Experimental measurement of turbulent aerosol jet characteristics

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Abstract. The fields of vector velocity components and their turbulent pulsations of aerosol jets at low Reynolds numbers have been measured experimentally by an optical method. Smoke image velocimetry (SIV) technique based on digital processing of images with high particle concentration has been employed to obtain results quantitatively and qualitatively compared with direct numerical simulation results.

1 Introduction

Turbulent aerosol jets are complex multiphase flows in which the dispersed liquid phase is carried by a directed turbulent gas flow. Significant interest in this area has increased sharply in 2019 due to the outbreak of the COVID-19 pandemic, namely, to study the spread of aerosol flows from the nasal cavity during sneezing. However, understanding and modeling the evaporation and dissipation of dispersed liquid droplets in a turbulent jet remains one of the poorly studied modern problems in the mechanics of multiphase media. This is primarily due to the complexity of the analytical description of unsteady processes of mass, momentum, and turbulent energy transfer between phases. The fundamental works in this subject are [1-3], where the d-square law was formulated. The law states that the surface of a drop decreases linearly with time in quiescent media with uniform and fixed thermodynamic properties. Using the d-square law, the well-known rapid-mixed model was formulated for homogeneous [4, 5] and inhomogeneous [6] droplet characteristics.

However, in a recent work [7] on direct numerical simulation of an aerosol jet, the question was raised about the validity of the d-square law in the region of low Reynolds numbers of the order of 10000. The authors found that the use of this law based on environmental conditions leads to a significant increase in the drop evaporation rate. Obviously, such theses require experimental confirmation.

As for most experimental studies, the methods of experimental measurements of aerosol jets are divided into contact and non-contact methods; each method is associated with some own difficulties. For contact methods, such as hot-wire anemometry, firstly, the problem is aerosol liquid droplets getting on the hot-wire anemometer filament, which provokes the wire to burn out and the device to fail. Secondly, based on the operation principle of the hot-wire anemometer, the ingress of liquid drops onto the wire significantly affects the heat transfer by which the sensor is calibrated, therefore, the results of velocity measurement

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will turn out to be wrong. The forced exclusion of the liquid phase from the flow of the aerosol jet makes it possible to give only a qualitative assessment of the process, which is not always correct. For single-phase liquid flows, non-contact methods for estimating dynamic velocity fields such as laser Doppler anemometry, PIV (Particle image velocimetry), PTV (Particle tracking velocimetry) and variations of these methods are also well known and successfully used. The above methods are based on tracking the displacement of separate particle in flow. In two-phase gas/liquid flows, these methods have also found their successful application in many cases. The case touches mainly about problems with a clearly expressed interface. However, in the case of aerosol flows, the size of liquid droplets is commensurate with the size of particles, but as a rule their concentration significantly exceeds the recommended one for PIV (about 6 particles per 32x32 pixel digital image fragment). Under these conditions, the algorithm of the PIV method is not able to correctly track each unique particle, which leads to an error in measuring the velocity.

In relation to all other similar studies, the present paper uses a relatively new optical field SIV (Smoke image velocimetry) method for measuring the dynamics of instantaneous velocities [8] to measure the characteristics of aerosol jets for the first time. The main difference between the SIV technique and the PIV and PTV methods is the use of many times higher tracer concentration (discrete aerosol drops in present case), so the SIV method has no problems with velocity measurements in zones that are almost completely filled with aerosol particles. The paper is aimed to obtain the characteristics of turbulent aerosol jet and to find out the validity of the d-square law using the DNS results [7].

2 Experimental setup

The experimental setup included: a compressor for creating a flow of a gaseous medium, a storage tank for liquid, liquid and gas rotameters, a nozzle, an ultrasonic transducer for creating dispersed liquid droplets, an optical measurement system for instantaneous velocity fields (SIV), and an external jet blowing system. The mass flow rate of atmospheric air was provided by the compressor with flow control using the gas rotameter. The liquid flow was supplied from the storage tank with small pressure in the air cushion and was regulated by the liquid rotameter. After the rotameter, the liquid entered the acoustic transducer, where it was divided to drops up to 100 μm in size under the action of mechanical vibration of the emitter membrane. A suspension of drops was supplied to the air flow. At the last stage, the gas-liquid mixture was supplied to a 300 mm long and 9.8 mm exit section diameter nozzle, where the final mixing of the phases and additional dividing of the liquid droplets were obtained. In order to eliminate the resulting effect of the external environment on the jet (lateral fluctuations of air flows in the room), the jet was blown from bottom by a steady uniform air flow with a diameter of 400 mm and turbulence intensity of less than 5%.

The measurement area was illuminated by a continuous diode-pumped solid-state laser (DPSS-Laser) KLM-532/5000-h. The flow pattern in the jet symmetry plane was recorded with a monochrome high-speed camera Fastec HiSpec with the frame resolution of 665 × 110 pixels (scaling factor of 0.1961 mm/pixel), frame rate f=2530 1/s and recording time of 3.5 s. The camera was equipped with a Navitar 1"F/0.95 lens with manual focus control. To visualize the flow pattern, dispersed water drops were used; therefore, unlike the general practice of using optical methods, the gas flow was not seeded with foreign particles.
3 Results

Figure 1 shows a high-speed digital recording frame of the aerosol jet flow at Re=6000. The frame clearly shows areas where the concentration of aerosol particles is similar to the separate particle distribution as in PIV measurements (discrete white dots on a black background - the right side of the figure), however, the left side of the figure shows areas of high tracer concentration visually looked like structures smoke. The Smoke Image Velocimetry (SIV) technique is adapted to digital processing of smoke-like images so as separate particle images.

![Image](image-url)

**Fig. 1.** High-speed digital recording frame of the aerosol jet flow at Re=6000 (from left to right).

![Graphs](graph-url)

**Fig 2.** Aerosol jet characteristics in cross sections obtained from SIV measurements at Re=6000; *left*: velocity profiles U at different distances z and x from the nozzle exit of R radius; *right*: velocity distribution along the jet axis compared with DNS.
The velocity vector components and its turbulent fluctuations of the aerosol jet measured by the SIV method were compared with the results of direct numerical simulation [7] (Figs. 2, 3). The velocity fields of the gaseous medium and the characteristic trajectories of dispersed liquid particles of variable mass showed good both qualitative and quantitative agreement.

Fig. 3. Aerosol jet characteristics in cross sections obtained from SIV measurements at Re=6000; top: velocity field; bottom: field a streamwise turbulent velocity fluctuations u'u'.

4 Conclusions

Comparison of aerosol jet velocity characteristics obtained from SIV measurements with the results of direct numerical simulation shows that the SIV method can be used to study such problems. The good spatial resolution of the fields of the velocity components and their turbulent fluctuations makes it possible to visualize the coherent structures of aerosol jets using the Q-criterion. In the future, these results of SIV measurements are planned to be used for estimation the eulerian mass fraction of liquid phase and the evaporation rate of dispersed droplets of aerosol jets. This can be obtained from the grayscale level of a pixel to a function of aerosol concentration, where black color means zero concentration of the liquid phase, and the grayscale level at the nozzle exit serves as a calibration value of the known initial concentration. Based on these data, the validity of the d-square law at low Re number values can be verified.

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