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PROGRAMME

LDA MEASUREMENTS OF LOCAL VELOCITIES INSIDE THE GAS PHASE IN HORIZONTAL STRATIFIED/ATOMIZATION TWO-PHASE FLOW

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Abstract: New experiments, using Laser Doppler Anemometry (LDA), have been carried out to measure local axial velocities inside the gas phase, in horizontal stratified/atomization air-water pipe flow. Mean local velocities, RMS values and other statistical information have been obtained by analyzing the instantaneous velocity records. From the velocity profiles a secondary flow pattern is inferred with an upward motion at the pipe wall and a downward motion at the vertical pipe centerline. The new measurements are assessed in connection with already reported data of liquid layer characteristics and wall shear stress, obtained under the same flow conditions. The calculated velocity spectra clearly exhibit the influence of the large waves on the gas phase, near the interface.

Key words: air-water flow, stratified/atomization flow, velocity profiles, LDA, secondary flow.

INTRODUCTION

An adequate description of the stratified/atomization flow regime is considered very useful in understanding atomization processes as well as in modeling the neighbouring (and more complicated) annular flow regime. Even though several studies have appeared in the literature in recent years, stratified pipe flow has not been adequately researched. Andritsos & Hanratty (1987) reviewing available models point out their main drawbacks. Two of them are the neglect of possible lateral variation of local shear stress close to the pipe wall, and the assumption of a velocity profile applicable to full pipes. Indeed, Paras & Karabelas (1992) report that only in the immediate vicinity of the solid surface does the liquid motion resemble the well-known behavior of single phase flow, but beyond that the flow field (inside thin liquid films) is strongly influenced by the wavy gas/liquid interface. Measurements of instantaneous local axial velocities are presented here in order to gain essential information on the flow structure inside the gas phase and to improve modeling of this complicated flow field.

Velocity measurements of some relevance to this study have been reported by Hanratty & Engen (1957), Cohen & Hanratty (1968), Gayral et al (1979), Fabre et al (1983), Hagiwara et al (1987) and Lee (1992). Their data have been obtained in channels of rectangular cross-section (except those of Hagiwara et al who conducted their experiments in a 49.4 mm i.d. horizontal tube) using techniques such as impact tubes, hot wire and hot film anemometry. These techniques present serious difficulties due to the unavoidable probe interference with the flow and the problems arising from the presence of droplets inside the gas phase. Thus, the non-intrusive LDA technique is employed in this work.

Of particular relevance to this work are a few recent studies. The variation of the streamwise gas velocity was measured with an impact tube, in a horizontal (9.53 cm i.d. pipe) air-water flow, by Dykhno et al (1994). They suggested that, for experiments with little or no entrainment, there exist two or more secondary flow cells with an upward motion at the pipe wall and a downward motion at the center of the pipe. However, in experiments with a relatively large amount of liquid droplets entrained in the gas space a different secondary pattern, with downward motion at the pipe wall and upward motion at the pipe center, was reported to exist and was attributed to the pressure gradients associated with droplet stratification in the gas space. Jayanti et al (1990) studied numerically the secondary flow mechanism, in the gas phase, in a pipe with circumferentially varying wall roughness. They showed that the generated secondary current was too weak to significantly contribute to the film thickness circumferential distribution in horizontal annular flow. Direct measurements of secondary flow in the annular flow regime were made by Flores et al (1995), using a twin axial vorticity meter. The two rotors of the meter remained stationary when only air was passing through the test rig. However, introduction of water into the line caused rotor counter-rotation clearly indicating an upward motion at the pipe wall and a downward one at the pipe center.

In this paper the experimental technique is outlined and the main results drawn from the local axial velocity measurements are presented and discussed.

EXPERIMENTAL TECHNIQUE

The velocity measurements were carried out in a horizontal flow loop, where air-water two-phase flow was established in a 50.8 mm i.d. pipe with a 16 m long straight section. The test section was made of a high precision glass, positioned about 300 diameters downstream of the mixing section of the two phases, where the flow is considered to be fully developed. An LDA set-up was successfully used in order to make measurements of local axial velocities within the gas phase. The experimental loop together with the general arrangement of the LDA system, which operates in the fringe mode, were described in more detail elsewhere (Paras & Karabelas 1992). The intersecting beams form an ellipsoidal measuring volume (comprised of fringes) with major and minor axes (in air) 91 and 23 μm, respectively.

In general, experiments conducted with LDA, especially for the study of gaseous flow, rely on tiny particles (suspended in the continuous medium) which cross the measuring volume to provide velocity information. Thus, some seeding is always required and it is of critical importance for the good quality of measurements. The requirement for good Doppler signals and the dynamics of the flow suggest a particle diameter in the order of the LDA fringe spacing (Drain 1980). Since for this experimental set-up the fringe spacing is 1.06 μm, suitable particles must have a diameter of 0.5 to 1 μm.

An air jet atomizer (designed and constructed in this laboratory) is used to produce liquid particles of the desired diameter. Small droplets are generated inside a Plexiglas box by passing air through a nozzle, which draws liquid from the reservoir by the venturi effect and breaks it up into a fine spray. In an effort to produce particles suited for such measurements, a special fluid developed by Domnick & Martinuzzi (1994) for seeding purposes is employed. This liquid is a mixture of water and a commercially available fog-fluid of unknown exact composition. The main chemical constituent of the fluid is diethylene-glycol and the aerosols thus generated are according to these authors non-toxic, non-corrosive, non-abrasive and with very suitable light-scattering properties.

DESCRIPTION OF THE EXPERIMENTS

The axial velocity measurements reported here were obtained in the wavy stratified flow, in the so-called atomization flow regime. The selected range of superficial liquid velocities was 2-10 cm/s whereas for the superficial gas velocity three different flow conditions were tested; i.e. 6, 12 and 16.5 m/s. The flow conditions for the various experiments are summarized in **table 1.** The average film thickness h_o values were taken from a paper by Paras et al (1994), for the same runs made here.

Table 1. Main parameters and experimental conditions

Run	U_G (m/s)	U_L (cm/s)	h_o (mm)	Flow regime
KO	6.0	6.0	12.8	wavy stratified
A	11.9	1.9	3.69	wavy stratified
C1	11.9	4.0	4.40	atomization
I	11.9	5.9	6.70	atomization
B1	11.9	8.0	6.50	atomization
A1	11.9	10.0	7.60	atomization
B	16.5	1.9	2.34	atomization
J	16.5	5.9	4.81	atomization

In each run, measurements of local instantaneous axial velocity were made along the vertical pipe diameter, starting at a distance as close as 1mm from the pipe top and ending 1-2 mm far from the air/water interface to avoid light reflections which might result in erroneous data. Measurements along the horizontal pipe diameter (90° to the vertical) were also obtained. Before the main experiments, the velocity profile in single phase air flow was measured to assess the overall accuracy of the non-intrusive optical technique.

For the LDA technique, the mean data rate varied from 100 up to 800 Hz, depending on the local mean velocity and the distance from the pipe wall. This sampling frequency was sufficient to allow frequency detection up to 50-400 Hz. The sample size for each run was 5000 points. Data acquisition and statistical analysis together with a signal reconstruction method were employed, by using an appropriate software package presented elsewhere (Paras & Karabelas 1992).

RESULTS

Figure 1 shows typical axial velocity profiles, on the vertical symmetry plane, where one can observe that the maxima of the velocity profiles are displaced slightly **downward** from the center of the gas space. In this figure the vertical coordinate is normalized with the distance ($D-h_w$) in the gas space between the top of the waves, h_w, and the pipe top, whereas the velocity is made dimensionless with its maximum value. One typical axial velocity profile, at 90° to the vertical, shown in **figure 2**, clearly exhibits a "moustache" shape, with a local minimum at the pipe center and two (symmetrically spaced) maxima. A similar "moustache" shape was obtained by Dykhno et al (1994) for velocity measurements at 90° to the vertical. This behavior could be attributed to secondary flow, with downward motion at the vertical symmetry plane and an upward flow at the pipe wall. Such a secondary current was probably generated by the non-uniform liquid film roughness, i.e. the observed decrease in liquid-film wave roughness from the bottom to the top of the pipe (e.g. Jayanti et al 1990; Flores at al 1995).

For the experiments described in this work the gas phase is considered to flow through a pipe with an upper surface hydraulically smooth and a lower surface covered by a water film moving slowly relative to the gas phase. Thus the air-water interface with respect to gas flow, is considered to be completely rough. Furthermore, except for the immediate vicinity of the top pipe wall and very near the gas/liquid interface, the axial velocity distribution may be represented by the following dimensionless formulae proposed for single phase flow (Schlichting 1960):

$u^+=5.5+5.75\log(y^+)$ (smooth wall) [1]

$u^+=B+5.75\log(y/k_s)$ (rough interface) [2]

where $u^+=u/u^*$, $y^+=yu^*/v$, u: the local mean axial velocity y: the corresponding distance from the pipe wall, k_s: the apparent interface roughness, v: air kinematic viscosity and u^*: friction velocity (different for each expression). The constant B is generally a function of the surface roughness and for our experimental data, in the range of the completely rough regime, it appears to have the value of 6.3, as shown below.

In **figures 3a** and **3b** the data points of all runs are presented and correlated quite well (max. error 10%) with expressions of the form [1] & [2], for the smooth upper pipe wall and the rough air-water interface, respectively. The values for the apparent interface roughness (k_s) were related to wave characteristics (roll wave height, intermittency), whereas the friction velocity (u^*) was obtained from the interfacial friction factor (f_i) proposed by Paras et al (1994), for the same runs reported here. Measurements of liquid film thickness, wall shear stress and pressure drop were used for determining f_i. The same well-known logarithmic relations were employed by many other investigators (e.g. Hanratty & Engen 1957 ; Ellis & Gay 1959; Gayral et al 1975; Jayanti et al 1990 etc.) in order to describe the flow field in the gas phase. Hansen & Vested (1991) assumed that the velocity profile in both the gas and the liquid phase could be described by the sum of two logarithmic profiles with the interface treated as a moving wall. This approach provided very good results for smooth stratified flow, whereas for wavy conditions it failed in comparison to the measured values especially near the interface.

From the calculated velocity spectra (**figure 4a**) it is clear that there is a significant influence of the large waves on the gas flow, near the interface. Most probably the characteristic (modal) values of the spectra near the air/water interface correspond to the frequencies of the large waves in the stratified/atomization flow regime (1-10 Hz) (**figure 4b**) obtained earlier (Paras et al 1994).

The secondary flow is expected to fluctuate apparently due to the variable interfacial roughness (Flores et al 1995). Since this roughness varies with a frequency corresponding to that of the large waves (Paras et al 1994), the secondary flow may be related to that frequency. The form (shape) of the spectra of the axial velocity close to the top pipe wall (y=1mm) seems to support this suggestion. However, this influence of the waves was not observed in the corresponding spectra near the wall for axial velocity measurements inside the liquid layer (Paras & Karabelas 1992). In logarithmic coordinates, the slope of the PSD curves in the high frequency range is roughly -5/3 close to the pipe top wall and near the interface, as in the case of turbulent single phase flow (**figure 4c**). This result suggests that the main (axial) flow retains the basic features of turbulent flow near the top pipe wall as well as close to the air/water interface.

In **figure 5** the fluctuating local velocities, made dimensionless with the friction velocity u^*, are plotted against the dimensionless distance y^+, from the pipe top. The streamwise fluctuation shows a maximum value of about 2.7 for y^+ in the range of 10-20. The same conclusion was drawn from velocity measurements made by Kreplin & Eckelmann (1979), in a fully developed single phase turbulent channel flow. **Figure 6** presents the RMS values of the axial velocity with respect to the distance y from the top pipe wall, on the vertical symmetry plane. It is clear that the intensity is high both near the top pipe wall and in the space above the gas-liquid interface, as one might have expected.

CONCLUDING REMARKS

The new LDA data in the gas phase of stratified/atomization flow are assessed in connection with already reported data of wavy liquid layer characteristics obtained in the same experimental set-up, under the same conditions, and found to be consistent. The time average velocity profiles on the vertical symmetry plane display a maximum generally below the middle (or center) of the gas space coordinate $y/(D-h_w)$. On the contrary, the axial velocity profiles on the horizontal symmetry plane (i.e. 90° to the vertical) clearly exhibit a "moustache" shape, with a local minimum at the pipe center, and **two** (symmetrically spaced) maxima. These trends are in general agreement with those observed in the data by Dykhno et al (1994), strongly suggesting the presence of secondary flow currents. Regarding the structure of such secondary currents, the new data seem to be in agreement with the observations made by Flores et al (1995), i.e. of two large counter-rotating vortices with respect to the vertical symmetry plane.

Well-known forms of the turbulent velocity profile seem to be quite satisfactory for correlating the data, not only at the pipe top but also in the lower strata of gas phase if the equivalent roughness of the wavy interface is properly taken into account.

The influence of large waves is quite significant near the interface, as expected. An interesting finding of this study (obtained from the velocity spectra) is that the influence of large waves may extend up to the pipe top (even at y≈1mm), probably through the secondary motion in the gas core.

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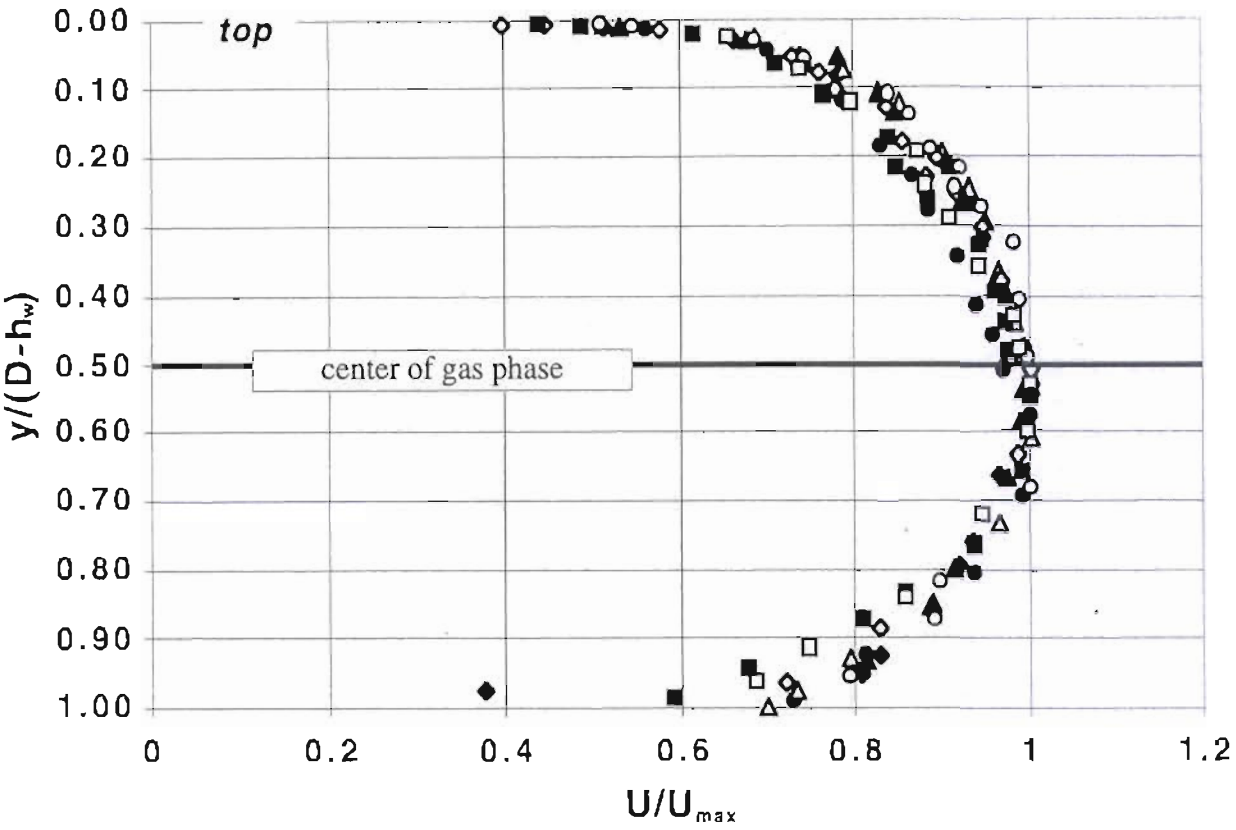


Figure 1. Typical axial velocity profiles along the vertical.

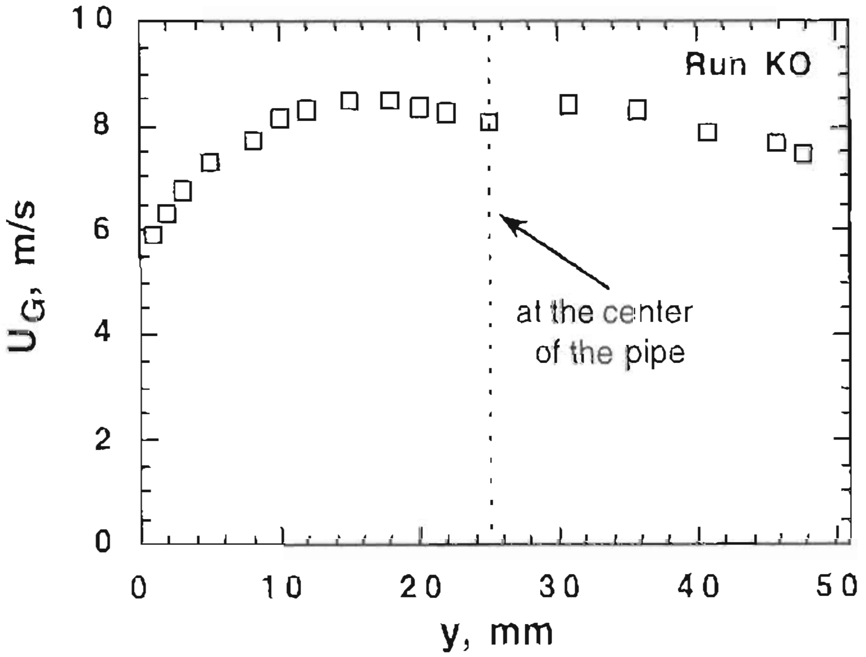
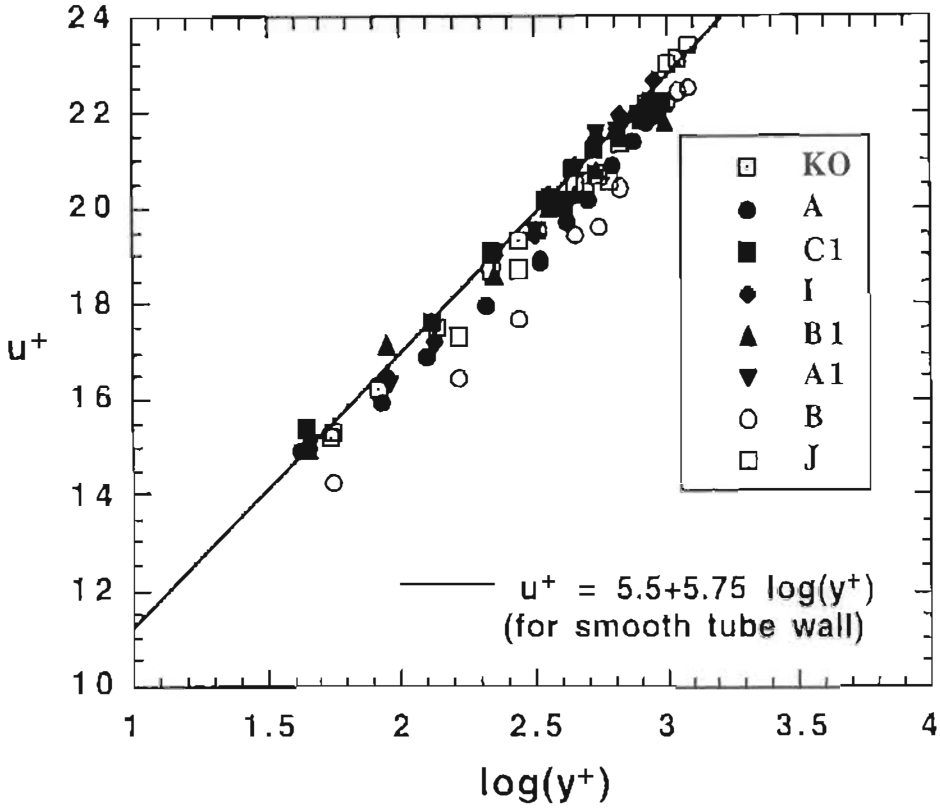
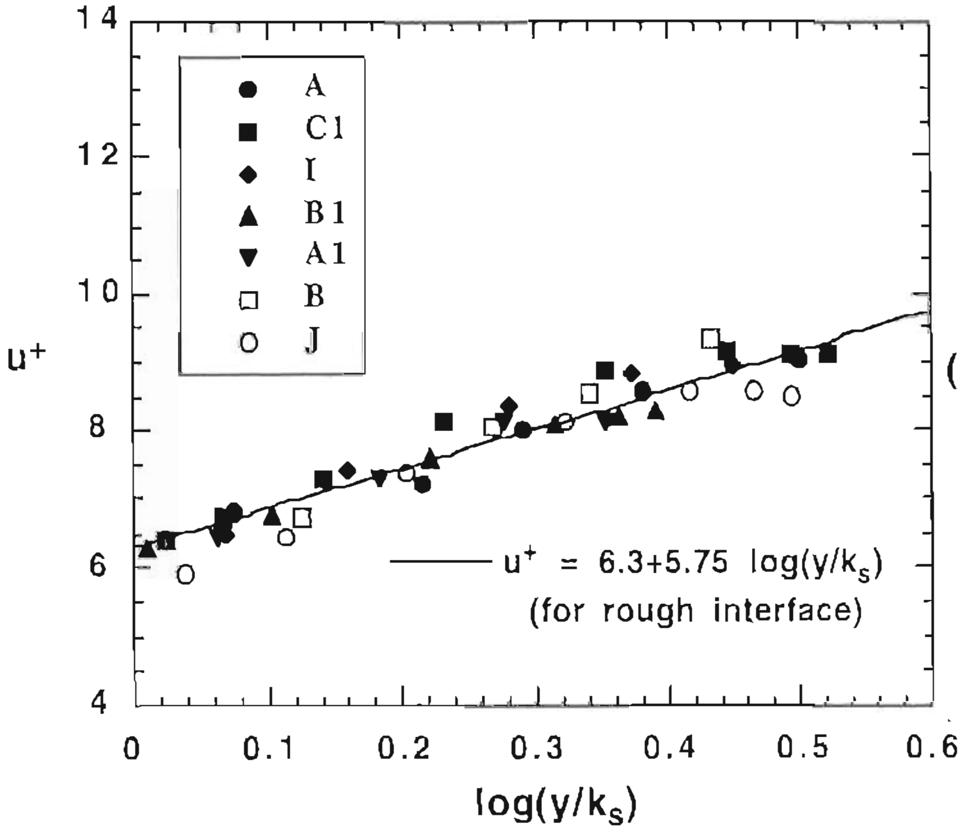


Figure 2. Typical axial velocity profile, at 90° to the vertical.


24
22
20
18
16
14
12
10
u+
1
1.5
2
2.5
3
3.5
4
log(y+)
KO
A
C1
I
B1
A1
B
J
u+ = 5.5+5.75 log(y+)
(for smooth tube wall)

(a)


14
12
10
8
6
4
u+
0
0.1
0.2
0.3
0.4
0.5
0.6
log(y/ks)
A
C1
I
B1
A1
B
J
u+ = 6.3+5.75 log(y/ks)
(for rough interface)

(b)

Figure 3. Velocity distribution for : a) smooth top pipe wall and b) air-water interface (all Runs)

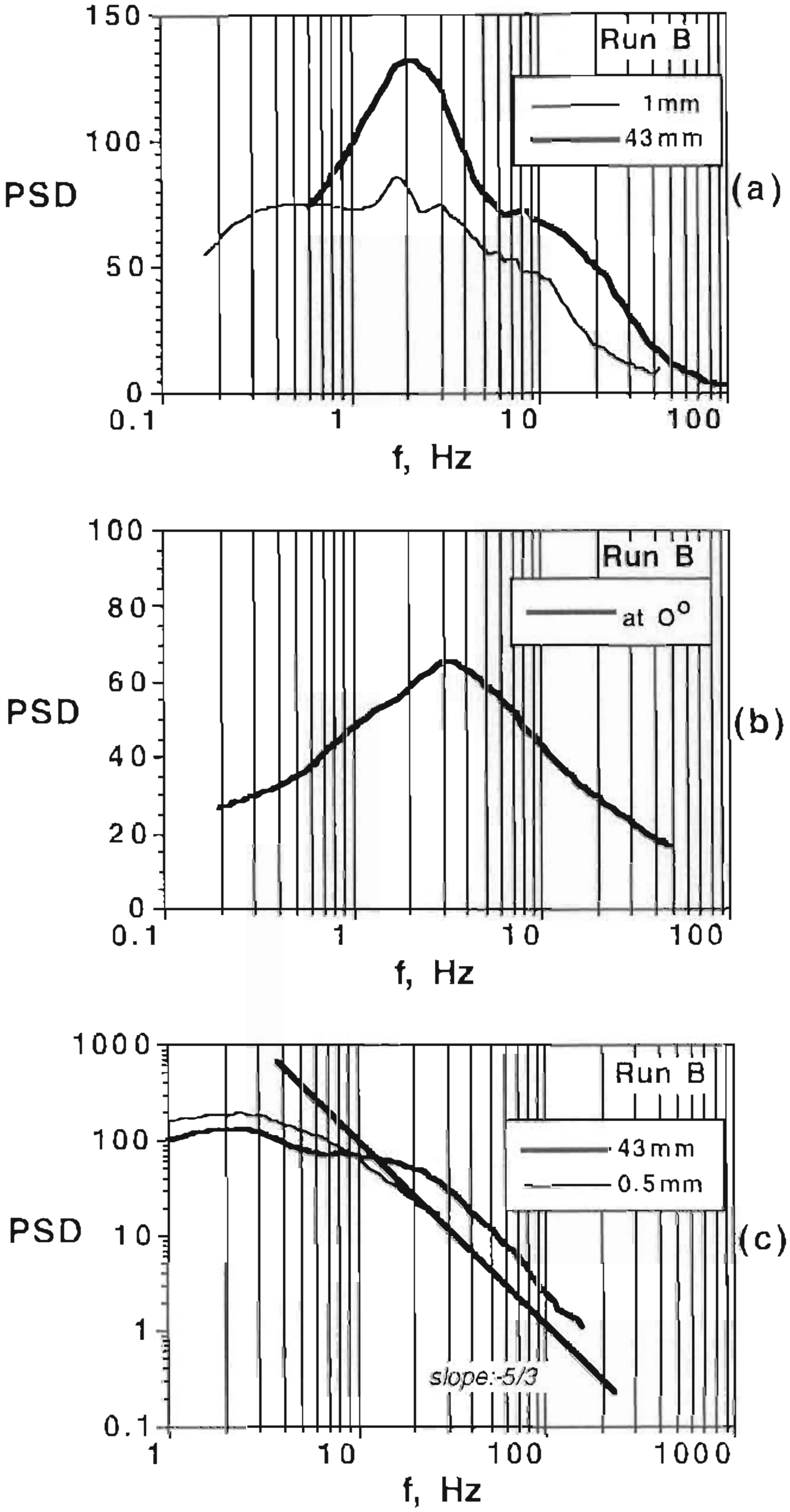


Figure 4. Typical spectra of: a) axial velocity close to the interface (43mm) and close to the top pipe wall (1mm), b) film thickness at the pipe bottom ($\Theta=0°$) and c) axial

velocity close to the interface (43mm) and close to the top pipe wall (0.5mm) in log-log coordinates (Run B).

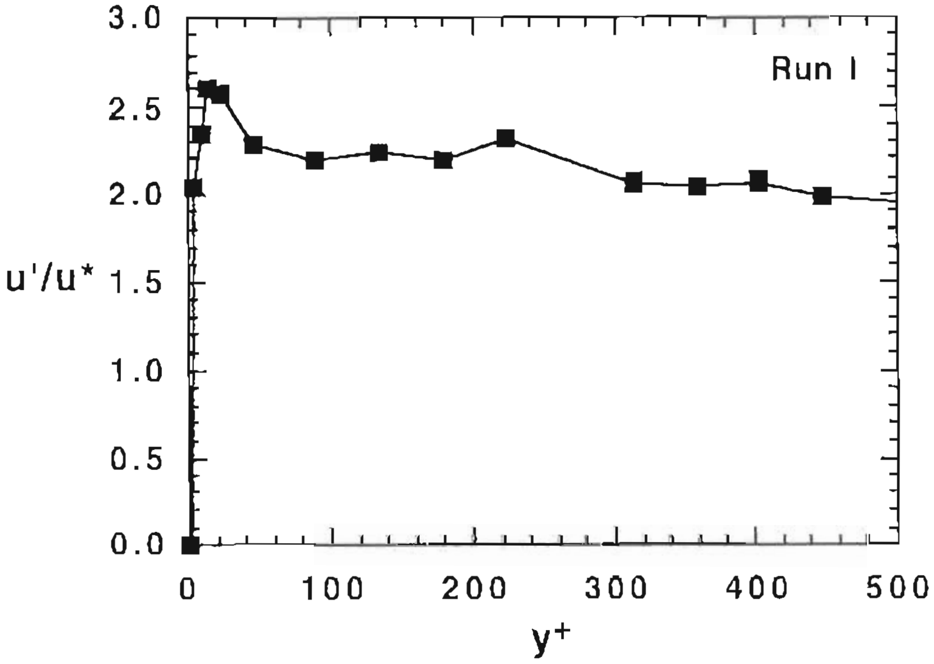


Figure 5. Distribution of turbulence intensity, for Run I.

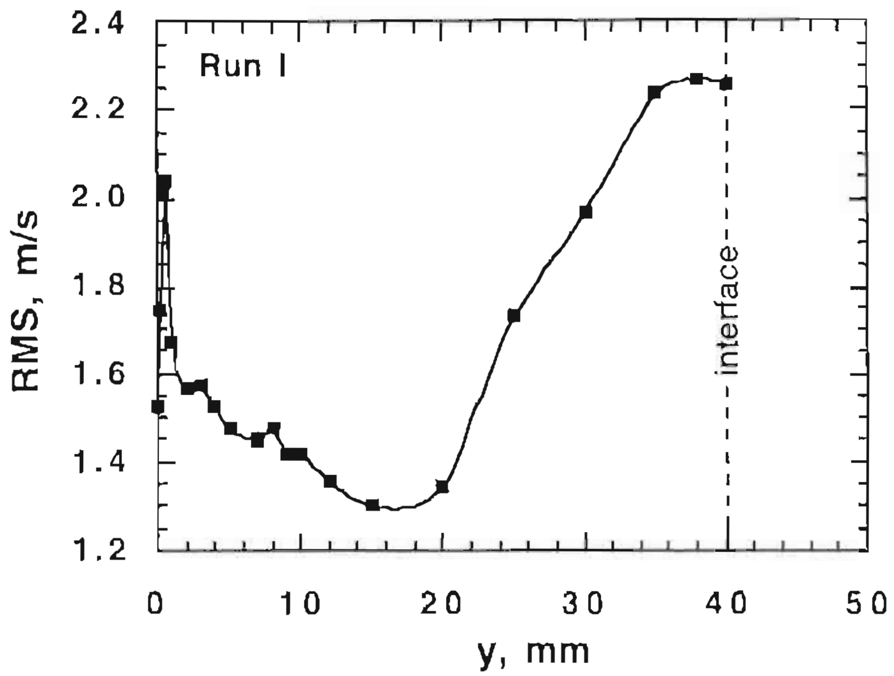


Figure 6. RMS values of the axial velocity on the vertical plane with respect to the distance from the top pipe wall.