Measurement of Turbulent Fluctuations in Pipe Flow by Ultrasonic Doppler Velocimeter

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The performance of Ultrasonic Doppler Velocimeter (UDV) for the measurement of turbulence fluctuations in pipe flow was investigated. For this purpose a circulatory water flow system was built and used. Change of amplitude of turbulent fluctuations with Reynolds number and radial position were obtained from direct velocity measurements by UDV. Root mean square (r.m.s.) values of velocity fluctuations in the probe direction that had been obtained from UDV measurements were compared with a past study in the literature. Measurement results revealed the over estimation of velocity fluctuations by UDV and artefacts on the velocity measurements of near wall region because of strong ultrasound-pipe wall interactions. Nevertheless, valuable and satisfactory measurements of turbulent fluctuations from the far half region of pipe were obtained by means of UDV.

Keywords: Ultrasonic Doppler velocimetry, Pipe flow, Measurement of turbulent fluctuations

1 INTRODUCTION

Accurately measurement of pipe turbulence is an important issue in several kinds of physical, chemical, and biomedical processes [1-2]. Despite of some well established flow measurement techniques, lately UDV has emerged as an important one with some advantages over the others like noninvasive measurement of opaque fluids and multidimensional flow mapping [3]. It is a valuable and successful tool for the measurement of steady flows like in laminar regime [4]. On the other hand measurement performance of ultrasonic Doppler methods should be investigated for fast transient flows like turbulent fluctuations [5]. Cloutier et al [6] had stated that further validation of Doppler ultrasound technique with laser Doppler anemometry or hot-film is necessary to be able to use in turbulent flow measurements.

The aim of this study is to assess the performance of UDV for the measurement of turbulent fluctuations in pipe flow. In the following sections a description of the experimental setup and UDV measurement parameters are given followed by the r.m.s. distribution of velocity fluctuations with radial distance and flow rate.

2 EXPERIMENTAL

2.1 Setup

The flow system shown in Fig. 1 consists of plastic tubing with 4.6×10^{-2} m inner diameter, a rotameter, a gate valve, a differential pressure transducer, two plastic tanks of 0.1 m^3 each, and a centrifugal pump. The straight tubing upstream of the measurement point is 4.5 m in length, which is sufficient to ensure fully developed flow (L/D ≈ 100) within the studied range of Reynolds number, N_{Re}. The distance between the measurement point and the end of the straight tubing is 1.5 m so that end effects are avoided in the measurements. A constant water head is maintained by pumping tap water from the lower tank to the upper one. Both the overflow from the upper tank and the return flow from the measurement are received in the lower tank. The constant head allowed operation at a steady average flow rate. Velocity measurements were conducted by DOP 2125 UDV (Signal Processing, Switzerland). A 4 MHz ultrasound (US) probe of 5×10^{-3} m diameter was installed on the pipe with an inclination angle of 70^o. The ultrasonic coupling between the pipe surface and the probe was provided by a water filled condom. In order to increase the US signal intensity, co-polyamide particles (60% 50μm – 40% 80μm, Signal Processing, Switzerland) were added to water at a concentration of 70×10^{-3} kg/m^3.

2.2 UDV measurement parameters

By means of UDV velocity measurements, change of turbulence intensity was estimated both with respect to N_{Re} at the pipe center and to radial position at N_{Re}=16730. 4096 velocity values for each measurement point were obtained by using the following UDV parameters: pulse repetition number=128 pulses/velocity value, sound speed in water (c) =1480 m/s, ultrasound emitting frequency (f_o) =4 MHz, pulse repetition frequency (f_{prf}) =7246 Hz, number of cycles in a pulse (N_c) =4, angle between probe and pipe (θ) =70^0.

3 RESULTS AND DISCUSSION

Measured velocity values by UDV were used for the evaluation of turbulence intensities. Change of axial mean velocity and corresponding fluctuation amplitudes in probe direction are shown in Fig. 2 as a function of N_{Re} at the pipe center and as a function of radial position at N_{Re}=16730. Amplitudes of turbulent fluctuations are obtained by taking the ratio of r.m.s. value of fluctuating velocity part in probe direction to the mean velocity in axial pipe direction at the measurement point. This amplitude is decreasing with increasing N_{Re} as compatible with the study of Gad el Hak [7]. Increasing amplitudes of turbulent fluctuations towards the pipe wall indicates the increasing turbulence intensity in this direction.

Normalized r.m.s. values of fluctuating velocity part were calculated and compared with the results reported by Laufer [8]. In his detailed characterization of turbulent flow through a pipe, Laufer employed a well established but invasive technique, hot-wire anemometry. In order to determine r.m.s. values, first longitudinal velocity distribution with respect to radial position in the pipe is constructed as shown in Fig. 3. Here each velocity point represents average of 4096 instantaneous velocity. As the averaging period covers 87.2 seconds that is well beyond the typical fluctuation period, those points can be considered as the time averaged point-wise velocities. In the r.m.s. calculations wall shear stress and friction velocity values are required. They were obtained by first smoothing the further half of velocity profile using an eighth degree even polynomial and then by evaluating wall shear rate [9]. The fitted polynomial is $V = -2.163\times10^{-8}\ r^8 + 1.569\times10^{-5}\ r^6 - 0.003648\ r^4 - 0.03106\ r^2 + 421.7$. Here V is velocity in mm/s and r is radial distance from the pipe center as mm. The reason of choosing the further half of velocity profile is because of dominant artifacts on the velocities of near probe half. These effects were investigated below. Shear rate at the far wall to the US probe (upper part of Fig. 3) from fitted function is -162.36 s^{-1} and corresponding shear stress for the water will be 0.1624 Pa. Hence friction velocity of $U_\tau = \sqrt{\tau_w / \rho}$ is 0.01274 m/s. Blasius empirical relation of wall shear stress for turbulent pipe flow [10] is,

$$\tau_w = \frac{1}{8}\lambda \rho v_{av}^2 \tag{1}$$

where $\lambda = 0.316 / N_{\mathrm{Re}}^{0.25}$ and v_{av} is average velocity in the pipe. τ_w from Eq. (1) is 0.4596 Pa and theoretical U_τ is 0.02144 m/s.

Small bias of velocity profile near the pipe center and probe side in Fig. 3 is because of wall reflections of US pulses. The position of measurement volumes that velocity bias is observed can be obtained from the following relation [11].

$$x_i = \frac{2D'}{\sin\theta} - \frac{c}{2f_{prf}} \tag{2}$$

Here x_i is the position of the wall echo in the measurement line, D' is the distance between US probe and faraway pipe wall in the radial direction, θ is Doppler angle, and f_{prf} is pulse repetition frequency (i.e. $1/T_{prf}$). Since probe was in a water filled condom and 20 mm above the pipe wall, D' is 66 mm for our 46 mm ID pipe. If the aforementioned measurement parameters are put in Eq. (2), x_i is going to be obtained as 38.3 mm. Therefore radial distance between near pipe wall and artifact observed measurement volume will be nearly 16 mm which matches well with the seen in Fig. 3.

Radial and axial r.m.s. measurements and their correlation had gotten from the study of Laufer [8] and used to obtain r.m.s. values in the probe direction (for θ=70° inclination from the axis of pipe) through the relation of,

$$\frac{\tilde{u}}{U_\tau} = \sqrt{\cos^2\theta \frac{\overline{v'^2}}{U_\tau^2} + \sin^2\theta \frac{\overline{\vartheta'^2}}{U_\tau^2} + 2\cos\theta \sin\theta \frac{\overline{v'\vartheta'}}{U_\tau^2}} \tag{3}$$

where v' is axial and ϑ' is radial velocity fluctuations. As it is seen from Fig. 4 measured r.m.s. distribution in the probe direction has close but higher values compared to the measurements from Laufer's study. Here it should be noted that Reynolds number for the study of Laufer is much higher than that of the current study. Hence r.m.s. of velocity fluctuations measured by UDV should be expected as lower than the data from Laufer's study. This over estimation of Reynolds stresses by UDV is also reported by Voulgaris et al. [12] compared to the laser Doppler velocimeter measurements. Far half measurements of pipe flow are giving better results in terms of velocity fluctuations as expected. This is mainly because of near wall effects on UDV signals and non-accurate near wall measurements of UDV for the used sizes of pipe and probe [13].

4 CONCLUSIONS

The main conclusions that can be drawn from the results of this study are,

- Near wall reflections and interactions of US signals deteriorate the quality of average velocity profile at close regions to the probe.

Moreover this deterioration is more prominent for the root mean squared velocity fluctuations. Hence far half measurements for a pipe flow should be used for turbulence investigations.

- Root mean squared velocity fluctuations that were obtained from measured velocity values by UDV are a bit higher compared to the ones obtained by hot-wire anemometry in a reference study. This over estimation of turbulent fluctuations by UDV can be attributed to the relatively poor temporal and spatial resolution of the technique.
- Nevertheless, for moderate flow rates UDV is giving valuable and useful data in terms of statistics of turbulent velocities.

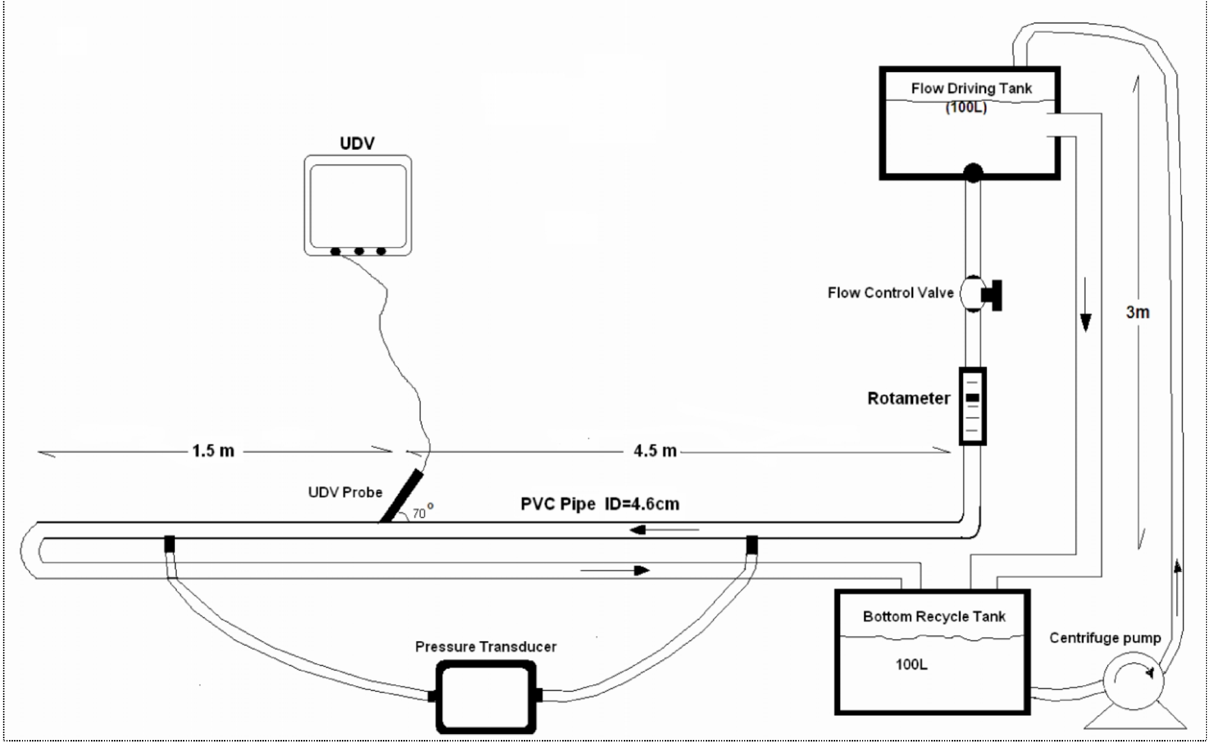

Figure 1: Experimental flow system

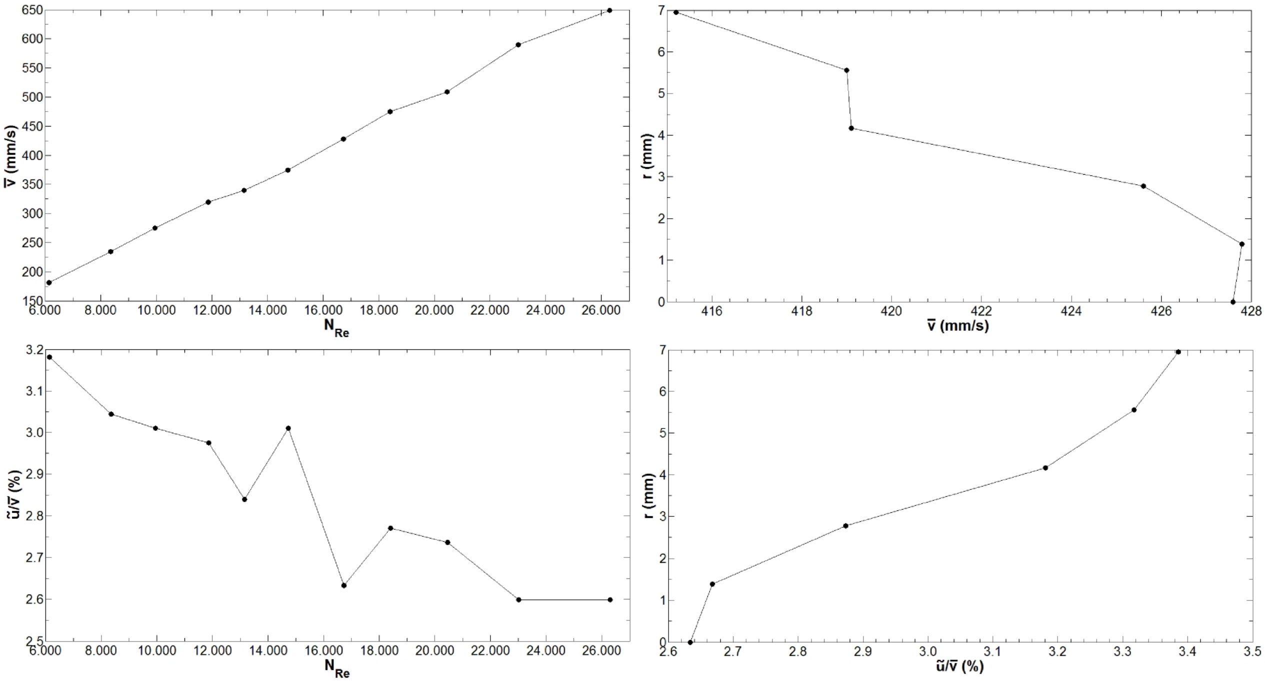

Figure 2: Mean velocity in axial pipe direction at the pipe center (upper-left) and at some radial positions for N_{Re}=16730 (upper-right). Amplitude of turbulent velocity fluctuations in probe direction at the pipe center (lower-left) and at some radial positions for N_{Re}=16730 (lower-right)

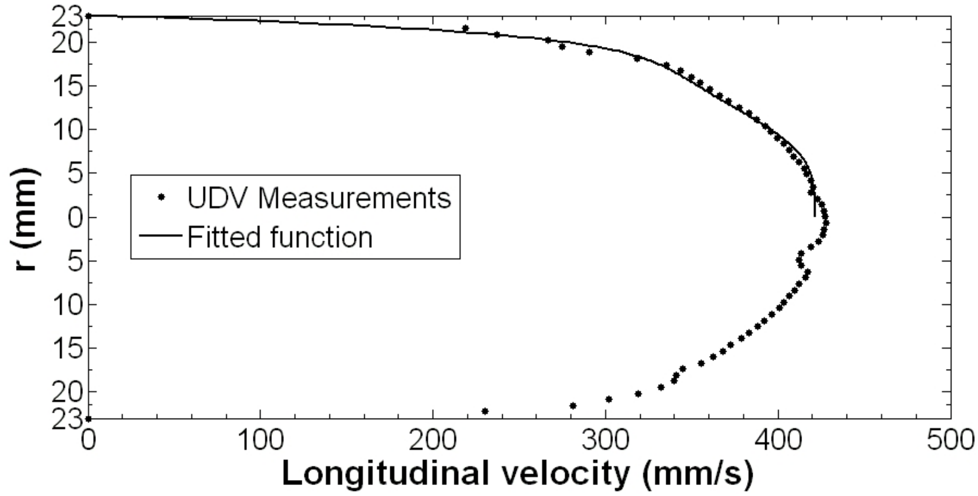

Figure 3: Longitudinal average velocity in the pipe measured by UDV for N_{Re}=16730 and fitted polynomial function.

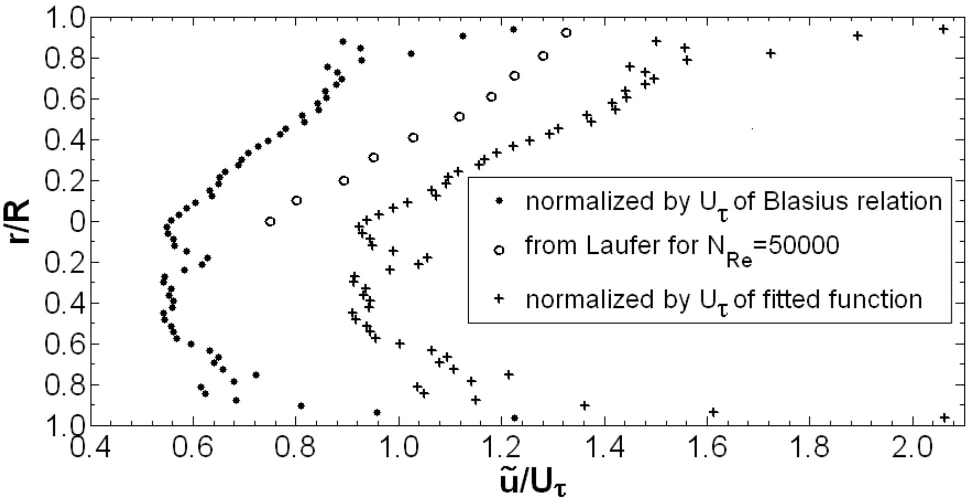

Figure 4: Normalized distribution of r.m.s. of fluctuating part of velocity in the probe direction along pipe diameter for N_{Re}=16730.

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