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Influence of Seeding Particles on Particle Image Velocimetry Measurements in Single-Phase Turbulent Pipe Flow

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ABSTRACT

Particle Image Velocimetry (PIV) is a widely used technique for flow measurement in fluids. It is an optical method for flow visualization, which is non-invasive and, to a large degree, non-intrusive. In order to enhance the signal from reflected laser light, seeding particles are added to the fluid, which have similar density as the working fluid and are of similar or smaller sizes as the smallest eddies in the flow. Ideally, such seeding particles follow the flow motion at all scales, however, in realistic flow they might affect the velocity measurement, in particular the flow statistics of higher orders.

In the present study, PIV measurements are performed in turbulent pipe flow using two types of seeding particles made of different materials, sizes and concentrations. Seeding particles made of borosilicate glass in the form of hollow spheres have diameters of 9-13 µm and density of 1.1 g/cm^3. Fluorescent seeding particles are larger spheres with diameters of 20-50 µm, made of polymethyl methacrylate (PMMA) with density of 1.19 g/cm^3 and filled with Rhodamine B. Seeding particles have been added to demineralised water using various concentrations. For each sample, fluid properties have been measured. Obtained PIV measurements of mean velocity and velocity fluctuations are compared with the results of Direct Numerical Simulation (DNS).

1 INTRODUCTION

Particle Image Velocimetry (PIV) is a state-of-the-art measurement technique for investigation of single- and multi-phase flows in basic research or industrial applications including nuclear power systems. The main idea of the PIV is tracking the motion of fluid parcels and reconstructing the fluid velocity field from the consecutive images of the seeding particles, which are added to the fluid. It is commonly assumed that seeding particles have negligible influence on the obtained velocity field, however, that may not be always the case. For example, seeding particles are made of different materials and sizes, which may affect particle motion in the fluid. In order to increase the spatial resolution of the deduced velocity field, one can apply larger seeding concentrations in the fluid, but that can alter fluid properties too. Since the seeding particles should be neutrally buoyant in the fluid, no significant deviation is expected in the density of the fluid and the fluid mixture. However, at high enough seeding concentration the viscosity may change. In addition, in two-phase flows seeding particles sometimes agglomerate at the bubble or droplet interfaces, which may also alter the surface tension of the liquid.

Several studies have been examining various aspects of PIV, however, there is limited research examining the effects of the seeding particles on the turbulent flow results. A method has been developed for uncertainty determination of PIV measurements as a function of particle image diameter, particle density, particle displacement and local shear [1]. It has been shown that the size of seeding particles had the largest influence on the velocity and acceleration in comparison to the other parameters. The influence of the particle parameters was larger at higher Reynolds number [2]. There are even more factors that may affect the quality of PIV measurements in two-phase flows [3]. Thus, in the present study we examined two types of seeding particles, which we use in our laboratory, and various concentrations of both seeds. PIV measurements of turbulent pipe flow have been compared with the results of Direct Numerical Simulation (DNS) [6].

2 EXPERIMENT

2.1 Experimental facility

Measurements have been performed in an experimental facility, which has been designed for investigations of slug flow regimes [4] and is shown in Figure 1. It consists of a pump, regulation valves, Coriolis flow meter, temperature sensor, water tank and a heat exchanger, which keeps the water temperature constant during the measurements.

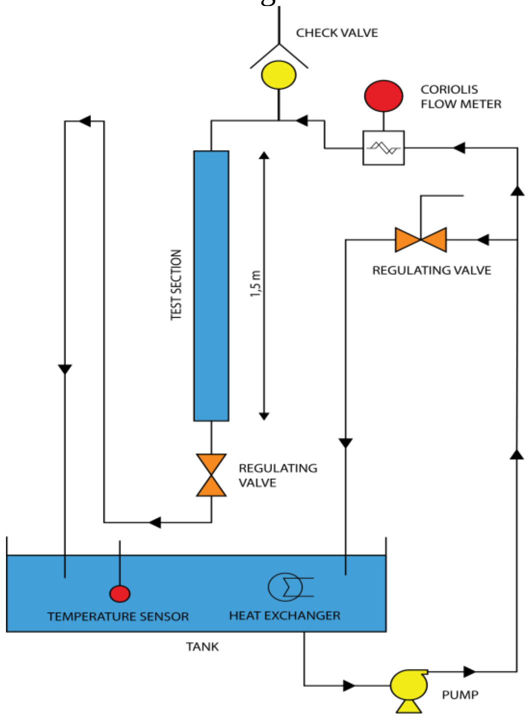

Figure 1: Scheme of the experimental facility.

In the present study PIV measurement have been performed in single-phase turbulent pipe flow. The test section is a vertical pipe made of borosilicate glass with inner diameter of 26 mm and length of 1.5 m. In order to minimize the optical distortions, the pipe is surrounded by a glass box filled with water. The measurement plain corresponds to the symmetry plane of the pipe and is located at about 45 D_h downstream the inlet bend to the test section. Temperature was kept constant during the measurement at 22 °C. The flow parameters of the measurements are given in Table 1.

Table 1: Flow parameters

Test	Flow rate [ml/s]	Temp [°C]	Viscosity [mPa-s]	Reynolds number	Seeding particles	Seeding concentration
1	97.0 ± 0.5	22 ± 1	1.02 ± 0.07	4600 (1 ± 0.1)	Glass	N_0 + N
2	96.3 ± 0.5	22 ± 1	1.02 ± 0.07	4600 (1 ± 0.1)	Glass	N_0 + 2N
3	95.9 ± 0.5	22 ± 1	1.02 ± 0.07	4600 (1 ± 0.1)	Glass	N_0 + 4N
4	96.6 ± 0.5	22 ± 1	1.02 ± 0.07	4600 (1 ± 0.1)	Glass	N_0 + 8N
5	95.9 ± 0.5	22 ± 1	1.02 ± 0.07	4600 (1 ± 0.1)	Glass	N_0 + 16N
6	95.5 ± 0.5	22 ± 1	1.02 ± 0.07	4600 (1 ± 0.1)	PMMA	C_1
7	97.0 ± 0.5	22 ± 1	1.02 ± 0.07	4600 (1 ± 0.1)	PMMA	1.6 C_1
8	96.7 ± 0.5	22 ± 1	1.02 ± 0.07	4600 (1 ± 0.1)	PMMA	2.7 C_1

2.2 Seeding particles

Seeding particles can change the fluid properties, i.e., density and viscosity. Since the seeding particles must be neutrally buoyant in the fluid, they have similar density as the fluid. Thus, addition of seeding particles does not change fluid density much. Contrarily, large concentration of seeding particle might change the fluid viscosity. For that reason, we have measured several samples with different seeding particles and their concentrations. The viscosity of the samples was measured at 22°C±0.1°C at shear rate of 50 s^{-1} with a CC 27 cylindrical system using a Physica MCR 301 rheometer [5]. Samples with the largest and the smallest seeding concentrations have been measured for demineralized water with hollow glass spheres as well as PMMA particles (Table 1). The span of seeding concentration extends for a factor of 16 in the samples with hollow glass spheres whereas in the samples with PMMA particles it spans for only a factor of 2.7. It should be noted that N_0 corresponds to a small initial concentration of hollow glass spheres, which cannot be removed from the system with fresh refilling of the system with demineralized water. Namely, the particles stick to the surfaces, which makes them very hard to remove completely from the system. Nevertheless, we have estimated from the obtained images that N_0<N, where N is a controlled amount of seeding particles added to the fluid for each consecutive test. In the case of fluorescent PMMA seeding particles, initial concentration was zero, because it was the first time we used them in the system.

2.3 PIV settings

PIV measurements have been performed using LaVision double cavity Nd:YLF 527nm laser and Phantom v 1212 high-speed camera. The measurements have been obtained at the lowest sampling rate of 200 Hz using dual cavity mode. Post-processing has been applied on 24800 images, which corresponds to a duration of 124 seconds.

In the post-processing velocity vectors were calculated using maximal expected velocity of 1.2 m/s and spatial resolution of 1.6 mm. We applied multi-pass vector calculation starting from initial windows size of 256×256 pixels (overlap of 50%) and final windows size of 32×32 pixels (overlap 75%).

3 RESULTS

Fluid viscosity has been measured and it has the same value of 1.02±0.07 mPa-s for all the samples as shown in Table 1. The applied seeding concentrations are listed in Table 1 and shown in Figure 2. The field of view is the same size on all the images in Figure 2. Clearly, the seeding particles are much smaller for hollow glass spheres (tests 1-5) than for fluorescent PMMA particles (tests 6-8). Figure 2 shows also that the applied range of concentrations for hollow glass spheres is much larger than for the PMMA particles. In fact, 70 % larger concentration of PMMA particles in Test 8 with respect to Test 7 is not noticeable in the obtained images. Thus, larger concentrations of PMMA particles would be desirable.

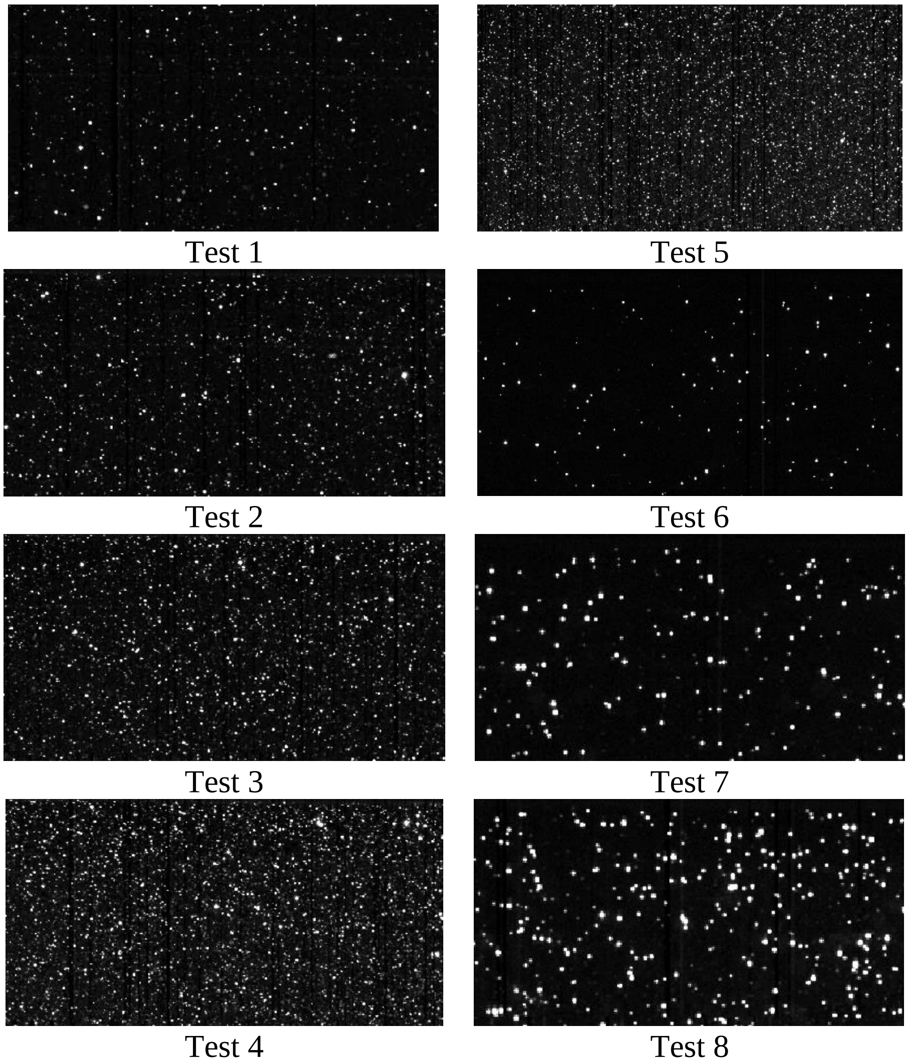

Figure 2 : Various seeding concentrations using hollow glass spheres (tests 1-5) and fluoroscent PMMA particles (tests 6-8).

We have analysed the calculated velocities from tests 1-5 and test 7. Figure 3 shows comparison of the obtained mean streamwise velocity, streamwise velocity fluctuations and wall-normal velocity fluctuations with respect to the DNS results of [6]. Is should be noted that the Reynolds number is 5300 in the DNS, which is slightly larger than 4600 in the experiment. Nevertheless, the measured mean streamwise velocity component is in a very good agreement with the DNS for all the performed tests. The obtained measured velocity is about 5% larger when PMMA particles are applied instead of hollow glass spheres. Since the discrepancy is rather small, more tests are needed to explain it.

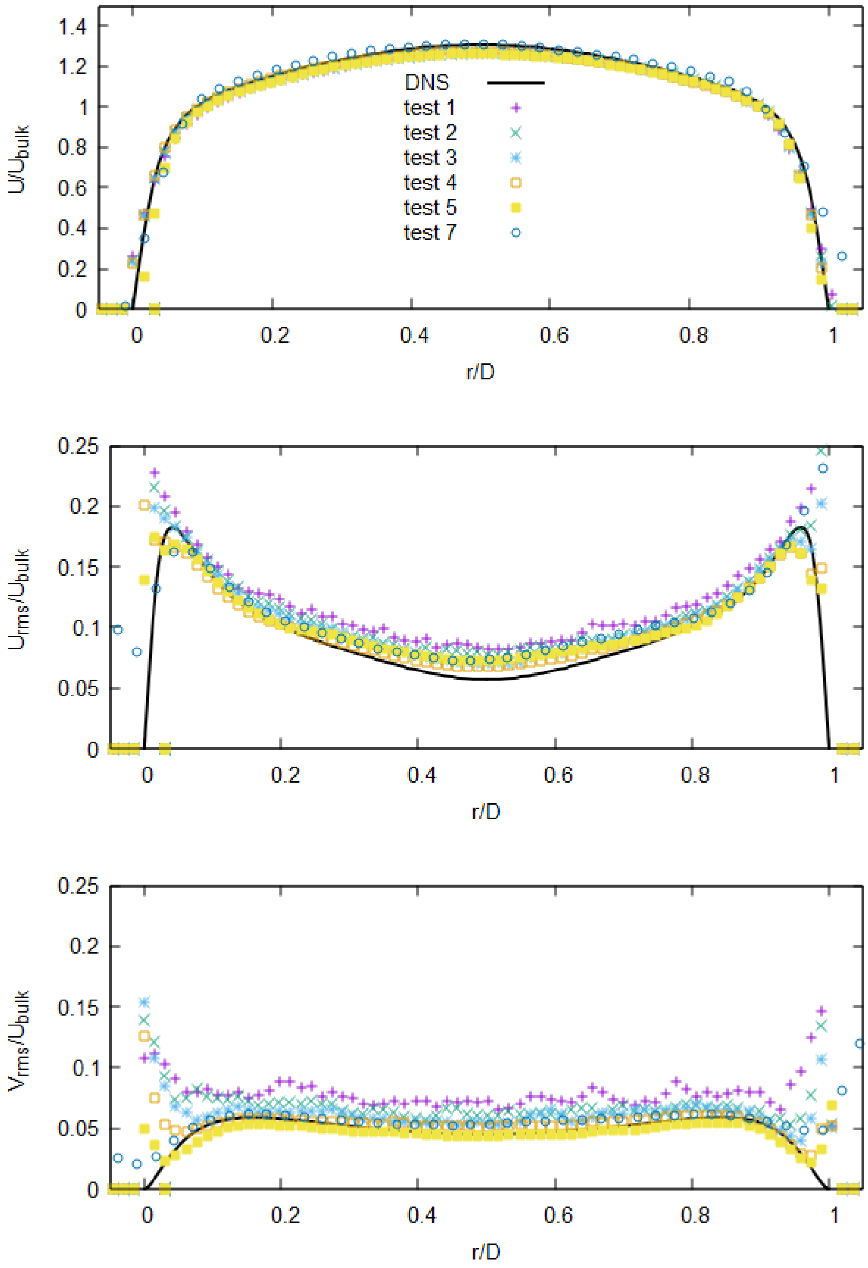

Figure 3: Comparison of the DNS results with the measured mean streamwise velocity component (top), streamwise velocity fluctuations (middle) and wall-normal velocity fluctuations (bottom).

The measured velocity fluctuations show improved agreement with the DNS results when larger seeding concentration is applied. Everywhere except in the near-wall region, a very good quantitative and qualitative agreement with the DNS results is obtained for tests 3-5 as well as test 7. Contrarily, up to 40% overestimation of the velocity fluctuations is observed for low seeding concentration in the bulk region, i.e., tests 1-2. It should be noted that all the tests were post-processed with same settings. Thus, overestimation of the velocity fluctuations could be related with too small numbers of seeding particles in the applied interrogation windows. This will be further investigated. Larger discrepancies of velocity fluctuations are observed in the near-wall region. In general, the measurements gradually improve with the increased seeding concentration. Further improvement could be achieved with larger seeding concentration, longer recorded statistics as well as larger magnification, which improves spatial resolution of the boundary layer. However, refraction of light is significant in the region closer than 1 mm from the pipe wall and location correction would also be needed for accurate measurement.

4 CONCLUSIONS

Effect of the seeding particles on PIV measurements have been investigated for single-phase turbulent pipe flow. Two types of seeding particles with different particle sizes, seeding concentrations and slightly different densities have been used: hollow glass spheres and fluorescent seeding particles made of PMMA. Obtained PIV measurements of the mean streamwise velocity component agree well with the DNS result for all the considered cases. Contrarily, both measured velocity fluctuation components, i.e., the streamwise and wall-normal, have shown systematically decreased measured values with the increased seeding concentration. The measurements with the largest seeding concentrations have the best agreement with the DNS result. Thus, measurements with even larger seeding concentration of the PMMA particles would be desirable in the future work. In order to improve spatial resolution of the measured momentum boundary layer, larger magnification factor of the camera lens is needed.

Fluid viscosity is similar for all the measured samples with the considered seeding concentrations. Measurement error for the investigated samples using rheometer and cylindrical system CC 27 is 7 %.

The PIV measurements have been obtained at about 45 D_h downstream the inlet bend, which introduces asymmetry in the flow. Nevertheless, no significant asymmetry is observed in the obtained velocity profiles, which agree well with the fully developed turbulent pipe flow from the DNS results.

ACKNOWLEDGMENTS

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REFERENCES

[1] B. H. Timmins, B. W. Wilson, B. L. Smith, P. P. Vlachos, “A method for automatic estimation of instantaneous local uncertainty in particle image velocimetry measurements”, Exp Fluids, 53, 2012, pp. 1133-1147.

[2] T. Hadad, R. Gurka, “Effects of particle size, concentration and surface coating on turbulent flow properties obtained using PIV/PTV”, Exp. Therm. Fluid Sci, 45, 2013, pp. 203-212.

[3] Y. Liu, C. Wang, Y. Qian, X. Sun, Y. Liu, “Uncertainty analysis of PIV measurements in bubbly flows considering sampling and bubble effects with ray optics modeling”, Nucl. Eng. Des., 364, 2020, 110677, pp. 1-14.

[4] B. Mikuž, J. Kamnikar, J. Prošek, I. Tiselj, “Experimental observation of Taylor bubble disintegration in turbulent flow”, Proc. 28th Int. Conf. Nuclear Energy for New Europe, Portorož, Slovenia, September 9-12, Nuclear Society of Slovenia, 2019.

[5] Anton Paar available at https://www.anton-paar.com/corp-en/ (visited on 31st of August 2021).

[6] G. G. K. El Khoury, P. Schlatter, A. Noorani, P. F. Fischer, G. Brethouwer, A. V. Johansson, “Direct numerical simulation of turbulent pipe flow at moderately high Reynolds numbers”, Flow Turbul. Combust., 91, 2013, pp. 475-495.