MEASUREMENT OF PHASE INTERACTION IN DISPERSED GAS-PARTICLE TWO-PHASE FLOW BY PHASE-DOPPLER ANEMOMETRY

by

Mohamed Ali MERGHENI, Hmaied BEN TICHA , Jen-Charles SAUTET, Gille GODARD, and Sassi BEN NASRALLAH

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For simultaneous measurement of size and velocity distributions of continuous and dispersed phases in a two-phase flow a technique phase-Doppler anemometry was used. Spherical glass particles with a particle diameter range from 102 up to 212 μm were used. In this two-phase flow an experimental results are presented which indicate a significant influence of the solid particles on the flow characteristics. The height of influence of these effects depends on the local position in the jet. Near the nozzle exit high gas velocity gradients exist and therefore high turbulence production in the shear layer of the jet is observed. Here the turbulence intensity in the two-phase jet is decreased compared to the single-phase jet. In the developed zone the velocity gradient in the shear layer is lower and the turbulence intensity reduction is higher.

Keywords: *phase-Doppler anemometry, gas-particle, turbulence*

Introduction

Turbulent two-phase flow occurs in many industrial applications, such as in pneumatic transport of particulates, circulating fluidized beds, cyclone separators, and chemical reactors. Interaction between the particles and the gas lead to the changes in the level of the gas phase turbulence intensity. See, for instance, the recent book by Crowe *et al*. [1].

Historically, considerable efforts regarding numerical predictions have been made, where the methods may be divided in two main categories, namely the Eulerian approach and the Lagrangian approach. In the Eulerian approach the dispersed phase is treated as a continuum, and has been reported by several researchers Elgobashi *et al*. [2] and Simonin [3]. The Lagrangian approach predicts the particle motion in the continuous phase by solving the equation of particle motion directly Berlemont [4, 5], Desjonqueres [6] and Sommerfeld *et al*. [7]. However, despite some successes, difficulties still remain in connection with models representing the various physical aspects of turbulent particle motion. Consequently, it becomes imperative to conduct experiment to yield data which improve the basic understanding of the fundamental phenomena.

It is from this point of view that many experiments have been performed on particle-laden flows. Hestroni and Sokolov [8] measured a decrease of turbulence intensities in the two-phase jet compared to single-phase jet for Stokes numbers St $\ll$ 1. For higher Stokes numbers Prevost *et al.* [9, 10] measured decreased turbulence intensities in the two-phase jet compared to the single-phase jet. Later the experimental works of Lee and Durst [11], Modarress *et al*. [12], Tsuji *et al.* [13], and Hardalupas *et al*. [14] provided much needed data to help understand the behaviour of two-phase turbulent free jets. Longmire and Eaton [15] investigated the structure of a particle-laden round jet. In contrast, until very recently it has been difficult to find in the literature a well documented experimental study of a two-phase turbulent coaxial jet. In fact, for understanding of the turbulence modulation and its driving effects further turbulence analysis with statistical measurements of turbulence modulation and detection of the influence of the dispersed phase on the turbulence structure in the two-phase jet are necessary. A specific need for experimental investigations of phase interaction is providing fast simultaneous and correlated measurements of continuous and dispersed phases in the flow field.

For non-intrusive measurements of interactions between different particle size distributions and the turbulent carrier flow, phase-Doppler anemometry (PDA) is a well-established method. PDA is a laser-optical measurement technique for simultaneous measurement of particle velocities and sizes. This optical method detects the light scattered by an individual particle during its path through the interference volume of two intersecting laser beams. The PDA determines the particle velocity from the signal frequency shift as in conventional laser Doppler velocimetry systems. If the experimental setup is well suited to the optical properties of the particles, the phase difference between two signals detected simultaneously by two detectors at different positions is proportional to the (spherical) particle diameter. Therefore, the particle diameter is determined from the phase difference of the signals.

The objectives of the experimental study is part of a research effort aimed at the measuring the mean and fluctuating velocity distributions of two-phase turbulent coaxial jets under condition of velocity ratio, particle loading ratio, and particle sizes.

This paper presents experimental results from a study of gas-phase turbulence modulation in the presence of particles.

Experimental setup

The generation of the two-phase jet

In order to analyse the turbulent structure in the two-phase flow, simultaneous measurements of tracers ($d = 5$ μm) and particles ($d_p = 102$-212 μm) have been carried out with the experimental setup of the two-phase turbulent coaxial jet illustrated in fig. 1. It is very important to note the definition of turbulent Stokes number St, which is defined as the ratio of the particle response time to the fluid response time, characterizes the responsiveness of the particle to the fluid-phase turbulent fluctuations [14]. A value of St larger than one corresponds to unresponsive particles, with a value less than one corresponding to responsive particles. $\mathrm{St} = \tau_p/\tau$, where τ_p and τ are the particle and fluid response time, respectively, $t_p = d_p\rho_p/18\,\mu$ and $\tau = D/U$,where D is the pipe diameter and U is the fluid-phase mean axial velocity. The seeding particles used to measure the single-phase velocity in the present investigation have St approximately equal to 0.34 and are highly responsive to the fluid velocity fluctuations. In contrast, the St values for the ranges of particles ($d_p = 102$-212 μm) are significantly larger than one, which indicate that the particle motion for these particles are unresponsive to the fluid velocity fluctuations.

In this experimental investigation, the mean exit velocity of the central jet and the annular jet are $U_0 = 31.9$ m/s and $U_a = 7.4$ m/s, respectively. The central jet diameter D and the annular jet diameter D_a are 6 mm and 18 mm, respectively. Air supplied by a blower passed the flowmeter, colsonic and was then separated into two lines. In one line, glass particles were sup-

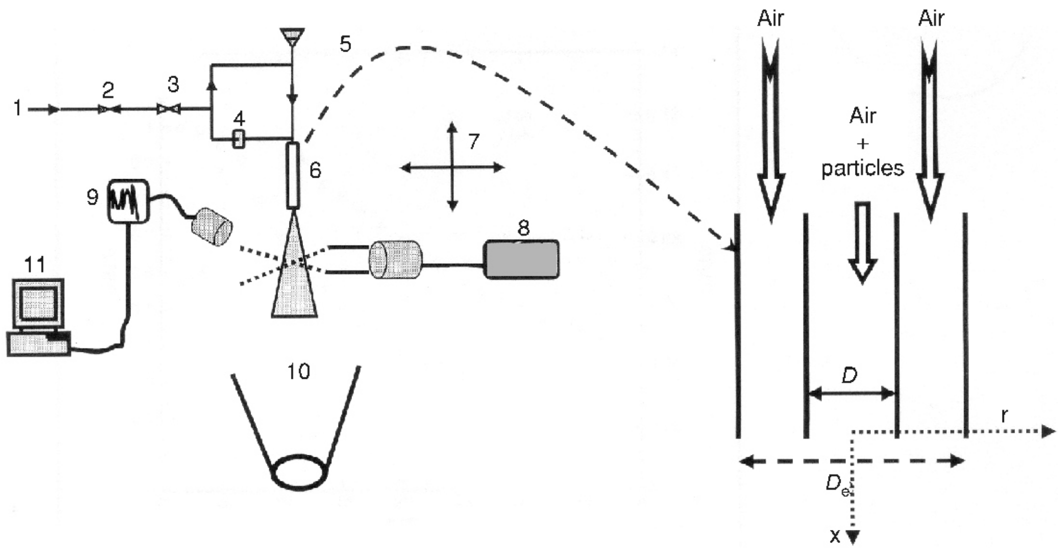


Figure 1. Experimental setup for the two-phase jet

1 – air, 2 – flowmeter, 3 – colsonic, 4 – tracers generator, 5 – particle feeder, 6 – nozzle, 7 – displacement system for tube, 8 – PDA, 9 – signal processor, 10 – particle collector, 11 – computer

plied by a gear feeder powered with a variable speed motor. The other line passed through the tracer generator. The air and particles were passed a central tube. The annular jet is encemenced by tracer particles [16].

The stream wise direction is the x-axis and the radial direction is r-axis. The vertical jet flow discharges into ambient air. The exit Reynolds number based on the central tube diameter *D*, is $1.2 \cdot 10^4$. Since the PDA measurement volume is fixed at a certain point in space, the pipe is mounted on a two axis displacement system driven by a personal computer. The tube is aligned by a cathetometer. Experiments were performed using glass particle with a material density of 2500 kg/m^3. The particle loading ratio $\Phi = 0.22$, defined as the ratio of the total solid mass flow rate to the mass flow rate of the air at the nozzle exit.

Optical scheme and measurements

A two-component laser phase-Doppler system (Dantec) was used. The beam emitted from an argon laser is divided into beams of wavelengths λ_1 = 514.5 nm and λ_2 = 488 nm for two-component velocity measurements. The optical system is composed of a Bragg cell unit creating a 40 MHz frequency shift in order to avoid directional ambiguity, transmitting and receiving optics, photomultiplier (PM), and a numeric oscilloscope was used for on-line control of the Doppler signals and the optimisation and tuning of the electronics. The receiving optics is placed 28° to the forward scatter direction, to minimize the contribution of reflected light. Doppler bursts are processed by the Dantec 58N81 phase-Doppler signal processor. Table 1 summarizes the relevant optical parameters of the PDA. All data are transferred to a PC before being post-processed by customized FORTRAN programs. A single measurement at a given point generally comprises 5000 particles. Five radial profiles (x = 0.5-30D) and the centreline profile are measured. The gas velocity is obtained by averaging the velocity measurements in the size class 0-5 μm, particles of this size class have been verified to be good tracers for the gas-

Table 1. Optical parameter of the PDA system

	Axial channel	Radial channel
Transmitting optics		
Wave length of the laser [nm]	514.5	488
Focal length of the front lens [mm]	500	500
Beam separation [mm]	38	38
Beam diameter [mm]	2.2	2.2
Expander ratio	1	1
Fringe spacing [μm]	21	21
Receiving optics		
Focal length of the lens [mm]	401.5	
Collection angle [º]	28	

eous phase. Two-phase measurements are made in two stages in order to measure the velocities of both the gas and the particles. The first stage involves making measurements of the gas in the presence of the particles. The second stage involves measurements of the larger particle only [16].

Results and discussion

In this section, measurements of the velocity of gas phase and of the dispersed phase, are reported and analysed.

Single-phase flow

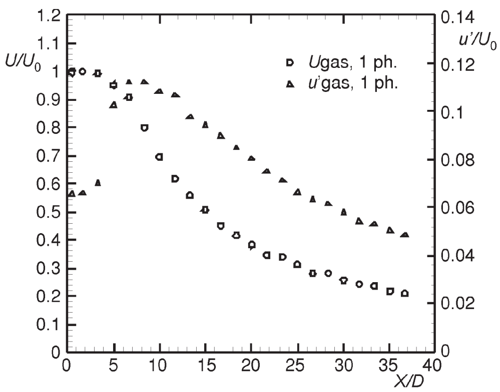


Figure 2. Axial profiles of mean velocity and turbulence intensity in the centre of the single phase coaxial

We now present experimental results for the single-phase flow. Figure 2 shows the variation along the axis of the jet of the mean axial velocity along the centreline, U_c, and of the turbulence intensity, u'_c/U_0 for the jet with exit velocity, $U_0 = 31.92$ m/s. Regarding the length of the potential core this figure reveals that the potential core is of about 4*D* length, a result which is consistent with those of other investigators [17]. The extent of the potential core is defined as the distance from the orifice (or exit plane of the nozzle) to the point of intersection of the constant, issuing velocity in the jet axis and the curve of the hyperbolic decrease of the centreline velocity (U_c). Figure 3 shows that the relative turbulence intensities for the jet increase rapidly from the exit plane until a distance of ten diameters then they increase slowly through a distance of about 25 diameters to tend to an asymptotic value of 23%, which is in agreement with the results of Warda *et al.* [17].

In order to obtain a better definition and, possibly a deeper physical understanding of the flow field of a coaxial jet, not only the radial profiles of the longitudinal mean velocities are need to be displayed but also the corresponding profiles of turbulence intensities should be considered. Some of the radial profiles of both mean velocity and turbulence intensity that are measured at various axial stations are presented. Figure 4 presents the mean longitudinal velocity, while fig. 5 show the corresponding profiles of the longitudinal turbulence intensity for the same axial stations.

Figure 6 shows the relative intensities u'/U_c for the jet, at various axial distance to the nozzle (x/D = = 10, 20, and 30), its on comparison with the results of Prevost *et al*. 27% (without co-flow) [9]. These

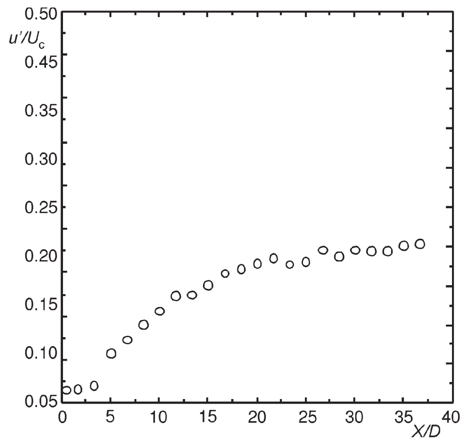


Figure 3. Axial profiles of the relative turbulence intensity in the centre of the single phase coaxial jet

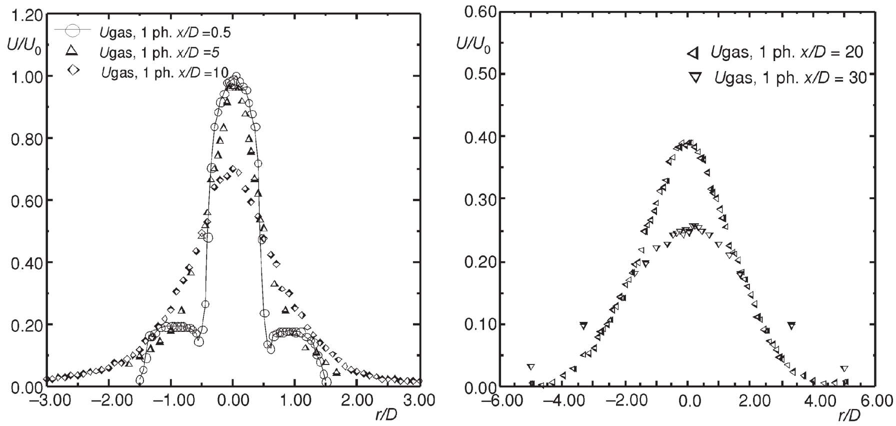


Figure 4. Radial profiles of mean velocity of single-phase jet in the section: *x/D* = 0.5, *x/D* = 5, *x/D* = 10, *x/d* = 20, and *x/D* = 30

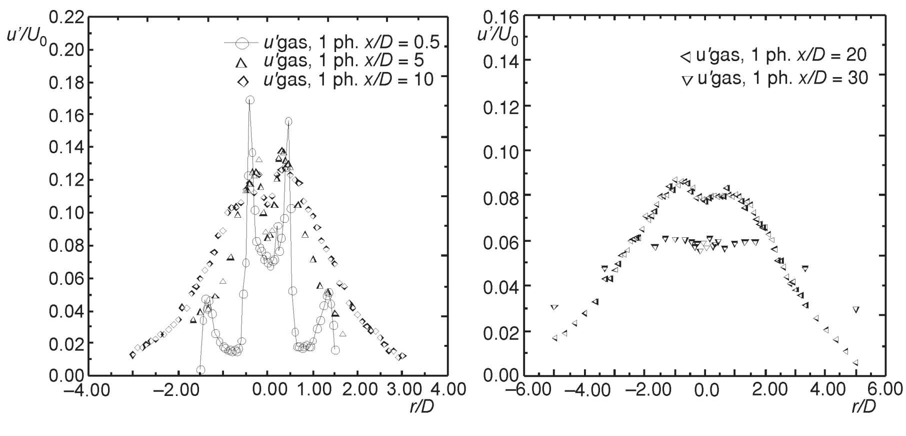


Figure 5. Radial profiles of turbulence intensity of single-phase jet in the section: *x/D* = 0.5, *x/D* = 5, *x/D* = 10, *x/D* = 20, and *x/D* = 30

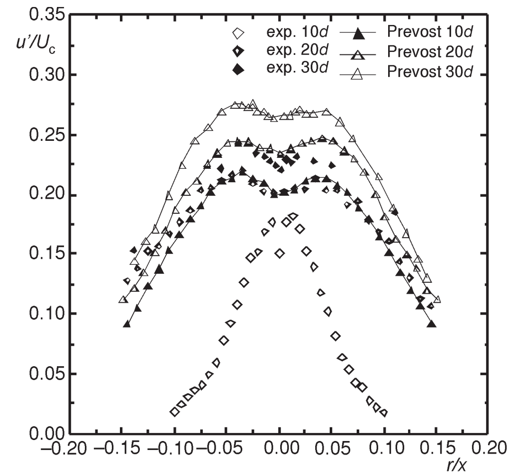


Figure 6. Radial profiles of the relative turbulence intensity of the single phase coaxial jet

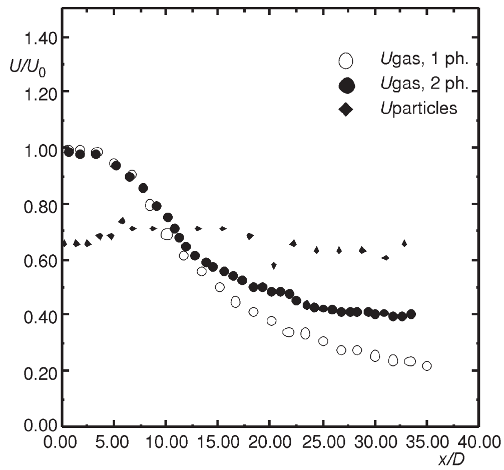


Figure 7. Axial profiles of mean velocity in the centre of the single and two phase jet

experimental results indicate a significant influence of the co-flow on the structure turbulent jet. Here the turbulence intensity is reduced compared to the jet without co-flow.

Two-phase flow

Figure 7 shows the axial profiles of the mean velocity for dispersed particle, the measurement mean velocity of the jet single-phase jet compared to the two-phase jet. The velocity profiles are normalized by the mean velocity in the centre of the nozzle exit (U_0 = 31.9 m/s). We can observe a noticeable relative velocity between the gas phase and the dispersed phase at the exit. This phenomenon was already observed before by Hardalupas *et al.* [14]. It is due to the flow-particle interaction in the tube and to the presence of rebounds of particles along the wall of the tube [14]. Planar visualisations at the exit of the tube by a thin laser sheet have supported this hypothesis. Due to this relative motion near the exit, the particles are accelerated by the gas along the seven first diameters until they reach the mean gas velocity.

Figure 8 shows the radial profile of the mean axial velocity, normalised with the single-phase gas velocity in the centre of the nozzle exit, of single-phase jet compared to the two-phase jet at the x/D = 0.5. A typical velocity profile is observed, velocity reaches its maximum at the centre of the flow (r = 0) and is reduced near the wall (r = 0.5D). In the two-phase jet the mean axial velocity profile of the continuous phase is nearly the same as the single-phase jet's profile. The insufficient acceleration length of the tube and the collisions at the tube wall entail that the

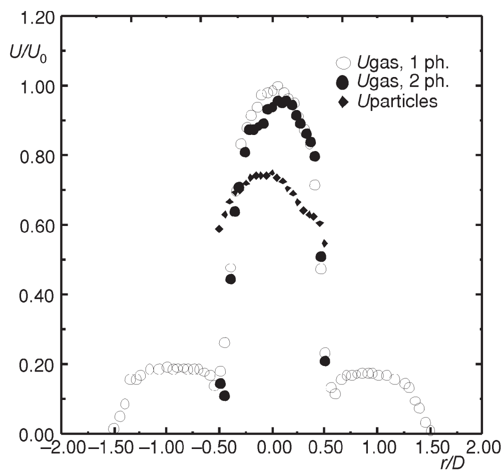
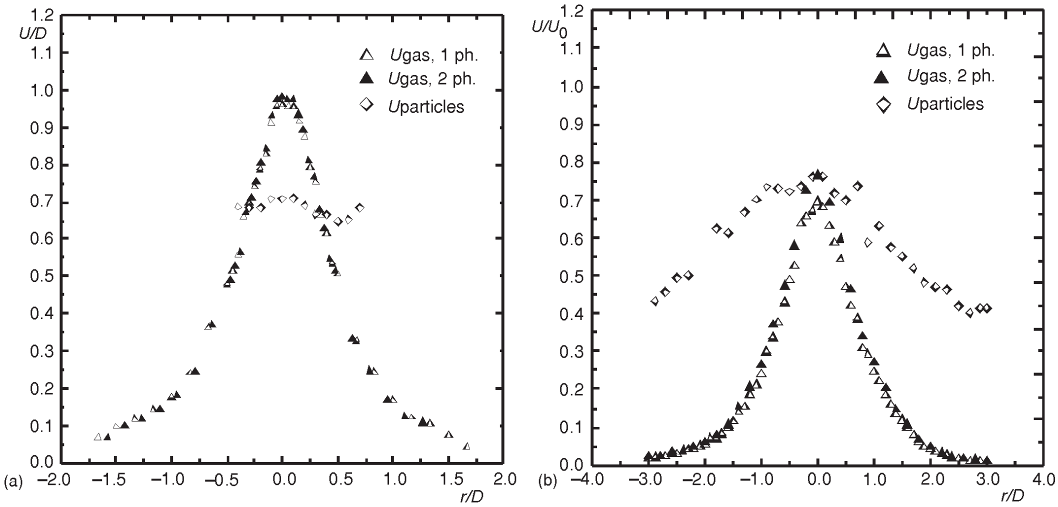


Figure 8. Radial profiles of the axial mean velocity of single and two-phase jet at x/D = 0.5

dispersed phase velocity is almost steady at a value 0.75 of the gas velocity in the centre of the profile. Therefore, the particle velocity is lower compared to the continuous phase velocity in the centre of the flow, but higher than the continuous phase velocity in the wall region.

Figure 9 shows the mean axial velocity, normalised with the single-phase gas velocity in the centre of the nozzle exit, of single-phase jet compared to the two-phase jet for radial profiles at various axial distances (*x/D* = 5, 10, and 20). The gas velocities show typical jet flow profiles. In the shear area of the two-phase flow, particle velocities are higher than the gas velocity because of the mass inertia of the particles. Due to momentum transfer from the particles to the fluid in the shear area, the velocity of the gas phase is higher at *x/D* = 10, which results in a lower spreading rate and higher gas velocities in the whole profile of two-phase jet in comparison to single-phase jet. At larger distances to the nozzle (*x/D* = 20) the mean velocity in the two-phase is higher than the single-phase jet owing to the presence of particles.



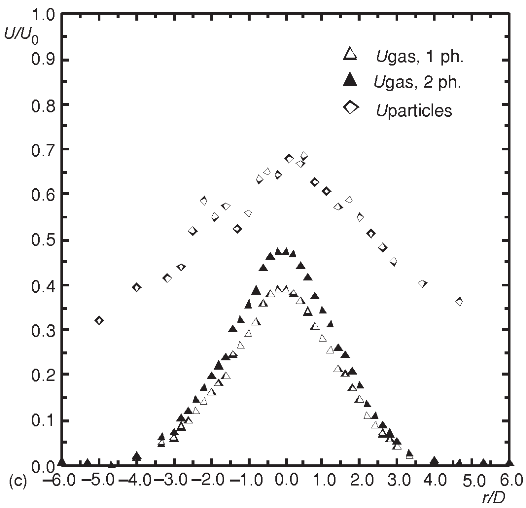


Figure 9. Radial profiles of the axial mean velocity of single and two-phase jet in the section
(a) x/D = 5, (b) x/D = 10, and (c) x/D = 20

Figure 10 shows the turbulence intensity for the single-phase jet compared to the two-phase jet for radial profiles at various distances (*x/D* = 5, 10, and 20). The profiles are nor-

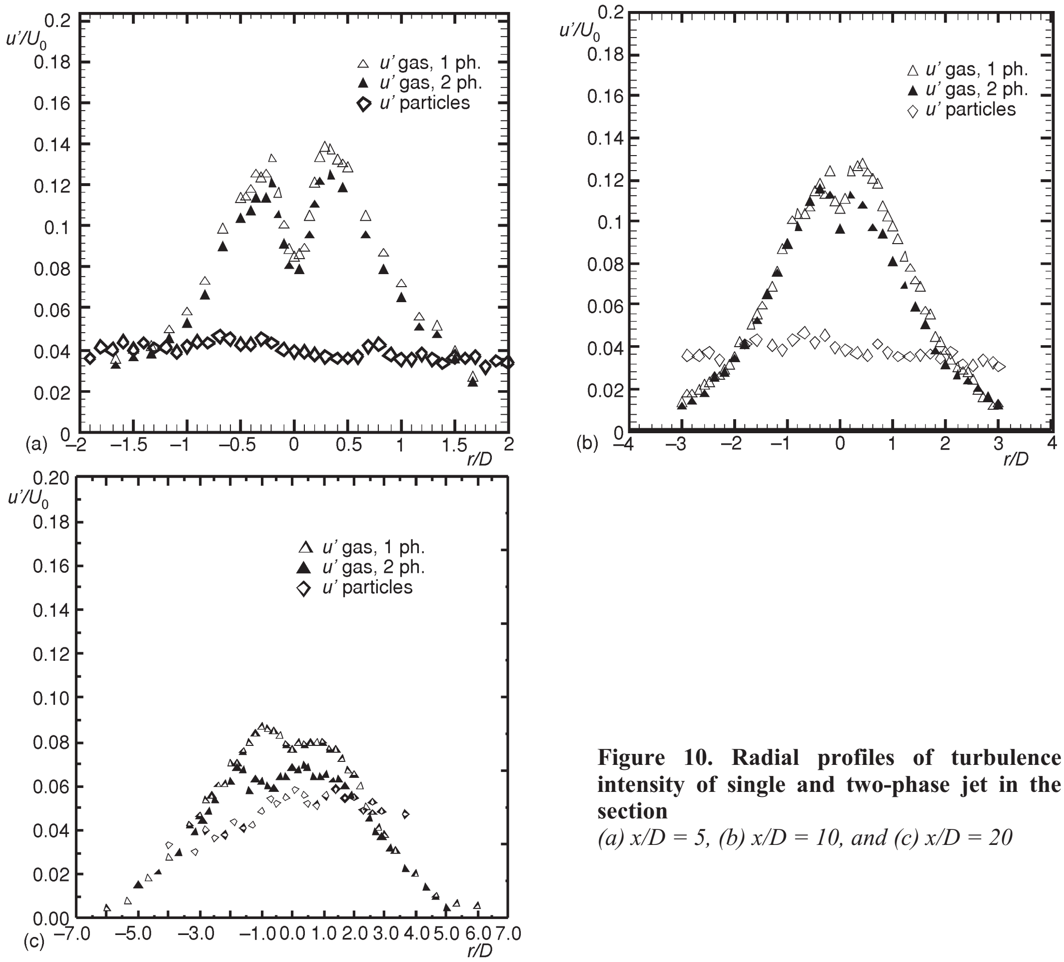


Figure 10. Radial profiles of turbulence intensity of single and two-phase jet in the section
(a) x/D = 5, (b) x/D = 10, and (c) x/D = 20

malised by the single-phase gas velocity in the centre of the nozzle exit. In the two-phase jet the turbulence intensities are reduced in comparison to the single-phase jet and the differences of turbulence intensities becomes more important for increasing axial positions.

Conclusions

An experimental study of the effect of solid particles on the flow characteristics of axisymmetric turbulent coaxial jet were presented in this paper. Measurements were obtained by using a PDA allowing size and velocity measurements. In this two-phase flow an experimental results are presented which indicate a significant influence of the solid particles on the flow characteristics. The height of influence of these effects depends on the local position in the jet. Near the nozzle exit high gas velocity gradients exist and therefore high turbulence production in the shear layer of the jet is observed. Here the turbulence intensity in the two-phase jet is decreased compared to the single-phase jet. In the developed zone the velocity gradient in the shear layer is lower and the turbulence intensity reduction is higher.

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Nomenclature

D	– centre jet diameter, [mm]
D_a	– annular jet diameter, [mm]
d_p	– particle diameter, [μm]
U	– mean velocity, [ms^{-1}]
u'	– fluctuation velocity, [ms^{-1}]
x	– axial distance
r	– radial distance
Re	– Reynolds number ($=\rho UD/\mu$), [–]
St	– Stokes number ($=\tau_p/\tau$), [–]

Greek letters

μ	– dynamic viscosity, [kgm^{-1}s^{-1}]
ρ	– gas density [kgm^{-3}]
ρ_p	– particle density, [kgm$^{-3]}$)
τ	– fluid response time, [s]
τ_p	– particle response time, [s]
Φ	– particle-loading ratio

Subscripts

a	– anular jet
c	– axis of central jet
p	– particle
0	– central jet

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Authors´ addresses:

M. A. Mergheni, J.-C. Sautet, G. Godard
CORIA UMR 6614 CNRS —Université et INSA de ROUEN,
Avenue de l'Université, BP 12, 76801 Saint Etienne du Rouvray, Cedex, France

H. Ben Ticha , S. Ben Nasrallah
LESTE Ecole Nationale d'Ingénieurs de Monastir, 5019 Monastir, Tunisie

Corresponding author M. A. Mergheni
E-mail: mohamed-ali.mergheni@coria.fr

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