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BRIEF COMMUNICATION

EXPERIMENTAL DATA ON INLET AND OUTLET EFFECTS ON THE TRANSITION FROM STRATIFIED TO SLUG FLOW IN HORIZONTAL TUBES

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1. INTRODUCTION

The prediction of flow regimes in horizontal multiphase pipe flow is important for reliable design of gas–oil pipeline transportation systems. A considerable amount of experimental data is now available in the form of flow maps; see, for instance, Barnea *et al.* (1980) and Sakaguchi *et al.* (1979). However, the precise geometry of the test section with inlet and outlet is often not reported, although this may have an effect on the transition.

The present work is an attempt to clarify the influence on the stratified–slug transition of varying inlet and outlet conditions.

2. EXPERIMENTAL DETAILS AND RESULTS

Four series of air–water experiments were carried out with the apparatus illustrated in figures 1 and 2, for two different inlet and two different outlet conditions. The slightly down-sloping inlet was adjusted until the smoothest flow was obtained ($\Theta_i \approx -20°$), whereas the positively inclined inlet ($\Theta_i \approx 45°$) gave the maximum disturbance (from large amplitude waves to slug flow).

The standard test section consisted of transparent acryl piping, of length (L) 9.95 m and i.d. (D) 2.42 cm. The influence of inlet conditions on the stratified–slug transition was also investigated with $D = 4.00$ cm and $L = 12$ m in a slightly different setup. Phase velocities were measured at the points indicated in figure 1, and all superficial velocities, U_{SL} and U_{SG}, refer to standard conditions (10^5 Pa, 15°C). The outlet pressure was 10^5 Pa in all cases, and the system pressure slightly above this, depending on the flow rate.

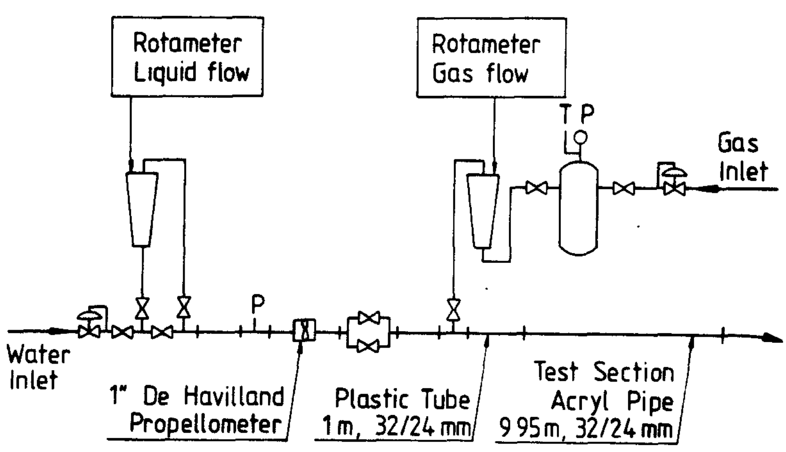

Figure 1. Experimental setup.

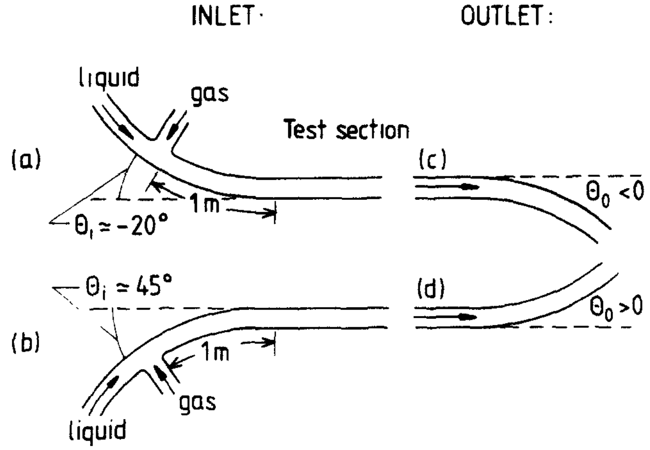

Figure 2. Schematic diagram of the inlet and outlet of the test section.

The stratified–slug transition maps (figures 3–8) were obtained by increasing the liquid flow rate in steps for a fixed gas rate, starting well in the stratified region. Experiments close to the transition line with low flow rates required very long observation times, up to 10 min, due to the slow increase of holdup in the pipeline. If no transition was observed during this period, the flow was defined to be stratified, and if unstable, the flow was defined to be slug, even though a single

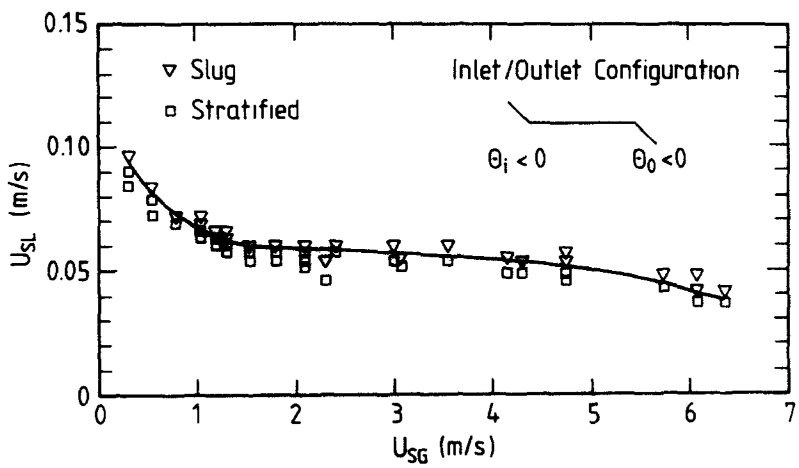

Figure 3. The transition stratified–slug flow for horizontal tubes (i.d. = 2.42 cm, $\Theta_i < 0$, $\Theta_0 < 0$).

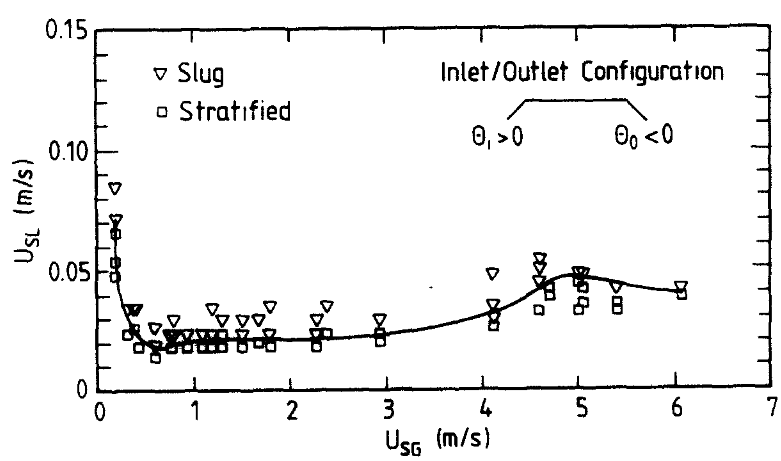

Figure 4. The transition stratified–slug flow for horizontal tubes (i.d. = 2.42 cm, $\Theta_i > 0$, $\Theta_0 < 0$).

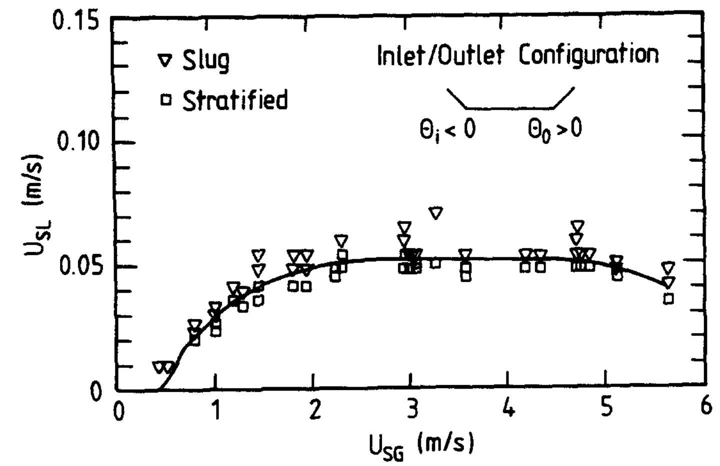

Figure 5. The transition stratified–slug flow for horizontal tubes (i.d. = 2.42 cm, $\theta_i < 0$, $\theta_0 > 0$).

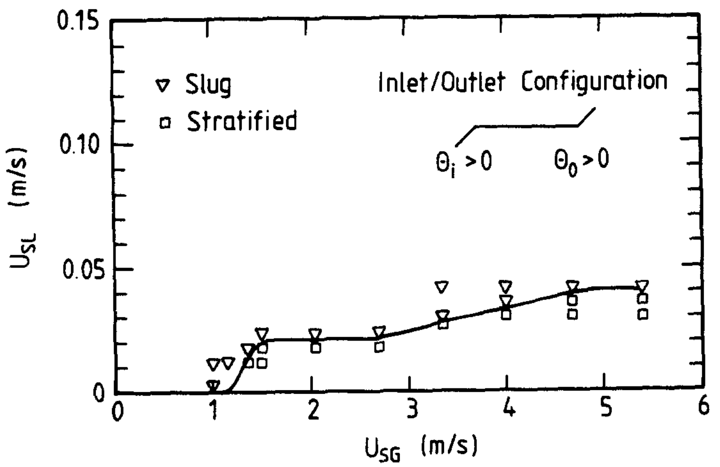

Figure 6. The transition stratified–slug flow for horizontal tubes (i.d. = 2.42 cm, $\theta_i > 0$, $\theta_0 > 0$).

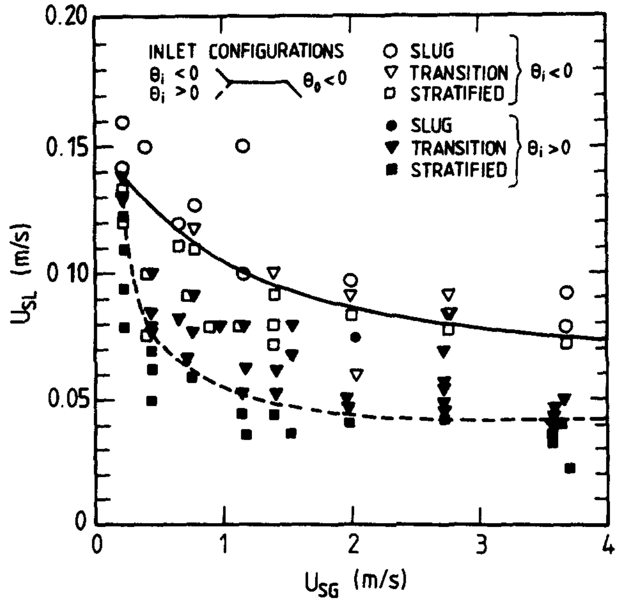

Figure 7. The transition stratified–slug flow for horizontal tubes (i.d. = 4.00 cm, $\theta_i \gtrless 0$, $\theta_0 < 0$).

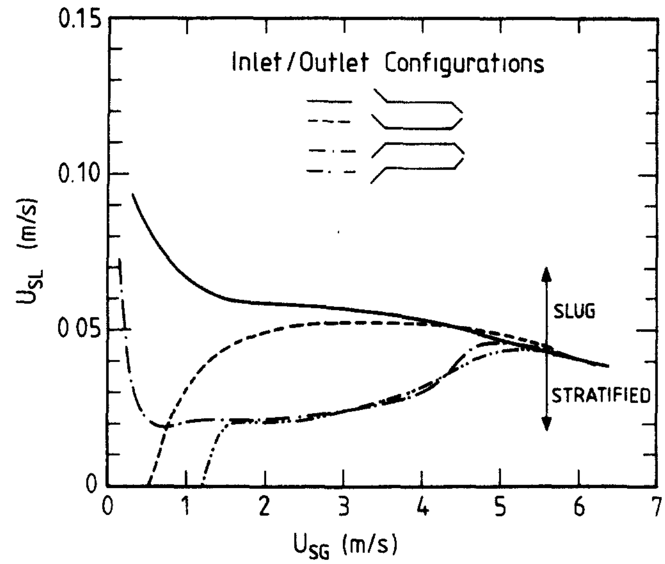

Figure 8. The influence of different inlet/outlet conditions on the transition stratified–slug flow in horizontal tubes ($D = 2.42$ cm).

slug, only, was seen. It had, however, to fill the entire tube cross-section and traverse its whole length, i.e. not die out before the tube end.

The experimentally observed transitions are presented in figures 3–6 for the 2.42 cm dia tube, and in figure 7 for the 4.00 cm one. Agitated inlet liquid flows, represented by $\Theta_i > 0$ in figures 7 and 8, lead to transitions to slug at half the liquid rates required for the smooth flow cases ($\Theta_i < 0$). The effect is most pronounced for the smaller-diameter tube (figure 8), where the observed transition line is reduced by a factor 3 over wide ranges of superficial gas velocities. As expected, for large gas velocities, $U_{SG} \geqslant 4.5$ m/s for $D = 2.42$ cm, the transition becomes independent of both inlet and outlet conditions, see figure 8.

Figure 8 also illustrates another (obvious) effect that might occur in a piping system where a horizontal section has been connected to an upwardly inclined pipe ($\Theta_0 > 0$). Below a certain gas flow rate, there will be no appreciable gas drag, and the liquid holdup in the horizontal pipe increases until a slug forms, no matter what the liquid flow rate is, provided it is greater than zero. It is further independent of the outlet pipe length (L_0) or inclination, as long as $\Theta_0 > 0$ and

$$L_0 \sin \Theta_0 \geqslant D.$$

3. DISCUSSION

A strong effect of upstream and downstream conditions on the stratified–slug transition has been observed. The downstream effect, which to the authors' knowledge has not been previously reported, is caused by a filling up of the horizontal tube before the restriction caused by the up-sloping part can be overcome. It is analogous to the terrain slugging phenomena observed by Schmidt *et al.* (1979) and predicted by Bendiksen *et al.* (1982).

The limiting superficial gas velocity is dependent on the flow conditions in the horizontal part as well as in the riser.

In the riser, a pure slug flow will be able to transport large amounts of gas at zero or negative superficial liquid velocity, and one will observe a filling up of the horizontal tube until slug flow occurs, and the horizontal pipe is emptied by the transport of a long solid liquid slug.

If the riser produces a lot of bubbles in the slugs, the flow becomes more homogeneous and less gas may be transported up the riser with a non-positive liquid flow, i.e. the limiting gas flow decreases.

For low liquid flows and long horizontal sections the time required to fill up the pipe will be very long and this may disguise the transient behaviour.

As mentioned, the inlet effect indicates that slug or agitated flow upstream of the horizontal test section will introduce slug flow at a superficial liquid velocity a factor of 3 lower than for stratified

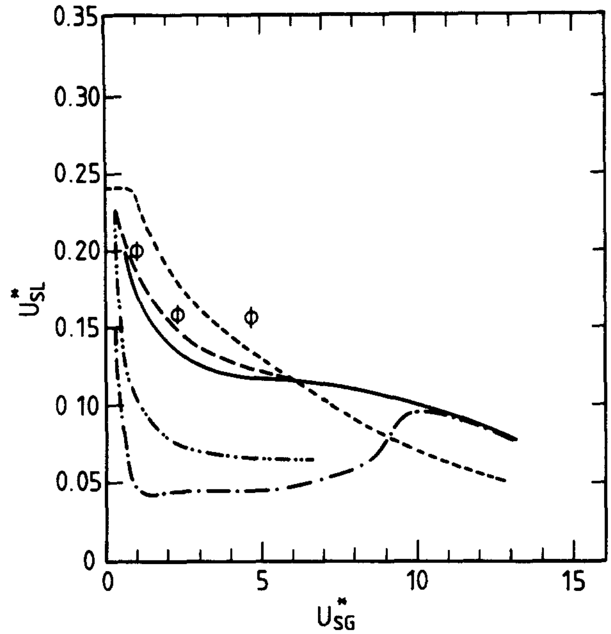

Figure 9. A comparison of our non-dimensional data on the transition stratified–slug flow with others. *Our data.* $\theta_0 < 0$, $\theta_1 < 0$: —— $D = 2.42$ cm, – – – $D = 4.00$ cm. $\theta_0 < 0$, $\theta_1 > 0$: —·— $D = 2.42$ cm, —··— $D = 4.00$ cm. ϕ, Barnea *et al.* (1980). ----- Sakaguchi *et al.* (1979).

upstream conditions. This is true even for test section lengths exceeding 400 D. The reason seems to be that any small transient produced by the agitated flow upstream, may produce a liquid slug, which once formed, will keep its identity over very long distances.

We believe that the reported effects may well explain the discrepancies between flow charts reported in the literature.

In figure 9 the data have been made non-dimensional by means of the tube diameter and compared to other investigations (Sakaguchi *et al.* 1979; Barnea *et al.* 1980):

$$U^*_{SG} = \frac{U_{SG}}{\sqrt{gD\left(1 - \frac{\rho_G}{\rho_L}\right)}}$$

and

$$U^*_{SL} = \frac{U_{SL}}{\sqrt{gD\left(1 - \frac{\rho_G}{\rho_L}\right)}}.$$

The reference points from Barnea *et al.* (1980) are taken from a log–log flow-regime map, and are thus associated with some uncertainties. These data are in fair agreement with our results with smooth down-sloping inlet conditions.

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