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Tracking characteristics of tracer particles for PIV measurements in supersonic flows

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Abstract The tracking characteristics of tracer particles for particle image velocimetry (PIV) measurements in supersonic flows were investigated. The experimental tests were conducted at Mach number 4 in Multi-Mach Wind Tunnel (MMWT) of Shanghai Jiao Tong University. The motion of tracer particles carried by the supersonic flow across shockwaves was theoretically modelled, and then their aerodynamic characteristics with compressibility and rarefaction effects were evaluated. According to the proposed selection criterion of tracer particles, the PIV measured results clearly identified that the shockwave amplitude is in good agreement with theory and Schlieren visualizations. For the tracer particles in nanoscales, their effective aerodynamic sizes in the diagnostic zone can be faithfully estimated to characterize the tracking capability and dispersity performance based on their relaxation motion across oblique shockwaves. On the other hand, the seeding system enabled the tracer particles well-controlled and repeatable dispersity against the storage and humidity.

1. Introduction

The occurrence of shockwaves with physical interruption in compressible flows, where a significant flow deceleration occurs across a very thin region, challenges the applications of measurement techniques.[1] With the appearance of short interframing-time CCD cameras and nanosecond-duration double-pulsed Nd:YAG lasers, the recent extension of PIV technique in supersonic flows becomes mature and practical. Haertig et al.[2] performed nozzle calibration measurements in a shock tunnel at Mach number 3.5 and 4.5. Scarano[3] conducted a series of investigation on supersonic turbulent wakes as well as shockwave turbulent boundary-layer interaction. A challenging application of particle image velocimetry (PIV) was pioneered by Schrijer et al.[4,5] to investigate the flow over a double ramp configuration in a Mach number 7 flow. Schrijer and Walpot[6] pointed out that the reliability of PIV applications under extreme high-speed conditions demands smaller relaxation time of the tracer particles. Nanoparticle-based planar laser scattering (NPLS) method[7] was also

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developed to demonstrate the tracking ability of nanoparticles to capture the space-time structure in supersonic flows.

The quantitative determination of the particle tracking characteristics is commonly conducted by PIV measurements with the evaluation of the particle response time across a stationary shock wave. Earlier study demonstrated a response time of 3–4 μs for TiO_2 and more than 20 μs for Al_2O_3 particles.[8] Another PIV measurement claimed a relaxation time below 2 μs for TiO_2 particles from the particle velocity profile downstream of an oblique shockwave.[9] Then, the nanostructured Al_2O_3 aggregates around 10 nm in diameter yield a relaxation time of 0.27 μs, which is an order of magnitude reduction with respect to the compact TiO_2 nanoparticles.[10] A more recent discussion is given by Ragni et al.[11], who obtained the relaxation time of different solid particles in the range of 0.4–3.7 μs based on a systematic investigation. However, few investigation takes the characterization of compressibility and rarefaction effects into consideration. This motivates the present efforts to experimentally and theoretically analyze the particles' motion allowing for measurement conditions variation to develop the seeding-particle-selection and seeding-distribution techniques within a higher Mach number regimes.

The experiments were conducted by PIV techniques in Multi-Mach Wind Tunnel (MMWT) of Shanghai Jiao Tong University (SJTU). The tracer particles' motion across a shockwave was theoretically modelled considering compressibility and rarefaction effects and then experimentally analyzed from PIV measurements. It can yield qualitative information on particles' motion to estimate the available size of tracer particles in selection before experiments and analyze their effective aerodynamic diameters after experiments. In order to reach the requirements for tracer particles, advances in the seeding system integrating a pressurized vessel with a fluidized bed enabled the seeded particles to track the supersonic flows.

2. Experimental apparatus and procedure

Fig. 1 shows the diagram and components of MMWT, which is capable of providing supersonic and hypersonic flows with nominal Mach number Ma_∞ = 2.5, 3, 4, 5, 6, and 7, respectively. The blowdown-suction operation pattern extends the test duration time up to 20 s. The present experiments to analyze the characteristics of particles are operated at the freestream condition of nominal Mach number 4. The velocity of the supersonic mainflow in the test cabin is 800 m/s with total pressure of 0.5 MPa and total temperature of 400 K.

2.1. PIV system setup

Fig. 1 shows a double-frame digital PIV system composed of the laser, CCD camera, and synchronizer. The solid-state frequency-doubled Nd:YAG laser with a wavelength of 532 nm has a nominal energy of 500 mJ (stability ±4%) per pulse. Lasers are available with pulse width about 5 ns, and repetition rate of 1–10 Hz. The test cabin holds three windows with 200 mm diameter, which can be optically accessible for PIV measurements. PIV pictures within the illuminated region are taken from the front view by an IPX-11M CCD camera (4000 × 2672 pixels, 11 M resolutions, 12 bits). The camera uses high-performance progressive-scan interline CCD chips, capable of acquiring two images with a minimum pulse separation of 200 ns and framing rate of 5 Hz. The time interval between pulses is a critical parameter, i.e. the particles moving time t, for matching the PIV system to the flow velocity. The particle images are recorded at 5 Hz resulting in 50 image pairs per tunnel run. A 105 mm SIGMA lens at $f\#$ = 2.8 is carefully chosen to gain the particle images with sufficient collected energy and reduce the image blur due to aero-optical aberrations. The camera is fitted with a narrowband-pass 532 nm filter to minimize ambient light interference and almost tangential to the wall to alleviate the reflections.

2.2. Particles' seeding technique

Fine and non-agglomerated particles are required for PIV measurements under the extreme high-speed conditions. TiO_2 particles with nominal diameter of 30 nm are chosen as the tracers in the present flow measurement. However, the humidity and prolonged storage make these particles a strong tendency to form agglomerates several times larger than the

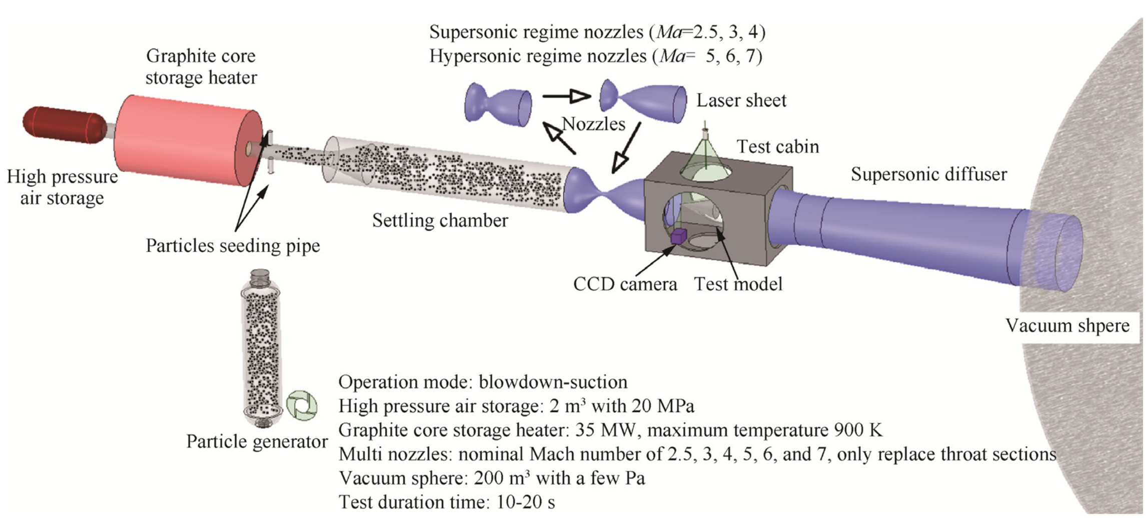

Fig. 1 Multi-Mach numbers wind tunnel (Ma_∞ = 2.5–7) and PIV system setup.

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