Int. J. Multiphase Flow, Vol. 3, pp. 603–607. Pergamon/Elsevier, 1977. Printed in Great Britain

BRIEF COMMUNICATION

THE TRANSITION TO SLUG FLOW IN THE PRESENCE OF LARGE WAVES

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(*Received* 15 *February* 1977; *received for publication* 27 *April* 1977)

INTRODUCTION

In a study of slug flow pattern in horizontal ducts Kordyban & Ranov (1970) proposed that the formation of slugs is due to the Kelvin–Helmholtz instability of the wave. This was further explored by Wallis & Dobson (1973) as well as Taitel & Dukler (1976) who presented the methods by which the transition to slug flow can be predicted without the necessity of knowing the characteristics of the interfacial waves. If the wave instability, however, is indeed the cause of the slug formation then the wave height and its proximity to the channel top ought to be of some importance to the determination of transition.

This work was undertaken first to provide some experimental data in support of wave instability as the cause of slug formation and then, to compare the experimentally obtained transition data to the relationships of Wallis & Dobson and Taitel & Dukler.

EXPERIMENTAL PROCEDURES

The tests were performed in a channel of rectangular cross sections, 15.2 cm wide and 4.6 m long. Total depth of the channel was varied by the insertion of spacers and the tests were run at the depths of 10.2, 5.08, and 2.54 cm. The downstream end of the channel was equipped with a beach to minimize the reflection of the waves, while the upstream end contained the air inlet and a wave maker.

The wave profile was measured by electrical conductivity gages consisting of two platinum wires 0.127 mm in diameter and 1 mm apart. Their operation and the calibration procedures have been described previously (Kordyban 1977).

In order to obtain the photographs of slug formation a section of the channel was enclosed in black matte paper except for the front face and a slit near the center of the channel was provided so that only a central plane in the channel was illuminated. Polystyrene beads were used for the visualization of internal flow. The Graflex still camera at a shutter speed of 1/20 sec was triggered by a needle gage which contacted the crests of only the highest waves.

The data to determine the conditions at transition to slug flow were obtained as follows. For a particular value of the liquid level the air flow was increased in steps and for each step the slope of the channel was adjusted to produce a constant mean liquid level in the channel. This was done to duplicate some of the conditions under which Wallis & Dobson performed their tests. Near the transition to slug flow the steps were quite small and the oscillograph recording the wave profile was run continuously. When slugs finally occurred the run was discontinued and the wave record just prior to the first slug was used in the evaluation of data.

The tests were performed for a series of water levels for each of the three channel depths. Some tests were run with machine-generated waves which were longer and higher and these tests served to check whether higher waves on a particular mean level would have an influence on the transition.

RESULTS AND DISCUSSION

In a previous paper the author (Kordyban 1977) proposed that the wave instability occurs in the vicinity of

$$\frac{1.35 V_c^2}{g h_c} \frac{\rho_G}{\rho_L - \rho_G} = 1 \qquad [1]$$

where V_c is the average velocity at the wave crest, h_c is the distance from wave crest to top of channel, g is the acceleration of gravity, and ρ_L and ρ_G are the densities of liquid and gas, respectively.

One interpretation of [1] is the statement that the instability expressed by this equation occurs when the upward force due to the pressure at the wave surface exceeds the force of gravity. In order to observe such wave visually some of the highest waves were photographed just prior to their transition to slugs and three representative photographs are shown in figure 1. It may be observed in figure 1a that the instability occurs first downstream of the crest where the liquid appears to leave the lee slope of the wave. This liquid entering the gas space becomes more prominent in figure 1b and can be seen as the white area downstream of the crest. In figure 1c the formation of a slug is well advanced. The lee side is completely enveloped in the liquid spray filling the entire gas space. Another interesting feature may be seen here, namely, that the motion of the whole wave proceeds at a much higher velocity as compared with 1a or

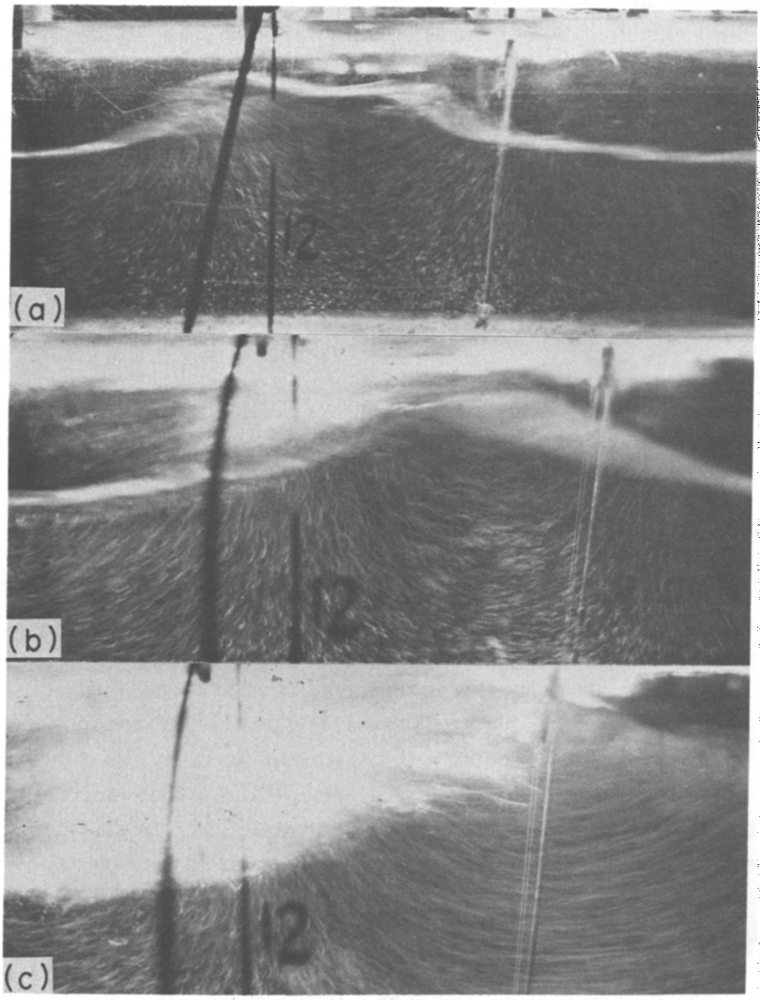

Figure 1. Photographs showing development of a slug.

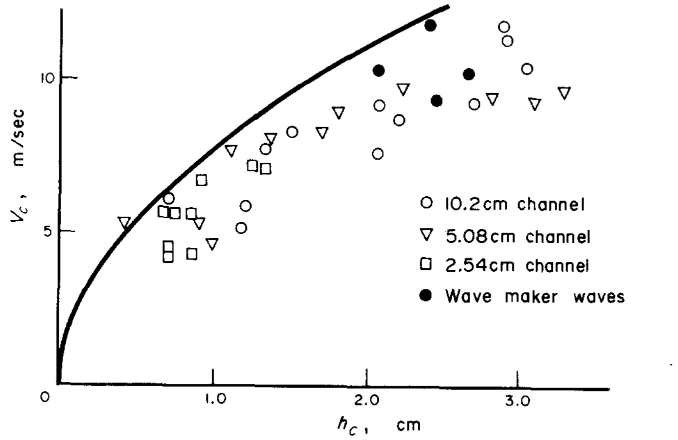

Figure 2. Relationship of velocity at crest, V_c, to wave crest distance to top of channel, h_c, for highest waves just prior to the onset of slugging.

1b which is evident from the length of the polystyrene bead traces. It thus confirms the well-known fact that the slug travels at a much higher velocity than the wave.

The observation that the instability occurs first on the lee side of the wave is in line with the experimental evidence that the pressure minimum occurs somewhat downstream of the crest (Kordyban 1973).

In order to determine how close the criterion of [1] corresponds to actual transition, the highest waves just prior to the occurrence of the first slug were examined to determine the relationship between V_c and h_c; the results are shown in figure 2. While the points fall somewhat below the curve of [1], the use of this equation as an approximation does not appear unreasonable. The quantity h_c, however, is not an easily determinable quantity and one must seek other criteria to establish the transition to slug flow.

Wallis & Dobson (1973) have proposed the following equation for the transition to slug flow

$$j^* = \frac{1}{2}\alpha^{3/2} \qquad [2]$$

where j^* is a nondimensional gas velocity and α is the void fraction. Figure 3 shows the

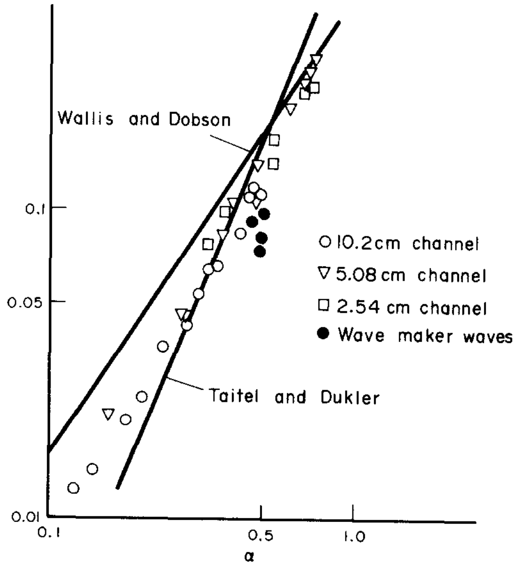

Figure 3. Transition in the presence of large waves compared to relationships of Wallis and Dobson, and Taitel and Dukler.

transition to slug flow found in this work compared to the curve of [2]. The data fall below the curve, but still follow a rather clean straight line, indicating that there must be a relationship between α, or mean channel depth, and the wave height. Such a relationship is evident from figure 4 for the air velocities which just initiate slug flow and for a particular fetch. The fact that a relationship describing the transition to slug flow cannot be entirely independent of the wave characteristics is demonstrated by the machine generated waves which were much higher and the transition to slug flow occurred at a lower gas velocity.

It is interesting to note that our transition data can be brought into a rather good agreement with Wallis & Dobson relationship if α is based on the air flow cross section defined by the r.m.s. wave crests as may be seen from figure 5. This finding seems to extend the Wallis–Dobson relationship to the cases where large waves are present.

The present data can also be compared to the investigation of Taitel & Dukler (1976) in which the transition relationship of Wallis & Dobson was modified to

$$j^* = \alpha^{5/2}.$$

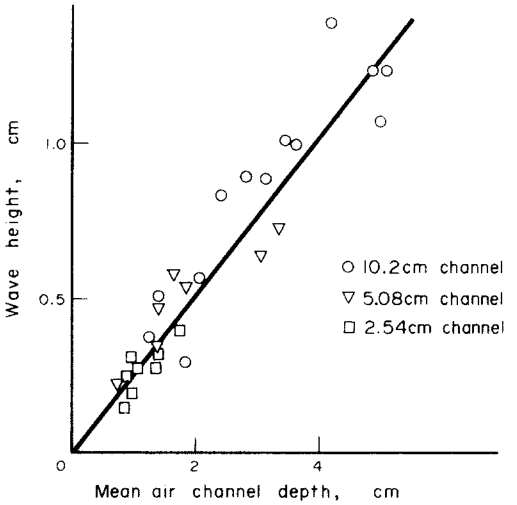

Figure 4. Wave height as a function of mean air channel depth at a distance of 3.48 m from the inlet.

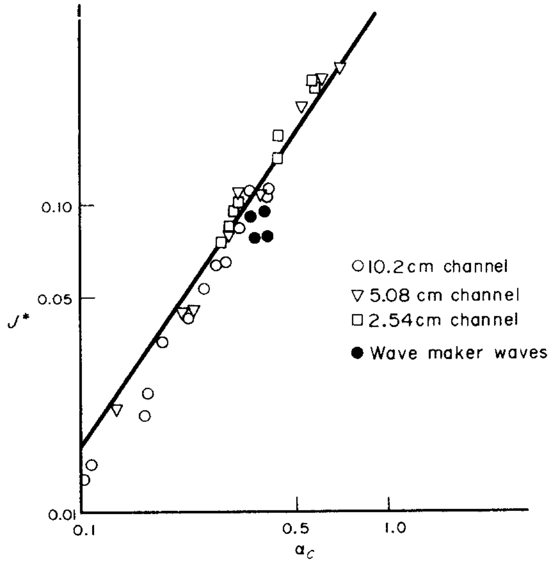

Figure 5. Transition to slug flow with void fraction based on wave crests as compared with Wallis and Dobson relationship.

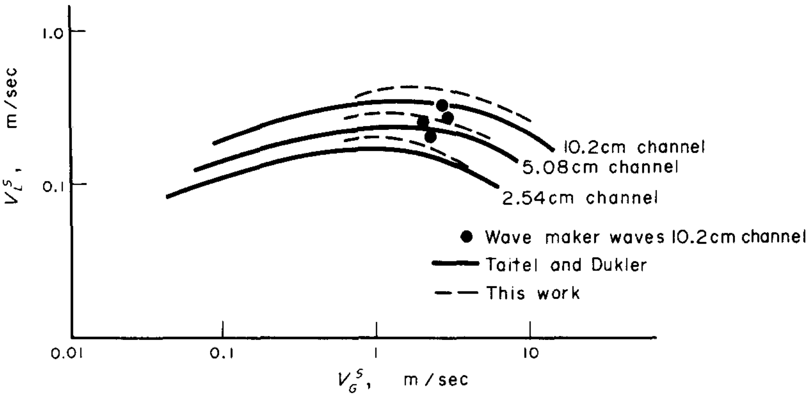

Figure 6. Curves of transition to slug flow based on the data in this work as compared to work of Taitel and Dukler.

This relationship is also shown in figure 3 and one may note that this simple and somewhat arbitrary relationship approximates the data quite well.

In their paper Taitel & Dukler develop their expression further to determine the transition to slug flow in terms of gas and liquid superficial velocities. To achieve this the authors write the force balance equations for liquid and gas and assume the friction factor at the interface to be equal to that at the walls. While this is a reasonable assumption for smooth stratified flow, it appears to be considerably in error for wavy flow where the friction factor could be larger than five times that for a smooth wall (Kordyban 1974).

To check the significance of this simplification the procedure of Taitel & Dukler was adapted to the flow between parallel plates. The data from our experiments for the transition to slug flow were used and the friction factor was calculated as described by Kordyban (1974). The transition curves thus found for three different distances between parallel plates are shown in figure 6 as compared to the same curves found by the method of Taitel & Dukler. As may be observed, the differences are not great.

It thus may be concluded that, when accurate transition from wavy to slug flow is needed the wave characteristics have to be established, but for the approximate determination of the transition the Taitel–Dukler relationship will serve well.

This paper is dedicated to Professor T. Ranov on the occasion of his retirement from the Faculty of the State University of New York at Buffalo.

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