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FLOW PATTERN TRANSITION FOR GAS–LIQUID FLOW IN HORIZONTAL AND INCLINED PIPES

COMPARISON OF EXPERIMENTAL DATA WITH THEORY

DVORA BARNEA, OVADIA SHOHAM and YEHUDA TAITEL
School of Engineering, Tel-Aviv University, Ramat-Aviv, Israel

and

A. E. DUKLER
Department of Chemical Engineering, University of Houston, Houston, TX 77004, U.S.A.

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Abstract—Experimental measurements of flow patterns for gas–liquid flow in inclined pipes are reported. The results compare well with a recently published theory for the prediction of flow patterns in horizontal and inclined pipes (Taitel & Dukler 1976).

INTRODUCTION

The prediction of flow patterns is a central problem in two phase gas–liquid flow in pipes. Design parameters such as pressure drop and heat and mass transfer are strongly dependent on the flow pattern. Hence, in order to accomplish a reliable design of gas–liquid systems such as pipe lines, boilers and condensers, an *a priori* knowledge of the flow pattern is needed.

Although extensive research on flow patterns has been conducted, most of this research has been concentrated on either horizontal or vertical flow. For horizontal flow the earliest and perhaps the most durable of pattern maps for two phase gas–liquid flow was proposed by Baker (1954). Many more have been suggested: Kosterin (1949), White & Huntington (1955), Govier & Omer (1962) and Mandhane *et al.* (1974). Al-Sheikh *et al.* (1970) defined a variety of dimensionless groups and concluded that no two groups characterize all of the transitions and all of the data. Taitel & Dukler (1976) proposed a physical model capable of predicting flow regime transition in horizontal and near horizontal two phase flow. In this work the flow pattern boundaries were predicted analytically and it was shown that for each inclination angle every transition boundary can be represented by two dimensionless groups.

Very little work has been published on the effect of inclination on two phase flow in pipes. Bonnecaze *et al.* (1971) and Singh & Griffith (1970) studied slug flow in inclined pipes but they deal with only one flow pattern and with a limited extent of inclination. Gould *et al.* (1974) published flow pattern maps for horizontal and vertical flows and for upflow at 45° inclination. They also presented a model for predicting pressure distribution in two phase flow through vertical, inclined and curved pipes. Beggs *et al.* (1973) investigated the effect of pipe inclination on liquid holdup and pressure loss. The problem of pressure drop in inclined flow was treated by Savigny (1962). Greskovich (1972) studied holdup in gas–liquid downflow. Oshimowo & Charles (1974) investigated vertical downflow in bends.

The present work reports new data on flow pattern transitions for gas–liquid flow in inclined pipes. The flow of air and water through 2.55 and 1.95 cm pipes is studied at flow angles as large as 10°. The analytical model for predicting flow pattern for horizontal and near horizontal pipe as proposed by Taitel & Dukler (1976) is tested by comparison with the experimental results.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The experimental apparatus consisted of an air–water supply system containing a water pump, air and water flow meters and test section in which the two phase flow is visually observed and the flow pattern recorded.

Air was supplied at 60 N/cm^2 from a central compressed air line through an oil separator. The air passed through a regulating valve to maintain a constant pressure and then through gas rotameters. Air flow rate was controlled by valves upstream of the meters. Liquid was supplied from a tank and circulated through the system by a centrifugal pump.

Two different inlet sections were used. The first was a "tee" type with water entering on the run and air on the branch. The second inlet section was a "mixer" type where air was introduced circumferentially into the pipe through uniformly distributed small holes. Two test sections were fabricated of Plexiglas tubing with inner diameters of 1.95 and 2.55 cm. The tubes were each 3 m long supported on a steel frame which could be inclined with the horizontal. Flow temperature and pressures were measured.

The flow pattern in the test section was determined by visual observation. Careful preliminary runs were made for horizontal flow in order to define, classify and categorize the flow pattern. Some of the transition boundaries were found to be sharp but most of them were gradual with respect to the flow rate changes. Experiments were carried out with horizontal pipes for upward inclination angles of 0.25, 0.5, 1, 2, 5 and 10° and for downward angles of 1, 2, 5 and 10°. Inclination angles reported in this work are accurate to $\pm 0.03°$.

CHARACTERISTIC FLOW PATTERNS FOR HORIZONTAL AND INCLINED FLOW

The designation of flow pattern has been based largely on individual interpretation of visual observation. While some instrumental methods of analysis have been proposed (Hubbard & Dukler 1966, Jones & Zuber 1975), these are not simple to use and have thus not found widespread application. Furthermore, for many purposes of design a simple approximation to the location of the gas and liquid phases suffices as a description. For these reasons it is important to specify as precisely as possible the features of the flow used to characterize the pattern designated, and in this work the following apply:

Stratified (*S*). Liquid flows at the bottom of the pipe with gas at the top. The interface can either be smooth (SS) or wavy (SW).

Intermittent (*I*). In this flow pattern the inventory of liquid in the pipe is non-uniformly distributed axially. Plugs or slugs of liquid which fill the pipe are separated by gas zones which contain a stratified liquid layer flowing along the bottom of the pipe. The liquid may be aerated by small bubbles which are concentrated toward the front of the liquid slug and the top of the pipe. The intermittent pattern is usually subdivided into slug (SL) and elongated bubble (EB) flow patterns, but the distinction between them has not been clearly defined in the past. In this work the elongated bubble pattern is considered the limiting case of slug flow when the liquid slug is free of entrained gas bubbles. With this criterion the elongated bubble-slug transition is quite sharp and easy to identify.

Annular (*A*). The liquid flows as a film around the pipe wall. A liquid film surrounds a core of high velocity gas which may contain entrained liquid droplets. The film at the bottom is normally thicker than at the top depending on the flow rate of liquid and gas. At the lowest gas rates at which transition to annular from slug flow is observed, most of the liquid flows at the bottom of the pipe. The upper walls are intermittently wet by large aerated, unstable waves sweeping through the pipe. This is not slug flow which requires a competent bridge of liquid nor is it fully developed annular flow which requires a stable film over the entire pipe perimeter. Thus, it is designated as the wavy annular pattern (WA). Nicholson, Aziz and Gregory (1978) also recognized the existence of this hybrid pattern between annular and slug flow and designated it as "proto-slug" flow.

Dispersed bubble (*DB*). The gas phase is distributed as discrete bubbles within a continuous liquid phase. In these experiments transition to this pattern is defined by the condition where bubbles are first suspended in the liquid or elongated bubbles which contact the top of the pipe are destroyed. When this first happens most bubbles are located near the top. At higher liquid rates these bubbles are dispersed more uniformly.

RESULTS AND DISCUSSION

Horizontal test section. The results obtained in this experiment are compared in figure 1 with the coordination of experimental data for small tubes represented by the Mandhane map. Very good agreement exists with the other data used to build Mandhane's map for the basic transition from the stratified pattern to either the intermittent or annular pattern. These transitions take place over a narrow change in flow rates, are quite distinct and are easily reproduced by different investigators.

The Mandhane dispersed bubble-intermittent flow boundary is located at higher liquid rates than these new data. The difference results from differences in definition. Mandhane *et al.* (1974) distinguished elongated bubble from bubble flow only when the bubbles were distributed more or less uniformly throughout the liquid. From a modelling point of view, it seems more logical to consider the flow pattern as being dispersed bubble once small bubbles are observed in a continuous liquid and the elongated bubbles disappear. As a result, our dispersed bubble regime transition appears at a lower liquid flow rate compared to Mandhane's map. In the flow regime maps presented by Baker (1954), Hoogendoorn (1959) and Govier & Aziz (1972), the dispersed bubble-intermittent transition line is located at lower liquid rates than in Mandhane's map.

The extent of the annular flow pattern region also differs from that presented by Mandhane. A closer observation shows that our transition boundary agrees well with Mandhane's if the wavy annular regime (the black triangular points in figure 1) is considered slug flow. As discussed above, wavy annular flow has been interpreted as slug flow by some previous investigators. Thus, this discrepancy is based on a difference in interpretation of the nature of wavy-annular flow as discussed above.

The slug-elongated bubble transition boundary has not been well defined. Mandhane followed the description of Govier & Aziz (1972) in which the distinction between elongated bubble and slug flow is based on "bubble shape" and film thickness below the bubble. Figure 1 shows that the criteria of no gas holdup in the liquid slug is consistent with previous data for

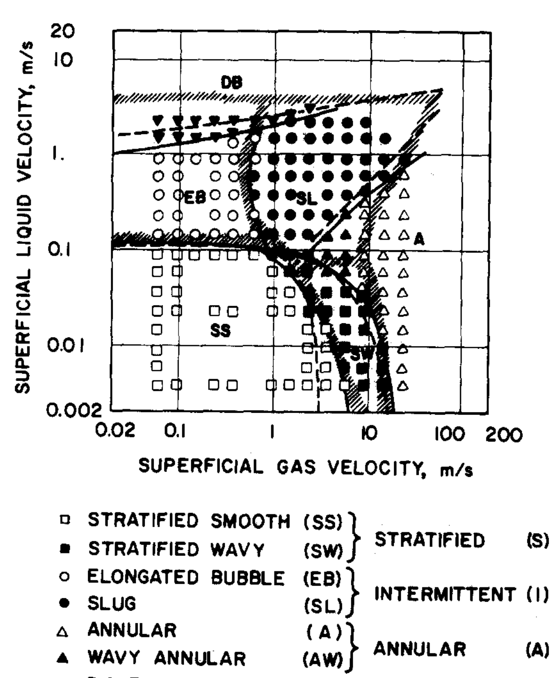

Figure 1. Comparison of data for 2.5 cm horizontal tube with Mandhane *et al.* (1974) Map and Taitel–Dukler (1976) theory. //// Mandhane; — Experiment; -- Theory.

elongated bubble–slug transition in spite of the vague definition. Indeed, the experimental elongated bubble to slug transition compares well with Mandhane's map.

Effect of inclination on flow regime. The effect of upward and downward inclination on flow pattern transition was carefully examined. Some typical results are shown in figures 2–7. The data shown were obtained in the 2.55-cm pipe with similar results observed for the 1.95-cm pipe. The effect of the entrance section was found negligible for all flow pattern boundaries except for the stratified smooth-stratified wavy transition. In figures 2–7 results for the "mixer" type entrance section are shown.

The major effect of inclination on the flow patterns is observed in the transition between stratified and intermittent or annular regimes. In downflow (figures 5–7) the liquid moves more rapidly and has a lower level in the pipe owing to downward gravity forces. As a result, higher gas and liquid flow rates are required to cause transition from stratified flow and the stratified flow region is considerably expanded as the angle of inclination increases. Conversely, upward inclination cause intermittent flow to take place over a much wider range of flow conditions (figures 2–4). The stratified-intermittent transition boundary is very sensitive to the angle of inclination and even for upward angles of less than 1° the regime of stratified flow shrinks into a small bell-shaped region. For upward inclinations higher than 10° stratified flow is not observed at all (for the observed range of liquid and gas flow rates).

Stratified smooth flow is not seen for upward inclination except for very small angles (less than 0.25°). For downflow, contrary to the case of horizontal and upflow where waves are generated from the action of the "wind" on the interface, natural instability of the interface occurs as a result of flow due to gravity even in the absence of gas flow. Thus, for negligible gas flow rates the transition from smooth to wavy interfaces depends only on the liquid rate as clearly indicated by the "horizontal" transition line which is independent of the gas flow rate. Unlike the stratified smooth-stratified wavy transition for horizontal flow, where the change is quite sharp, in downflow the location of this transition cannot be accurately determined. In addition, changes from stratified smooth to wavy depend on the type of entrance section being used. The tee-type entry section resulted in a transition boundary at a liquid flow ratio 2–4 times

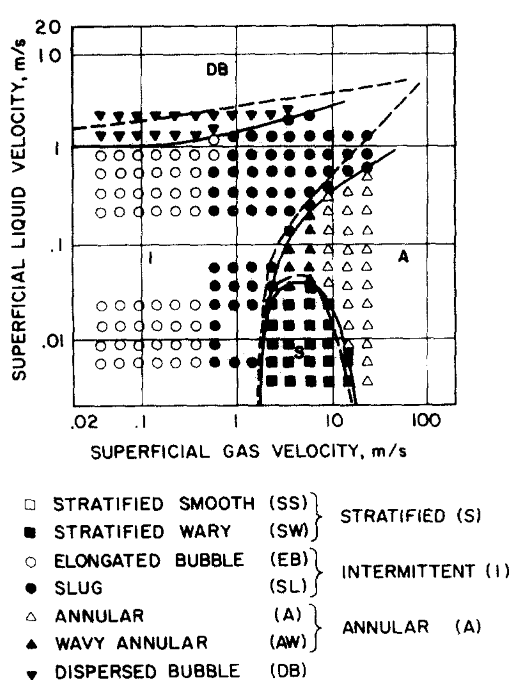

Figure 2. Experiment vs theory. 0.25° upward inclination of a 2.5 cm pipe. —, experiment; ---, theory.

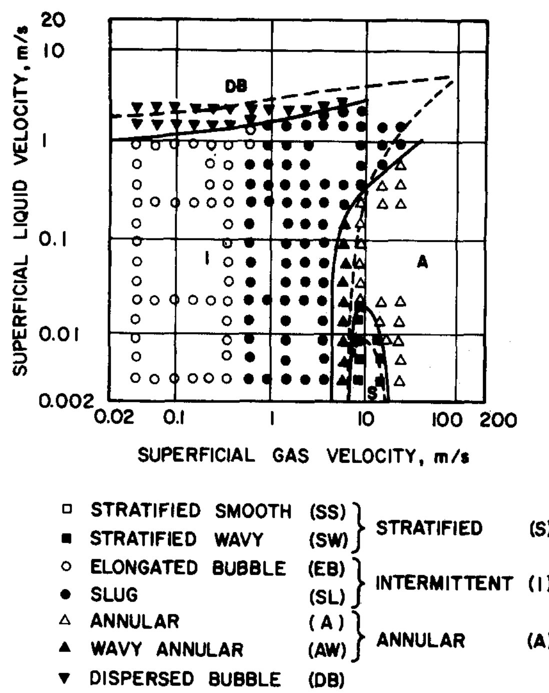

Figure 3. Experiment vs theory. 2° upward inclination of a 2.5 cm pipe. —, experiment; ------, theory.

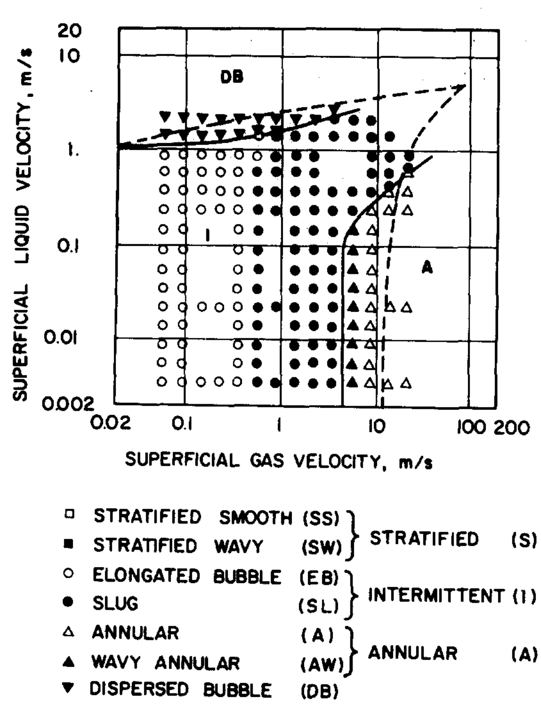

Figure 4. Experimental vs theory. 10° upward inclination of a 2.5 cm pipe. —, experiment; -----, theory.

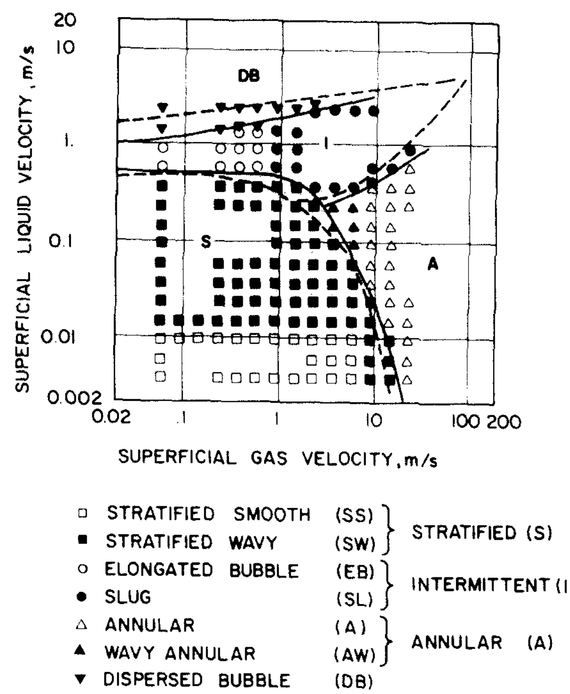

Figure 5. Experimental vs theory. 1° downward inclination of a 2.5 cm pipe. —, experiment; -------, theory.

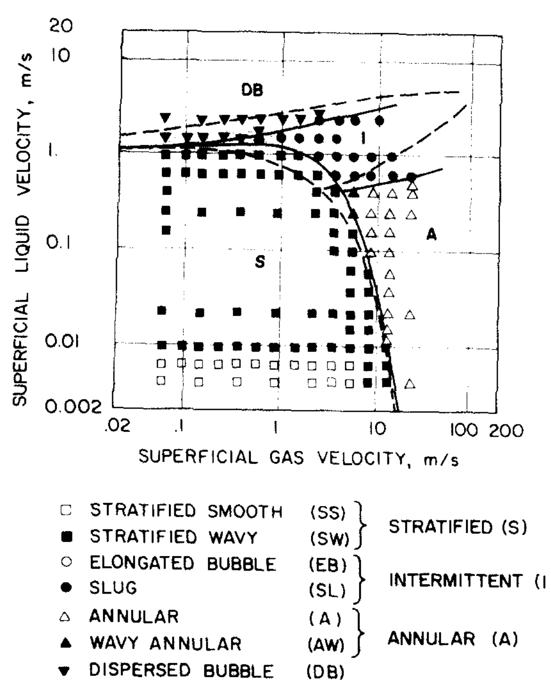

Figure 6. Experimental vs theory. 5° downward inclination of a 2.5 cm pipe. —, experiment; ------, theory.

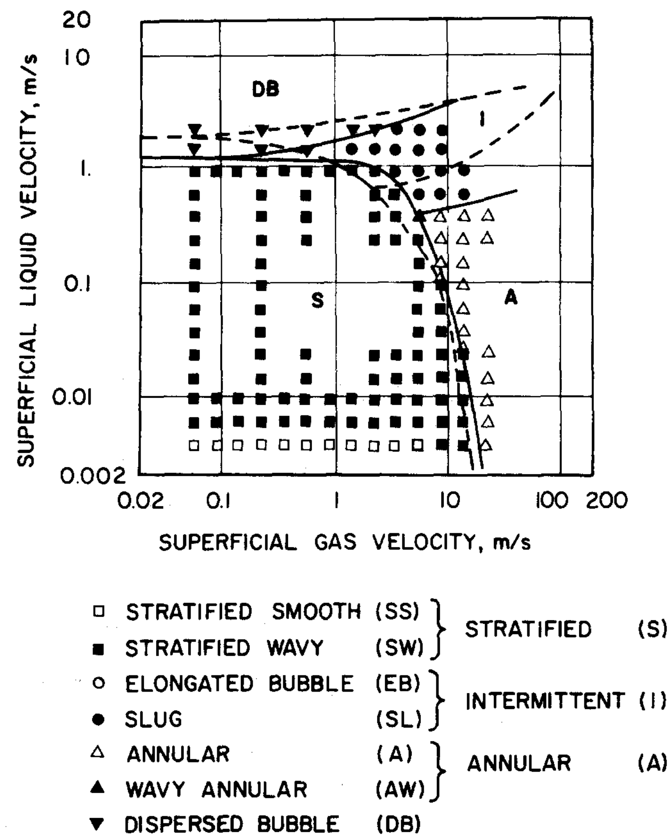

Figure 7. Experimental vs theory. 10° downward inclination of a 2.5 cm pipe. —, experiment; ------, theory.

higher than that for the mixer-type section. Because of the difficulty in accurately determining this transition, the results should be treated with caution.

The experimental data show that for upward inclinations the flow rate space over which the intermittent pattern exists expands at the expense of the stratified pattern while for inclined downflow the result is just the opposite. An isolated region of stratified flow occurs so that as the gas rate is decreased, flow pattern transitions from annular to stratified and then back to annular or slug flow can be observed (see figure 3). This unexpected result is confirmed both from experiment and theory.

Comparison of the theoretical model with experimental data. The results of these experiments are compared with the theoretical model previously published by Taitel & Dukler (1976) in figures 2–7. This theory was designed to predict the flow pattern transitions for horizontal and "near horizontal" flows. At the time the theoretical model was conceived, experimental verification was possible only for the horizontal case because of the lack of data for inclined pipes. Now it is possible to check the validity of this model for inclined pipes as well as determine quantitatively the range of inclination angles for which the theory can be considered valid.

The broken lines in figures 1–7 represent the theoretically predicted transition boundaries. The agreement between experiment and theory is indeed remarkable up to ±10° inclinations, except for the stratified smooth to wavy transition for downward inclinations.

For horizontal flow (figure 1) very satisfactory agreement exists with respect to all transition lines. The apparent discrepancies are of the same order as the experimental error.

The comparisons displayed in figures 2–7 lead to the conclusion that the model presented by Taitel & Dukler (1976) is applicable to inclined pipes to ±10° inclination with good accuracy. The agreement is particularly well demonstrated for inclined upflow (see figures 2–4) where the bell-shaped stratified region is quite accurately predicted. Experimental measurements not displayed here show that for angles from 10 to 30°, the theories while not accurate can give a reasonable estimate of the pattern.

The only exception to this agreement is the transition boundary between stratified smooth and stratified wavy patterns especially for downward flow. The theoretical model fails to correctly account for the start of the wavy stratified pattern for downward flows. According to the model, the waves are caused by the gas flow as a result of transfer of energy between the gas and liquid phase. However, as has been observed waves will develop on the surface of a falling film in the absence of gas flow. The existence of these waves depends on the liquid flow rate and the level of the interface and this changes significantly with inclination. Because the disagreement is so substantial, the theoretical results which are based on Taitel & Dukler (1976) for this transition are not displayed on the graphs to avoid confusion.

Theories for predicting conditions for wave formation on films flowing on inclined planes have been presented by Benjamin (1957), Yih (1969), Stoker (1957), Krantz & Goren (1970), Whittaker (1966), Hanratty & Hershman (1961) and many others.

Depending on the particular model used, the criteria for the first appearance of waves is described in terms of Reynolds number, Froude number and sometimes the Weber number. The usual approach is to perturb the Navier–Stokes equations leading to an Orr–Sommerfield type equation which is solved either numerically or by various approximate means to determine the condition for stability. A fairly comprehensive review of existing solutions is given by Fulford (1964) and Krantz & Goren (1971).

Although results of the various investigators differ from each other, the general agreement is that the interface is unstable at a very low Reynolds number of the order of 5–50 depending on the angle of inclination. As a typical example, consider the classical treatment by Yih (1969) who showed that the critical Reynolds number for the generation waves is given by

$$R_c = \frac{5}{6}\cot\alpha\,. \qquad [1]$$

According to this result the interface is always unstable for the vertical plane (in practice, it is unstable for very low Reynolds numbers) and always stable for the horizontal case ($\alpha = 0$). However, for inclination over 1°, the critical Reynolds number is less than 50. Comparison with these experiments shows that even for the mixer-type entrance element, smooth interfaces were observed at much higher Reynolds numbers. Also, the trend as given by [1] does not agree with observation.

Its suggested the fact that smooth stratified surfaces were obtained at flow rates where the theoies predict a wavy interface may be due to entrance phenomena and the low rate of amplification expected at low liquid rates (Benjamin 1957). This hypothesis may be supported by the fact that in the "tee" type entrance section the interface was smooth at liquid flow rates two to four times higher than for the "mixer" entrance section.

SUMMARY AND CONCLUSIONS

Experimental results were collected for a water–air system in 2.55- and 1.95-cm pipes and compared with the theoretical prediction of Taitel & Dukler (1976) up to ±10° inclination. Over this range the agreement between experiment and theory has been found to be very good. At larger inclinations the trends predicted by the theory are correct but quantitative predictions are inaccurate.

These results are considered as experimental proof of the validity of the theory that until now has been tested only for horizontal pipes. The theory fails to predict the stratified-smooth to stratified wavy transition for inclined pipes. This is significant only for downflow.

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