

Electronic supplementary materials

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Flow structure and mixing characteristics of a transverse jet in supersonic crossflow under varied boundary layers

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Section S1: Calibration of experimental parameters

Prior to experimental testing, a calibration wedge is employed to determine the mainstream flow Mach number. The grayscale flow field image (Fig. S1) reveals the shock wave position through abrupt intensity transitions. Using the measured wedge angle (θ) and shock wave angle (β), the mainstream Mach number is calculated as 2.68 via the θ - β -Mach relation.

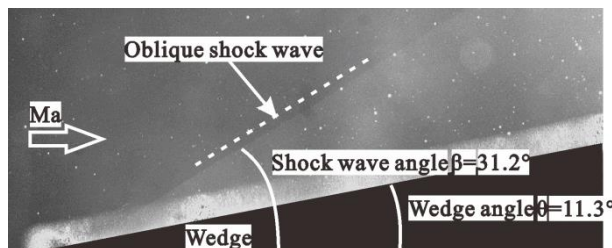


Fig. S1 Calibration of mainstream Mach number using a wedge

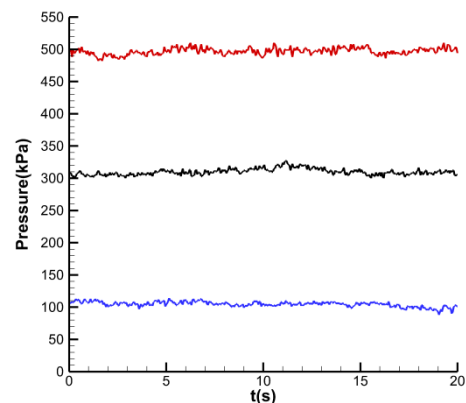


Fig. S2 Injection total pressure

The injection total pressure was systematically set to 100, 300, and 500 kPa to establish dynamic pressure ratios (J) of 1.64, 4.92, and 8.19, respectively, relative to the mainstream flow. Fig. S2 documents the experimentally measured injection total pressure, confirming supply pressure fluctuations remained below 5% throughout testing.

Section S2: Assessment of Particle Density

The primary objective of this assessment was to ensure that each interrogation window contained a sufficient number of particles to satisfy the stringent accuracy requirements of the cross-correlation algorithm.

An adaptive thresholding method combined with morphological filtering was first employed to identify tracer particles from the raw PIV image (Fig. S3(a)). This procedure effectively eliminated noise-induced spurious signals, yielding a total of 142889 valid particles. The interrogation window size was set to 32 pixels×32 pixels, and the entire image was partitioned into a grid of such windows. Fig. S3(b) presented a contour map of the particle count per window, revealing that regions of lower particle concentration were predominantly located within the boundary layer.

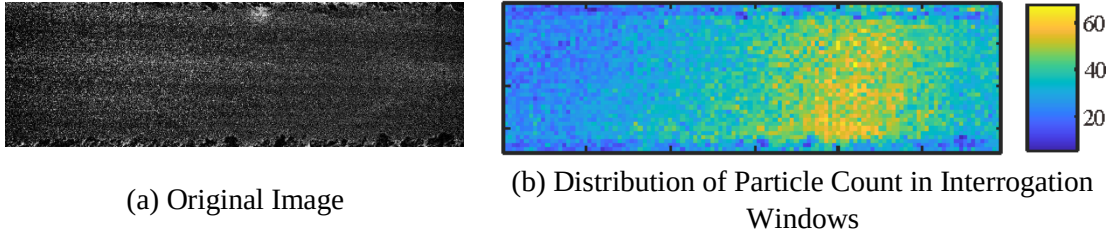


Fig. S3 Sample Particle Images and Distribution Analysis

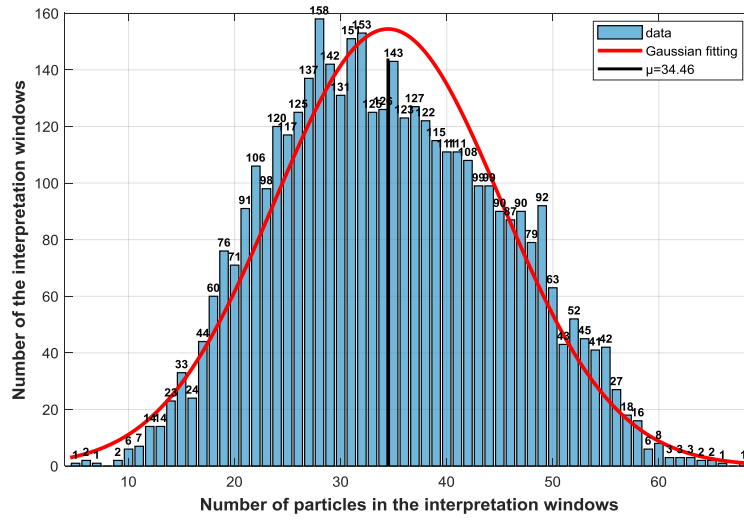


Fig. S4 Statistical Histogram of Particle Distribution Per Interrogation Window

The particle count within each interrogation window was subsequently analyzed statistically. A Gaussian distribution was fitted to the histogram of particle counts, as illustrated in Fig. S4. The distribution exhibited a mean particle count of $\mu=34.46$ per window, with a standard deviation of $\sigma=10.67$. Approximately 95.9% of the interrogation windows fell within the $\mu \pm 2\sigma$ range, indicating a statistically robust distribution.

In the present dataset, 99.7% of the interrogation windows contained no fewer than 10 particles to ensure a sufficiently high detection probability during cross-correlation processing, thereby confirming the adequacy of particle seeding density. Furthermore, the coefficient of variation ($C_v=\sigma/\mu$) was calculated to be 0.31, indicating a reasonably uniform particle concentration across the entire field of view. Collectively, these quantitative metrics demonstrated that the particle seeding quality fulfilled the requirements for high-precision PIV computations.

Section S3: Calibration of boundary layer thickness

To investigate the influence of boundary layer thickness on the flow dynamics, two experimental configurations with distinct nozzle-to-orifice distances were implemented. Fig. S5 compares the velocity profiles for both configurations, confirming the proportional relationship between nozzle-orifice distance and boundary layer thickness. The distances of 80 mm and 280 mm between the nozzle exit and jet orifice generated boundary layer thickness $\delta=1$ mm and $\delta=4$ mm, respectively, while maintaining identical mainstream velocities and jet parameters.

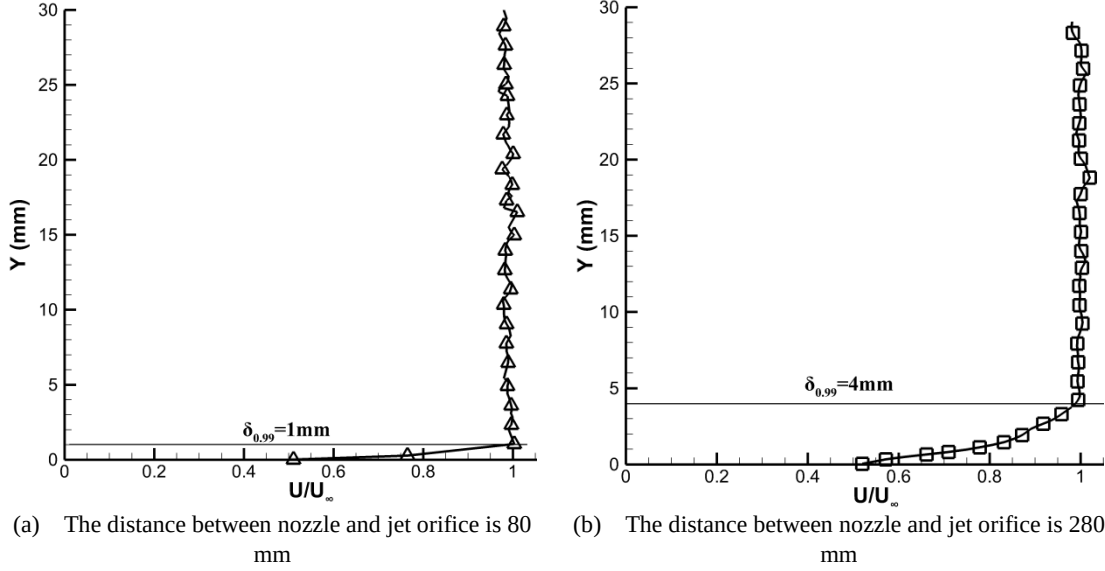


Fig. S5 Developing velocity profile in entrance region

Section S4: Analysis method for jet penetration depth

Tracer particles were uniformly introduced into the mainstream flow. Nevertheless, inhomogeneous distributions of particle concentration emerged as a result of the jet-mainstream mixing process, which manifested as pronounced grayscale variations in the acquired images. To quantify the jet penetration depth, time-averaged grayscale images were generated, with 90% of the maximum grayscale value adopted as the threshold for penetration depth quantification.

Edge detection was performed using the Canny algorithm, which formed the basis for identifying jet penetration boundaries. For statistical robustness, penetration boundary coordinates along the x axis were aggregated from transient images (Fig. S6). These data were assumed to follow a normal distribution, with a confidence interval of $1-\alpha$ ($\alpha=0.05$). Valid penetration depth measurements were derived exclusively from samples within this confidence interval. The mean value of these validated samples defined the final penetration depth, as illustrated in Fig. S7.

A statistical analysis was performed on the penetration boundaries extracted from multiple transient grayscale images. The average relative standard deviation (RSD) was calculated across all boundary points of the transverse jet penetration, as illustrated in Fig. S8. As the number of images included in the statistical sample increased, the average RSE progressively decreased. The difference between the statistical results obtained from 100 images and those from 120 images was less than 1%. Therefore, it

could be concluded that the statistical outcome based on 100 images met the requirement for convergence.

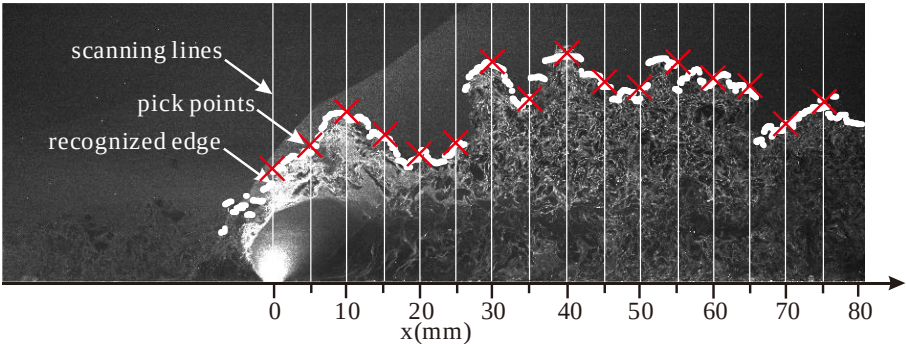


Fig. S6 Diagram of edge detection and jet penetration boundary extraction

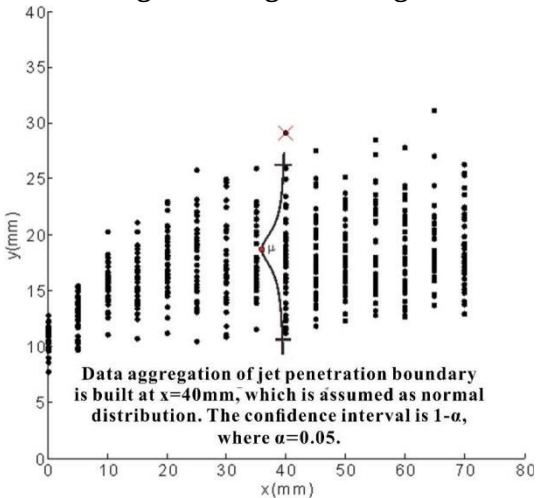


Fig. S7 Diagram of jet penetration depth execution process

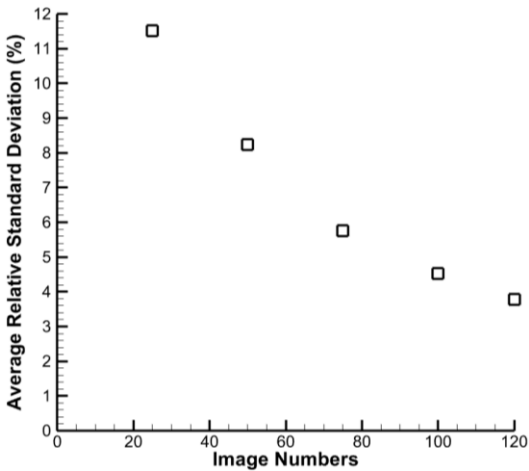


Fig. S8 Relationship between the number of images and the average relative standard deviation of the penetration boundary