comparison with Weisman data; $D = 5.1$ cm, $\mu_L = 150$ cP, $\rho_L = 1.23$ g/cm^3.

Crowley *et al.* (1984, 1986) have examined the effect of high-viscosity liquids in large-diameter pipes on the stratified–slug transition boundary. The 1984 data show that at high gas flow rates, where the interface is expected to be rough, the Taitel–Dukler (1976) model is valid only if an interfacial shear is used which is an order of magnitude larger than for a smooth surface. However, the 1986 data, taken at low gas rates where a smooth interface existed, show that the transition for high-viscosity liquids takes place at liquid superficial velocities much lower than for water. This is as predicted by the theory.

SUMMARY AND CONCLUSIONS

This work has demonstrated the importance of pipe length on the stratified–nonstratified transition. A theoretical framework is presented which shows the conditions under which pipe length is important and when it can be neglected in determining the transition boundaries. For low-viscosity fluids these pipe length effects are unimportant but for high-viscosity liquids the transition from stratified flow can be profoundly influenced.

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