Int. J. Multiphase Flow Vol. 19, No. 3, pp. 527–529, 1993
Printed in Great Britain. All rights reserved

0301-9322/93 $6.00 + 0.00

BRIEF COMMUNICATION

TO CHURN OR NOT TO CHURN

G. F. HEWITT and S. JAYANTI

Department of Chemical Engineering & Chemical Technology, Imperial College of Science, Technology & Medicine, Prince Consort Road, London SW7 2BY, England

(Received 15 January 1993)

This paper has been prepared in response to the communication "The myth of churn flow?" by Mao & Dukler (1993). In their paper, Mao & Dukler present evidence regarding the existence of churn flow, concluding that churn flow is really a manifestation of slug flow (or plug flow) and that it may not exist as a separate entity. The evidence presented consists primarily of data from three experiments, carried out presumably at pressures close to atmospheric, in which the gas velocities are, respectively, 0.76, 1.4 and 3.42 m/s with a constant liquid superficial velocity of 0.322 m/s. At the lower velocity, the flow was clearly slug (or plug) flow, whereas the flow with a gas superficial velocity of 3.42 m/s was designated originally as churn flow by Mao & Dukler (1989). However, in the paper discussed here, they note that the ensemble-average quantities within the slug and the Taylor bubble did not differ radically from those found in slug flow and they conclude, therefore, that what they had designated as churn flow, was in fact a manifestation of slug flow.

It is perhaps worth digressing slightly to give an historical perspective of the appellation "churn" as used in describing gas–liquid flow regimes. Essentially, one can discover at least three uses of the term:

1. The "churn turbulent" bubbly flow regime as defined, for instance, by Zuber & Findlay (1965). Essentially, this regime is delineated to allow specific forms of the drift flux model to be used over certain ranges of gas and liquid velocity.
2. The "churn flow" regime defined by Taitel *et al.* (1980). This was seen as a form of developing slug flow; the longer the pipe, the more likely the flow was to correspond to classical slug (or plug) flow rather than to a flow with apparently churning motion which was defined, in this case, as the churn flow regime.
3. "Churn flow" as an intermediate region between slug flow and annular flow. This regime has been recognized as a regime of fully developed flow, occurring even in very long tubes. It has been delineated by many authors in the literature (e.g. Hewitt & Hall-Taylor 1970). As we see it, this third type of churn flow has the following unique characteristics:
    - (a) The regime is entered from slug flow by the formation of flooding-type waves and these persist as a characteristic of the regime throughout. Such waves are absent in both slug flow and annular flow *per se*. In fully developed churn flow, such waves are formed repeatedly and transport liquid upwards (Hewitt *et al.* 1985; Govan *et al.* 1991).
    - (b) Between successive flooding waves, the flow of the liquid phase in the film region near the wall reverses direction and is eventually entrained by the next upward moving wave.

Thus, as we see it, the existence of flooding-type waves is a characteristic feature of this regime and these waves govern transport processes throughout the regime. Investigations by Jayanti & Hewitt (1992) show that the onset of churn flow, as defined in this third category, is well-described by the flooding wave hypothesis. Furthermore, recent photographic evidence shows clearly the formation of flooding waves within the Taylor bubbles in slug flow as the transition is approached.

It seems very probable that some of the confusions arising with regard to churn flow are of a semantic rather than physical nature. We may illustrate this by considering the case originally considered to be churn flow by Mao & Dukler (1989) but now categorized by them (Mao & Dukler 1993) as being indistinguishable from slug flow. If we apply the analysis described by Jayanti & Hewitt (1992) to this case, we calculate that the gas velocity for transition to the third type of churn flow defined above (at the specified liquid flow rate) would have been 6.0 m/s. This is very considerably higher than the actual experimental value (3.42 m/s), indicating that the flooding transition had almost certainly not taken place. It seems, therefore, not unreasonable to assume that the type of churn flow observed is of the second category and that this is where the confusion has arisen.

One must be sympathetic to the assertion by Mao & Dukler (1993) that it is probably not worth making a distinction between the second form of churn flow defined above and plug (or slug) flow. In the spirit of wishing to reduce to a minimum the number of alternative flow regime specifications, would it not also be sensible to define the third category of churn flow as a subset of annular flow?

The whole purpose of designating a specific flow regime is to enable models to be applied in that regime which are of a distinctive character; by dividing the full range of flows into specific regimes, the hope is that improved phenomenological prediction is possible. On the basis of this, can a case be made for retaining the designation "churn flow" for the third category defined above? We strongly believe that this is so for the following main reasons:

(1) Within churn flow of the third category, the flooding waves are a predominant phenomenon and there are periodic reversals of the liquid film flow as demonstrated in the photographic and analytical studies of Hewitt *et al.* (1985). This is so different from the unidirectional film flow in annular flows at higher gas velocities that the same phenomenological models are hardly likely to be applicable. For instance, the average interfacial friction is much higher than would be expected for a film of equivalent thickness in annular flows with unidirectional film flows and with no flooding waves present. Information on this point is available from the work of Govan *et al.* (1991).

(2) In churn flow of the third kind, the flooding waves promote extensive entrainment. Thus, we see that entrained fraction and entrainment rate *decrease* with increasing gas velocity at a given liquid flow rate, manifesting the reduction in the frequency of the flooding waves as the gas velocity decreases. The mechanism of entrainment is the "undercutting" or "bag breakup" mechanism (Azzopardi 1983). In contrast, in annular flow at high gas velocities (where the flooding waves have ceased to exist but where large disturbance waves of a somewhat different nature are the cause of entrainment), the entrained fraction and entrainment rate increase with increasing gas velocity and the breakup mechanism is different ["ligament breakup"—see Azzopardi (1983)].

(3) Because of the nature of the creation of the droplet, droplet deposition in churn flow of the third kind is often dominated by radial velocities imparted at the point of droplet creation. At high gas velocities, where ligament breakup is dominant, this effect is less significant.

It will be seen from the above that the phenomenological models required for churn flow of the third kind are quite different from those for annular flow and there seems a good justification for retaining the distinction. It should be emphasized that this form of flow covers a wide range of flow velocity. Here, we may cite the work of Owen (1986); for a pressure of 2.4 bar and for a superficial liquid velocity of 0.3 m/s, the transition (of the third kind) from slug-to-churn flow occurs at around 3.5 m/s and some of the characteristics of this form of churn flow persist up to velocities greater than 10–15 m/s. As it happens, many industrial systems are operated in this range and, if we are to have adequate phenomenological models, then we must be prepared to recognize it as being different!

On reflection, we wondered if it might be clearer to describe churn flow of the second category as "churn–slug" flow and churn flow of the third kind as "churn–annular" flow. This might avoid some of the confusion which is obviously occurring in the literature whilst still retaining (certainly in the case of churn–annular flow) the capability of a separate category in view of the very different phenomena occurring.

REFERENCES

AZZOPARDI, B. J. 1983 Mechanisms of entrainment in annular two-phase flow. UKAEA Report AERE-R11068.

GOVAN, A. H., RICHTER, H. J. & SCOTT, A. 1991 Flooding and churn flow in vertical pipes. *Int. J. Multiphase Flow* **17**, 27–44.

HEWITT, G. F., MARTIN, C. J. & WILKES, N. S. 1985 Experimental and modelling studies of annular flow in the region between flow reversal and the pressure drop minimum. *Physicochem. Hydrodynam.* **6**, 69–86.

JAYANTI, S. & HEWITT, G. F. 1992 Prediction of the slug-to-churn flow transition in vertical two-phase flow. *Int. J. Multiphase Flow* **18**, 847–860.

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

MAO, Z. S. & DUKLER, A. E. 1993 The myth of churn flow? *Int. J. Multiphase Flow* **19**, 377–383.

OWEN, D. G. 1986 An experimental and theoretical analysis of equilibrium annular flows. Ph.D. Thesis, Univ. of Birmingham, U.K.

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

ZUBER, N. & FINDLAY, J. A. 1965 Average volumetric concentration in two-phase flow systems. *J. Heat Transfer* **87**, 453–468.