TWO-PHASE FLOW OF LIQUID-SOLID MIXTURE IN INCLINED PIPES

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ABSTRACT

The purpose of the present experimental work is to study the effect of pipe inclination on the velocity profile and the frictional pressure drop along the pipe for a liquid-solid flow. The mixture used was coarse sand and water flowing in the heterogeneous flow regime which is the most practical regime for slurry transportation. A closed loop hydraulic circuit was used to satisfy the concept of constant loading of solid particles during each experiment. The measured velocity profiles showed that both the proportion by volume of the solid particles in water and pipe inclination have a significant effect on the velocity distributions. The experimental results of the frictional pressure drop along the pipe were used to obtain an empirical correlation to predict this drop as a function of the mean velocity, concentration and the angle of inclination.

INTRODUCTION

Two-phase flow is the simplest form of multiphase flows. One of the most common types of two-phase flow in industrial processes and solid transportation is the liquid-solid flow. Examples are found in the production processes of paints, paper, food and in the transport of coal, ores and sand using water as a conveying fluid, either in open channels or through pipes. One of the most important applications of sand-water flow through inclined pipes is the dredging and filling processes. When solid particles are transported with a liquid through a pipe, five flow regimes may be discerned depending on the properties of the conveying liquid, the properties of the transported solid and the characteristics of the pipe line [1]. These five hydrodynamic regimes are: homogeneous, heterogeneous, intermediate, saltation and capsule flow. Each of these regimes may in turn have several subregimes.

The heterogeneous flow occurs when the solid particles are coarse, having a density different from that of the liquid. In this case the mean velocity of flow allows partial separation of the particles from the liquid resulting in a somewhat seperate behaviour of the two phases. The particles move by the frictional drag imposed on them by the liquid. This type of flow is characterized by the absence of chemical interaction between the particles and the conveying liquid. Also, due to the difference in densities, concetration distribution across the pipe cross-section exists. Obviously, the flow velocity must be high enough to maintain the solid particles in suspension. These characteristics make the heterogeneous regime the most practical regime for conveying solids in pipe lines for long distances.

Most of the previous investigations in this subject [2to8] were concerned with heterogeneous flow in horizontal pipes, while Round and Kruyer [9] studied the suspension of spheres in inclined tubes. This shows that the flow in inclined pipes did not recieve the same attention although the gravity force may have a significant effect.

The purpose of this paper is to investigate experimentally the characteristics of heterogeneous flow of sand-water mixture in an inclined pipe at different concentrations, flowrates and inclination angles. The velocity profiles were measured in two perpendicular directions across the section using two Pitot-cylinders while the frictional pressure drop along the pipe was measured by four piezometer tubes connected to four pressure tapping holes.

EXPERIMENTAL SET-UP

In order to study the liquid-solid flow in an inclined

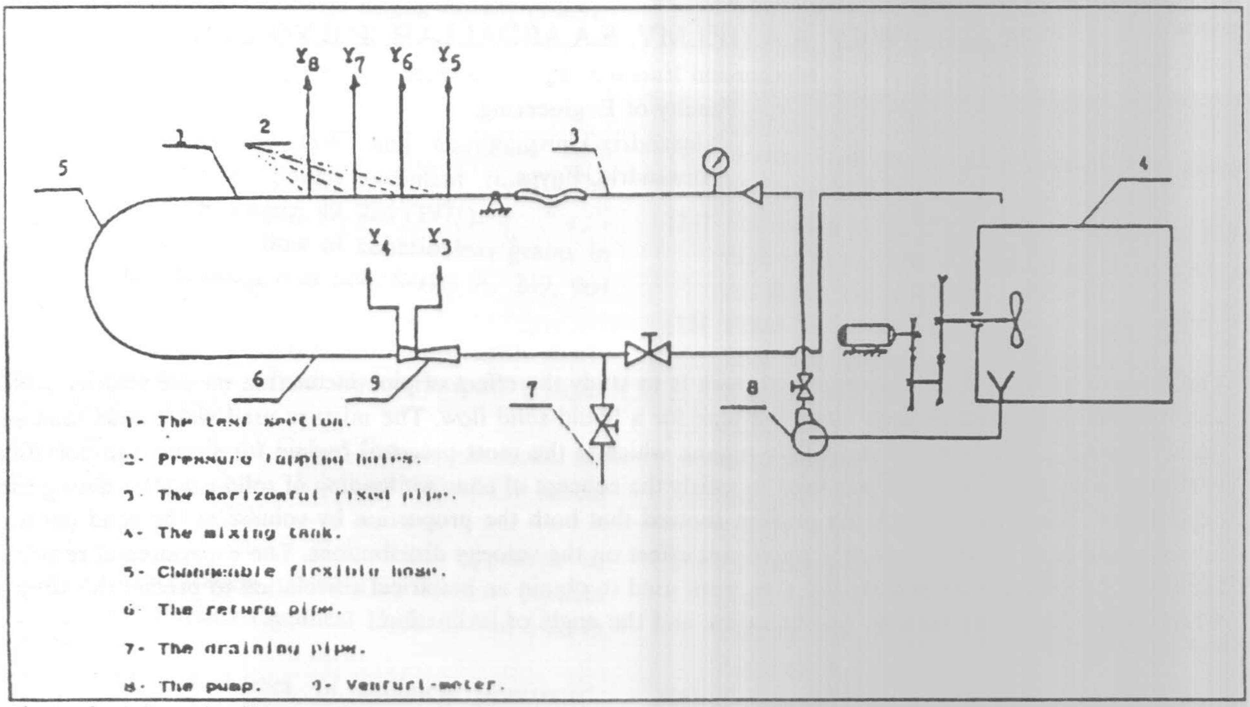


Figure 1. Schematic diagram of the hydraulic circuit.

pipe, the experimental set-up shown in figure (1) was used. The hydraulic circuit forms a closed loop to have constant loading of sand particles during each experiment. The propeller in the mixing tank maintains continuous stirring of the solids with the liquid to keep a homogeneous mixture.

A centrifugal pump was used to pump the mixture from the tank to the circuit. The suction pipe of the pump was connected to the bottom of the mixing tank and the delivery pipe was connected to a fixed horizontal pipe. This pipe leads,through a flexible hose, to a plexiglass test section mounted on a pivoted steel beam which allows the pipe to have inclination angles between -15 and 30° to the 2horizontal. Both the fixed pipe and the test section were 33 mm inner diameter and 6 mm thick.

Four tapping holes, 0.6 mm diameter were drilled on the test section 0.75 m apart from each other and connected to the upper ends of four piezometer tubes. These tubes were connected at their lower ends and were used to measure the frictional pressure drop along the pipe.

Two traversing Pitot-cylinders were used for measuring the velocity profiles across the pipe along two perpindicular diameters using the technique described in [8]. One of these diameters always lies on a horizontal plane, so the velocity profile along it will be indicated as the horizontal velocity profile. The profile along the perpendicular diameter will be indicated as the normal velocity profile. The two Pitot-cylinders were located in the test section 0.5 m from each other to avoid the effect of any disturbance in the flow field. The test section was connected to the return horizontal pipe by an interchangeable flexible connection. This connection was changed with each inclination angle to fit the new relative position of pipes without any constrictions.

The return pipe was equipped with a standard venturi-meter connected to a U tube manometer. This venturi was calibrated with mixture flow rate at each concentration used in the experiments using a graduated tank and a stop watch. A tee connection was used near the end of the return pipe with one branch leading to the mixing tank while the other was used either to have flow samples or to drain the circuit.

The experimental work was carried out at volumetric concentrations of 3,5 and 7 % and pipe inclination angles of - 15, 0, 15 and 30° to the horizontal. Three values of discharge were chosen taking into consideration that the flow should lie in the heterogeneous flow regime. To satisfy this condition, the characteristic number (N_I) had to be larger than the critical value separating the saltation and the heterogeneous flow regimes.

A critical no. N_I of 40 was proposed by Zandi and Covatos [5]. The values of N_I for the present study ranged between 75 and 180 based on the following specifications of the seived sand used in the experiments:

average diameter of particles = 2.13 mm ,
specific gravity = 2.66 ,
free settling velocity = 0.22 m/s ,

These values and the volumetric concentration were measured using the techniques described in [8].
Accordingly the flow rates considered are 1.31, 1.48 and 1.6 lit/s.

RESULTS AND DISCUSSION

Figure (2) represents the velocity distributions at C_v = 3 % for the considered flow rates at different inclination angles. In the figure, the vertical axis represents (X/D), where X is the distance from the pipe wall along the diameter, and D is the pipe inner diameter. The horizontal axis represents($\sqrt{2gH}$), where H is the head difference between the two ends of the Pitot- cylinder.

From these figures, it is clear that the velocity distribiution in the horizontal plane is nearly symmetrical around the pipe axis, while the velocity distribution in the normal direction is biased towards the upper part of the pipe. This is due to the high specific gravity of the sand used in the heterogeneous flow regime which means higher concentration of the sand particles at the lower part of the pipe. Since the velocity of the particles is less than the liquid velocity, the sand particles will be dragged by the liquid causing the liquid velocity to decrease.

In order to verify the above interpretation, two experimental techniques were employed. Firstly, photographic picture were taken for the flow at a flow rate of 1.32 lit/s (i.e.mean velocity of mixture = 1.54 m/s), and a volumetric concentration C_v of 3 %. The duration of the camera was adjusted at 0.01 second, and the picture is shown in figure (3). The traces seen in the picture represent the distances travelled by the solids during the exposure time of the camera. The mean velocity of solid particles was calculated from the picture and it was found to be nearly 1 m/s. Hence the mean velocity of solid particles is less than that of the mixture by about 0.54 m/s.

Secondly, to further assert the effect of the uneven distribution of the solid particles across the pipe on the normal velocity profile the system was run using a mixture of PVC particles (specific gravity = 0.726 and average diameter = 4.3 mm) and water at 3 % concentration by volume. The normal velocity distribution was measured at angles of inclination 15, 0 and -15°, at a discharge of 1.487 lit/s. The results are shown in figure (4) which demonstrates that the velocity in the upper part of the pipe is less than its corresponding value in the lower part, i.e. the velocity profile is biased towards the lower part of the pipe. This is due to the higher concentration of the low density PVC particles in the upper part. Consequently the plastic particles will be dragged by the liquid in the upper part of the pipe causing the liquid velocity to decrease, which confirms the previous discussion.

Comparing the velocity profiles at different flow rates in figure (2), it can be seen that both the normal and horizontal velocity distributions increase by increasing the discharge i.e. the mean velocity increases to satisfy the condition of higher flow rate.

These remarks are confirmed in figures (5) and (6) at different concentrations.

Comparing the velocity distributions at concentration C_v = 5 %, and discharge $Q = Q_1$ and different inclination angles (figure 7), it can be concluded that the maximum velocity in the normal and horizontal planes tend to increase by decreasing the inclination angle causing the whole distribution to be closer to the parabolic form of the single phase laminar flow. Keeping a constant flow rate of the mixture at $Q = Q_1$ and fixing the inclination angle, by increasing the concentration, both the velocity distribution and the mean velocity decreases for the horizontal and normal planes as shown in figure (8). It should be noted that at low discharge ($Q = Q_1$)and high volumetric concentration (C_v = 7%), the sand caused the valves to be blocked and hence it was impossible to run the experiment at this condition.

Figure (9) represents the frictional pressure drop ΔH ($\Delta H = \Delta p/w + \Delta z$) in the test section versus the axial distance (L) for pure water at different flow rates and all inclination angles. Figure (10) represents the same relation at different concentrations. It is clear from these figures that the energy loss along the pipe is linear and increases by increasing the discharge. For pure water there is no effect for the inclination angle, while for the mixture the gradient increases by decreasing the pipe inclination. The effect of increasing the discharge is due to the resulted increase in the mean velocity of the flow which leads to higher friction loss. The effect of the inclination angle can be attributed to the previously discussed changes in velocity profiles of the mixture which means less velocity gradient at larger inclination angles. Comparing the

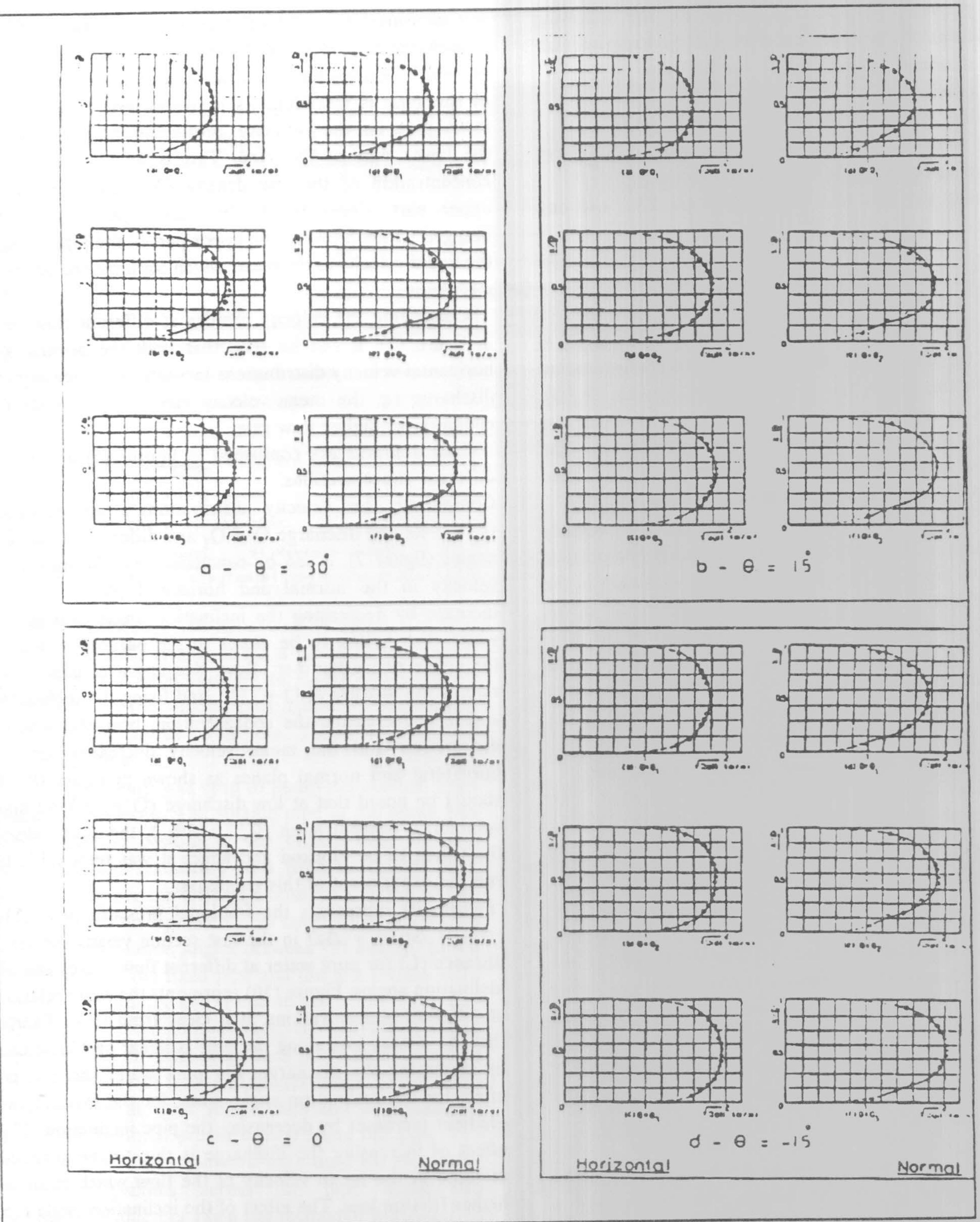


Figure 5. Velocity profiles in the horizontal and normal planes at different flow rates and angles (C_v = 5%).

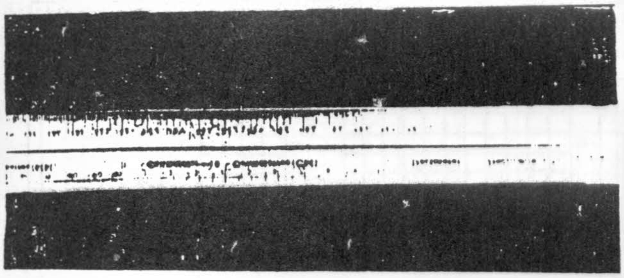


Figure 3. Photographic picture of the flow at camera duration tim2e of 0.01 S.

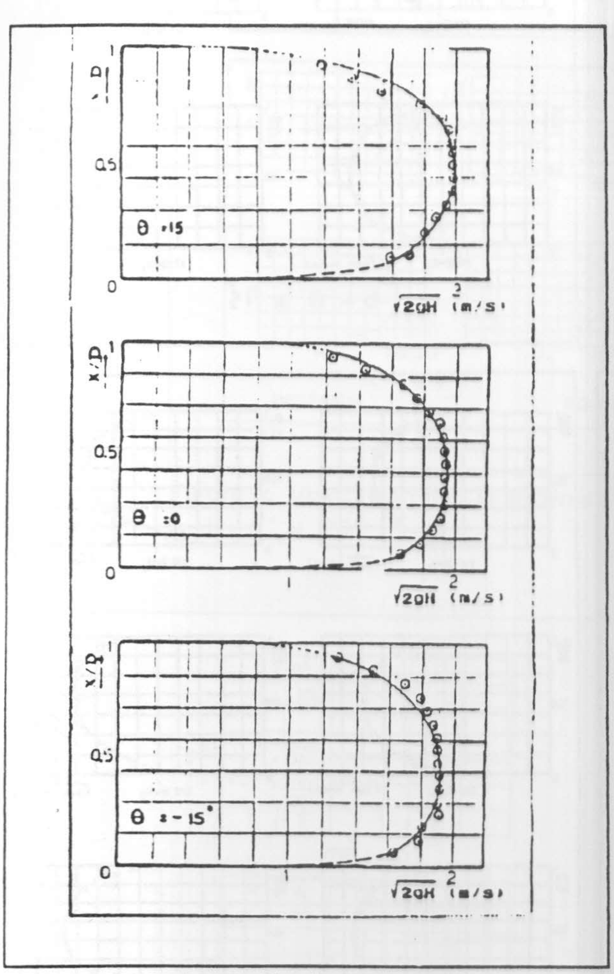


Figure 4. Velocity profiles in the normal plane using P.V.C. particles at different inclination angles (C_v = 3%, Q = Q_2).

frictional pressure drop at various concentrations, it can be seen that at the same discharge and inclination angle as the volumetric concentration increases, the energy loss decreases. Since increasing the concentration, keeping constant discharge of the mixure means that the liquid flow rate and consequently the mean velocity will decrease, leading to less energy drop.

The experimental data for frictional pressure drop was used to deduce an empirical correlation that relates that drop to the volumetric concentration, the angle of inclination of the pipe axis and the mean velocity of the flowing slurry. The techniques of curve fitting, regression and correlation are used throughout this analysis to obtain the best curve formula that fits the experimental points for each case of pressure distribution. Finally, the Gauss elimination algorithm method is used to relate the obtained system of emprical formulii leading to :

$$J_s = KV^2$$

where

J_s = frictional pressure drop per unit length = $\Delta H/L$

and $K \doteq [(15.05 \times 10^{-3} + 9.75\,\theta \times 10^{-5}) + C_v\,(0.655 - 0.11\,\theta) - C_v^2\,(9.0 - 0.125\,\theta)]$

This formula represents the relation between the factors affecting the flow of slurry in the following regime:

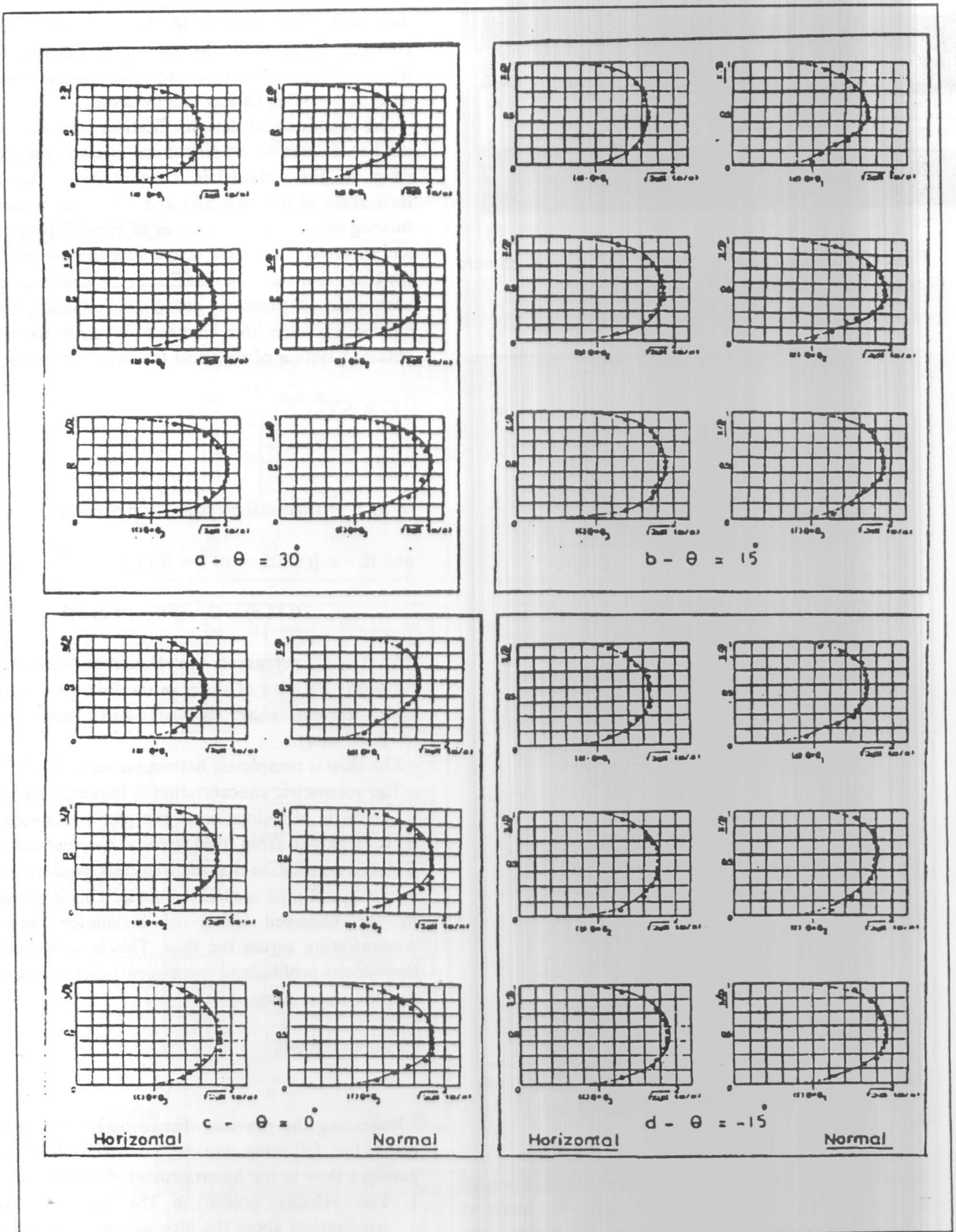
- The flowing slurry is water and coarse sand (d = 2.130 mm).
- The flow is completely heterogeneous (70 < N < 180).
- The volumetric concentration is between 3% and 7% .
- The angle of inclination of the pipe is between -15 and

It is apparent from the velocity distributions and the deduced correlation that the frictional pressure gradient is a function of pipe inclination angle. This is primarily due to the observed effect of inclination on particles concentration across the flow. This in turn would affect the velocity profiles and consequently the velocity gradient and the shear stress.

CONCLUSIONS

Regarding the previous discussion of the experimental results,the following can be concluded for liquid-solid particles flow in the heterogeneous flow regime:

1. The velocity profile in the horizontal plane is symmetrical about the pipe axis while in the normal



a - θ = 30°

b - θ = 15°

c - θ = 0°

d - θ = -15°

Figure 2. Velocity profiles in the horizontal and normal planes at different flow rates and angles (C_v=3%).

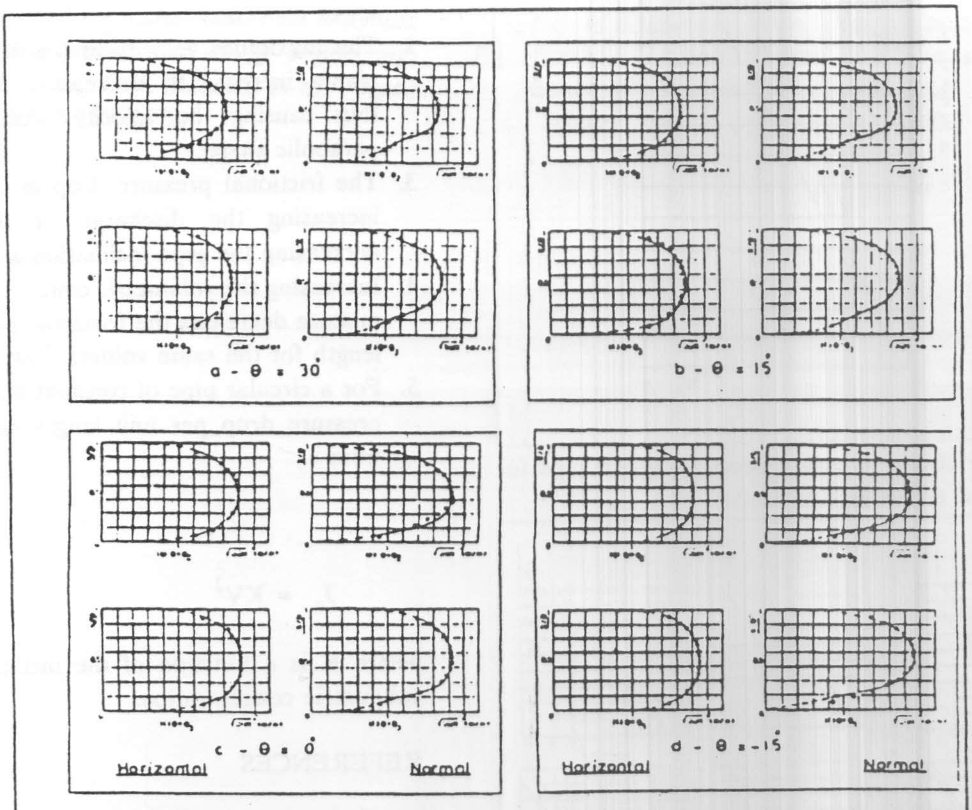


Figure 6. Velocity profiles in horizontal and normal planes at different flow rates and angles (C_v = 7%).

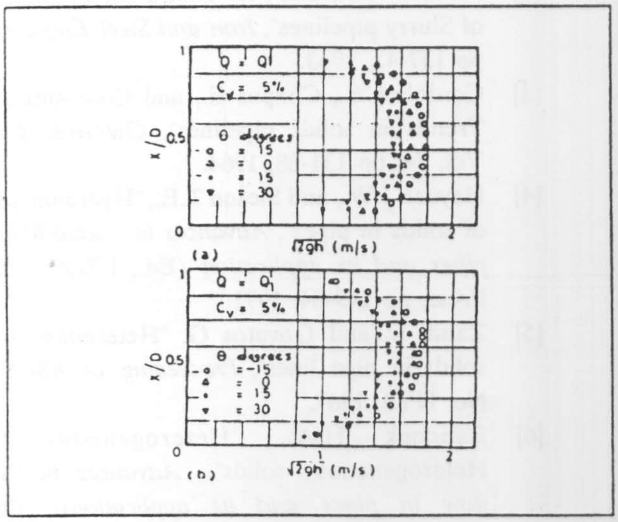


Figure 7. Effect of pipe inclination angle on the velocity profiles (a- horizontal b- normal).

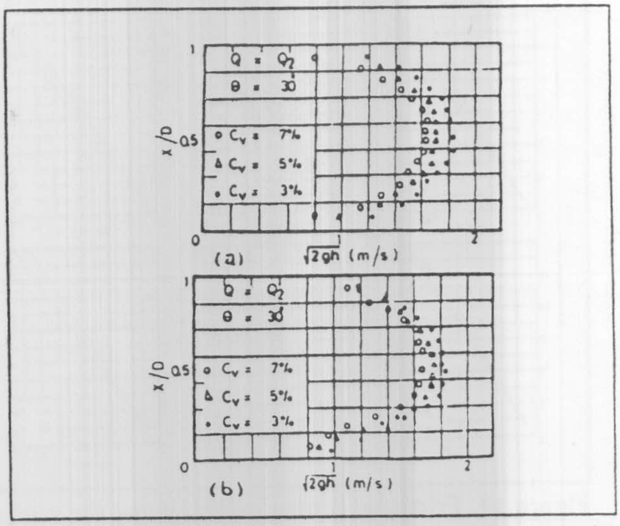


Figure 8. Effect of concentration on the velocity profiles (a- horizontal b- normal).

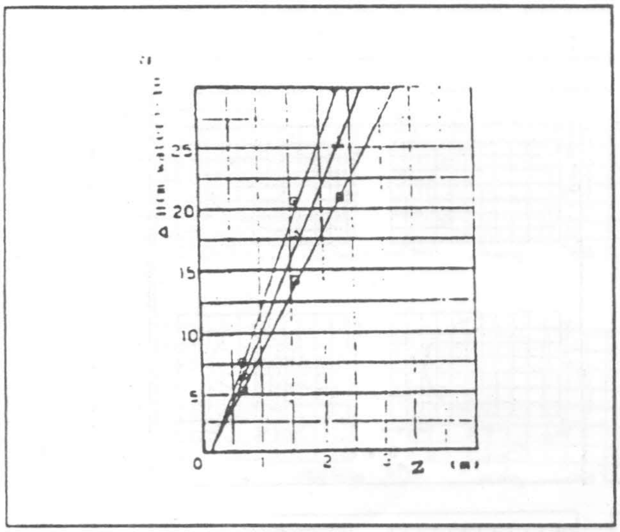


Figure 9. Frictional pressure drop along the pipe for pure water at all inclination angles.

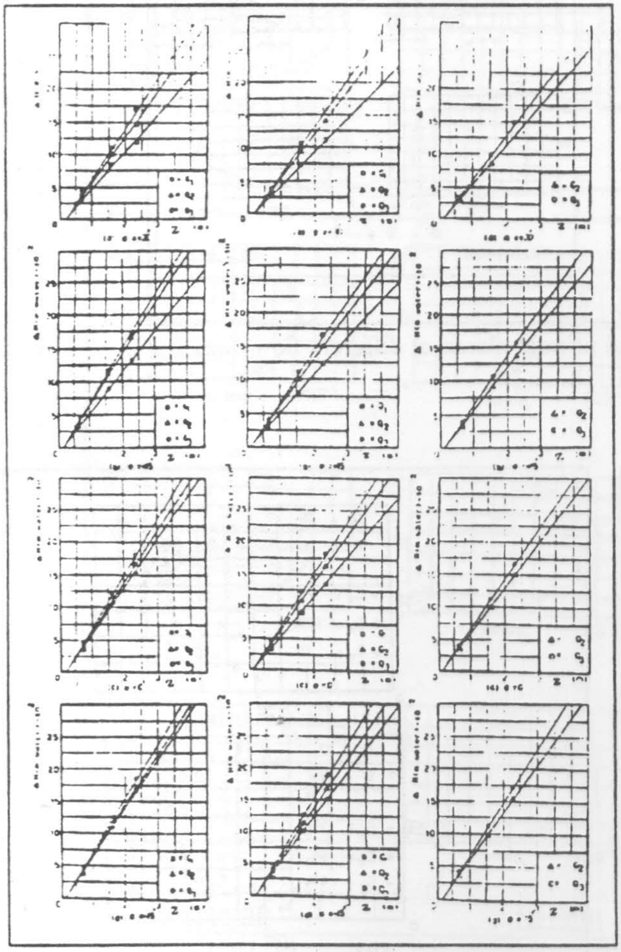


Figure 10. Frictional pressure drop along the pipe at different flow rates, angles and concentrations.

plane, the velocity in the region of higher concentration is less than its corresponding value in the region of lower concentration.

2. The maximum velocity in the horizontal and normal planes increase by decreasing the inclination angle, thus causing the velocity profile to approach the parabolic shape.
3. The frictional pressure drop in the pipe increases by increasing the discharge of the mixture and/or decreasing the pipe inclination angle.
4. Increasing the volumetric concentration of solids in the mixture decreases the frictional pressure drop per unit length for the same volume flow rate of mixture.
5. For a circular pipe of constant diameter, the frictional pressure drop per unit length can be written in the form :

$$J_s = Kv^2$$

$$J_s = KV^2$$

where K is a function of the inclination angle and the volumetric concentration.

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