Ultra-High-Speed 3D Astigmatic PTV in Supersonic Underexpanded Impinging Jets

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High-speed particle laden flows can be found in a number of applications such as particle impactors, needle free drug delivery systems and cold gas dynamic spray processes. Common to all these processes are the acceleration of micron-sized particles (1 – 100 µm) to very high particle velocities (300 – 1200 m/s) via a high-speed gas flow such that the particles attain sufficient kinetic energy to penetrate or deposit onto a solid substrate upon impaction. Understanding how the particle motion is affected by the highly unsteady, turbulent and three-dimensional nature of the supersonic gas flow requires experimental data to resolve the individual three-component three-dimensional (3C3D) particle velocity over time and length scales comparable to their velocity and size. However, this is exceedingly difficult to achieve at supersonic speeds due to the large dimensional difference between the very small particles (O(10⁻³) m) and their very large velocities (O(10³) m/s).

The present paper presents measurements of the 3C3D particle velocities in a particle-laden supersonic jet flow by means of astigmatism particle tracking velocimetry (APTV) [3].

Experimental Method

The supersonic underexpanded jet flow is produced via a converging nozzle of diameter D = 2 mm and the flow is characterised by the nozzle pressure ratio (NPR) defined as the ratio between the static pressure upstream of the nozzle, p, and the ambient pressure, p0. The micron-sized particles with mean diameter d = 110 µm and specific density ρ = 1.06 g/cm³ are suspended co-axially into the gas flow (see [1] for details). The imaging system consist of an ultra-high-speed digital camera (Shimadzu HPV-1) capable of recording 102 consecutive image frames at a rate of up to 1,000,000 fps. The camera has a sensor size of 312 px x 260 px and a pixel pitch of 0.63 µm. In order to increase the spatial resolution the camera is equipped with a customised long-distance microscope to achieve a magnification of approximately 3. Astigmatism particle tracking velocimetry (APTV) [3] is used to measure the 3C3D particle velocity. This method enables full 3C3D measurements of the particle velocity using a single camera. The depth position of the particles is coded in the 2D images by adding a cylindrical lens (f = 80 mm) between the high-speed camera and the long-distance microscope. The particle images appear elliptically distorted according to their depth position in the volume. Using image-processing methods, the particle images height and width are determined and related to the depth position by an appropriate calibration. The size of the measurement volume is approximately 6D × 8D × 6D in the x, y and z-direction. Particle illumination at MHz rates is provided by a pulsed high-power LED system capable of producing light pulsed of sufficient energy and short duration (~500ns) [4]. Based on the reconstructed 3D particle positions the particle trajectories are obtained via an advanced tracking scheme that takes advantage of the high temporal resolution by using information from previous time steps and neighbouring particles to increase robustness and accuracy of the tracking method [2].

Results and Conclusion

The instantaneous particle distribution and particle velocity for NPR = 6.0, Z/D = 4 is shown in Figure 1 using laboratory coordinates (x, y, z). The distribution of the reconstructed particle positions is symmetric with respect to the jet centre axis as is expected for an axis-symmetric jet. Two distinct velocity regions are noticeable; the first region corresponds to high-speed particles that exit the nozzle at x/D = 0 and impinge at the substrate at x/D = 4. Depending on the NPR, the particles leave the nozzle with an average velocity of approximately 100–120 m/s, which is significantly lower than the local gas velocity of 345 m/s (speed of sound) at the nozzle exit. In principle, the smaller the particles and the longer the nozzle, the higher the particle exit velocity. As a consequence, the averaged particle Mach number at the nozzle exit Map = 1 – u/c is a high as 0.65-0.7 meaning that shocks may form at the trailing end of the particles (see [1] for visualisations of the particle flow interaction). After leaving the nozzle the particles are continuously accelerated in the streamwise direction by the surrounding gas flow and reach average impact velocities of 150 and 180 m/s for NPR = 3.75 and 6.0, respectively. The particles are accelerate by the surrounding gas flows in a manner depending on the local flow structure (i.e. NPR, Z/D) and it is also shown, that the flow structure influences the impingement angle of the particles and that a recirculation region forms above the flat plate.

Fig. 1 Instantaneous particle distribution and streamwise particle velocity u. Flow is from top to bottom.