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BRIEF COMMUNICATION

OBSERVATION OF FLOODING IN THE TAYLOR BUBBLE OF CO-CURRENT UPWARDS SLUG FLOW

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INTRODUCTION

This brief communication is concerned with gas–liquid co-current upwards flow in tubes. In such flows, one may define "churn flow" as an intermediate regime between slug flow and annular flow. The appelation "churn" has also been used in the context of "churn-turbulent" bubbly flow and to a form of developing slug flow; Hewitt & Jayanti (1993, this issue, pp. 527–529) have attempted to clarify these definitions and what we refer to here is their "churn flow of the third kind", namely, a regime which is entered from the slug flow regime and from which is entered the annular flow regime. The characteristic of the churn flow regime is the existence of large waves of a type similar to those observed in counter–current flow. Locally, the liquid phase may oscillate in the flow direction, the waves being transported upwards with the intervening liquid film often draining downwards. There seems to be good circumstantial evidence that the breakdown of slug flow and the initiation of churn flow occurs due to the onset of flooding waves in the Taylor bubble region of the slug flow. This explanation of the transition was first proposed by Nicklin & Davidson (1962) and has been reported as giving a reasonable fit to the data by a number of investigators since then. Most recently, Jayanti & Hewitt (1992) showed that an even closer fit to the observed transition data could be obtained if account was taken of the length of the Taylor bubble. Despite the long history of this phenomenological explanation of the transition, direct observation of the formation of the flooding waves within the Taylor bubbles of slug flow has proved elusive. There are many reasons for this; firstly, the transition is really very sudden, and also very localized and very irregular. Using high-speed ciné photography, it has proved difficult to collect enough data to observe the occurrence. However, with the recent availability of very-high-speed video photography with relatively long recording times, the chances of capturing the event have increased significantly. It was for this reason that a series of experiments was carried out in collaboration between Imperial College and CENG, Grenoble, the latter laboratory having suitable high-speed video facilities. In this brief communication, we report that the flooding event within the Taylor bubble has been successfully captured on video, lending credence to the interpretation of the transition in terms of flooding.

EXPERIMENTAL METHODS AND RESULTS

The experiments were conducted at the BALI air-lift facility at the Centre d'Etudes Nucléaires de Grenoble, France. The test section was 8 m long with an inner diameter of 10 mm. Air and water were the working fluids and the flow rate of each was measured. A Kodak Spin Physics 2000 camera was used to take high-speed video films of the flow near the top of the test section. Using this camera, filming could be done at speeds of up to 2000 images/s. A stroboscope, which could operate at a frequency of up to 1000 Hz, and a powerful (500 W) lamp were set up to illuminate the

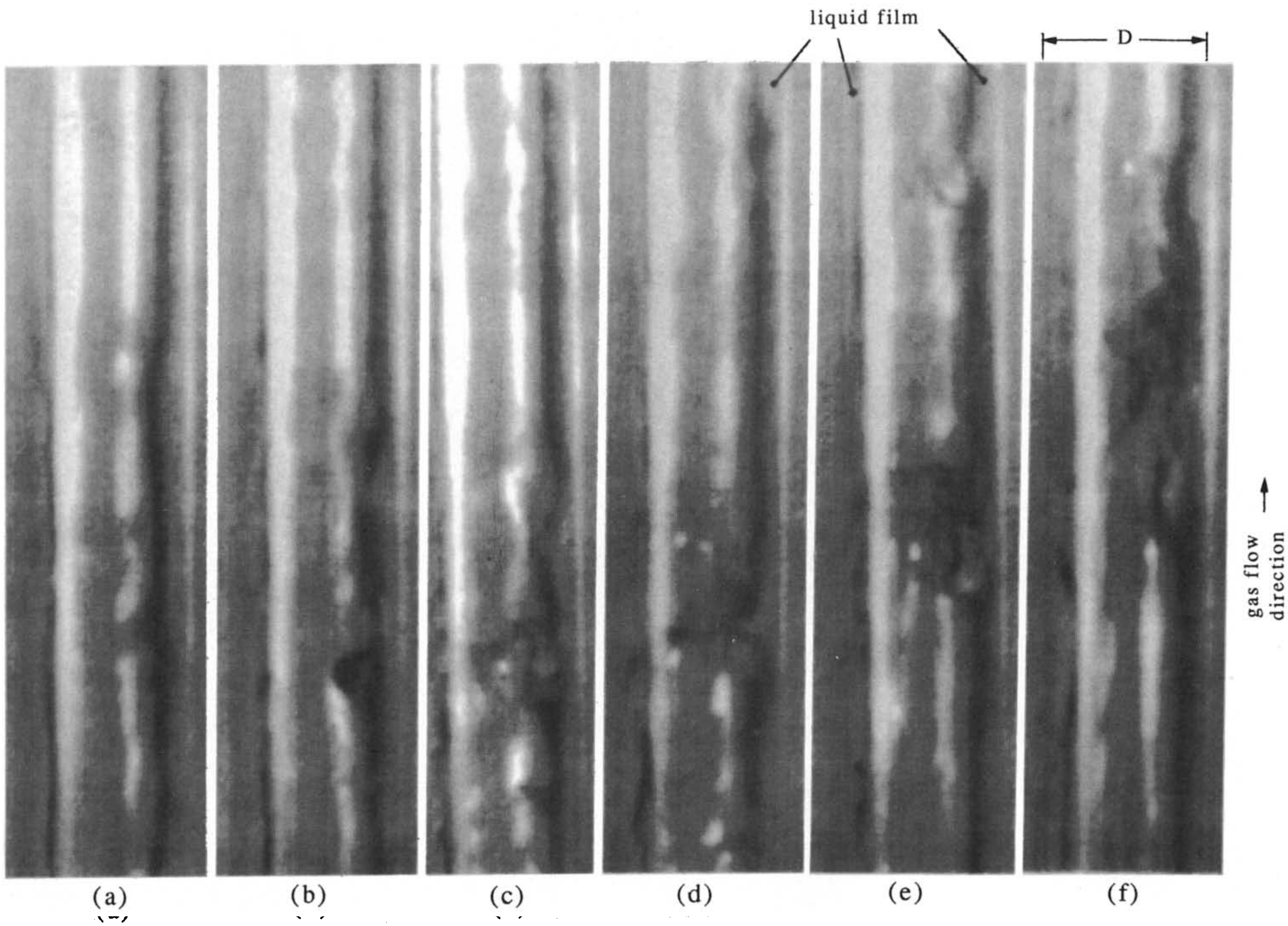

Figure 1(a–f). An extract from a high-speed video film of slug flow in gas–liquid vertical upward flow. The series of photoprints show the occurrence of flooding in the liquid film surrounding a Taylor bubble. The time elapsed between (a) and (f) was 25 ms.

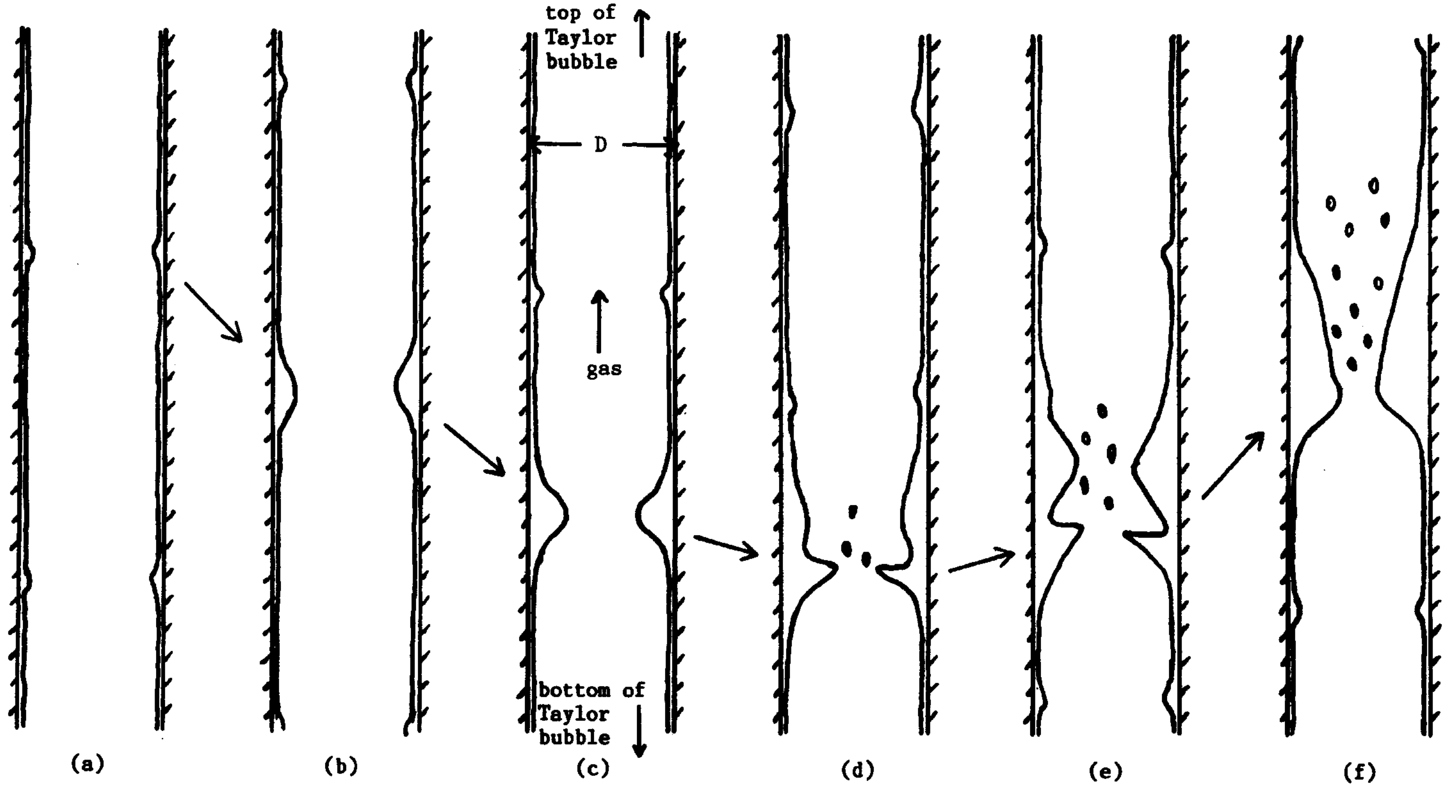

Figure 2(a–f). Schematic diagram of a flooding event in the Taylor bubble in co-current upwards slug flow. (a) Falling film waves; (b), (c) rapid growth of a wave; (d)–(f) entrainment and upward motion of a flooding wave. Gas flows upwards. The liquid in the film flows downwards except during flooding.

visualization section of the pipe. In a typical experiment, the liquid flow rate was fixed, and the gas flow rate was increased in steps. At each step, a short video film was taken after the flow became steady.

All the experiments were conducted at near-atmospheric pressure and a range of flow conditions was investigated. Although in the video output, a number of flooding events were observed in the Taylor bubbles, we will report in more detail here on one specific event. This occurred in slug flow in which the water superficial velocity was 0.9 m/s and the air superficial velocity was 3.5 m/s. Figure 1 shows the development of the flooding event in a sequence of prints of video frames lasting a total of 25 ms. As usual, prints from video frames lead to a considerable loss of information, and figure 2 shows a tracing of the flooding event. Over the full range of conditions tested, typical falling film waves were observed in the film falling down on the inside of the Taylor bubbles. However, as the transition is approached, an occasional wave may grow to a larger size spontaneously and wave growth continues, leading to a situation in which the wave starts to move upwards as shown in figure 2. The sequence of events is identical to that observed by McQuillan *et al.* (1985) in counter-current flow. We may conclude from this observation, and from similar events observed in other conditions in this sequence of experiments, that the flooding event within the Taylor bubble does indeed occur when conditions are close to those for transition.

DISCUSSION

It seems that there is both circumstantial and direct evidence for the flooding mechanism for the transition from slug to churn flow. However, it is interesting to speculate on the sequence of events that then lead to fully developed churn flow. Following the flooding event, the feed of liquid down the Taylor bubble and into the succeeding slug is reduced whilst, at the same time, the slug is draining into the next Taylor bubble at a rate which is substantially unaffected by the flooding process. Thus, the slugs would eventually collapse and liquid transport by the liquid slugs is now replaced by liquid transport by the large flooding waves. This process is a highly complex one, with the waves sometimes being large enough to partially block the tube. Always, these waves are associated with high liquid entrainment rates, and another characteristic feature of this regime is enhanced bubble entrainment into the liquid in the waves and in the residual slugs. Such bubble entrainment may also play a part in the collapse of the slugs.

If the model suggested by Jayanti & Hewitt (1992) is applied to the specific condition shown in figure 1, then the gas superficial velocity for transition is calculated as 4.0 m/s. This confirms that, though slug flow still persists, the transition is, indeed, being closely approached.

CONCLUSION

The experiments reported in this brief communication confirm that flooding waves are created in the Taylor bubbles as the transition to churn flow is approached. This provides direct evidence for the phenomenological description of the transition in terms of formation of flooding waves.

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