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LETTER TO THE EDITOR

DISCUSSION OF THE SLUG-TO-ANNULAR FLOW PATTERN TRANSITION FOR MICROGRAVITY CONDITIONS

In a recent paper by Dukler *et al.* (1988) on gas–liquid flow patterns and their transitions under microgravity conditions, the authors offer a preliminary model for the transition between the slug and the annular flow regimes. The model involves the simultaneous solution of:

- a two-phase, separated flow momentum equation for the annular flow regime
- a void–flow rate relationship, based upon a drift–flux concept, for slug flows.

When implementing this model, analysts should be aware that, depending upon the flow conditions (primarily the density ratio), there may be zero, one, or two solutions to this model in the form presented by the authors.

REVIEW OF THE KEY EQUATIONS

The two-phase momentum equation, [12], [13] and [14] from the Dukler *et al.* paper, can be rearranged in the form:

$$\left(\frac{U_{LS}}{U_{GS}}\right)=\left\{\left(\frac{\rho_G}{\rho_L}\right)^{0.8}\left(\frac{\mu_G}{\mu_L}\right)^{0.2}\frac{[1+150(1-\epsilon^{0.5})](1-\epsilon)^2}{\epsilon^{2.5}}\right\}^{0.556}, \qquad [1]$$

where the term $[1+150(1-\epsilon)^{0.5}]$ models the interfacial shear between the gas and liquid phases. (As the authors point out, this model for the interfacial shear remains to be verified by pressure drop data in the annular flow regime under microgravity conditions.)

The void–flow relationship, [7] from the previous paper, can be rewritten in the form:

$$\left(\frac{U_{LS}}{U_{GS}}\right)=\left(\frac{1}{C_0\epsilon}-1\right). \qquad [2]$$

Figure 1 plots the ratio of the superficial velocities from [1] and [2] as a function of the void fraction. The graph shows [1] with two values of the liquid–gas density ratio, one appropriate to the Dukler *et al.* microgravity experiments ($\rho_L/\rho_G = 833$) and the other appropriate to the Sundstrand (Chen & Downing 1988) microgravity experiments ($\rho_L/\rho_G = 29$). Equation [1] is plotted assuming turbulent liquid and gas phases. Equation [2] is plotted for various values of the parameter C_0 ranging from 1.0 to 1.25.

DISCUSSION OF RESULTS

Dukler *et al.* (1988) use a value of $C_0 = 1.25$ to compare with their own experimental data. As shown in figure 1 here, a single solution (for turbulent flow) occurs at a void fraction of approx. 0.76 and a velocity ratio of $U_{LS}/U_{GS} = 0.053$. In figure 6 of the Dukler *et al.* paper, the transition is plotted on a map of superficial liquid velocity vs superficial gas velocity. Since a constant void fraction produces a straight line on such a map, and since the ratio between the superficial gas and liquid velocities is 0.053 in the turbulent flow portion of the plotted transition, it can be seen that figure 1 is consistent with the result displayed by Dukler *et al.*

Figure 1 also shows that at the density ratio (29) of the Sundstrand experiments, there is no solution at all if $C_0 = 1.25$. The curves of [1] and [2] do not intersect.

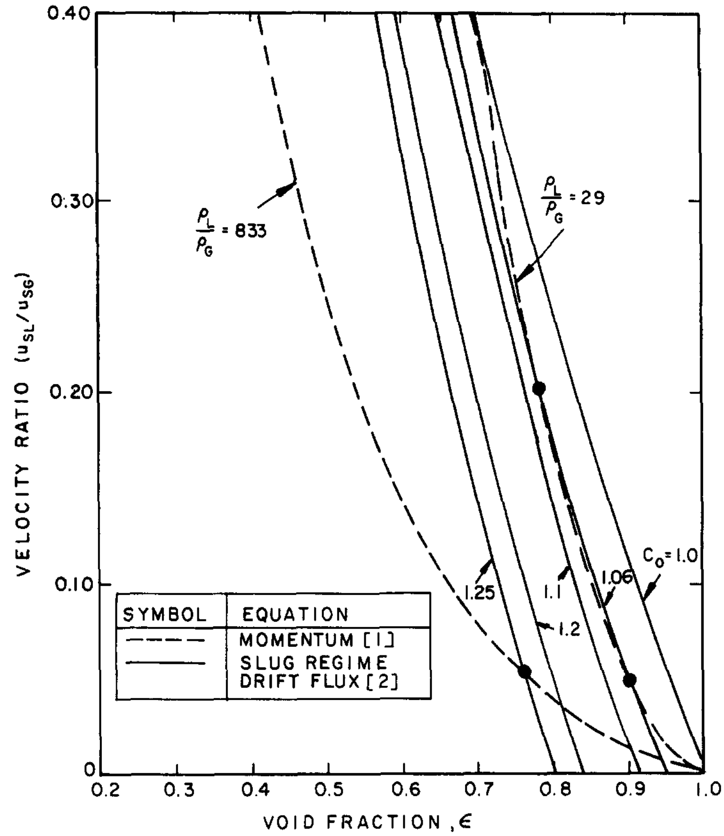

Figure 1. Solution for the slug-to-annular flow regime transition.

Chen & Downing (1988) have suggested using a value of $C_0 \cong 1.06$ for these experiments, based upon flow observations. Dukler *et al.* have used that recommended value in their comparisons. Figure 1 here shows that there are actually multiple solutions for these conditions. One solution occurs at $\epsilon = 0.78$ and $U_{LS}/U_{GS} = 0.2$. This is consistent with the data comparison presented by Chen & Downing which uses the analysis method described here. There is, in this case, a second solution at a higher void fraction of $\epsilon = 0.90$ and $U_{LS}/U_{GS} = 0.05$. The possibility of a second solution is not mentioned by either of the previous authors. It can also be seen from figure 1 that the solution is very sensitive to small perturbations in the value of C_0 or the density ratio, because the curves of [1] and [2] are nearly tangent to each other in the range of void fractions from 0.7 to 0.9.

Perhaps the authors could discuss the methodology for applying their analysis to other density ratios where experimental data do not empirically determine the value of the parameter C_0. In their approach, it is possible to have zero, one, or two solutions. Perhaps they could suggest a rationale for the selection of a particular solution when multiple solutions occur.

As a simple alternative, the existing data suggest that [1] simply be used with a constant void fraction of 0.76. Data from both the Dukler *et al.* and the Sundstrand microgravity experiments are consistent with this solution, and the possibility of zero or multiple solutions is avoided. This has the added advantage of being consistent with the models described by Barnea (1986) for the slug-to-annular flow regime transition. (Barnea recommends a constant void fraction of 0.76.) By this approach the analytical models at both earth gravity and microgravity would be in the same form and would compare well with existing data over that range of gravity levels.

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RESPONSE

Mr Crowley is quite correct in his analysis of our model. There are two such solutions. This is pointed out in the recent thesis by Janicot (1988) where he also demonstrates that for each fluid property pair there are maximum possible values of C_0. Consistent with our speculation as to the mechanism in the paper, we suggest that the transition from slug to annular flow takes place *at the smallest void fraction which satisfies both models*. This is the condition at which surface tension can first cause the fluid to wrap around the pipe in the annular configuration. It should be noted that we did not use the value of C_0 suggested by Chen & Downing as Crowley indicates. Our value was obtained directly from measurements we made on the Sundstrand films.

Crowley's suggestion that Barnea's model be used for this transition is unpalatable for the case of reduced gravity. That model is strongly dependent on the idea that the slugs contain about 30% voids at the high gas rates when transition to annular flow is observed, and this simply is not the experimental result for microgravity.

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