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AN EXPERIMENTAL STUDY OF WALL CONDITIONS IN HORIZONTAL TWO-PHASE FLOW.

S.V. Paras, N. Vlachos and A.J. Karabelas

Chemical Process Engineering Research Institute and Department of Chemical Engineering
Aristotle University of Thessaloniki Univ. Box 455 GR54006, Thessaloniki, Greece.

Abstract

Gas/liquid flow in horizontal pipes has been studied experimentally in a 50.8 mm i.d. pipe loop, with emphasis on stratified/atomization and annular flow to improve our understanding of flow characteristics of geothermal fluids close to the pipe wall.

Accurate time records of local liquid film thickness have been collected and statistically analyzed mainly to determine the characteristics of large disturbance waves which appear to be intimately related to the mechanism of liquid atomization. The analysis of these data showed that almost all wave characteristics exhibit similar behavior in both regimes. By combining signal cross-correlation data with visual observations, it is shown that the disturbance waves tend to deform rapidly, move on a plane inclined with respect to the vertical and cover an increasingly larger portion of the circumference with increasing gas velocity.

Measurements of the axial velocity component in the liquid layer of the atomization/ stratified flow regime are reported. An experimental facility based on Laser Doppler Anemometry permits accurate local measurements in the horizontal pipe. The data suggest that the liquid motion resembles the behavior of single phase flow only in the vicinity of the solid surface. Beyond that, the flow field is strongly influenced by the wavy gas/liquid interface and by the apparently intensive energy transfer from the very fast moving gas to the liquid layer.

INTRODUCTION

The main objective of this research is to improve our understanding of flow characteristics of two-phase geothermal fluids (mainly those of the annular and stratified/ atomization flow regimes) which influence scaling and corrosion in pipes. Furthermore, the good knowledge of the flow characteristics is a prerequisite to the successful handling of several other problems that appear during the design and operation of geothermal installations as well as during exploration and evaluation of new geothermal reservoirs.

Experimental work in annular and stratified/atomization flow regimes (*Figure 1*) has been undertaken because of the occurrence of these regimes in real systems. Despite the fact that stratified flow is considered simpler than annular flow and that several predictive models have been proposed (i.e. Andritsos & Hanratty, 1987) many important questions still remain unanswered. Moreover, the transition between stratified and annular flow regimes exhibits some features (droplet entrainment, relatively thick liquid layer at the pipe bottom) which are common to both neighboring regimes. Therefore, data and models for stratified/atomization flow are expected to serve as the basis for modeling (at least some aspects of) the more complicated annular flow regime.

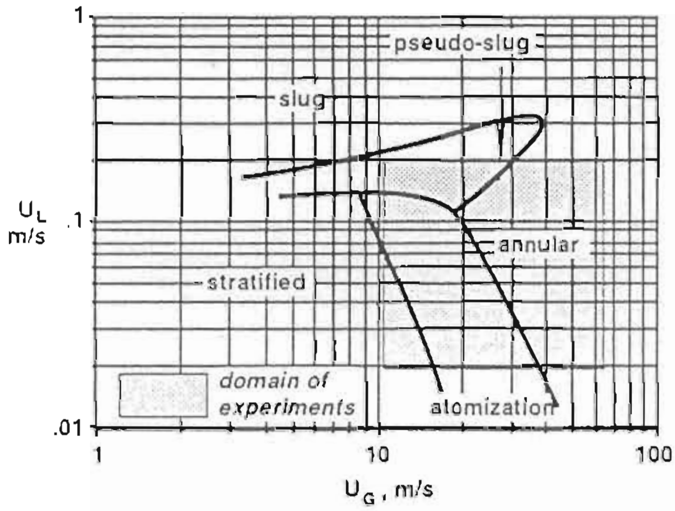

Figure 1. Domain of experiments.

Time records of the liquid layer thickness were taken at six circumferential positions (i.e. at $\Theta=0^o$, 45^o, 90^o, 135^o, 180^o and 315^o from the bottom of the pipe in annular and at $\Theta=0^o$ and 45^o in stratified/atomization flow) and were statistically analyzed. Time averaged and RMS values of the liquid layer thickness as well as other wave properties (dominant wave frequencies, wave celerities, wave height, steepness, intermittency) were obtained.

Well developed experimental techniques, such as hot wire or hot film anemometry, cannot be used for local velocity measurements inside thin liquid layers in horizontal pipe flow due to the unavoidable probe interference with the flow. Non-intrusive optical techniques, such as Laser Doppler Anemometry (LDA), are obviously a promising approach. The lack of relevant velocity data has some inevitable consequences. For example, all recent efforts to model liquid layers in horizontal two phase flow (e.g. Shoham & Taitel, 1984; Laurinat et al., 1985; Andritsos & Hanratty, 1987; Fukano & Ousaka, 1989) are based on well-known expressions for *single* phase flow, ignoring the effect of the wavy gas/liquid interface. Yet detailed film thickness measurements (e.g. Laurinat, 1982 and Paras & Karabelas, 1991) show quite large intensities (RMS over mean values) of film thickness fluctuations. Moreover, the flow visualization study carried out by Jayanti & Hewitt (1990) in horizontal annular flow, suggests that the influence of these fluctuations on the velocity distribution within the film is quite significant.

A Laser Doppler Anemometry unit permits accurate local measurements in a horizontal pipe. Measurements of the axial velocity component in the liquid layer of the atomization/ stratified flow regime are summarized here. The new information includes time averaged local velocities, RMS values, probability density distributions, and power spectra. Elimination of velocity bias and calculation of velocity spectra is accomplished by a recently developed "signal reconstruction" algorithm.

EXPERIMENTAL TECHNIQUES

The experiments were carried out in a horizontal flow loop described in a paper by Paras & Karabelas (1991). Two phase air/water flow develops in a 16m long straight section, of 50.8 mm i.d. The test section is positioned about 300 diameters downstream of the mixing section of the two phases where the flow is considered to be fully developed. The selected range of superficial velocity, was 2 to 20 cm/s for water and 10 to 66 m/s for air (denoted by U_L and U_G respectively).

Wave heights and liquid film thickness along the pipe in two-phase flow are measured using parallel wire conductance probes. The technique is based on the fact that the conductance between two parallel wires is uniquely related to the liquid level between them. Laser Doppler Anemometry (LDA) is used for measuring instantaneous local velocities. Carefully filtered water is circulated in the loop and it is seeded with monodisperse polystyrene spheres having a mean diameter 0.6 μm. The details of the LDA technique are described elsewhere (Paras & Karabelas, 1992).

FILM THICKNESS CHARACTERISTICS

The mean film thickness in general tends to decrease with increasing gas velocity, whereas the area of the interface increases and deviates significantly from the flat (time averaged) shape, assumed in computational procedures used for modelling wavy stratified flow. At higher gas flow rates (annular flow) the liquid film is almost symmetric around the pipe circumference, showing that the effect of gravity is almost negligible (similarity to vertical annular flow). For instance the value at the top of the pipe is almost 80% of the value at the pipe bottom.

In general, the RMS value of the film thickness varies with both superficial liquid and gas velocities, as shown in ***Figure*** *2*. It is evident that by increasing gas velocity the RMS value decreases rapidly, whereas it increases with liquid velocity. In particular for annular flow the influence of liquid flow rate on RMS values is less noticeable whereas the strong influence of gas flow rate still remains.

The power spectra of the film height time series were obtained by the Welch method. It is observed that at relatively small gas velocities (U_G up to 17 m/s) the dominant frequency is between 1 and 3 Hz, but at relatively higher gas velocities ($20<U_G<35$ m/s) it is shifted in the range 5-10 Hz. For $U_G>40$ m/s and for $U_L<12$ cm/s a portion of the wave energy is carried by waves of frequency greater than 15 Hz. The spectrum tends to flatten out drastically with increasing U_G, because energy is distributed uniformly among waves of higher frequencies and the liquid film thickness is also reduced. Details on the film thickness spectra are presented elswhere (Andritsos et al, 1992). In general, the frequency displays a tendency to increase with gas flow rate, as shown in *Figure 3*.

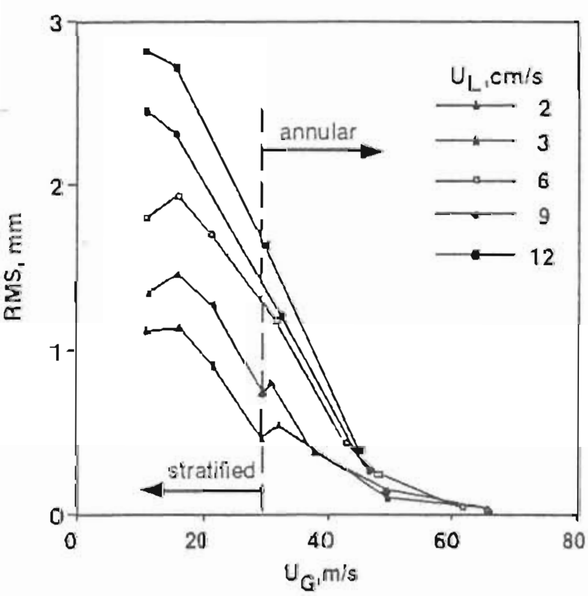

Figure 2. The effect of superficial gas and liquid velocity on RMS values of film thickness

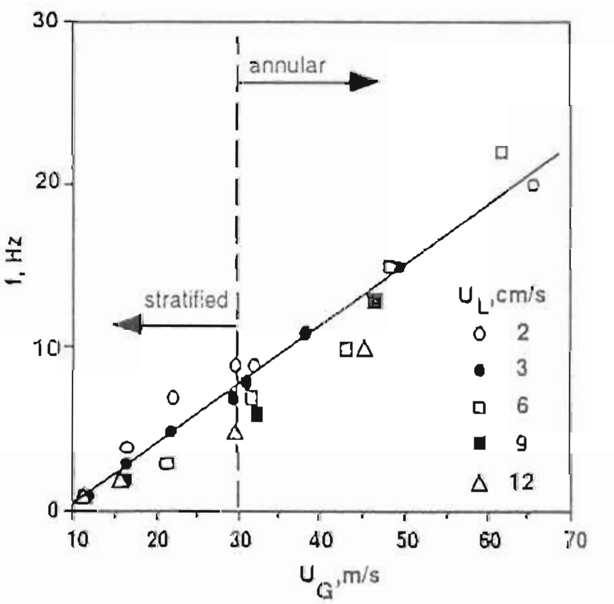

Figure 3. The effect of gas velocity on characteristic wave frequency, for various liquid velocities.

Wave celerities are obtained by calculating the cross-correlation function of two simultaneously recorded signals from locations at a distance Δx=9cm. As expected wave celerity increases markedly with the gas as well as with the liquid velocity. From *Figure 4* one can draw the conclusion that U_C data are fitted fairly well with the expression

$$U_C = 0.46+0.013(U_G)^2\sqrt{\frac{h}{D}}$$

where U_C, U_G, h and D denote wave celerity (m/s), superficial gas velocity (m/s), mean film thickness at the bottom of the pipe (m) and pipe diameter (m), respectively. Data by Fukano et al (1983) and Andritsos (1992) are also included in *Figure 4* and are in good agreement with the proposed expression.

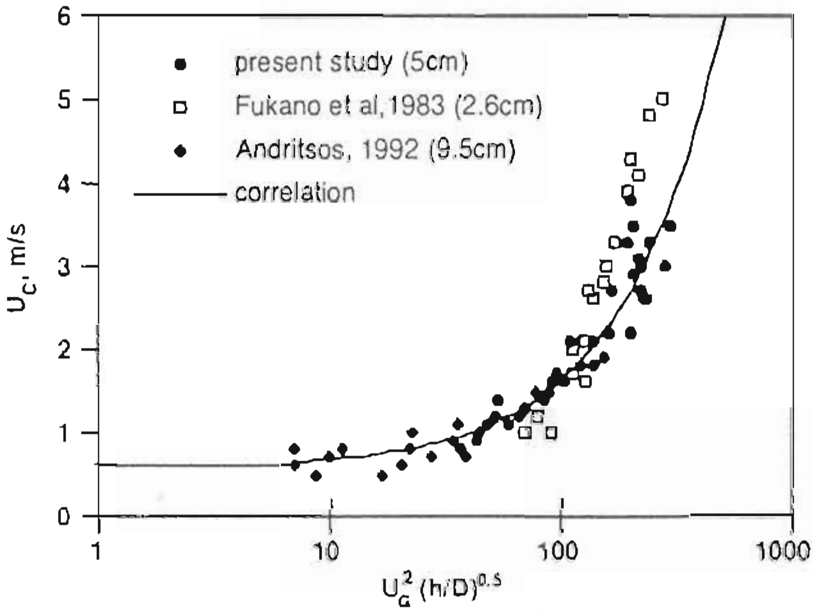

Figure 4. Wave celerity correlation; data from various studies.

Large wave intermittency, defined as the fraction of total sampling time corresponding to passage of large waves is useful in the description of processes occurring at the gas-liquid interface (Schadel, 1988). The approach followed for determination of the large wave intermittency as well as its amplitude and length is described in a paper by Paras & Karabelas (1991). For relatively low gas velocities; i.e., for U_G<30m/s large wave intermittency increases with gas velocity whereas it is almost independent at gas velocities above 30m/s, having a value between 0.3 and 0.4 . Intermittency is a weak function of liquid velocity.

As expected, there is a strong influence of gas flow rate on the large wave height. The influence of superficial liquid velocities on the large wave height is noticeable only at relatively low gas velocities; i.e., for U_G<40 m/s. At higher gas flow rates (annular flow), the mean large wave height at the pipe bottom ($\Theta=0^o$) is found to be a linear function of the RMS value of the film height:; i.e., $h_w=4\ h_{RMS}$.

MEASUREMENTS OF LOCAL VELOCITIES INSIDE THE LIQUID FILM

The axial velocity measurements reported here were obtained in the so-called *atomization* flow regime (*Figure 1*) and were part of an effort to gain information on the flow structure inside thin liquid layers in horizontal pipe flow. Velocity data were obtained for four different flow conditions (*Table 1*) corresponding to wavy stratified and atomization flow regimes.

Table 1. Experimental flow conditions

Run	A	B	C	D
U_L, cm/s	10.2	7.6	4.0	2.4
U_G, m/s	11.9	11.9	11.9	11.9

Figure 5 presents the axial velocity distributions for Run A and for three different circumferential positions, i.e. 0^o, 10^o and 20^o. An inflection point is observed at y=1.5 mm (y^+=60). Up to this distance from the pipe wall there is no appreciable difference between measurements at the three different angles, whereas for higher y the velocity decreases with an increase of the angle Θ.

Figure 6 presents the main results of the normalized mean velocities obtained at $\Theta=0^o$ and $\Theta=20^o$. The velocity data are normalized with respect to a friction velocity U^* calculated by the method proposed by

Andritsos & Hanratty (1987). The von Karman theoretical predictions for single phase flow are represented by the solid curve (Schlichting, 1960). Deviations from the model predictions are observed, which are larger for thinner layers (Runs C & D). Strumolo et al (1985) report similar results for velocity measurements inside falling films which are covered by waves. Cheung & Street (1988) by measuring the velocity field beneath an air-water interface with an LDA technique have concluded that where waves are dominant, the mean velocity profiles have slopes different than 2.5 in the logarithmic region.

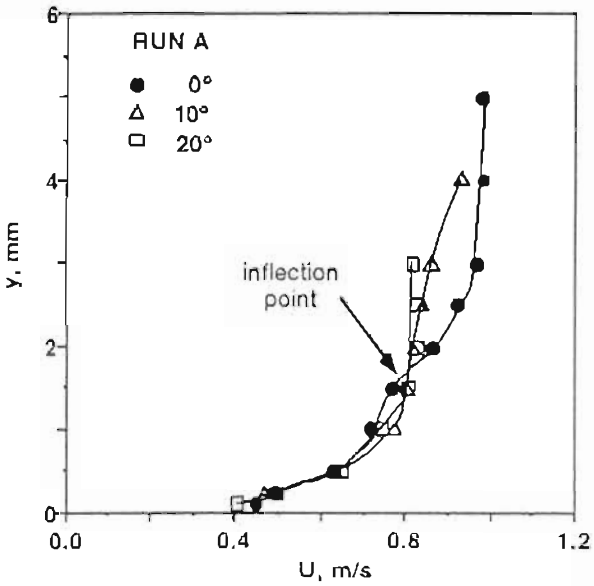

Figure 5. Axial velocity profiles at various angular positions ($\Theta=0^o, 10^o$ & 20^o)

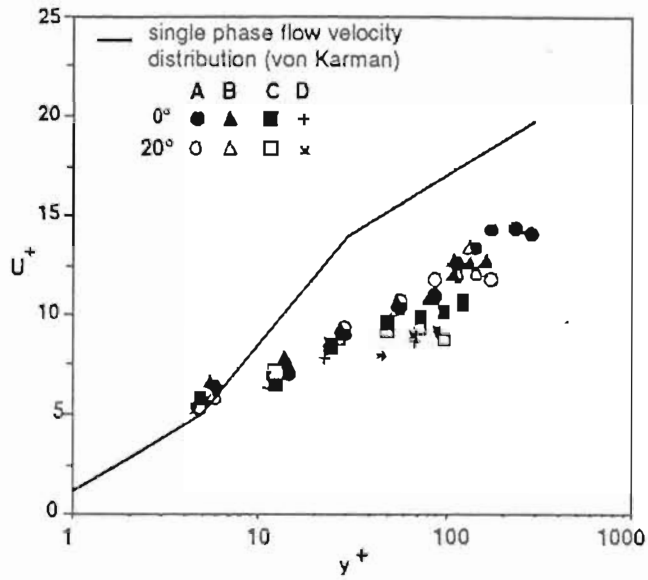

Figure 6. Distribution of the dimensionless axial velocity

The mean value of the axial velocity appears to be influenced by the presence of the large waves at the gas/liquid interface. Evidence in support of this argument is provided by the fact that the velocity measurements generally differ between positions equidistant from the wall but having different distances from the interface (*Figure 5*)

Ueda & Hinze (1975) and Kreplin & Eckelmann (1979) found that in fully developed turbulent flow the axial velocity fluctuations normalized with the friction velocity U^* exhibit a maximum value between 2.8 and 3 at approximately $y^+=13$ for various Re (5000-82000). *Figure 7a* shows that there is good agreement between the above result and the data of this work, near the wall region ($y^+<50$).

Measurements at $\Theta=20^o$ for the thin layers of Run C and D, show a maximum at the same y^+, but the ratio u'/U^* is almost double that corresponding to $\Theta=0^o$(*Figure 7b*). This behavior is attributed to the influence of the interfacial waves on the velocity fluctuations. This influence is evident even close to the pipe wall.

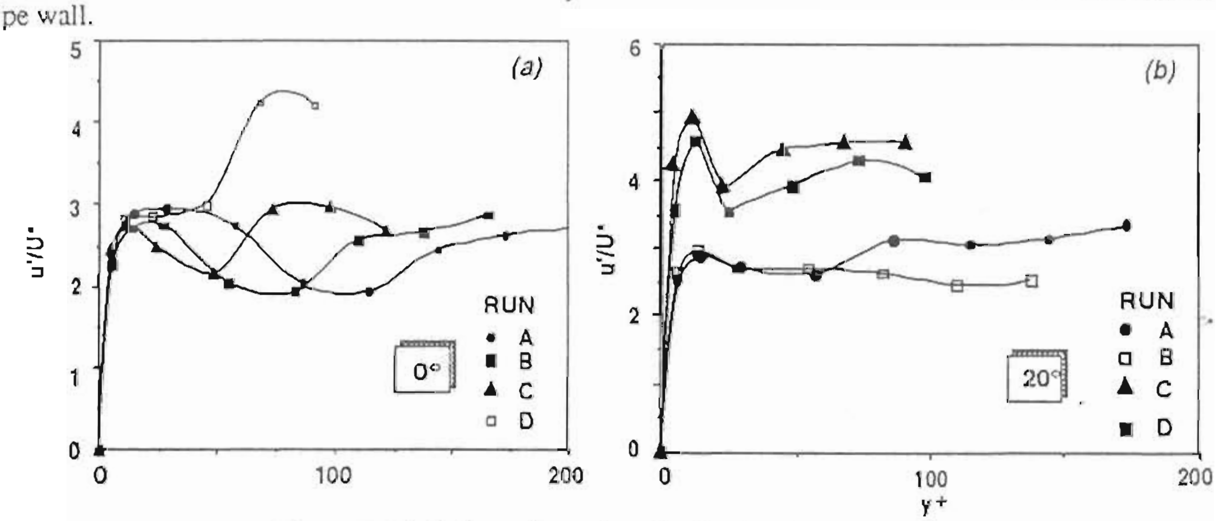

Figure 7. Turbulence intensity distribution ($\Theta=0^o$ and 20^o)

The calculated velocity spectra reinforce the argument of the significant influence of the large waves on the liquid film flow-field. ***Figure 8a*** shows the PSD (power spectral density) for two points (Run A), at y=5 mm (close to the interface) and y=0.1 mm (close to the pipe wall). ***Figure 8b*** shows the PSD for Run D for y=2 mm and y=0.1 mm. It is believed that the characteristic modal values of the spectra correspond to the frequencies of the large waves in stratified flow (1-10 Hz) (Andritsos, 1986).

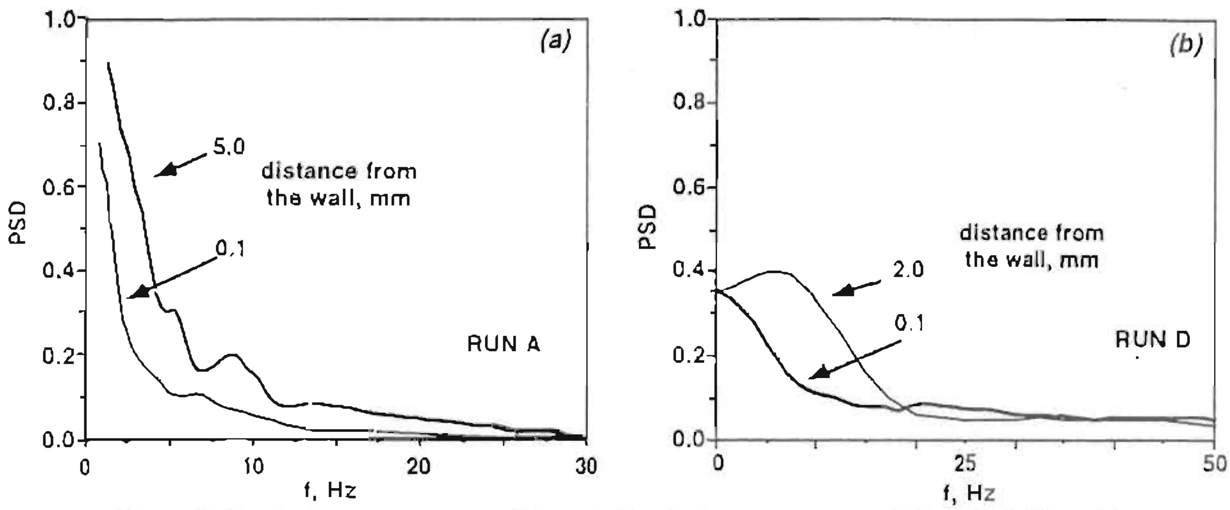

Figure 8. Typical power spectra of the axial velocity component: a) Run A, b) Run D

Figure 9 shows that in logarithmic coordinates the slope of the PSD curves in the high frequency range is roughly -5/3. This result is additional evidence that the flow within the thin liquid films is **turbulent**.

Kinetic energy transport through the air/liquid interface with turbulent coherent structures (i.e. vortices), and existence of strong normal velocity components could be an explanation for the low mean axial velocities. These structures are very likely accompanying the large disturbance waves and are created by the large change of the velocity gradient close to the interface.

There are no other measurements, with similar geometry and flow conditions, available for comparison. However, some trends in our data are in agreement with those obtained by Fabre et al (1983) and Cheung & Street (1988) for stratified air/water flow in a horizontal channel .

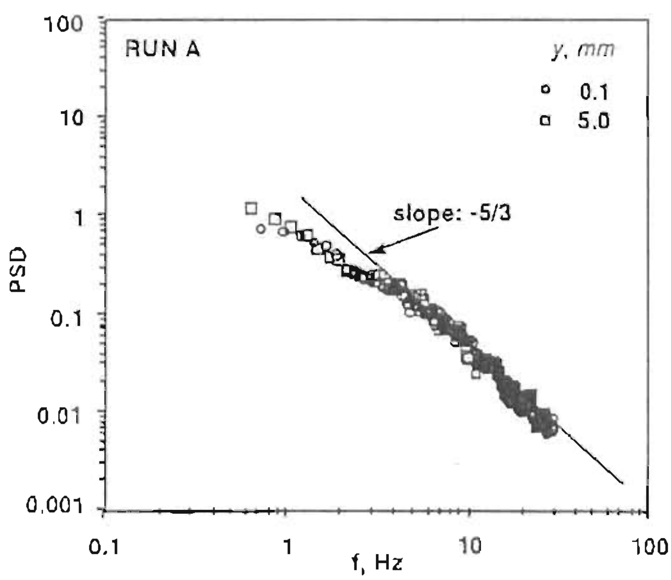

Figure 9. Power spectral density (PSD) of the axial velocity flactuations at various wall distances, $\Theta=0^o$

VISUAL OBSERVATIONS

Visual observations were made in the plexiglas test section of the flow loop, in order to obtain additional information on the wave structure. The waves could be "frozen" by using light pulses from a strobe. "Ring-shaped" wave structures were observed covering a large portion of the pipe circumference. For low gas flow rates (U_G<40 m/s) these waves covered the lower half of the pipe and moved, at an angle with respect to the pipe cross-section, with their front at the bottom. They appeared to cover a larger portion of the circumference with increasing gas velocity, while their characteristic angle was gradually diminished to zero. The deformation or decay of these waves is very rapid and it is possibly caused by viscous forces in the liquid film.

CONCLUDING REMARKS

With low viscosity fluids, by increasing the gas velocity above $U_G \approx 10$m/s the wavy stratified flow changes considerably, entering a transition regime i.e. stratified/atomization. Notable features of this regime include the appearance of disturbance waves, with a characteristic frequency (≥1Hz) strongly dependent essentially only on U_G, the drastic change of the average gas/liquid interface profile from flat to "concave", and of course the onset of atomization.

Interpretation of the film thickness data suggests that the dominant waves spread in the lateral direction and that their celerity is almost linearly increasing with U_G. Film thickness and local velocity spectra display similarities, clearly showing the influence of waves on flow conditions near the pipe wall. Furthermore, they indicate that a certain class of dominant interface waves may not make its influence felt close to the wall if the liquid layer in that location is thick enough, but it may have a significant effect at locations in the pipe circumference where the liquid film is thin. It is also very likely that the mechanism of liquid atomization will be closely related to these waves as already indicated elsewhere (Paras & Karabelas, 1991b).

The velocity measurements made using Laser Doppler Anemometry suggest that only very close to the solid surface (sublayer) may the liquid motion resemble the well-known behavior of single phase flow. The new result obtained here is that somewhat farther from the wall (y^+>10) the time-averaged axial velocity, U^+, is significantly smaller than that for single phase flow, whereas the intensity of velocity fluctuations, u'/U^*, is higher.

The type of experiments and the results presented here suggest that additional work on this flow regime may be quite rewarding in clarifying some key issues of separated two phase flow, such as the spreading of liquid film on the wall in horizontal pipes and droplet atomization. Understanding the relative influence of these two mechanisms in promoting annular flow is certainly a topic of high priority.

From the viewpoint of modelling scaling in stratified flow, the new results suggest that presently available methods (e.g. Andritsos & Hanratty, 1987) provide only a first estimate of the required wall shear stress, U^*. However, recently made direct measurements of wall shear stress show that such methods must be modified to take into account the influence of waves on the wall conditions.

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