PIV imaging of discharge-induced blast waves: Numerical reconstruction of an actual velocity field

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Abstract Particle image velocimetry (PIV) is applied here to capture expanding cylindrical and semi-cylindrical blast waves induced by nanosecond volume and surface discharges, respectively. To quantify and predict the bias errors associated with PIV imaging of such transient high-speed flows, we present a numerical particle tracking methodology. The modified numerical velocity fields are in remarkable agreement with the PIV data. The results show that, at operating pressures under 250 Torr, the bias errors and uncertainties of PIV measurements may easily exceed 30%. Our results offer new possibilities for successful future validation of numerical models against velocimetry experiments.
Keywords: PIV, CFD, high-speed flows, shock waves

1 Introduction

Localized energy deposition from nanosecond pulsed surface or volume gas discharges have been studied intensively from the viewpoint of active flow control [1][2]. Fast energy thermalization in the short-pulse discharges results in formation of high-speed pressure or blast (shock) waves that can manipulate an external flow in a desirable manner [3][4]. Computational fluid dynamics (CFD) simulations combined with state-of-the-art quantitative flow visualization techniques, such as PIV, can become an incredibly powerful tool to investigate the discharge-induced fluid flow. It is well established, however, that, in high-speed flows, the discontinuities in the velocity field due to shock and blast waves cause the velocity of seeding particles to significantly diverge from that of the surrounding fluid [5][6]. This imperfect particle response decreases the PIV measurement accuracy and thus hinders the direct comparison between experimental and simulation data for such flows.

While ongoing studies have been investigating the possibilities to improve the accuracy of particle-based velocimetry techniques when applied to complex high-speed flows, we propose the methodology to numerically quantify and predict experimental bias errors associated with particle inertia. To validate our proposed methodology, we performed particle image velocimetry (PIV) measurements of an expanding semi-cylindrical and cylindrical blast wave induced by a pulsed plasma discharge. Then we simulated the dynamics of the tracer particles in the resulting transient flow, as predicted by CFD, and compared the obtained velocity profiles with the PIV data. Here, we do not consider uncertainties linked to optical distortions or polydispersity of the particles.

2 Experimental PIV imaging

The experiments were conducted in a shock tube facility with a built-in discharge test chamber to measure flow parameters induced by nanosecond pulsed discharge of a special configuration [7]. Two sliding discharge arrangements, 30-mm in width and 100-mm in length, were mounted on the top and bottom walls of the test chamber, separated by 24 mm. The voltage pulse applied to the discharge electrodes was 25 kV; the discharge current reached 1 kA and lasted about 300 ns. The discharge could be operated in either a volume or a surface discharge mode. The surface discharge, when initiated at a pressure of 240 Torr, consisted of 4-6 discharge channels randomly distributed along the 100-mm discharge gap (Fig. 1). Pulsed energy deposition generated semi-cylindrical blast waves propagating outward from each discharge channel. The volume discharge mode developed at pressures of 120-160 Torr, when most of the discharge energy was localized into a single 24-mm long plasma column.

The velocity fields of the induced flow were captured at a specified time instant after the discharge pulse using a PIV system (LaVision). Solid particles of titanium dioxide (1 μm median diameter) served as the flow tracers and were illuminated by a double-pulse 532 nm laser (180 mJ per pulse). A 2.5-mm thick vertical laser sheet was oriented perpendicular to the surface discharge channels or along the axis of the plasma column. The interval between two laser pulses was set to 2 or 3 µs. The images were recorded by a LaVision ImagerProX2M camera and processed using a multi-step cross-correlation algorithm (DaVis software). Fig. 1 (left) shows an example PIV velocity field of a semi-cylindrical blast wave from a surface discharge channel captured 7.5 µs after the discharge pulse; and figure 1 (right) shows the corresponding radial velocity profile (blue squares).

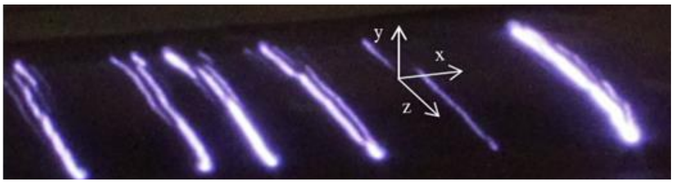

Fig. 1 Photograph of the sliding surface discharge in air at 240 Torr.

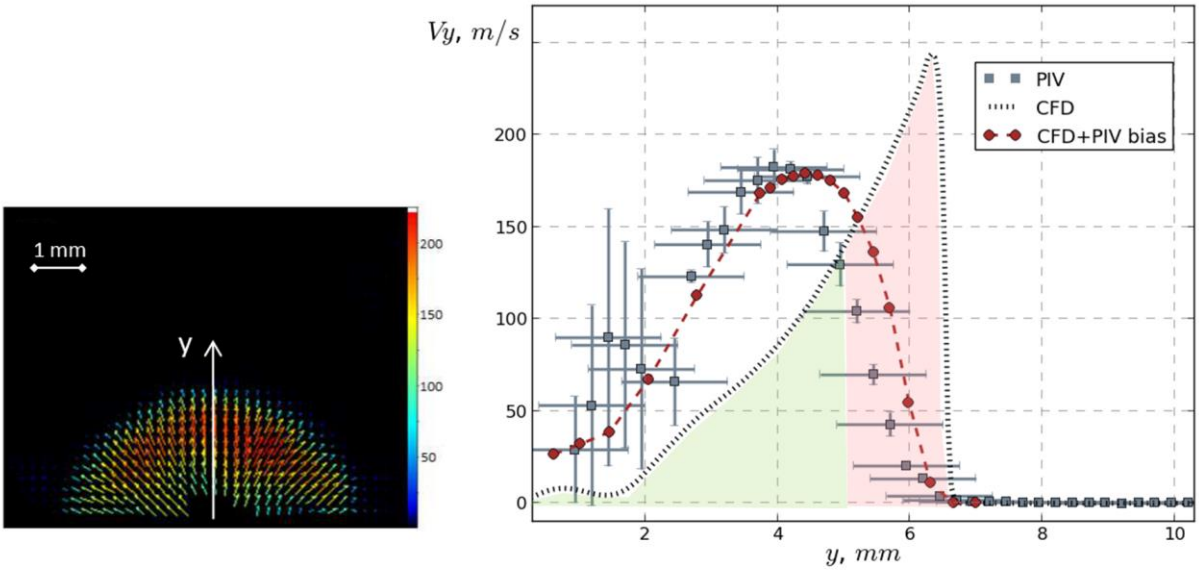

Fig. 2 PIV velocity vector field of a semi-cylindrical blast wave from a surface discharge channel 7.5 µs after the discharge pulse (left) and corresponding PIV, CFD and modified CFD velocity profiles along the y-axis (right).

3 Numerical methodology

The numerical simulations were performed using an in-house CFD code for solving 3D compressible unsteady Navier-Stokes equations [7]. The pulsed energy deposition was modelled as an instant increase in energy within a cylindrical (volume discharge channel) or semi-cylindrical volume (sliding surface channel). The CFD simulations gave time-varying flow parameters (density, velocity, temperature, etc). These parameters were then used to model the dynamics of “virtual” tracer particles in the discharge-induced transient flow. For that, we integrated the particle trajectories using different formulations for the particle drag coefficient available in literature [8][9]. We also took into account that the PIV measured particle velocity is averaged over the separation time between two laser pulses.

Fig. 2 also plots the velocity profile at time instant 7.5 µs obtained from the CFD simulation and the corresponding velocity profile of “virtual particles” calculated using the numerical particle tracking methodology. Pink area marks the locations in the flow behind the blast wave where the particle velocities are lower than that of the surrounding fluid. The particles are accelerated by the blast wave reaching their maximum velocity ~2 mm behind the front. The value of maximum velocity is about 30% lower than the CFD-predicted value. Further downstream, the accelerated tracer particles move faster than the surrounding fluid due to inertia (green area in Fig. 2).

As seen in Fig. 2 (right), the trajectories of “virtual” particles within the CFD-predicted flow field are in good agreement with those of the PIV particles. If we assume that the unmodified CFD simulation accurately predicts the actual flow velocity field, we can quantify the error of the PIV data. This error results in: 1)

broadening of the velocity profile near the blast wave front; 2) shifting of the position of the velocity maximum; 3) much lower values of the measured velocity maximum.
In the experiments with a cylindrical blast wave from a column-shaped pulsed discharge initiated at pressures 120-160 Torr, we found that the discrepancy between the fluid and the particle velocity profiles is even larger. The maximum measured velocity was generally more than 50% lower than the CFD-predicted value (without particle tracking). This may be explained by increased particle inertia in rarefied flows.

4 Conclusions

Flow velocity fields generated by nanosecond pulsed discharges have been measured using a new numerical methodology. The methodology provides a way to quantify and predict the uncertainty of PIV measurements in high-speed transient flows related to the dynamics of the tracer particles. The methodology has been tested on the PIV measurements of cylindrical and semi-cylindrical blast-waves induced by pulsed surface and volume discharges. The results have shown remarkable agreement between the velocity profiles of PIV and "virtual" tracer particles. Since the response of particles to discontinuities like shock waves is always limited, incorporating sources of PIV bias errors into CFD models has potential as a new way of interaction between numerical simulations and experimental flow velocimetry.

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