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INTERMITTENT GAS–LIQUID FLOW IN UPWARD INCLINED PIPES

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Abstract—Experimental measurements of flow patterns, pressure gradients and liquid holdup for intermittent two-phase flow in upward inclined pipes are reported. Comparison of this new experimental evidence is made with the Taitel & Dukler theory and the intermittent flow model as modified by Nicholson *et al.*

INTRODUCTION

Simultaneous flow of two or more immiscible phases is of general interest to petroleum, chemical and nuclear industries. Transportation of hydrocarbon mixtures in pipelines, operations of evaporators, chemical reactors, boilers, refrigerators, etc. are a few examples in point.

The gas and oil industries are presently entering an era of increasing dependence on hydrocarbon production from offshore fields. Due to environmental factors and remote locations, much of this production will best be transported to processing facilities in pipelines as two and three-phase mixtures. Operation of oil and gas gathering systems, compressors and pumps depend on accurate calculation of pressure drop which in turn depends on the liquid holdup and other factors.

Up to now most of the research effort has been focussed on horizontal and vertical two-phase flow. Commercial pipelines, however, follow normal terrain variations and consist almost entirely of uphill and downhill inclined sections. It was the subject of this study to investigate flow patterns and characteristics of intermittent two-phase flow in an upward inclined pipe. Experimental measurements were obtained for various pipe inclinations. The flow pattern variations with gas and liquid velocities were compared with the Taitel & Dukler (1976) theory. The data on pressure gradient and liquid holdup were compared with existing semimechanistic models (Dukler & Hubbard 1975; Nicholson *et al.* 1978) for intermittent flow.

FLOW REGIMES

Several flow pattern maps based on extensive data gathering have been proposed for horizontal flow: Baker (1954), Hoogendoorn (1959), Govier & Omer (1962), Eaton *et al.* (1967) and Mandhane *et al.* (1974) to name a few.

Mandhane *et al.* (1974) proposed a flow pattern map for gas–liquid flow in horizontal pipes based on extensive flow pattern observations; the effect of physical properties of the fluids is included. Taitel & Dukler (1976) proposed a model for predicting flow regime transitions in horizontal gas–liquid flow. The transition mechanisms are based on physical concepts and a generalized flow regime map was presented. A good agreement with experimental data was found not only for horizontal pipe but also for pipes with up to 10° of inclination (Barnea *et al.* 1980).

Very limited work has been directed towards prediction of flow regime boundaries in inclined pipes. Gould *et al.* (1974) published flow pattern maps for horizontal and vertical flow and for upflow at 45° inclination. Mukherjee (1979) has reported extensive data on inclined two-phase flow. Spedding & Nguyen (1980) compared the flow regime maps developed by others with air–water experimental data for conditions from vertically downward flow to vertically upward flow. Recently, Barnea *et al.* (1985) proposed a model for predicting flow pattern transitions in inclined upward pipes. It covers the entire range of upward inclinations from horizontal to vertical.

Numerous other authors have published work on flow pattern maps in pipes for two-phase flow which deserve mention (Weisman *et al.* 1979; Taitel *et al.* 1980; Spedding & Chen 1981; Weisman & Kang 1981; Barnea *et al.* 1982a,b).

The simple model proposed by Taitel & Dukler (1976) was used to compare the transition boundaries with the experimental observations. The friction factor for rough pipes was used as proposed by Taitel (1977).

INTERMITTENT TWO-PHASE FLOW

Intermittent flow was the most dominant flow regime observed for the angles considered in this study. The bulk of the work on intermittent flow has been directed towards horizontal pipes. Sevigny (1962) investigated the problem of pressure drop and Singh & Griffith (1970) and Bonnecaze *et al.* (1971) studied slug flow in moderately inclined pipes. Beggs & Brill (1973) proposed an empirical model for predicting pressure drop and liquid holdup for all angles of inclination. Mukherjee (1979) has reported data for pressure gradient and liquid holdup in inclined pipes. Spedding & Chen (1982) have reported data for pressure gradients for all angles of inclination.

The first detailed analysis of the intermittent flow was done by Dukler & Hubbard (1975). The model requires the experimental values of slug frequency and liquid holdup in the slug. Later, Nicholson *et al.* (1978) modified and extended the model to cover the entire range of intermittent flow; empirical correlations were used for the slug holdup and the slug length.

Taitel & Dukler (1977) proposed a model for slug frequency during gas–liquid flow in horizontal and near horizontal pipes. Maron *et al.* (1982) presented a closed model for slug flow which permits the prediction of all slug characteristics. The model is based on new concepts of boundary layer relaxation in a mixing region at the slug front and its recovery at the slug back. Recently, Barnea & Brauner (1985) proposed a method for estimating the slug holdup.

In this work, the Nicholson *et al.* (1978) version of the Taitel & Dukler model (1975) was used; the effect of angle of inclination was incorporated by adding the gravity term to the momentum equation for the liquid film.

Pressure gradient

The total pressure loss across one slug unit consists of three terms: pressure drop across the mixing zone, ΔP_{mix}, pressure drop due to friction, ΔP_f, and the pressure drop due to hydrostatic head, ΔP_{hh}:

$$\Delta P_t = \Delta P_{mix} + \Delta P_f + \Delta P_{hh} \qquad [1]$$

The first term ΔP_{mix} is the pressure loss due to acceleration of the slow moving liquid in the film to the average slug velocity, V_s. This term is given by:

$$\Delta P_{mix} = \rho_L E_{lfe}(V_t - V_{fe})(V_t - V_s) \qquad [2]$$

where E_{lfe} and V_{fe} are the liquid holdup and velocity of the film at its end part and V_t is the slug translational velocity. The second term is the pressure loss due to frictional effects in the liquid slug and this is given by:

$$\Delta P_f = \frac{2 f_1 \rho_M V_s^2 l_s}{D} \qquad [3]$$

where l_s is the slug length and f_1 is the friction factor based on the mixture Reynolds number, R_{em}. The last term in [1] is given by:

$$\Delta P_{hh} = \rho_M g \sin(\beta) l_s \qquad [4]$$

where

$$\rho_M = \rho_L E_{ls} + \rho_G (1 - E_{ls}) \qquad [5]$$

The average pressure gradient becomes:

$$\frac{\Delta P_t}{L} = \frac{\Delta P_{mix} + \Delta P_f + \Delta P_{hh}}{l_u} \qquad [6]$$

where the slug unit length, l_u, consists of the slug and film lengths

$$l_u = l_s + l_f \qquad [7]$$

Average liquid volume fraction

The average liquid volume fraction, E_l, can be calculated from the material balance equation:

$$E_l = \frac{E_{ls} l_s + \int_0^{l_f} E_{lf} \mathrm{d}x}{l_s + l_f} \qquad [8]$$

where the volume fraction in the film is integrated over the film length.

EXPERIMENTAL APPARATUS

The main component of the flow loop is a 24 m pipe installed on an inclinable trestle which can be set at angles of up to 10° uphill or downhill. Test section is made of a transparent acrylic tube of 25.8 mm ID. The fluid system used in all experiments consists of two component air–oil mixtures at room temperature and pressures of up to about 350 kPa. The compressor provides a maximum of 8.5 scm^3/s. The oil used is a light refined machine oil for 6.5 mPas viscosity and 860 kg/m^3 density at 23°C.

Single-phase oil and air flows are metered separately using both orifices and rotameters. The two phases are then brought together in a simple tee mixer at the test section entrance. Upon leaving the test section, the flow enters a 2.5 m high separator tank where the air is vented out of the building through an exhaust valve manifold and the oil is returned in a closed loop to storage tanks and the pumping system. Overall test section pressure is controlled via the air exhaust valves on the separator tank.

The liquid system consists of a pair of steel storage tanks of 1.4 m^3 capacity with three pumps mounted in parallel to feed the test section (0.75, 5.25 and 18.7 m^3/s pumps). Oil is first drawn through a filter before entering the suction side of the pumps. On the discharge side, oil first passes through a heat exchanger to remove pump heat and then enters the liquid flow meters. Oil not required by the test section is shunted back to the storage tanks via a pressure actuated return valve. To insure that the oil stays dry, a calcium chloride bed with associated plumbing is attached to the storage tanks and it is possible to batch circulate the oil through this dryer.

In addition to metering the inlet flow of the two phases, pressure and liquid holdup measurements are made on the acrylic test section. Electronic pressure transducers measure the test section pressure drop via pressure taps placed along the tube. A capacitance sensor developed at the University of Calgary is used to provide a continuous and nonintrusive measurement of average liquid holdup over the volume of the sensor. These capacitance sensors are about three pipe diameters long and are fitted with pressure taps so that both pressure and liquid holdup are measured at the same pipe location. Signals from both types of transducers varied with time according to the spatial distribution and were digitized by computer for the measurement of such quantities as slug translational velocity, slug length and slug frequency.

RESULTS AND DISCUSSION

The effect of upward inclination on flow pattern transitions is shown in figures 1–4. The data are reported for four angles of inclination: 0°, +1°, +5° and +9°. Dotted lines on these figures indicate the visually observed flow regime divisions. The intermittent regime was the one most extensively observed.

The intermittent regime has been divided into three subregions denoted as elongated bubble (EB; characterised by laminar flow in the liquid slugs and long transient bubble trials), elongated bubble with dispersed bubble (EB + DB; characterised by the onset of turbulent flow in the liquid and the subsequent appearance of dispersed bubbles in the liquid), and finally, slug flow (SL; shown as the region in which the gas fraction in the liquid slug exceeds 10%).

As shown in figure 1, only one observation of stratified flow was made in the case of horizontal pipe. The earlier study by Mandhane *et al.* (1974) and the theory by Taitel & Dukler (1976) suggested that stratified flow should be expected at higher gas and liquid superficial velocities. Barnea *et al.* (1980) established that there is a strong sensitivity of

SYMBOLS USED IN FIGURES 1 – 4.

□ = DB : DISPERSED BUBBLE

▽ = A : ANNULAR

■ = ST : STRATIFIED

× = SL : SLUG

\+ = EB+DB : ELONGATED BUBBLE + DISPERSED BUBBLE

△ = EB : ELONGATED BUBBLE

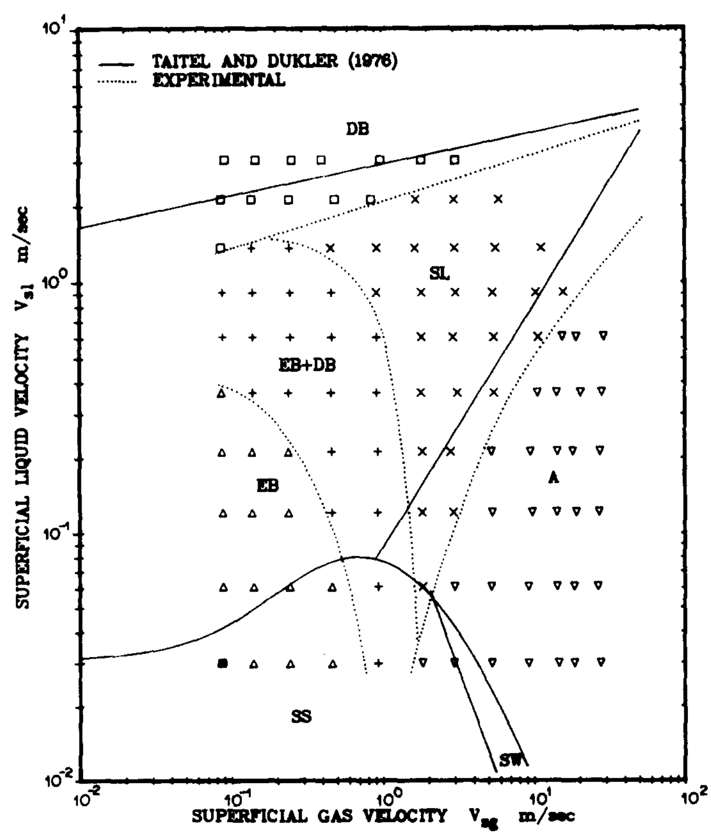

Figure 1. Flow pattern map for horizontal 25.8 mm pipe.

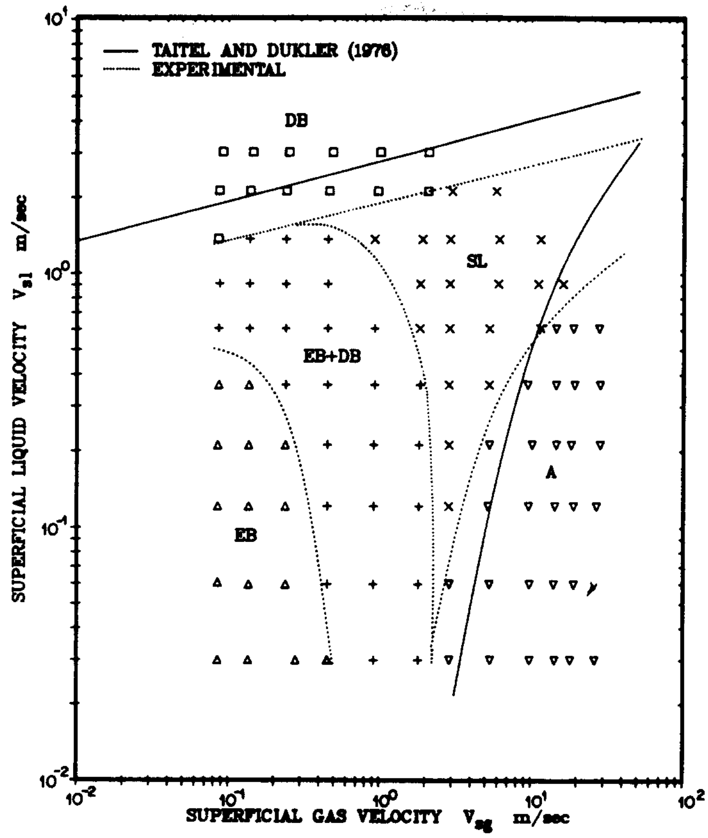

Figure 2. Flow pattern map for 25.8 mm pipe at inclination of +1°.

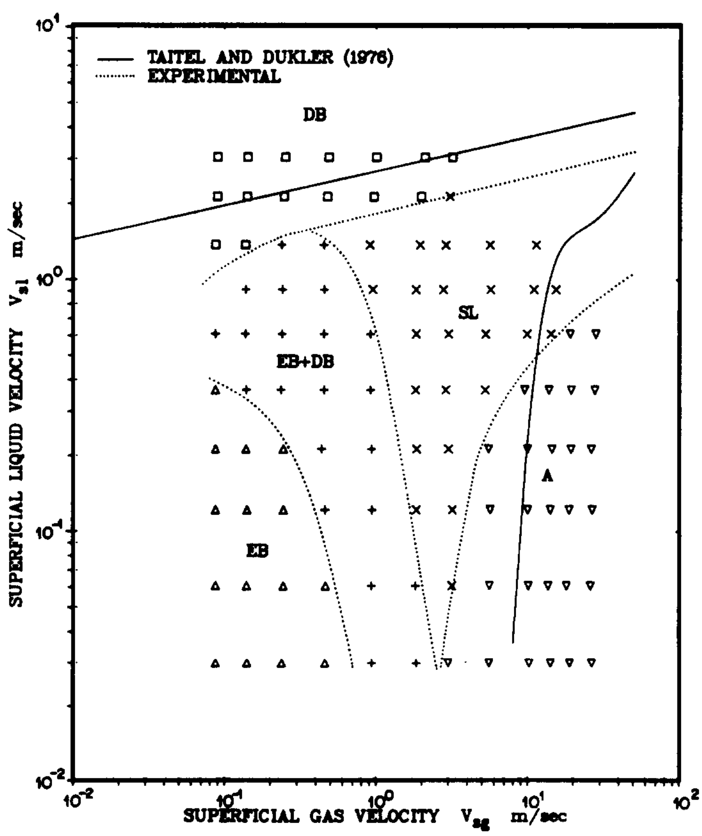

Figure 3. Flow pattern map for 25.8 mm pipe at inclination of +5°.

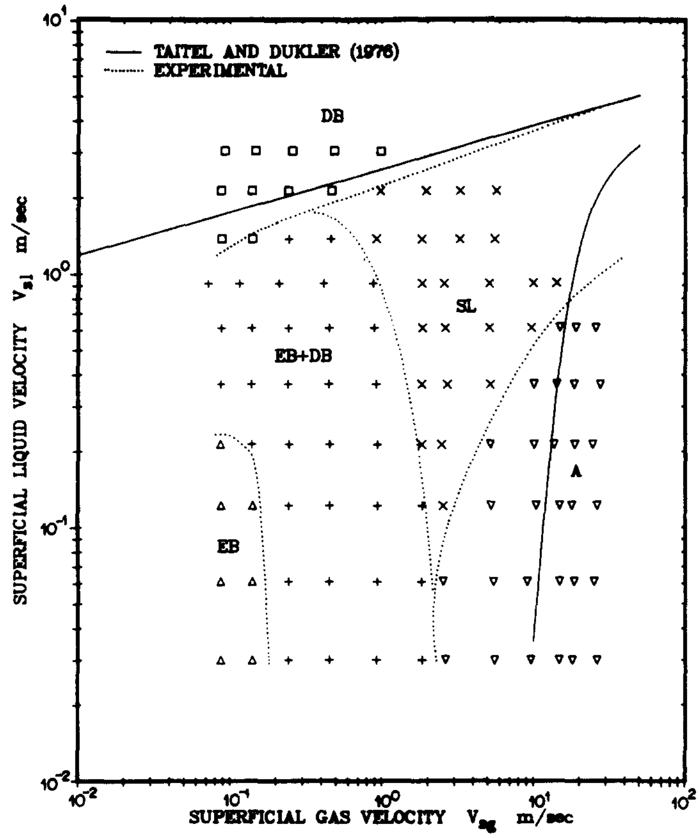

Figure 4. Flow pattern map for 25.8 mm pipe at inclination of +9°.

flow regimes on the angle of inclination. The authors thus speculate that the limited occurrence of stratified flow in this study may have been caused by minor inclination of the test section such as less than 0.01°.

In addition to the observed flow regimes, the Taitel & Dukler (1976) theory predictions are also plotted in these figures; in general there is a good agreement with the experimental results. Although no comparison with the work of Barnea *et al.* (1980,1985) is possible as the angles of inclination and the system differ, the general agreement between the results of the two studies is noticeable. The small region of stratified flow reported by Barnea *et al.* (1980,1985) is not observed because the lowest liquid rate used in this study is well over the value corresponding to the stratified flow occurrence.

The data on intermittent upward flow are presented in terms of pressure gradient and liquid holdup as a function of the superficial gas velocity using liquid superficial velocity as a parameter. The plotted results for pressure gradient using [6] are shown in figures 5–7 for the angles considered. Single-phase liquid pressure drop is plotted along the ordinate axis ($V_{sg} = 0$) and single-phase gas pressure gradient is also plotted (the straight line on the right of the plot indicated with $V_{sl} = 0$) as the two natural boundaries to the two-phase pressure loci. Most data exhibit good agreement with predicted values.

The effect of inclination on pressure gradient is evident by inspecting figures 5–7. For low V_{sl} and V_{sg} values, the pressure drop behavior is dominated by the hydrostatic pressure drop. This is particularly evident with the higher inclinations. For high V_{sl} and V_{sg} values, the pressure drop behavior has become almost independent of the angle and is largely determined by the frictional term.

The liquid holdup as a function of V_{sg} is plotted in figures 8–10. For the angles considered, liquid holdup is only slightly dependent on the angle of inclination. This observation is consistent with the work by Mukherjee (1979). For small angles, the viscous effects have a tendency to mask dependence of pipe inclination on liquid holdup. Beggs & Brill (1973) report greater sensitivity for liquid holdup on the angle of inclination. One has to keep in mind that the viscous effects were negligible in their study.

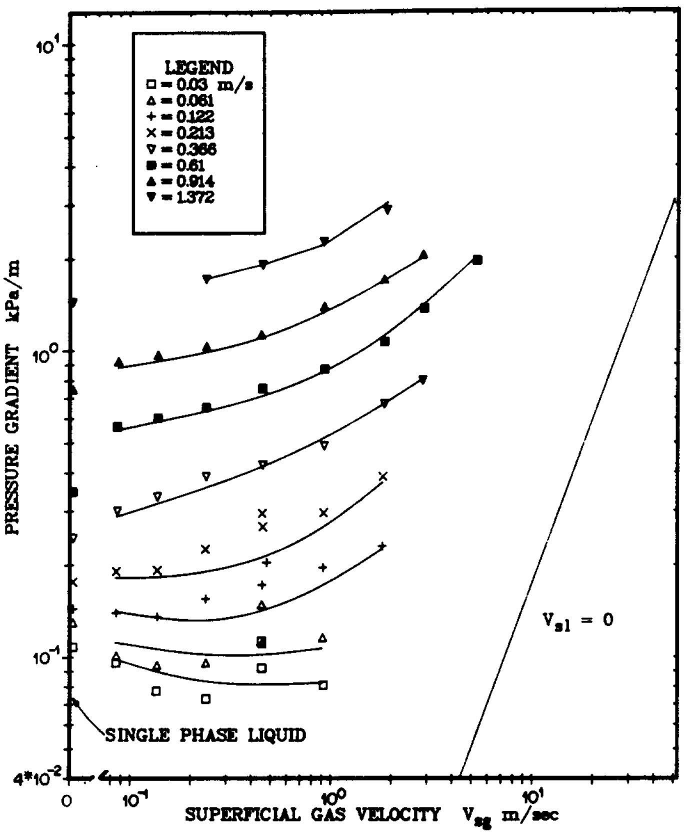

Figure 5. Experimental and calculated pressure gradient in 25.8 mm pipe at inclination of +1°.

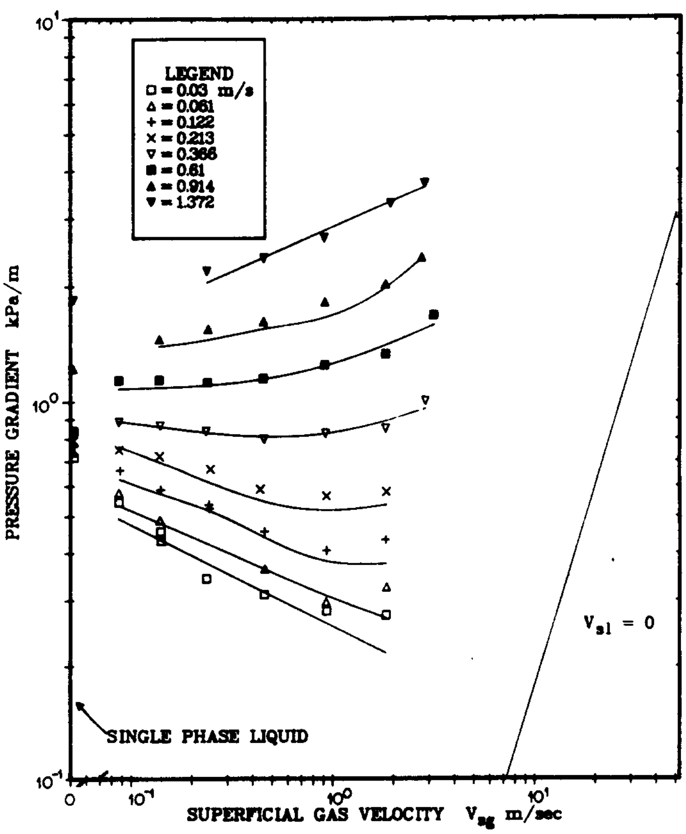

Figure 6. Experimental and calculated pressure gradient in 25.8 mm pipe at inclination of +5°.

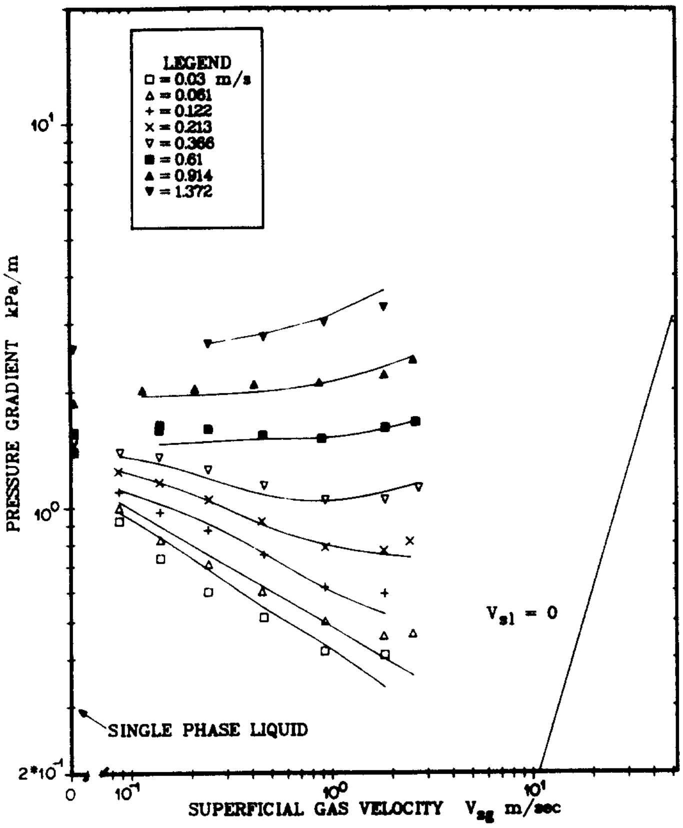

Figure 7. Experimental and calculated pressure gradient in 25.8 mm pipe at inclination of +9°

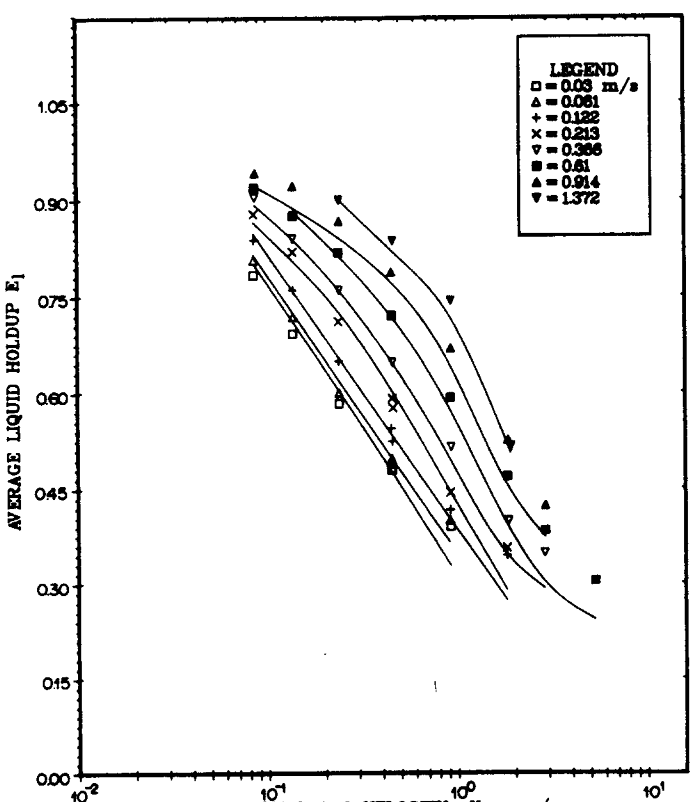

Figure 8. Experimental and calculated liquid holdup in 25.8 mm pipe at inclination of +1°.

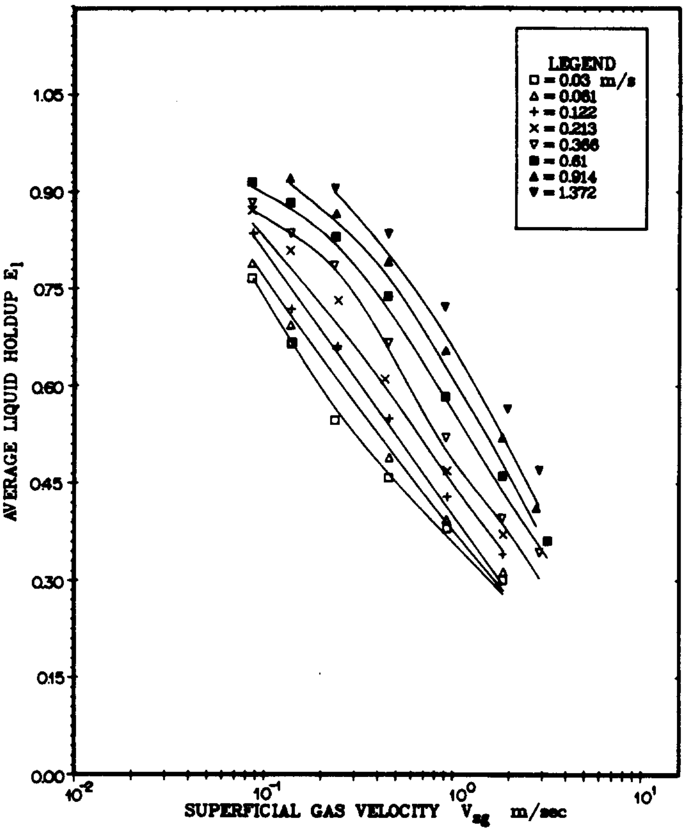

Figure 9. Experimental and calculated liquid holdup in 25.8 mm pipe at inclination of +5°.

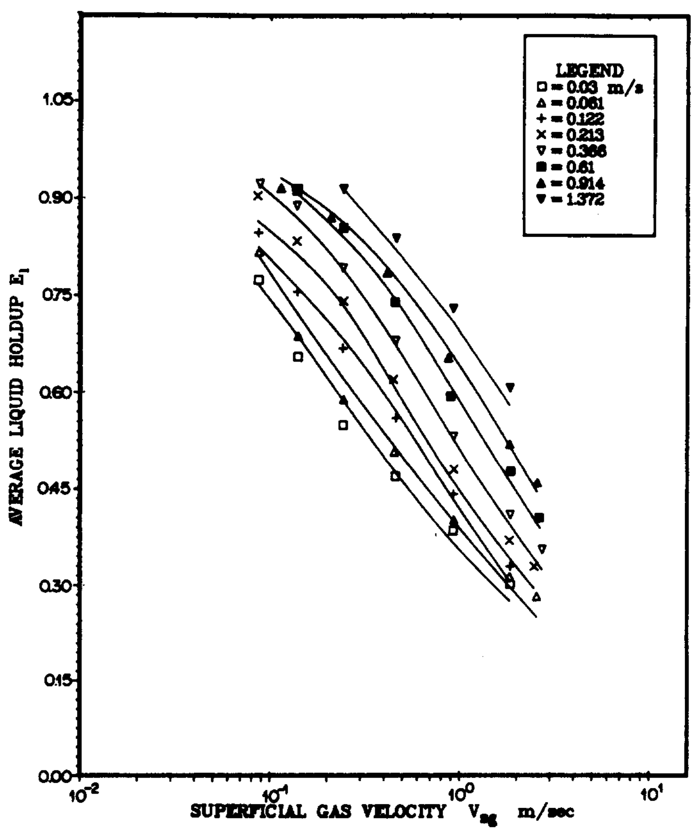

Figure 10. Experimental and calculated liquid holdup in 25.8 mm pipe at inclination of +9°.

CONCLUSIONS

Experimental data were gathered for an air–oil system in a 25.8 mm pipe at $+1°$, $+5°$ and $+9°$ of inclination. The flow pattern data were interpreted by using the theoretical predictions of Taitel & Dukler (1976). The agreement between theory and experiment is good. The results also compare well with a similar work by Barnea *et al.* (1985).

The pressure drop data on intermittent flow were used for verification of the modified model of Nicholson *et al.* (1978). A good agreement was found for most combinations of the flow and pipe variables.

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