FRICTIONAL PRESSURE LOSS MEASUREMENT IN TWO-PHASE LIQUID FLOW

Peter L. Spedding and John J.J. Chen

Department of Chemical and Materials Engineering
University of Auckland

ABSTRACT

Frictional pressure loss measurements are reported for two-phase air-water flow in a 4.55 cm diameter inclined pipe. The data are presented as graphs of shear-or frictional velocity against total velocity V_T and show as discrete curves depending on V_{LS} the superficial liquid velocity. The frictional pressure loss is shown to be dependent on the flow regime present in the flow conduit. In general the separated flow regimes seem to be the preferred mode of transport as far as frictional pressure loss is concerned. Further the frictional pressure loss for pipes inclined one or two degrees from the horizontal is much higher than for the horizontal case.

INTRODUCTION

A large number of investigations have been carried out to determine the pressure loss characteristics of two-phase flow in horizontal and vertical conduits. Despite the extent of this work there still exists a number of problems in presentation and prediction of frictional pressure loss for these systems. In general the application of concepts such as similarity and dimensional analysis to the case of two-phase flow seems to have fallen well short of expectations, particularly with regards to certain flow regimes. Under these circumstances an approach to pressure loss prediction through modelling and semi-empirical correlation is perhaps more logical. Most models proposed so far usually are applicable, if not actually derived, for a specific flow pattern or regime. Often use of these models has not been possible without a great deal of simplification or by extensive application of empirically derived factors. However, the results obtained can give reasonable prediction for a narrow range of application. The most widely employed empirical correlation appears to be of the Lockhart-Martinelli type (1949) where the use of two-phase friction multipliers have allowed helpful predictions to be made for certain flow regimes. Recently Taitel and Dukler (1976) and Spedding and Chen (1980) have demonstrated that the method can be extended theoretically to give useful predictions for the separated flow regimes which are in agreement with measured values. The best that can be achieved for the other mixed flow regimes is to employ empirical correlations for the estimation of frictional pressure loss.

By contrast little work has been reported on pressure loss in inclined pipes and therefore it is to be expected that conclusions are even more indefinite than for the horizontal case. The overall pressure loss in an inclined two-phase system is composed of the frictional, elevational and expansion pressure loss.

$$\left(\frac{\Delta P}{\Delta l}\right)_{TP} = \left(\frac{\Delta P}{\Delta l}\right)_f + \left(\frac{\Delta P}{\Delta l}\right)_g + \left(\frac{\Delta P}{\Delta l}\right)_e \qquad [1]$$

The latter is only of importance when $G_T > 2700$ kg $m^{-2}s^{-1}$ and therefore can be ignored in the present case. The elevational pressure loss component is found from the corresponding holdup values measured in the same apparatus by Nguyen and Spedding (1977)

$$\left(\frac{\Delta P}{\Delta l}\right)_g = \left(\rho_L \bar{R}_L + \rho_G \bar{R}_G\right) g \sin\alpha \qquad [2]$$

and therefore a suitable correction can be applied to the measured two-phase pressure loss in order to obtain the frictional pressure loss. The calculation of this correction can constitute a considerable source of error particularly when the holdup values are not measured but are estimated by some form of correlation. It is perhaps for this reason that there is considerable variation in the frictional pressure drop data reported in the literature by various different workers.

EXPERIMENTAL

Frictional pressure drop data were measured for co-current two-phase air-water flow in a 4.55 cm internal diameter perspex tube set at angles from vertically upwards to vertically downwards. Details of the actual experimental apparatus are given elsewhere by Nguyen (1975). Air flow rates of up to 500 kg h^{-1} and water flow rates of up to 6000 kg h^{-1} could be accommodated in the test apparatus. The air and water were metered using an orifice meter and suitable rotameters respectively and then mixed in an annular mixing section which led to the initial calming section of the apparatus. The test section of 1.21 m length was set centrally between the inlet calming section and a similar downstream calming section of the apparatus. Except for vertically downwards flow, the air and water mixture emerging from the apparatus was separated in a cyclone which was so arranged as to avoid back pressure waves being passed back through to

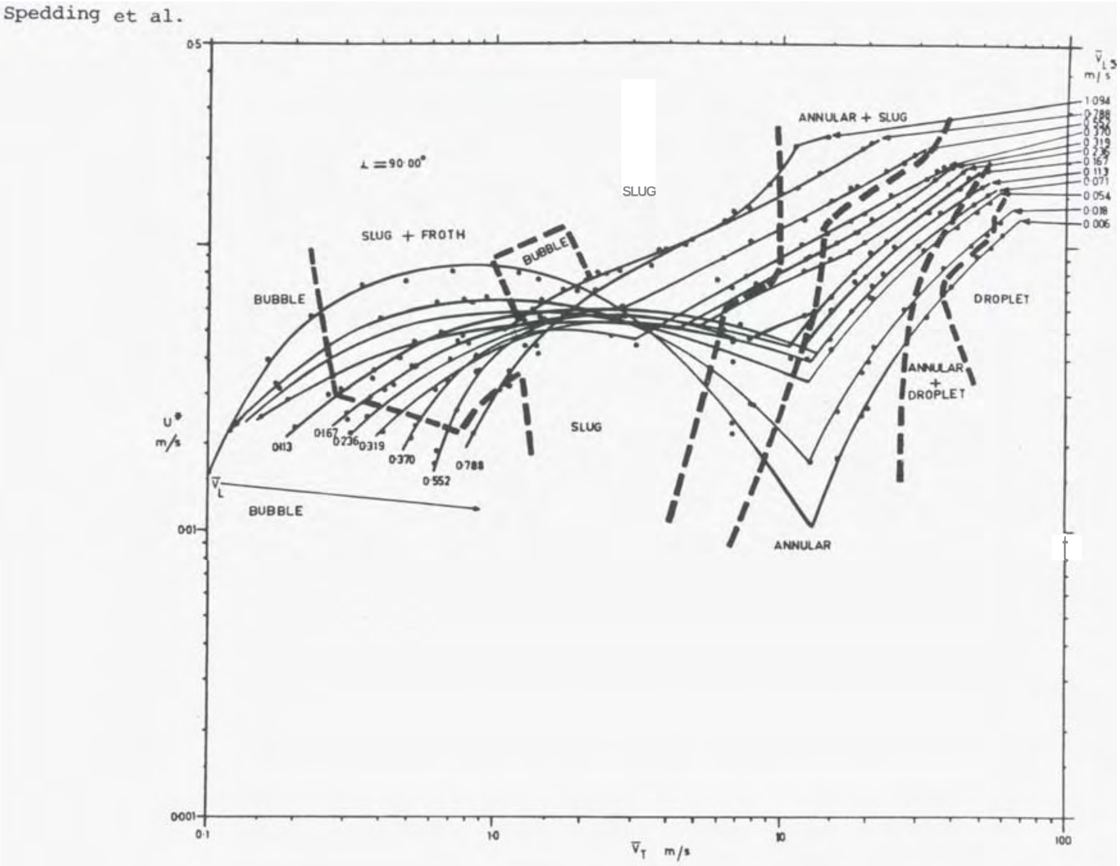
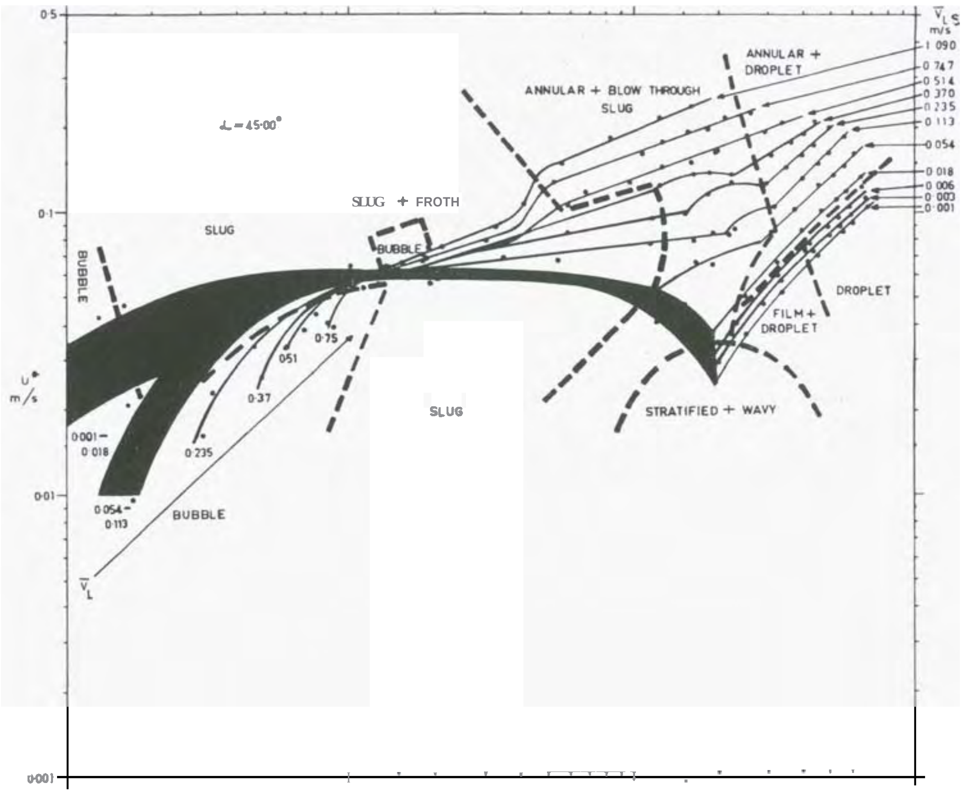


Fig. 1 Frictional pressure loss for air-water two-phase co-current flow in a pipe at an angle of 90.00° from the horizontal.

the test section. The whole test section was held rigidly to a supporting frame so as to eliminate any movement particularly when the slug flow regime was achieved in the pipe. The pressure tapping points were connected directly to a cylindrical separation chamber or a piezometer ring such as to ensure either gas or liquid but not both phases were presented to the pressure tapping lines leading away to the measuring manometers. Any inclusion of a secondary phase in these measuring lines will invariably lead to inaccurate results in the recorded pressure loss values so particular care was exercised to ensure all measuring lines were single phase. Generally the pressure measured on the recording manometer exhibited fluctuations if other than separated flow was present in the apparatus. If excessive fluctuations occurred, the pressure tapping lines from the lower side of the separators were used so that the pressure measuring lines were filled with water. Each of these pressure measuring lines were connected to an 18 litre water filled plastic container which was joined to one leg of an overhead manometer. These two containers were thin walled and therefore flexible enough to act as damping devices by accommodating any pressure fluctuations. The actual pressure measurements were made on the overhead manometer whose legs extended from each of the damping containers upwards to at least 1.5 m beyond the total height of the overall rig when it was placed in the vertical position. The water level registered on the lower tapping point indicated the actual gauge pressure and since the lines were separated as well as being individually damped there was minimal interaction due to pressure fluctuation. The water level difference registered on the overhead manometer required correction for the different densities of the liquid and the two-phase mixture. The legs of the manometer were 1.27 cm in diameter so there was little likelihood of adverse miniscus effects occurring. When the pressure fluctuations were negligable the gas side pressure tapping lines from the top of the separators were used and these proved to provide better overall accuracy at low total flow rates. For these readings an inclined methanol filled manometer was used to record the pressure loss. Temperature measurements were recorded but no attempt was made to regulate this variable.

The experimental procedure used was to set the pipe angle and the liquid flow rate and then to vary the gas flow rate from minimum to the possible maximum. The angles of inclination from the horizontal which were examined were +90.00°, +70.00°, +45.00°, +20.75°, +2.75°, 0°, -6.17°, -20.00°, -44.75°, -67.75°, -90.00°. Care was taken to ensure the accuracy of the data not only by repeating the measurements but to carefully recheck any result which appear not to follow or fit into a logical sequence.



Because of space limitations only the more important data are presented here. An examination of previous work which is reported in the literature showed that there is considerable variation in the methods which are used to present frictional pressure loss data. Most workers use a modification of the Lockhart-Martinelli (1949) pressure loss parameters or a modified friction factor. The major difficulty with the first method is that it is known that for two-phase flow in horizontal tubes that the resulting predictions are not good particularly with certain flow regimes where mass velocity and pipe diameter effects are in evidence. The use of two-phase friction factors or dimensionless variables such as the Reynolds or Froude numbers suffers from the disadvantage of the difficulty of determining the value of the two-phase physical parameters such as density or viscosity. Indeed the most useful correlations appear to be obtained when the independent variable used is based on the flow rates of either the velocity or the volumetric flow.

After careful consideration it was decided to present the data as plots of shear or frictional velocity defined as

$$U^* = \sqrt{\frac{\tau_w}{\rho_L}} = \sqrt{\left(\frac{\Delta P}{\Delta l}\right)_f \frac{D}{4\rho_L}} \qquad [3]$$

against $\bar{V}_T$ the total velocity of the phases. Hopefully such a method of data presentation will help highlight any important features of the data and will eliminate any effect of diameter. With this method of presentation, the-resulting curves show a logical progression with V_{LS} the superficial liquid velocity.

DISCUSSION

The representative data used and presented in Figs 1 to 5 are worthy of discussion in a general way as they exhibit rather certain important features. Commencing with the case of horizontal flow in Fig. 3, it can be seen that the frictional velocity exhibits, in the main, a characteristic pattern against the total velocity $\bar{V}_T$ that depends on the flow regime in the pipe. This frictional velocity pattern shows a systematic increase in U^* corresponding with an increase in V_{LS} the superficial liquid velocity. Initially at low Q_L rates the frictional velocity is independent of $\bar{V}_T$ and depends only on $\bar{V}_{LS}$ in the stratified flow regime which is confined to the region $V_T \leqslant 1.0$ m/s and $V_{LS} \leqslant 0.1$ m/s. U^* exhibits a rising straight line relation with $\bar{V}_T$ as the latter is increase beyond 1.0 m/s. The flow patterns covered in this region are the stratified wavy, the annular, the annular plus droplet and the film regimes. The other flow patterns appear

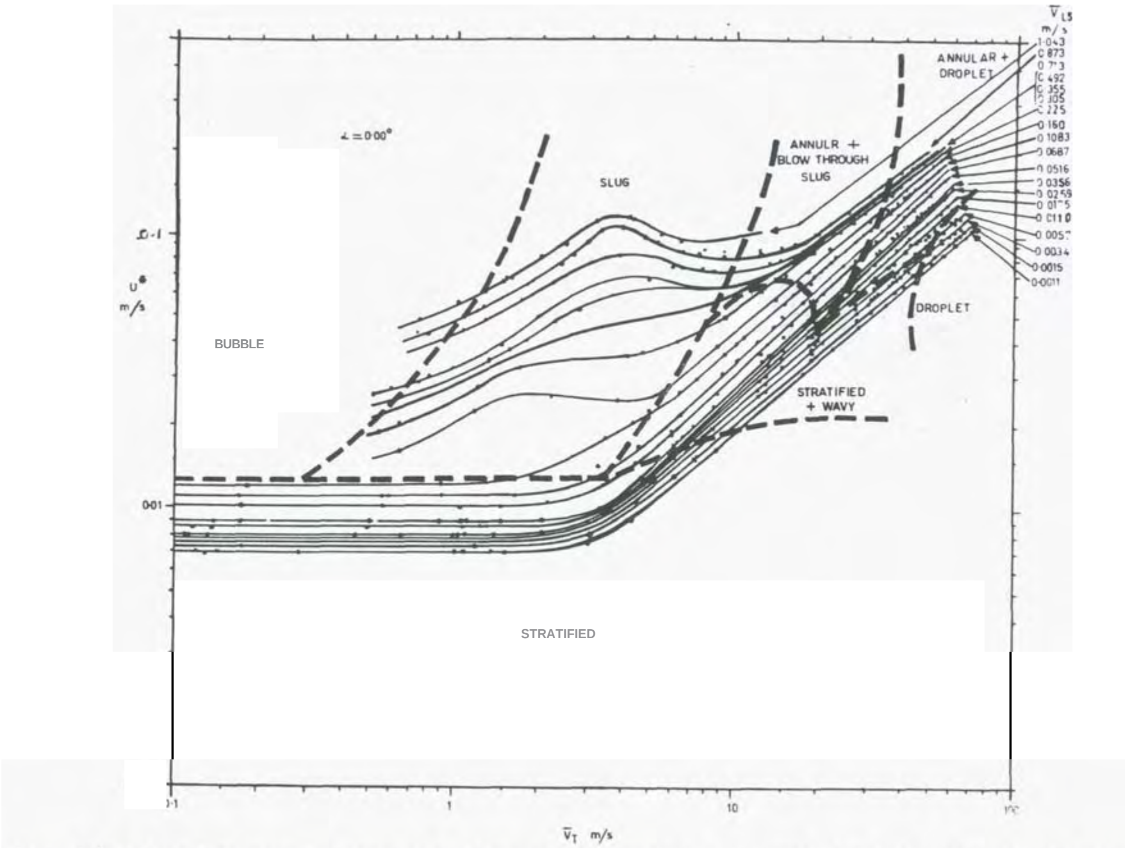


Fig. 3 **Frictional pressure loss for air-water two-phase co-current flow in a horizontal pipe.**

when $\bar{V}_{LS}$ > 0.1 m/s and are the bubble, slug and annular blow through slug regimes which are characterised by much larger corresponding pressure losses with **a** maximum in the U* value appearing in the slug regime at V_T values of between 1.5 to 3.5 m/s.

When positive angles of inclination are given to the pipe the purely stratified regime is eliminated and replaced in the main by slug flow which again is characterised by a maximum in the pressure loss value. The rising straight line portion of the U* against V_T relationship is maintained for the stratified wavy, annular, droplet, film and the annular plus droplet regimes. However, these regions are moved to a correspondingly higher $\bar{V}_T$ value above 12 m/s. Furthermore, as the angle of inclination is increased the corresponding frictional pressure loss is increased and there is a marked tendency for the U* against $\bar{V}_T$ relation to move into the upper portion of the diagram, that is the corresponding frictional pressure loss is increased.

By contrast with a negative angle of inclination, the stratified plus wavy regime is extended to cover almost all the region below $\bar{V}_T$ = 1.0 m/s until at the vertical downward flow position the predominant regime becomes the annular flow type and the maximum in the pressure loss for the slug regime vanishes. In general, downward flow is characterised by smooth curves which are at a higher frictional pressure **loss** than for the corresponding horizontal case.

It is clear from the data and the discussion so far that the frictional pressure **loss** is dependent on the flow regime present in the pipe. The slug flow regime should particularly be avoided as it gives **a** correspondingly greater frictional pressure loss except for the case of vertically downward flow. In general it is advantageous to try and ensure that the two-phase flow is in the separated flow regime area. For example, in the vertical upward flow case of Fig.1 the bubble flow and slug flow regimes are predominant at total velocities V_T below 5 m/s and are characterised by comparatively high frictional pressure losses of a fluctuating nature. However, there exists a rather narrow operating range at V_T about 10 m/s in the separated annular flow regime where the frictional pressure loss is substantially smaller than that obtained for the other flow regimes **such** as the slug flow regime, which occured at a lower total flow rate.

The frictional pressure loss recorded for horizontal flow was observed to be smaller than for the corresponding conditions with the pipe inclined just a few degrees either side of the horizontal. With positive upward inclination the slug or bubble flow regime is encountered while

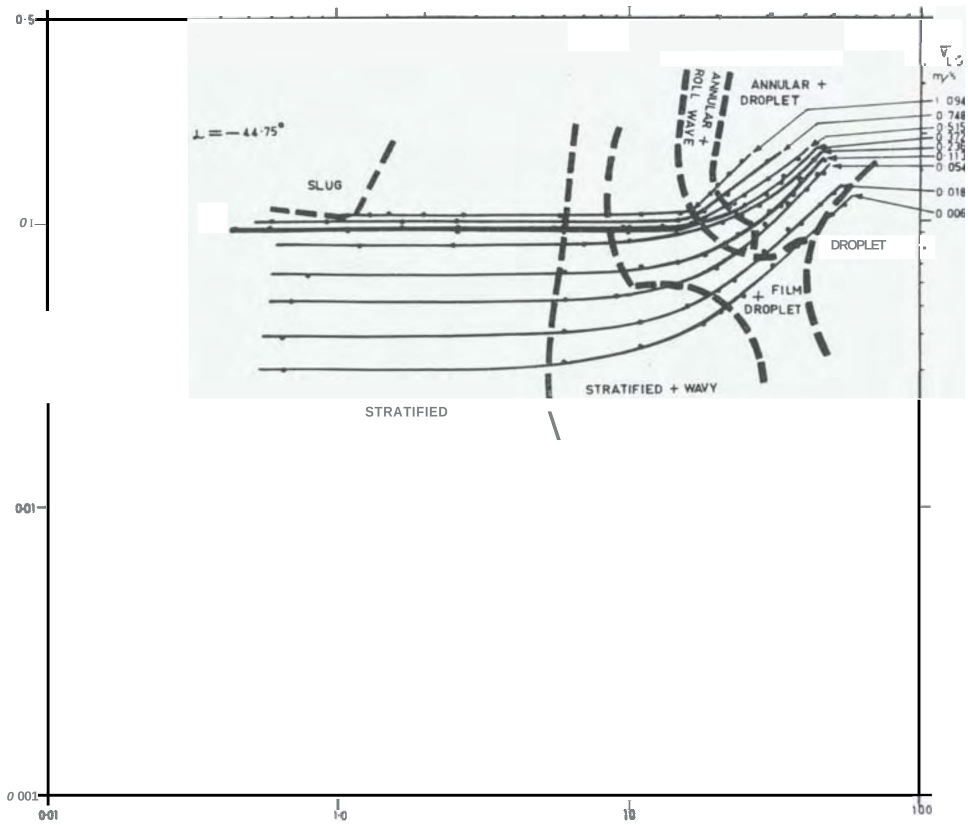


Fig. 4

for downward
to occur for

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NOMENCLATURE

D Pipe diameter (m)

g gravitational constant (m s^{-2})

l pipe length (m)

P Pressure (kg m^{-1} s^{-2})

Q Volumetric flow (m^3 s^{-1})

$\bar{R}$ Holdup

α angle of inclination from the horizontal (degrees)

τ shear stress (kg m^{-1} s^{-2})

ρ density (kg m^{-3})

Subscripts

e expansion

f frictional

g gravitational

G Gas

L Liquid

TP Two-Phase

w wall

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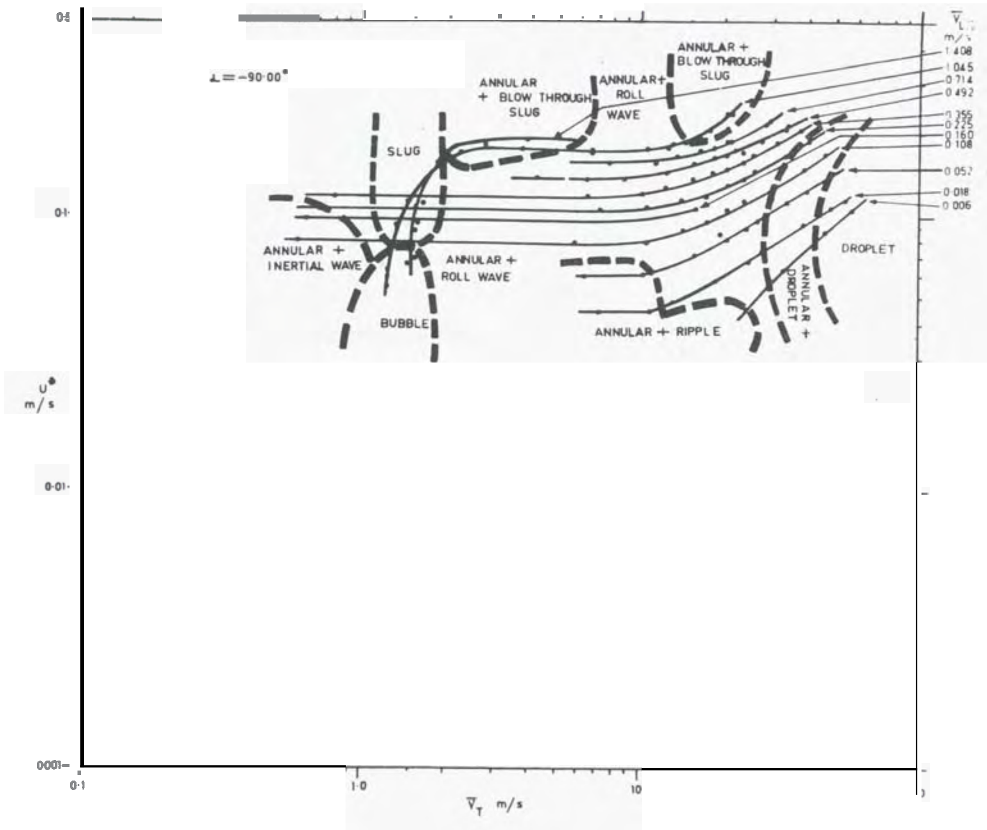

Fig. 5 Frictional pressure loss for air-water two-phase co-current flow in a pipe at an angle of -90.00' from the horizontal.

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