BRIEF COMMUNICATION

THE MYTH OF CHURN FLOW?

Z. S. Mao and A. E. Dukler

Chemical Engineering Department, University of Houston, Houston, TX 77204, U.S.A.

1. INTRODUCTION

Churn flow has long been accepted as a distinctive flow pattern in vertical upward gas–liquid flow. The flow conditions at which it exists have been located on a flow pattern map between slug flow which occurs at low to moderate gas rates and annular flow which is observed at high gas flow rates. Many investigators have identified the existence of this pattern based on visual observations of flow in transparent tubes and from the study of simple conductance probe time traces (Govier & Aziz 1972; Oshinowo & Charles 1974; Taitel *et al.* 1980; Mishima & Ishii 1984). Attempts have also been made by these same investigators to model the transition from the slug to churn flow pattern.

This brief communication presents detailed evidence that appears to suggest that there is little justification for considering churn flow to be a separate and distinct flow pattern. Rather this evidence suggests that the churn flow pattern is a simple and continuous extension of the condition of slug flow and no transition actually exists. This observation must be considered preliminary at this time. However, it is presented now to stimulate further discussion and research on the matter and perhaps to prevent investigators from undertaking unproductive avenues of research.

2. VISUAL EVIDENCE

Stable slug flow is characterized by steady upward motion of a quasi periodic array of alternating Taylor bubbles and liquid slugs at a constant speed of propagation. Except for effects due to decreased gas density, the lengths of the bubble and slug remain constant as they rise. The propagation velocity is uniformly upward and is the same for the front of the bubble and the front of the slug.

As the gas rate increased *visual observations made through the tube wall* suggest that the flow becomes chaotic in nature. That is, the readily observed well-defined slug and Taylor bubble lengths are no longer clearly discernible through the tube wall. The position of the front of the bubble or slug which was moving uniformly upward becomes oscillatory in nature and one seems to see large lumps of liquid moving downward as well as upward. This oscillatory behavior displays irregular periods. The liquid film falling around the Taylor bubble, which is characteristic of slug flow, can no longer be seen. On the presumption that these observations characterize a distinctive flow pattern, a number of authors have suggested a variety of models for predicting this transition between the slug and churn flow pattern (Nicklin & Davidson 1962; Wallis 1969; Taitel *et al.* 1980; Mishima & Ishii 1984; McQuillan & Whalley 1985; Brauner & Barnea 1986). Now we intend to show that the data raise questions as to whether such a transition actually exists.

3. INSTRUMENTAL EVIDENCE

Mao & Dukler (1989) provide the following data taken during slug flow of air and water in a 50.6 mm dia vertical tube:

- The axial profile of the void fraction in the liquid slug.
- The thickness profile of the liquid film around the Taylor bubble.

● The propagation velocities of the front and back of the bubbles and slugs.

● The axial profile of the magnitude and direction of the wall shear stress along the bubble and slug.

The measurement techniques and data processing methods are discussed in detail in the paper. All quantities reported represent the sample mean of profiles measured in about 200 slugs or Taylor bubbles. An error analysis indicates a coefficient of variation in each case of $<5\%$.

Experimental evidence: exhibit A

Figure 1 displays time traces of the output from an axially located radio frequency (RF) probe facing downward into the rising flow. Three seconds of data are shown for each of three gas flow rates, all at the same liquid rate. A positive voltage output indicates the presence of liquid at the tip. U_{SL} and U_{SG} are the superficial velocities of the liquid and gas, respectively. Now visual observations made through the walls of the pipe indicate the following: for $U_{SG} = 0.76$ m/s, a well-established pattern of slug flow is visually apparent; at $U_{SG} = 1.41$ m/s, slug flow exists with occasional intermittent periods where oscillatory or downflow of liquid slugs seems to be taking place; and when $U_{SG} = 3.42$ m/s, one "sees" churn flow with all of the chaotic characteristics described above. Note even when the system seems to be churning the RF probe clearly shows well-defined regions where the liquid essentially bridges the pipe, followed by regions where no liquid exists in the central region.

The RF probe can be used to conditionally sample the output of the conductance probes used to measure the thickness of the liquid film around the Taylor bubble. Figure 2(a) shows the profile of such a film thickness for well-developed slug flow. But if the same data are processed for the two higher gas rates [figures 2(b), (c)], it becomes evident that a clearly defined thin liquid film exists during what was observed to be churn flow. Note also that the terminal thickness of this film is not dramatically different between the three conditions.
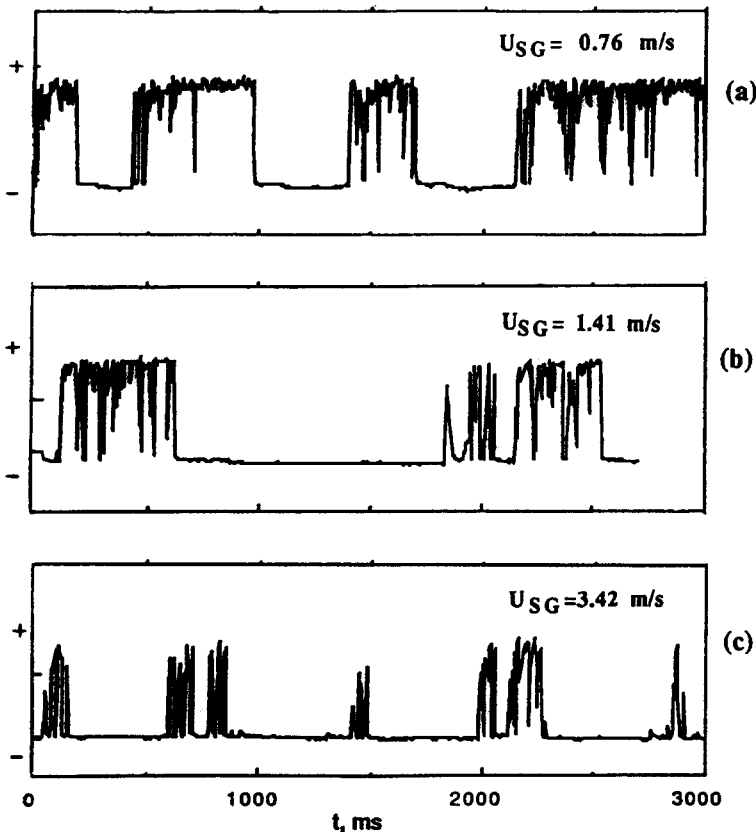

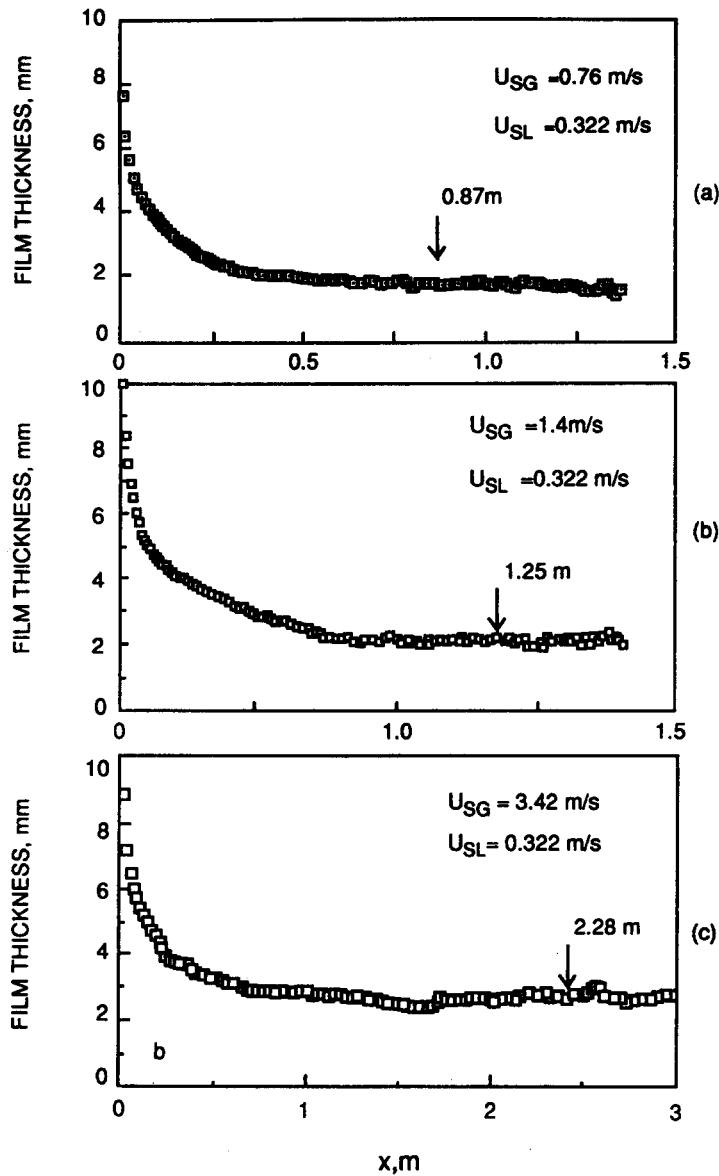Figure 1. Voltage signal from the axially located RF probe; $U_{SL} = 0.322$ m/s.

Figure 2. Axial profiles of the liquid film thickness around Taylor bubbles (arrows indicate the mean bubble length).

The RF probe can also be used to conditionally sample the presence of the liquid slug and the voids profile can be measured. These results are shown in figure 3 for the three flow conditions. Since these profiles represent the sample mean of about 200 slugs, there is a wide distribution of the slug lengths. The arrows in each case represent the mean slug length. There is a steady decrease in the length of the liquid packet as the gas rate is increased sufficiently to create what appears visually to be churn flow. However, in all three cases the profile suggests the existence of a coherent liquid slug. In this respect, the voids profile in figure 3(c) for a flow condition which appears to be churn flow is no different than that for figure 3(a)—a condition which is clearly slug flow. The void fraction which exists at the front of the slug in figure 3(c) is extremely high. However, it is not difficult to visualize a highly frothy region being carried at the front of a more coherent less aerated liquid, since the frothy front is moving upward at an identical velocity to that of the slug which carries it.
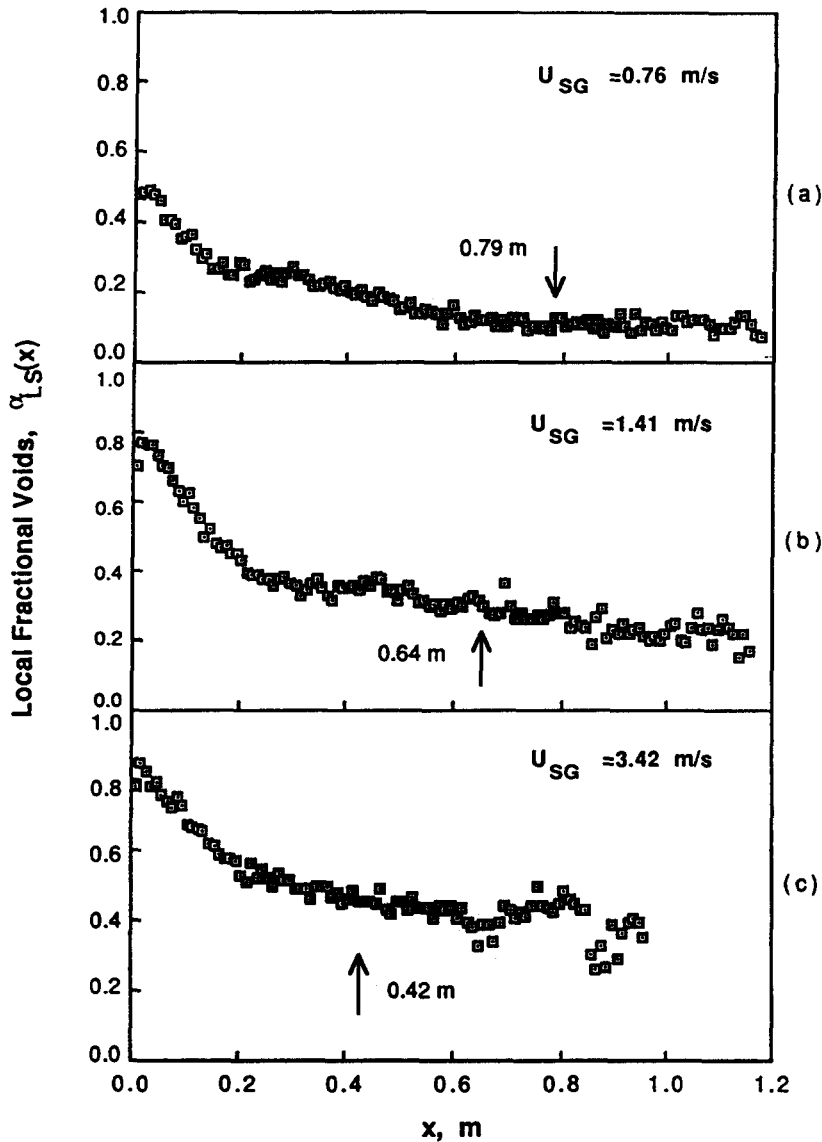
Figure 3. Axial profiles of the local void fraction in the liquid slug; $U_{SL} = 0.322$ m/s (arrows indicate the mean slug length).

Experimental evidence: exhibit B

In the Mao & Dukler (1989) experiments the average propagation velocity for the 200+ Taylor bubbles and liquid slugs included in any run was obtained from the cross correlation of the output of two axially positioned parallel wire conductance probes. The delay time measured as individual slugs passed the two probes was also used to compute the velocity of each slug. By observing which probe registered the presence of the slug first it is possible to determine the direction in which each slug was propagating. Table 1 lists the percentage of slugs which were moving downward for the three gas flow rates already considered, all at $U_{SL} = 0.322$ m/s. For the condition of "churn" flow the liquid *appeared* visually to be oscillating with lumps of liquid falling downward in the manner used to characterize churn flow (Taitel *et al.* 1980). However, instrumental measurements indicated that very few of the liquid slugs actually did move down and the extent to which they did was no different for what was visually perceived to be slug flow than that perceived to be churn flow. In all cases this is attributed to occasional overtaking of two successive Taylor bubbles.

Table 1

U_{SG} (m/s)	Pattern	Downflow (%)
0.76	Slug	0.9
1.41	Slug/trans	2.1
3.42	Churn	1.7

Experimental evidence: exhibit C

Fernandes *et al.* (1983) presented a model which could be used to calculate the detailed characteristics of slug flow. Among these were the void fraction averaged over a representative unit cell consisting of one Taylor bubble and one liquid slug. Experiments were carried out for 24 flow rate pairs where slug flow was observed to exist. Measurements were made of the cell average voids using fast-closing valves. For 23 of the 24 runs the computed void fraction and the measured one agreed to within 7%. The estimated error in measurement was about 6%. The standard deviation between measured and computed values was 3.1%.

Fernandes (1981) carried out 18 runs over the range of flow rates where churn flow was observed to exist. *The slug flow model was used to compute the average voids of a cell unit.* The average voids were measured using the fast-closing valve system, as was done for slug flow. A comparison between measured and predicted values is shown in figure 4. Only three of the points lie outside the experimental error band. The standard deviation between the experiment and the slug flow model is 5.3%. One could thus observe that the agreement of the slug flow model with the measured void fraction for churn flow runs is about as good as the prediction of the model with data for slug flow runs. This would again seem to raise the question of whether the churn flow and slug flow patterns are significantly different.

4. A POSSIBLE EXPLANATION

Visual observation of two-phase flow can be notoriously deceptive. The presence of multiple interfaces which scatter transmitted and reflected light in complex ways create visual images which may not be correct. An insight into the confusion can be derived from the measurements of axial profiles of the wall shear stress as the liquid slugs passed the wall stress probe. Such measurements were made for the three gas rates discussed above, and the results are shown in figure 5. In well-established slug flow, a liquid film falls around the Taylor bubble. This film flows downward as a wall jet as it enters the front of the liquid slug, while the inner portion of the slug is moving upward. As a result, a shear layer is formed across which the velocity changes direction. In this region the wall shear stress is directed upward, counter to the direction of the wall jet. The shear layer contains a large amount of gas which the liquid entrains as it plunges into the slug. The presence of these bubbles combined with the highly disturbed wavy nature of the shear layer makes accurate visual observation difficult.
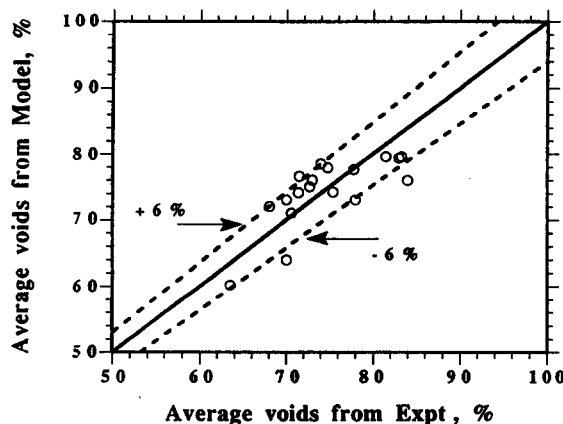
Figure 4. Measured average void fraction for churn flow compared with the prediction from a slug model.
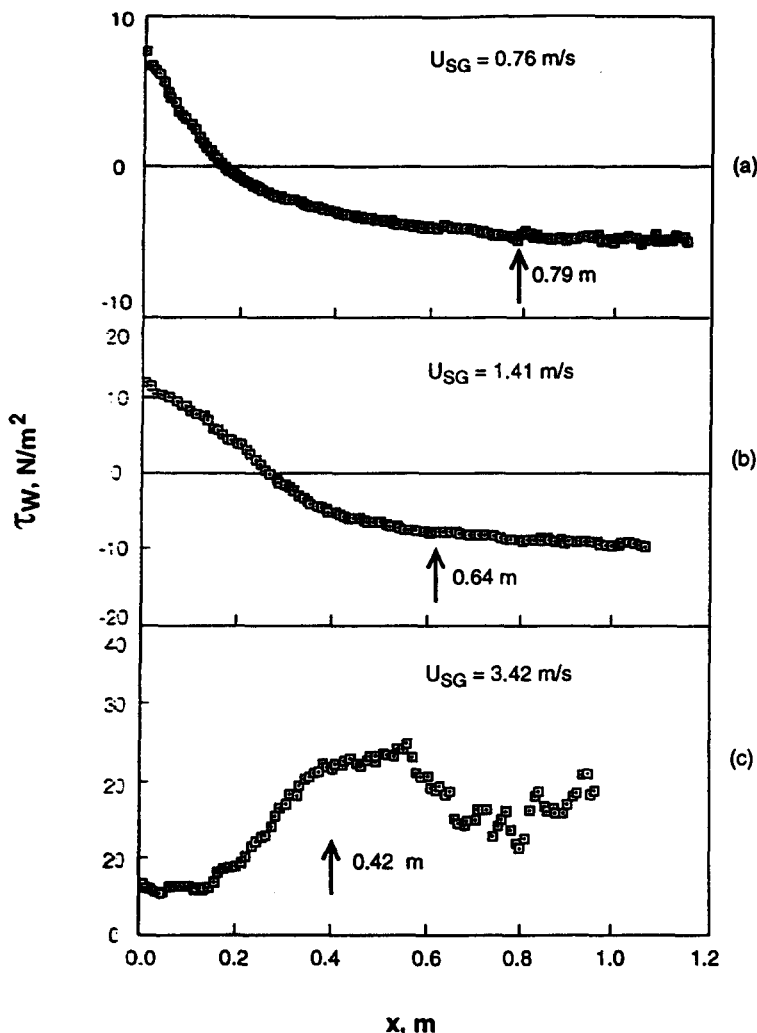
Figure 5. Axial profile of the local wall shear stress in the liquid slugs; $U_{SL} = 0.322$ m/s (arrows indicate the mean slug length.

As the jet moves downward it exchanges momentum with the larger body of the slug moving upward and it is eventually absorbed into the slug. Then the radial distribution of the velocity is upward everywhere and the shear stress at the wall is directed downward. Thus, as shown in figure 5(a), the shear stress is upward (positive) at the front where the jet and shear layer exist and downward (negative) once the plunging jet is absorbed. The point of zero shear occurs at about 25% of the length of the slug. For the higher gas flow rate shown in figure 5(b), the coherency of the shear layer disappears at about 40% of the length of the slug, beyond which no separate wall jet structure can be discerned. However, in figure 5(c) when the flow looks as if it is churning then *the wall shear stress is positive everywhere. This suggests that the film velocity on entering the front of the slug is high enough for the wall jet to penetrate through the entire slug length without losing its coherency.* Thus, it would appear that the illusion of chaotic liquid motion is probably due to the appearance of the bubble-containing shear layer as it extends along the entire slug. The impression of downward flow of the liquid also comes from looking at a highly chaotic visible shear layer containing a disproportionately high density of bubbles which is actually moving downward.

5. CONCLUSIONS

Evidence has been presented which suggests that the flow pattern which has been designated as vertical churn flow may not exist. Furthermore, this same evidence indicates that what has

heretofore been thought of as churn flow is simply a manifestation of slug flow and can be modelled using a slug flow analysis. If further experiment and theory shows this to be correct, the mapping and modelling of gas–liquid upflow systems can be significantly simplified.

REFERENCES

BRAUNER, N. & BARNEA, D. 1986 Slug/churn transition in upward gas–liquid flow. *Chem. Engng Sci.* **41**, 159–163.

FERNANDES, R. C. 1981 Experimental and theoretical studies of isothermal gas–liquid flows in vertical tubes. Ph.D. Dissertation, Univ. of Houston, TX.

FERNANDES, R. C., SEMIAT, R. & DUKLER, A. E. 1983 A hydrodynamic model for gas–liquid slug flow in vertical tubes. *AIChE Jl* **29**, 981–989.

GOVIER, G. W. & AZIZ, K. 1972 *The Flow of Complex Mixtures in Pipes.* Van Nostrand Reinhold, New York.

MAO, Z. & DUKLER, A. E. 1989 An experimental study of gas–liquid flow. *Expts Fluids* **8**, 169–182.

McQUILLAN, K. W. & WHALLEY, P. B. 1985 Flow patterns in vertical two phase flow. *Int. J. Multiphase Flow* **11**, 161–175.

MISHIMA, K. & ISHII, M. 1984 Flow regime transition criteria for two phase flow in vertical tubes. *Int. J. Heat Mass Transfer* **27**, 723–734.

NICKLIN, D. I. & DAVIDSON, J. F. 1962 The onset of instability in two phase flow. *Inst. Mech. Engrs Proc. Symp. Two Phase Flows.*

OSHINOWO, T. & CHARLES, M. E. 1974 Vertical two phase flow. Part II. Holdup and pressure drop. *Can. J. Chem. Engng* **56**, 438–450.

TAITEL, Y., BARNEA D. & DUKLER, A. E. 1980 Modelling flow pattern transitions for steady upward gas–liquid flow in vertical tubes. *AIChE Jl* **26**, 345–354.

WALLIS, G. B. 1969 *One-dimensional Two-phase Flow.* McGraw-Hill, New York.