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Fine-Scale Velocity Measurement of High-Pressure Transient Multiphase Jets via Adaptive Feature Enhancement and Improved Window Deformation PIV

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ABSTRACT: Quantitative measurement of the high-speed gas-liquid-solid multiphase jets generated during the transient discharge of high-pressure vessels remains a significant challenge. Traditional Particle Image Velocimetry (PIV) techniques often fail in these scenarios due to the intense self-luminous interference, high transient velocities, and the absence of pre-seeded tracer particles. To address these issues, this paper proposes a robust non-intrusive measurement scheme integrating an adaptive image enhancement strategy with an improved cross-correlation algorithm. First, a preprocessing framework combining Contrast Limited Adaptive Histogram Equalization (CLAHE) and frequency-domain high-pass filtering is developed to suppress background noise and reconstruct fluid textures into high-contrast “pseudo-particle” features. Second, a multi-grid iterative cross-correlation algorithm incorporating window offset and window deformation techniques is established to enhance measurement accuracy in strong shear flows. The algorithm’s performance was rigorously validated using synthetic particle images and a theoretical Rankine vortex model. Results demonstrate that the proposed method achieves optimal accuracy for feature diameters of 1.5–3.0 pixels and maintains robust performance even under high noise levels (normalized noise intensity < 0.4). The method was subsequently applied to visualize the thermal runaway venting of an NCM18650 lithium-ion battery. The evolution of the jet velocity field was successfully captured, revealing a maximum projected velocity of visible jet features approaching 130 m/s during the violent multi-directional ejection phase. Furthermore, fine-scale shear vortex structures within the jet boundary layer were clearly resolved, verifying the algorithm’s capability to capture detailed flow topologies. This study provides an effective optical measurement solution for analyzing the dynamics of complex, high-speed multiphase flows in harsh environments.

KEYWORDS: Particle image velocimetry (PIV); multiphase jet; image enhancement; window deformation; transient flow

1 Introduction

The thermal runaway (TR) of lithium-ion batteries is typically characterized by the violent ejection of high-temperature, high-pressure gas-liquid-solid multiphase jets, posing critical safety challenges in energy storage applications [1–4]. Quantitatively resolving the complex dynamics of these transient jets is fundamental for optimizing safety venting mechanisms, yet it remains a formidable task due to the extreme velocities (>100 m/s) and the harsh, self-luminous environment [5,6].

Currently, experimental investigations into the fluid dynamics of battery thermal runaway have predominantly focused on macroscopic characterization using diverse optical and intrusive techniques. Researchers such as Wang et al. [7], Chen et al. [6], and Chen et al. [8] employed high-speed visible and infrared cameras to parametrically study jet flame geometry (e.g., ejection angle, area duty cycle, and flame height) under various SOC and triggering conditions. Similarly, García et al. [9] combined high-speed Schlieren imaging with natural light photography to visualize the density gradients, estimating a peak primary jet velocity of 40 m/s. Regarding quantitative velocimetry, existing methods often rely on indirect estimations or low-resolution tracking, leading to significant discrepancies. Several studies attempted to deduce jet velocity from mass loss rates (e.g., Zhou et al. [10], Huang et al. [11]), reporting velocities of 8–42 m/s, but this bulk-average approach fails to resolve spatial distribution. Others employed manual particle tracking (Zou et al. [12], Mao et al. [13]), which is inherently subjective and sparse. Intrusive measurements using Pitot tubes (Qin et al. [14], Wang et al. [15], Jia et al. [16]) reported extreme velocities up to 270 m/s, but probes significantly disturb the flow field. On the computational side, Li et al. [17] performed CFD simulations predicting velocities up to 650 m/s, but lacked experimental validation. In summary, the wide variation in reported data and the limitations of current techniques—ranging from intrusiveness to low resolution—underscore the urgent necessity for a high-precision, non-intrusive, whole-field velocimetry approach.

More broadly, the present problem also belongs to the general class of optical measurement in complex dispersed or partially opaque multiphase flows. As reviewed by Poelma [18], such flows are difficult to quantify using conventional optical techniques because of limited optical access, reduced signal-to-noise ratio, cross-talk, and biased data drop-out. These challenges are particularly severe in battery thermal runaway jets, where the flow is highly transient, self-luminous, and composed of gas, droplets, and solid fragments. In this sense, the present work is motivated not only by battery-safety applications, but also by the broader need for robust feature-based velocimetry in harsh multiphase-flow environments.

Consequently, Particle Image Velocimetry (PIV) has become the preferred diagnostic tool to overcome these limitations. However, applying standard PIV to TR jets faces distinct challenges. Since pre-seeding artificial tracers is impossible, the method must rely on non-uniform “pseudo-tracers” (e.g., electrolyte droplets), which are often obscured by strong background halation, leading to a critically low signal-to-noise ratio (SNR). Furthermore, the jet boundary is dominated by strong shear layers. Conventional Fast Fourier Transform (FFT) based cross-correlation methods assume a “rigid window” displacement, failing to account for the rotation and deformation of fluid parcels. This results in “peak-shaving” and degraded accuracy in high-gradient regions, rendering standard algorithms insufficient for such extreme flows.

With the maturation of experimental PIV hardware, the research frontier has shifted towards optimizing velocity extraction algorithms to handle these complexities. Cross-correlation (CC) remains the fundamental method [19]. To address the limitations of fixed windows, Scarano [20] introduced the Window Deformation Iterative Multi-grid (WIDIM) algorithm. By progressively refining window sizes and iteratively deforming the windows to match the local flow gradients, WIDIM significantly reduces measurement errors in shear layers. Further refinements, such as the variational approach by Becker et al. [21], replaced rectangular windows with adaptive Gaussian-weighted windows. In parallel, Optical Flow and Deep Learning approaches [22–27] have emerged as hotspots. However, despite their potential, optical flow methods often struggle with robustness under large displacements and significant illumination changes typical of TR jets. Therefore, optimizing the robust WIDIM framework remains the most viable pathway for accurate velocimetry in battery safety research.

To address these specific limitations, this study proposes a robust optical measurement framework tailored for tracer-free, high-speed multiphase flows. We first introduce an adaptive image preprocessing

strategy combining CLAHE and frequency-domain high-pass filtering to suppress background noise. Furthermore, an improved multi-grid IWD algorithm is implemented that builds upon the foundational work of Scarano [20], incorporating adaptive window deformation to accurately resolve the high-speed jet core and the fine-scale structures within the shear layer. The proposed method is validated against synthetic particle images and a Rankine vortex model, and subsequently applied to characterize the spatiotemporal evolution of full-scale battery thermal runaway jets.

2 Methodology

To address the challenges of intense self-luminosity, low signal-to-noise ratio, and high velocity gradients inherent in high-pressure multiphase jets, a comprehensive optical measurement framework was established. The framework consists of two core stages: (1) Pseudo-particle feature extraction, which transforms continuous fluid textures into discrete traceable patterns; and (2) an improved iterative cross-correlation algorithm, which integrates window offset and deformation techniques to accurately resolve complex flow topologies.

2.1 Pseudo-Particle Feature Extraction via Adaptive Enhancement

The raw shadowgraph images of the multiphase jet are characterized by a narrow gray-level distribution and a lack of pre-seeded tracer particles, making them unsuitable for direct PIV analysis. A two-step preprocessing strategy was implemented to construct high-quality “pseudo-particle” features.

To address the non-uniform background illumination, five mainstream contrast enhancement algorithms (including HE, Gamma Correction, and CLAHE) were evaluated. As shown in Fig. 1, the visual comparison (a) and quantitative metrics (c,d) demonstrate that Contrast Limited Adaptive Histogram Equalization (CLAHE) achieves the best balance between dynamic range expansion and noise suppression. Specifically, the CLAHE-processed image maintains a high Peak Signal-to-Noise Ratio (PSNR) while achieving the highest information entropy (reaching 6.15), significantly outperforming other methods. Consequently, CLAHE (optimized with a tile size of 15×15 pixels and a clip limit of 0.01) was adopted as the standard preprocessing step.

To mitigate the “peak-locking” effect caused by the continuous cloud-like appearance of the jet, a Frequency-Domain High-Pass Filtering technique was subsequently applied. This process effectively strips low-frequency components—representing the overall jet contour and background glow—while retaining high-frequency texture information. The filtering is implemented via spatial subtraction using a Gaussian kernel:

$$I_{HP}(x, y) = I_{CLAHE}(x, y) - [I_{CLAHE}(x, y) * G_{\sigma}(x, y)] \quad (1)$$

where G_{σ} is a Gaussian low-pass filter with a standard deviation $\sigma = 4$. This operation reconstructs the fluid textures into discrete, high-contrast speckles with characteristic diameters of 2–3 pixels, as shown in Fig. 2, serving as effective “pseudo-particles” for cross-correlation.

In addition, it should be noted that high-temperature plume motion may introduce refractive-index-gradient-induced optical distortions, which manifest as smooth large-scale intensity fluctuations in shadowgraph images. The high-pass filtering step helps attenuate these low-frequency background variations together with halo and non-uniform illumination, thereby improving the robustness of the subsequent cross-correlation analysis to thermal-optical interference. Nevertheless, residual apparent distortion may still persist in strongly heated gaseous regions with weak visible textures.

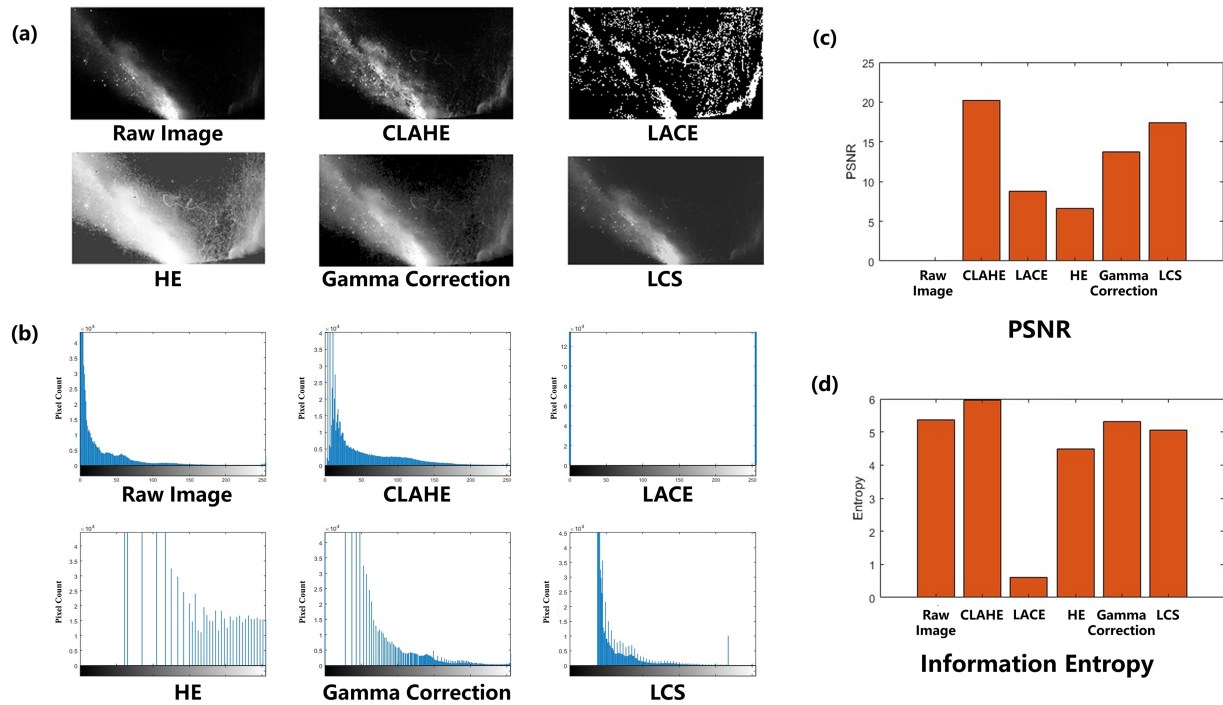


Figure 1: Performance comparison of different image enhancement algorithms: (a) visual effects; (b) gray-level distributions; (c) PSNR; (d) information entropy.

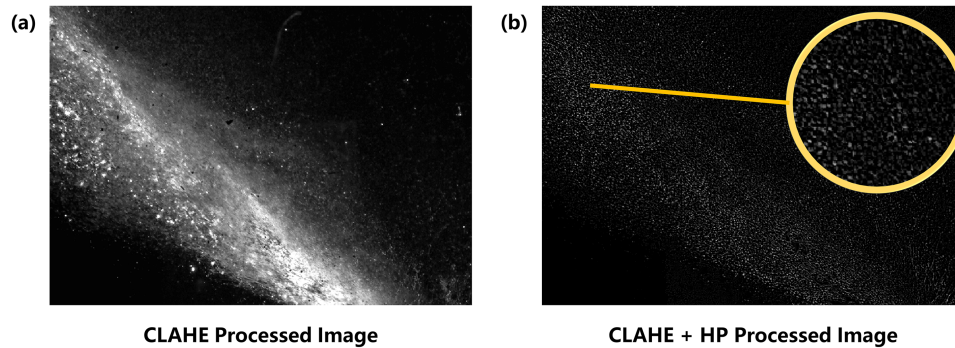


Figure 2: Effect of high-pass filtering on feature extraction: (a) image after CLAHE enhancement; (b) resulting pseudo-particle.

2.2 Iterative Window Deformation Cross-Correlation

Resolving the velocity field of a high-pressure transient jet presents two fundamental challenges: (1) a large velocity dynamic range (0~170 m/s), which risks particle loss in small windows; and (2) intense shear deformation at the jet boundary, which distorts particle patterns. To address these issues, an improved algorithm integrating Multi-grid Iteration, Discrete Window Offset (DWO), and Window Deformation was developed.

2.2.1 Multi-Grid Strategy with Discrete Window Offset

To reconcile the fundamental conflict between capturing large-scale displacements and resolving micro-scale turbulent structures, a coarse-to-fine Multi-grid Iterative Scheme is employed. The calculation process

follows a hierarchical pyramid structure, initiating with a large interrogation window (IW) size (e.g., 128×128 pixels) to reliably capture the full trajectory of high-speed fluid parcels that would otherwise exit smaller windows. The coarse displacement field obtained from the initial pass is then smoothed and used as a predictor for the subsequent level, where the IW size is progressively reduced (e.g., 64×64 to 32×32 to 16×16) with a 50% overlap ratio. The schematic of this iterative refinement process is illustrated in Fig. 3, showing how the displacement field is progressively refined from the coarse grid to the fine grid. This strategy effectively decouples the global flow topology from local fluctuations, allowing the algorithm to resolve fine details without losing track of the main flow.

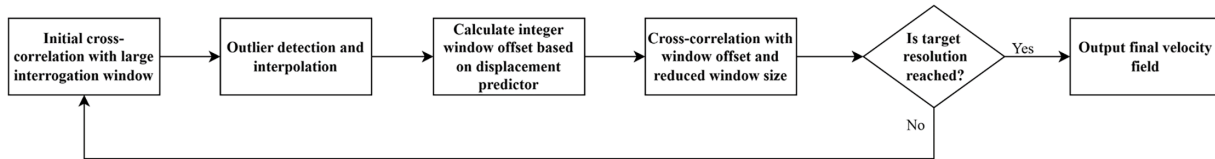


Figure 3: Schematic of the multi-grid iterative refinement process with discrete window offset.

Furthermore, to mitigate the “in-plane loss” phenomenon common in high-speed flows—where particles move entirely out of the interrogation area between frames—a Discrete Window Offset (DWO) technique is integrated into each iteration. By shifting the reading position of the IW in the second frame by an integer pixel amount (Δx , Δy) based on the displacement predictor from the previous pass, this adaptive mechanism ensures maximum spatial overlap of the particle groups. Consequently, the signal-to-noise ratio in high-velocity regions is significantly preserved, enabling robust measurement even when displacements are large relative to the final window size.

It should be noted that the present shadowgraph-PIV framework is inherently a planar measurement technique. The calculated vectors therefore represent the projected in-plane motion of visible jet features captured within the laser-illuminated imaging plane. While the DWO strategy effectively mitigates in-plane loss-of-pairs caused by large frame-to-frame displacements, it cannot fully compensate for decorrelation induced by true out-of-plane motion. Consequently, in strongly three-dimensional eruptive stages, out-of-plane transport may weaken local correlation peaks and increase the uncertainty of individual vectors.

2.2.2 Adaptive Window Deformation for Shear Flow

In the boundary layer of the jet, fluid parcels undergo significant rotation and shear deformation within the exposure time. Traditional rigid square windows fail to match these distorted patterns, leading to asymmetric broadening of the correlation peak and a consequent degradation in measurement accuracy. To address this limitation, a Window Deformation technique is integrated into the final iterations of the calculation. As illustrated in Fig. 4, the algorithm utilizes the local velocity gradient tensor derived from the previous iteration to model the deformation field. The interrogation window in the second frame is inversely deformed and re-sampled using high-order B-spline interpolation to match the geometric shape of the fluid parcel in the first frame. This adaptive correction effectively restores the correlation between deformed particle patterns, significantly suppressing spurious vectors in high-vorticity regions and enhancing the resolution of complex flow structures at the jet interface.

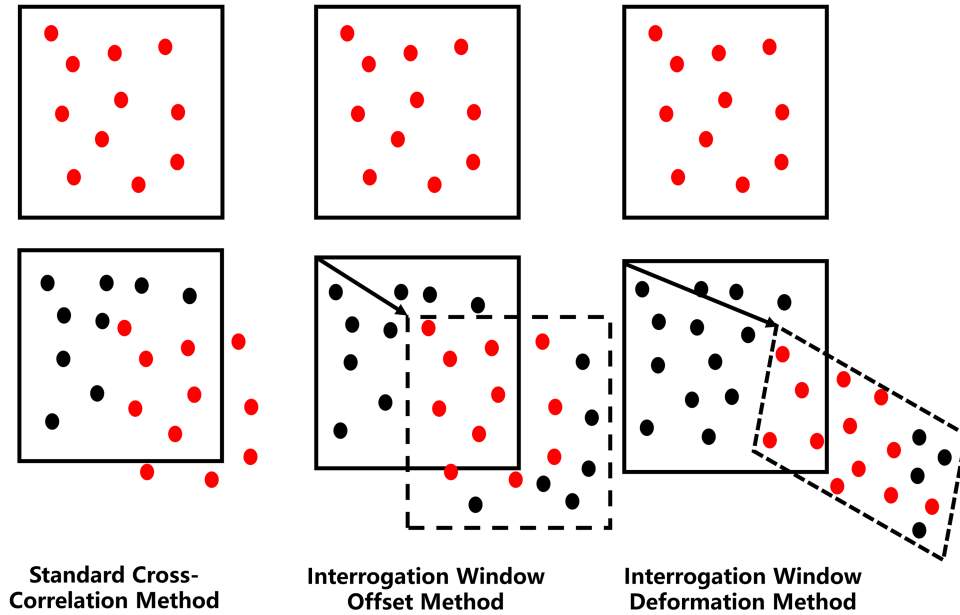


Figure 4: Schematic illustration of standard, offset, and deformed interrogation windows.

3 Performance Evaluation of the Algorithm

Before applying the proposed method to the complex jet flow, it is essential to quantitatively validate its accuracy and robustness under controlled conditions. This section evaluates the algorithm's performance using standard synthetic particle images generated via Monte Carlo simulation and a theoretical vortex model.

3.1 Accuracy Assessment via Synthetic Particle Images

To systematically analyze the influence of particle characteristics and environmental noise on measurement error, a series of synthetic image pairs were generated. The intensity distribution of each particle was modeled as a two-dimensional Gaussian function:

$$I(x, y) = I_0 \exp\left(-\frac{8\left((x - x_0)^2 + (y - y_0)^2\right)}{d_p^2}\right) \quad (2)$$

where I_0 is the peak intensity, (x_0, y_0) is the particle center, and d_p is the particle diameter. The measurement accuracy is quantified using the Root Mean Square Error (RMSE), defined as:

$$E_{\text{RMS}} = \sqrt{\frac{1}{N} \sum_{i=1}^N \left[(u_{\text{meas},i} - u_{\text{real},i})^2 + (v_{\text{meas},i} - v_{\text{real},i})^2 \right]} \quad (3)$$

As illustrated in Fig. 5, the particle diameter (d_p) plays a critical role in shaping the cross-correlation function. When the particle diameter is small ($d_p < 1.5$ pixels), the correlation peak becomes extremely sharp and occupies very few pixels, leading to the “peak-locking effect” where the sub-pixel Gaussian fitting is biased towards integer values. Conversely, as the diameter increases beyond 4.0 pixels, the correlation peaks broaden significantly (as seen in the 3D surface plots for $d = 7.5$ and $d = 10$), which reduces the sensitivity of peak localization and lowers the signal-to-noise ratio. The quantitative error curves indicate

that both the Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) are minimized when d_p falls within the optimal range of 1.5 to 3.0 pixels, where the RMSE is maintained below 0.05 pixels. This finding strongly validates the effectiveness of the preprocessing strategy proposed in Section 2.1, as the extracted “pseudo-particles” have a characteristic diameter of approximately 2.5 pixels, precisely matching this high-accuracy zone.

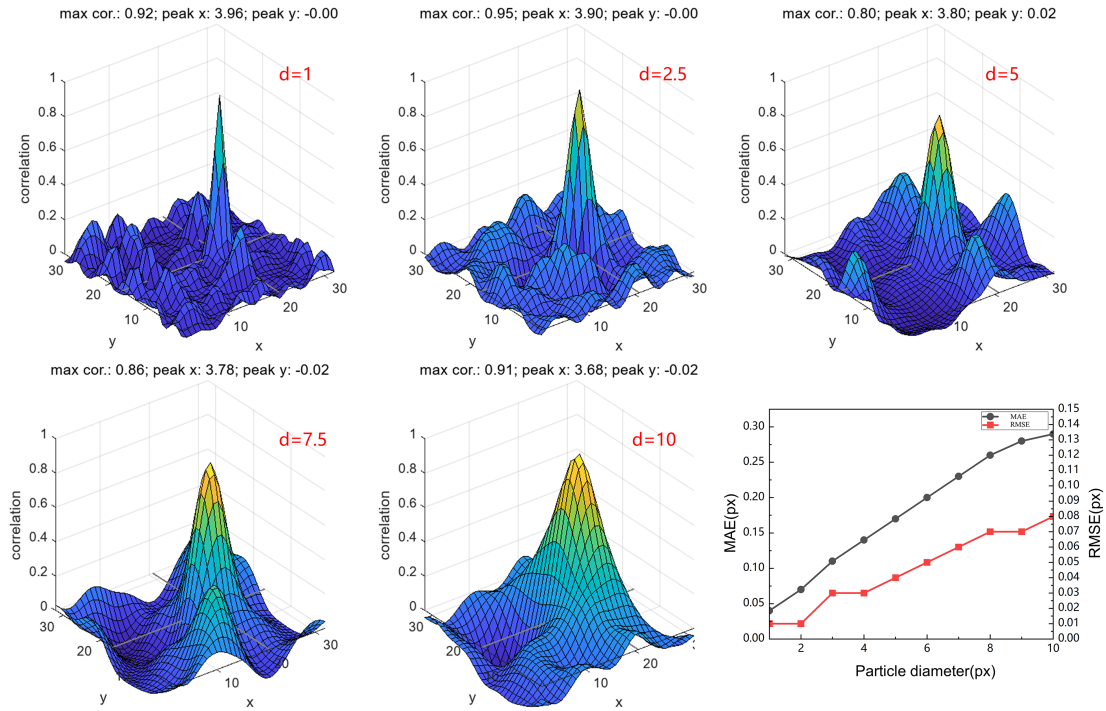


Figure 5: Effect of particle diameter on cross-correlation peak morphology and measurement error.

In addition to particle size, the seeding density (ρ) directly affects the reliability of the correlation calculation. As shown in Fig. 6, at low densities ($\rho < 5$ particles/IW), the lack of effective tracer pairs often leads to signal starvation and a high probability of spurious vectors. However, as the particle density increases, the effective information content within the interrogation window rises, causing the measurement error to decrease rapidly. The accuracy stabilizes once the density exceeds 10–15 particles/IW. Since the “pseudo-particle” field generated by the high-pass filtering algorithm typically yields a high feature density well above this saturation threshold, the proposed method ensures sufficient signal strength for reliable velocity extraction even in complex flow regions.

Furthermore, the robustness of the algorithm against environmental noise is critical, as the experimental high-pressure jet venting is inherently characterized by strong thermal radiation and scattering noise. To evaluate this, Gaussian white noise with varying intensities (I_n) was superimposed on the synthetic images. As illustrated in Fig. 7, the algorithm demonstrates a robust response profile. For low to moderate noise levels ($I_n < 0.3$), the RMSE remains stable below 0.05 pixels, indicating that the discrete window offset strategy effectively suppresses background fluctuations. Although a critical threshold is observed when I_n exceeds 0.4, causing a noticeable upward trend in error due to the distortion of the correlation peak, the algorithm maintains acceptable performance even under severe noise conditions ($I_n = 0.6$), with the RMSE controlled within 0.15 pixels. This confirms that the proposed method is capable of extracting accurate motion information from the low-SNR recordings typical of thermal runaway experiments.

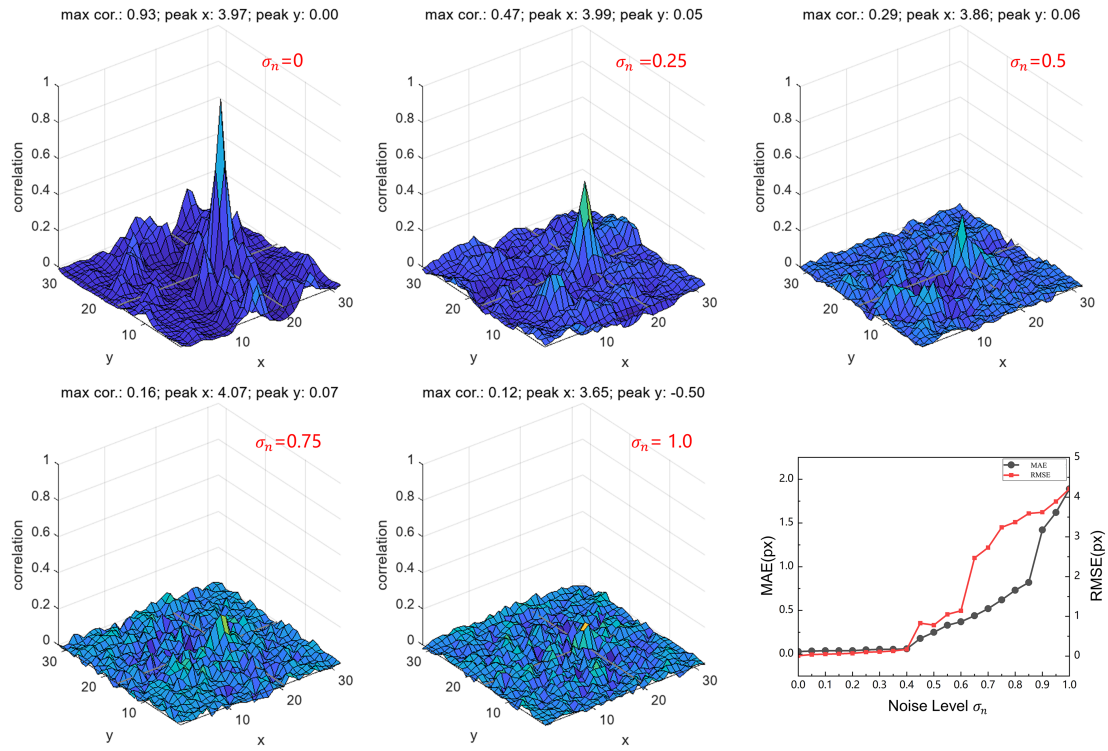


Figure 6: Effect of particle seeding density on cross-correlation peak morphology and measurement error.

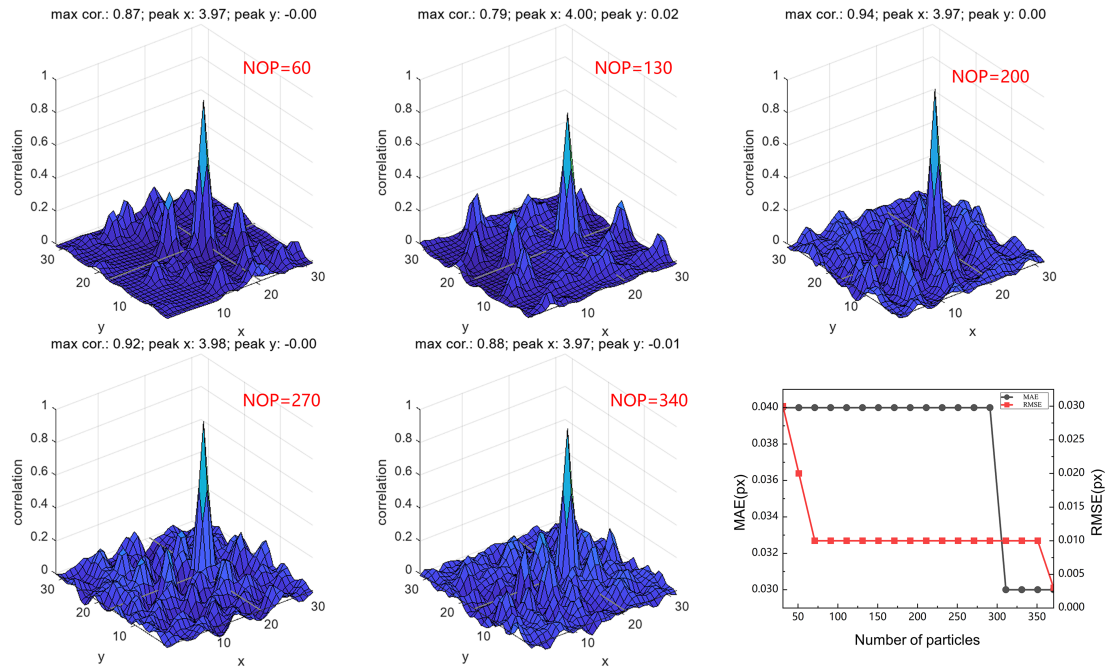


Figure 7: Effect of background noise intensity on cross-correlation peak morphology and measurement error.

3.2 Validation in Strong Shear Flow via Rankine Vortex

To evaluate the algorithm's capability in resolving high-gradient flow structures—which are critical for characterizing the shear layers of the jet—a synthetic Rankine Vortex flow field was generated. The Rankine vortex is an ideal benchmark model as it combines a central forced vortex (solid-body rotation) with an outer free vortex, creating a singularity in the velocity gradient at the vortex core radius (R). The tangential velocity u_θ is defined as:

$$u_\theta(r) = \begin{cases} \omega r, & r \leq R \\ \frac{\omega R^2}{r}, & r > R \end{cases} \quad (4)$$

where r is the radial distance from the vortex center, ω is the angular velocity of the core, and R is set to simulate a typical mesoscale vortex structure. This theoretical velocity field was applied to the synthetic particle images shown in Fig. 8a.

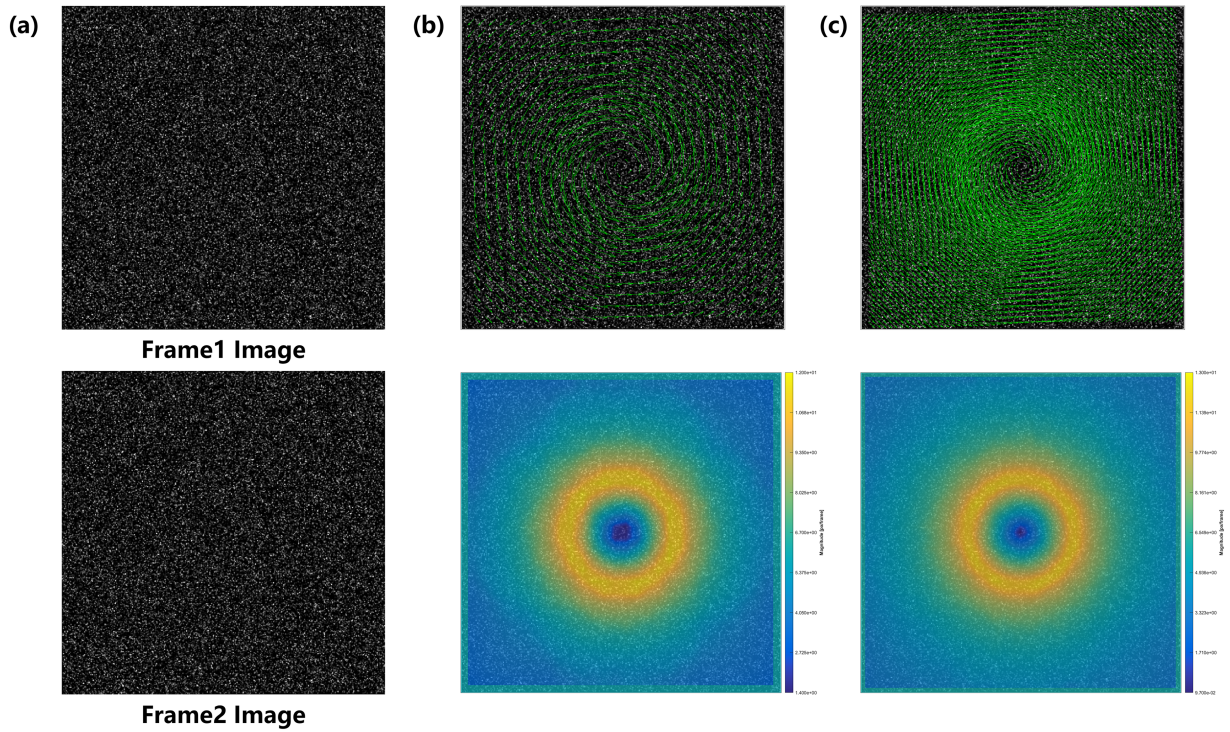


Figure 8: Validation of the algorithm using a synthetic Rankine vortex flow: (a) synthetic particle image pairs; (b) velocity vector field and contour map computed by the traditional cross-correlation algorithm; (c) velocity vector field and contour map computed by the proposed improved window deformation algorithm.

Fig. 8 presents a comparative analysis of the velocity fields reconstructed by the traditional algorithm and the proposed improved algorithm. The results computed by the traditional cross-correlation method are shown in Fig. 8b. It is evident that this method fails significantly in the central region of the vortex ($r < R$), where the rotational shear is most intense. The velocity vectors are sparse, creating a noticeable void, and the corresponding velocity contour map is discontinuous. This failure occurs because the rigid, square interrogation window used in standard PIV cannot account for the significant rotational distortion of the fluid parcels between frames, leading to a loss of correlation signal.

In contrast, the result from the proposed improved window deformation algorithm, shown in Fig. 8c, demonstrates superior performance. By iteratively deforming the interrogation window based on the local velocity gradient tensor, the algorithm effectively matches the rotational distortion of the particle patterns. The reconstructed velocity vector field is dense and smooth, accurately capturing the concentric circular motion across the entire domain, including the high-gradient vortex core. The corresponding velocity contour map further confirms the continuous and precise resolution of the flow structure. This qualitative comparison strongly validates that the window deformation technique is essential and highly effective for resolving complex, strong shear flows, such as those present in high-speed jet boundaries.

4 Experimental Results and Discussion

Based on the adaptive image enhancement preprocessing scheme and the improved multi-level window deformation cross-correlation algorithm constructed in previous chapters, this study applies the methodology to the visualization experiment of NCM18650 lithium-ion battery thermal runaway jets. By conducting full-field quantitative measurements on the acquired high-speed image sequences, this chapter aims to analyze the velocity field topology of the gas-liquid-solid three-phase jet during different evolution stages, revealing the momentum transport laws in the jet core and the vortex evolution characteristics in the shear layer, thereby verifying the practical engineering value of this non-contact optical measurement method.

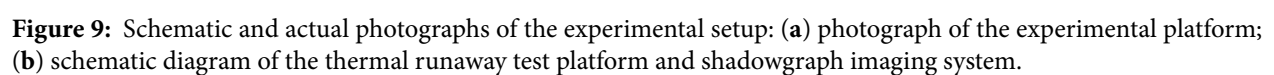
4.1 Experimental Conditions and Data Acquisition

The experimental study was conducted on a self-constructed high-pressure transient venting test platform, the schematic of which is illustrated in Fig. 9. The test specimen selected was a commercial NCM18650 cylindrical lithium-ion battery (Cathode material: NCM, Capacity: 2.4 Ah). To simulate thermal runaway, a customized copper heating block was employed to apply lateral heating to the battery within a sealed explosion-proof chamber, with the heating voltage set to 160 V. For flow visualization, a high-speed shadowgraph imaging system was established, comprising a Photron Fastcam Mini camera and a Vlite-Hi-527-30 high-power continuous laser source (wavelength: 527 nm) to precisely capture the highly transient jet flow field.

To accommodate the distinct velocity magnitudes of the two jet phenomena during thermal runaway, a multi-stage shooting strategy was formulated. For the primary jet, the recording was triggered when the battery surface temperature reached approximately 140°C, with a sampling frequency of 6000 fps and an exposure time of 8 μs to minimize motion blur of fine atomized droplets and other visible jet features. For the more violent secondary jet, triggered at approximately 170°C, the sampling frequency was adjusted to 2500 fps to record the prolonged eruption process. In the data processing stage, the CLAHE and high-pass filtering algorithms described in Section 2 were first applied to remove background halos and extract high-contrast “pseudo-particle” features. Subsequently, the velocity field was calculated using the window deformation-based cross-correlation algorithm established in Section 3. The final grid refinement scheme was determined as follows: the initial interrogation window size was 150 × 150 pixels, decreasing sequentially to 80 × 80, 40 × 40, and finally 10 × 10 pixels. To balance calculation efficiency and resolution, the calculation step was set to half the side length of each interrogation window, corresponding to a 50% overlap ratio.

For the primary-jet image sequence, the spatial calibration was 0.02098 mm/pixel (approximately 47.66 pixel/mm). The calibration procedure is provided in the Supplementary Material.

(a)



Meanwhile, the macroscopic irregular ejecta observed in the late secondary stage are not treated as ideal tracers. The present preprocessing and cross-correlation procedure mainly acts on localized high-frequency visible features, such as fine droplets, fragment edges, and surrounding textured structures, rather than

on the bulk low-frequency shape of a large solid block. When large opaque ejecta occupies a substantial portion of an interrogation region, the local correlation quality may deteriorate. In such cases, the resulting vectors are interpreted more conservatively, mainly for identifying transient high-speed regions and overall flow topology.

4.2 Characteristics of the Primary Jet

The primary jet occurs at the instant of safety valve opening, consisting mainly of released high-pressure gas and atomized electrolyte. While the detailed spatiotemporal evolution sequences are provided in Supplementary Material, the quantitative calculation results reveal significant phasic characteristics. In the initial stage (0–3.3 ms), the flow manifests as a typical liquid film or filament injection, which rapidly breaks up and atomizes. The jet front forms a distinct conical diffusion structure, with the spreading angle stabilizing in the range of 40° – 50° . Velocity field calculations indicate that the high-speed region is highly concentrated near the central axis of the conical jet, with a maximum resolved local feature velocity approaching 71 m/s initially, reflecting the strong momentum release driven by high-pressure gas. As the jet diffuses outward, the velocity in the boundary layer rapidly decays to the range of 10–30 m/s due to intense shearing and entrainment with the ambient air, forming a clear velocity gradient layer.

To quantitatively describe the attenuation law of the jet intensity, the curve of the average velocity within the jet core over time was extracted, as shown in Fig. 10. Within the 135 ms observation window, the average velocity exhibits a significant exponential downward trend. At the instant of valve opening ($t = 0$ ms), in this representative case, the jet intensity peaks with a maximum spatially averaged feature velocity of 57.02 m/s. Subsequently, the velocity drops most sharply during the liquid film breakup phase (0–3.3 ms). After entering the atomized jet phase (3.3–40 ms), the decay rate slows down, yet the local maximum velocity in the core region remains above 60 m/s at $t = 4.29$ ms. After approximately 40 ms, the average velocity falls below 10 m/s, marking the terminal phase of the primary jet where the flow field gradually becomes sparse. Notably, a distinct fluctuation in the velocity curve is observed around 19 ms, which is attributed to the transient pressure pulsation caused by the instability of chemical reactions inside the battery.

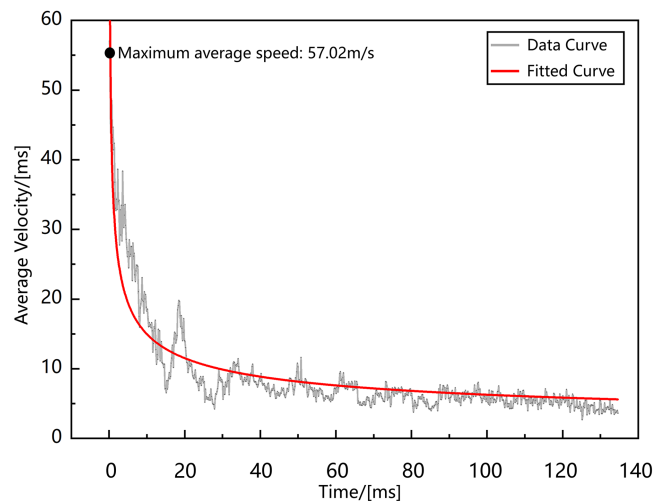


Figure 10: Time-history of the spatially averaged projected feature velocity in the primary jet core for one representative test.

4.3 Characteristics of the Secondary Jet

With the full triggering of thermal runaway, the secondary jet exhibits significantly more violent and complex fluid dynamic characteristics than the primary jet. Initiated when the battery surface temperature reaches approximately 180°C , this process involves four typical evolution stages: the plume stage, conical eruption stage, multi-directional bursting stage, and violent gas generation stage (detailed flow topologies are available in Supplementary Material). Initially, the flow is dominated by low-speed gaseous plumes driven by thermal buoyancy. As the internal separator melts completely causing an internal short circuit, the pressure rises sharply, driving the electrolyte and high-temperature particles to erupt in a regular conical shape, accompanied by visible electrical sparks and combustion.

The flow enters its most violent phase, the multi-directional bursting stage (953–1553 ms), when the internal structure of the battery undergoes local destruction, altering the pressure relief pathways. Utilizing the improved cross-correlation algorithm, the peak velocities during this chaotic phase were successfully captured. As shown in Fig. 11, at $t = 953$ ms and subsequent high-burst moments, the maximum resolved local feature velocity along the jet centerline approached 130 m/s. This high projected feature velocity is consistent with violent pressure-driven venting and intense internal thermal reactions during this stage.

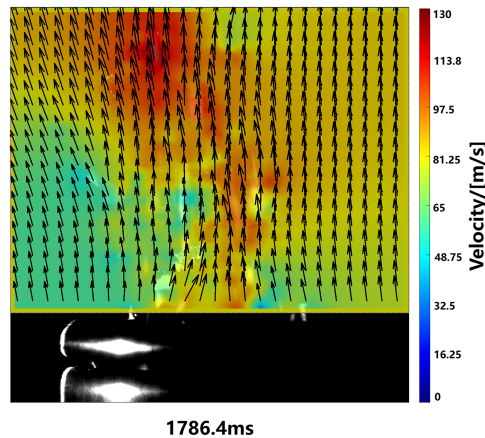


Figure 11: Instantaneous velocity contour map of the secondary jet during the multi-directional bursting phase.

Furthermore, during the late stage of this phase (e.g., 1552.8 ms), block-like structures were observed ejecting from the bottom, indicating severe damage to the internal jellyroll. The proposed window deformation technique played a critical role in resolving the strong shear and unsteady characteristics of this phase. Fig. 12 presents the detailed flow field of the shear layer at the jet edge, clearly resolving a series of continuous, fine-scale vortex structures. The resolved vortex structures are qualitatively consistent with Kelvin–Helmholtz-type instability induced by the strong velocity gradient between the high-speed jet core and the ambient air. These fine secondary vortices reveal the key mechanisms of energy dissipation and material mixing in the late stage of the jet, validating the algorithm’s superiority in resolving complex turbulent topologies.

Because the multi-directional bursting stage is highly three-dimensional, the velocity field obtained in this stage should be interpreted as the resolved planar component of the visible multiphase jet motion. Although local out-of-plane motion may introduce decorrelation and increase uncertainty, the present measurements still reliably capture the emergence of transient high-speed regions, the spatial organization of the shear layer, and the overall temporal evolution of the eruptive jet.

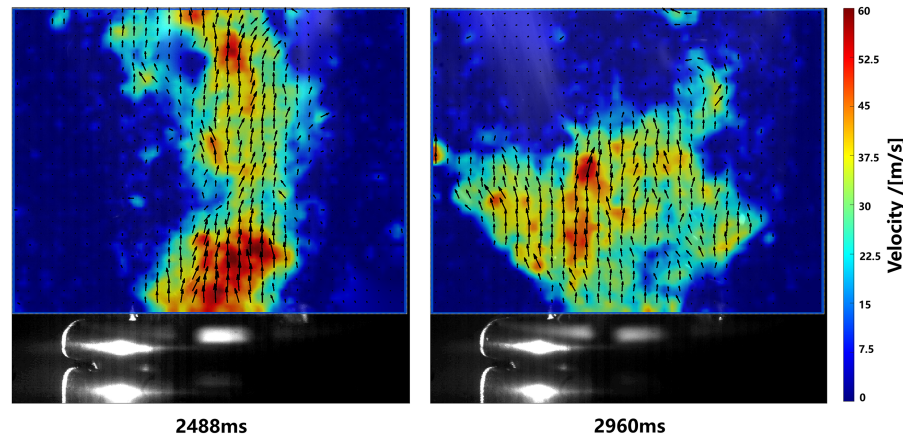


Figure 12: Fine-scale vortex structures resolved in the jet shear layer.

4.4 Performance Analysis of the Algorithm

Although synthetic particle tests have theoretically confirmed the algorithm's accuracy, the real-world thermal runaway jet presents a much harsher environment characterized by violent combustion and phase changes. During the intense eruption of the secondary jet, the flow field background is filled with numerous bright spots caused by high-temperature combustion and non-uniform illumination, leading to a sharp decline in the image signal-to-noise ratio (SNR). Under such low-quality image conditions, traditional fixed-window FFT cross-correlation algorithms are highly susceptible to background noise peaks, often generating chaotic spurious vectors in low-contrast regions and destroying the physical continuity of the flow topology. In contrast, the improved algorithm employed in this study first utilizes CLAHE and high-pass filtering preprocessing to effectively suppress background halos and enhance particle contrast. Combined with the dynamic error correction mechanism of the multi-grid iterative strategy, the algorithm progressively corrects mismatched vectors during calculation. The results demonstrate that the improved algorithm maintains excellent smoothness and density of the vector field, significantly reducing the outlier rate and exhibiting superior robustness under complex combustion conditions.

Beyond noise immunity, the ability to resolve fine flow structures is another key indicator of algorithmic performance. At the interface between the jet core and the ambient fluid, a strong velocity shear layer exists. Traditional algorithms, using rigid interrogation windows, cannot adapt to the stretching and rotational deformation of fluid parcels under strong shear, causing the velocity gradient within the window to be severely "averaged out". This leads to a peak-shaving effect, making it difficult to resolve fine vortex boundaries. The Window Deformation technique introduced in this paper overcomes this limitation by adaptively deforming and resampling the interrogation window based on the local velocity gradient tensor. In the analysis of the jet shear layer, the improved algorithm successfully resolved minute vortex structures with scales of only a few pixels. This precise capture of secondary flow features directly confirms that the proposed algorithm possesses high spatial resolution, meeting the requirements for quantitative research on the turbulence characteristics of high Reynolds number multiphase jets.

Besides combustion luminosity and background noise, thermal runaway jets may also generate Schlieren-like optical distortions due to strong temperature and density gradients. In the present study, such effects are not assumed to be entirely absent. However, because the velocity extraction is mainly based on enhanced high-frequency visible features rather than smooth density-gradient boundaries, and because the preprocessing suppresses low-frequency optical background variations, the resulting bias is considered

reduced but not fully eliminated. Accordingly, additional uncertainty may remain in plume-dominated regions with weak particulate textures.

4.5 Implications for Heat and Mass Transfer

The high-resolution velocity fields obtained via the proposed PIV methodology not only resolve the kinematic structure of the transient multiphase jet, but also provide a physically grounded basis for interpreting the coupled heat and mass transfer processes during battery thermal runaway.

Turbulent mixing and interfacial transport enhancement

The fine-scale vortex structures resolved in the jet shear layer (Fig. 12) play a dominant role in governing interfacial transport. These vortices, arising from Kelvin–Helmholtz-type instability under strong velocity gradients, substantially increase the effective interfacial area between the high-temperature ejecta and the ambient air. More importantly, their rotational motion induces continuous entrainment and engulfment processes, which significantly enhance scalar transport across the jet boundary.

From a transport perspective, this implies that the local convective heat and mass fluxes at the jet interface are strongly amplified compared to a laminar-like shear layer. The presence of coherent vortical structures promotes rapid mixing of hot gases and dispersed droplets with colder surroundings, thereby accelerating thermal energy dissipation and the dilution of combustible species. Consequently, the shear-layer instability acts as a key mechanism controlling the efficiency of heat removal and species dispersion in the early and intermediate stages of jet evolution.

Velocity-gradient-based mapping of turbulent transport

The measured velocity field further enables a qualitative assessment of turbulent transport intensity by invoking the Reynolds analogy, which establishes a correspondence between momentum and heat transfer in turbulent flows under a turbulent Prandtl number of order unity ($Pr_t \approx 1$).

In this framework, regions of strong velocity gradients—quantified by the local strain rate and shear intensity—can be interpreted as zones of elevated turbulent eddy viscosity, and thus enhanced turbulent thermal diffusivity. In the present measurements, these high-gradient regions are predominantly located along the jet boundary and within the multi-directional bursting interfaces (Figs. 11 and 12). The ability of the improved window deformation algorithm to accurately resolve these gradients provides a physically meaningful proxy for identifying spatial distributions of turbulent heat and mass transfer intensity.

Therefore, the PIV-derived velocity gradient field does not merely describe flow kinematics, but effectively serves as a transport indicator, enabling the localization of regions where turbulent heat flux and species mixing are expected to be maximized during the venting process.

Coupling between velocity decay and phase-change-driven mass transfer regimes

The temporal evolution of the jet velocity (Fig. 10) reflects a strong coupling between momentum transport and phase-change-driven mass transfer mechanisms. The observed exponential decay in the spatially averaged velocity can be interpreted as a macroscopic signature of successive transport regimes.

In the initial stage (0–3.3 ms), the rapid velocity drop corresponds to the breakup of a superheated liquid film, where flashing-induced phase change dominates the mass transfer process. The explosive boiling caused by rapid depressurization leads to intense two-phase momentum exchange and strong interfacial transport.

As the jet transitions into the atomized regime (3.3–40 ms), the decay rate decreases, indicating a shift in the dominant mechanism toward convection-coupled droplet evaporation. In this stage, heat transfer from the surrounding gas phase to dispersed droplets governs the rate of mass transfer, while turbulent mixing continues to enhance vaporization efficiency.

At later times (>40 ms), when the characteristic velocity falls below approximately 10 m/s, the flow enters a terminal regime where phase change is largely completed. The transport process becomes dominated by momentum dissipation, with particle motion governed primarily by aerodynamic drag and gravitational settling.

From a transport standpoint, this evolution represents a transition from phase-change-controlled mass transfer to convection-limited evaporation, and ultimately to momentum-controlled particle transport. The velocity decay curve therefore provides an experimentally accessible indicator of regime transitions in the coupled heat and mass transfer processes during thermal runaway.

This analysis also suggests a potential pathway for future work, where PIV-resolved velocity gradients may be coupled with scalar transport models to quantitatively estimate local heat and mass transfer coefficients in transient multiphase jet environments.

5 Conclusion

To address the challenge of quantitatively measuring the high-speed, strongly self-luminous, gas-liquid-solid multiphase jets generated during the transient venting of high-pressure vessels, this paper proposes a non-contact PIV measurement scheme based on adaptive image feature enhancement and an improved cross-correlation algorithm. By establishing synthetic particle test benchmarks, constructing a theoretical Rankine vortex model, and conducting thermal runaway venting experiments on NCM18650 lithium-ion batteries, the measurement accuracy, noise immunity, and capability to resolve complex flow patterns were systematically investigated. The main conclusions are as follows:

(1) Development of an Adaptive Image Feature Enhancement Strategy for Tracer-Free Complex Flows.

Addressing the lack of artificial tracers and the interference from intense combustion luminosity and non-uniform background in experimental flow fields, a preprocessing framework combining “CLAHE (Contrast Limited Adaptive Histogram Equalization) + Frequency-Domain High-Pass Filtering” was constructed. The results demonstrate that this strategy effectively suppresses thermal radiation backgrounds and low-frequency halos, significantly expanding the dynamic range of the images. Furthermore, by optimizing the Gaussian high-pass filter parameters, the continuous fluid mist background was successfully stripped away, and the fluid textures and dispersed droplets were reconstructed into high-contrast “pseudo-particle” speckle features with diameters of approximately 2–3 pixels. This processing workflow significantly improves image information entropy and signal-to-noise ratio, resolving the measurement failure issues common in traditional PIV under harsh multiphase environments due to “particle absence” and “low SNR”.

(2) Verification of High Accuracy and Robustness of the Multi-Level Window Deformation Algorithm in Strong Shear Flows.

A benchmark based on Monte Carlo simulation of synthetic particle images was established to quantitatively evaluate the algorithm’s performance. The results indicate that the improved algorithm exhibits excellent adaptability to feature sizes, achieving a minimum measurement error ($RMSE < 0.05$ pixels) within the feature diameter range of 1.5–3.0 pixels. It also demonstrates superior noise immunity, maintaining a measurement accuracy within 0.1 pixels even under severe conditions with a normalized noise intensity of 0.4. Particularly in the verification using the Rankine vortex strong shear flow model, the window deformation technique effectively overcame the “peak-shaving” effect caused by the rigid window assumption in traditional algorithms. It eliminated velocity gradient biases and controlled the maximum local relative error within 1.2%, proving the algorithm’s reliability in resolving high-vorticity and strong shear structures.

(3) Realization of Fine-Scale Measurement and Mechanism Revelation of High-Pressure Transient Jets.

Applying the proposed method to the lithium-ion battery thermal runaway venting experiment, the full-lifecycle flow field characteristics—from the breakup of the primary jet liquid film to the violent bursting of the secondary jet—were successfully captured and quantified. The experimental results show that the improved algorithm not only resolved a maximum local projected feature velocity approaching 130 m/s during the multi-directional bursting phase of the secondary jet, revealing the momentum surge caused by violent internal thermal reactions, but also clearly resolved the fine-scale strong shear vortex structures and their spatiotemporal evolution within the jet shear layer. This confirms that the measurement scheme established in this paper possesses the capability to measure wide-span velocity fields (0–130 m/s) and highly transient flows, providing reliable quantitative data support for the design optimization of high-pressure safety venting devices and the study of multiphase flow mechanisms.

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Nomenclature

Abbreviation	Description
CC	Cross-Correlation
CFD	Computational Fluid Dynamics
CLAHE	Contrast Limited Adaptive Histogram Equalization
DWO	Discrete Window Offset
FFT	Fast Fourier Transform
HE	Histogram Equalization
IW	Interrogation Window
IWD	Iterative Window Deformation
MAE	Mean Absolute Error

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Abbreviation	Description	
NCM	Nickel Cobalt Manganese (cathode material)	
PIV	Particle Image Velocimetry	
PSNR	Peak Signal-to-Noise Ratio	
RMSE	Root Mean Square Error	
SNR	Signal-to-Noise Ratio	
SOC	State of Charge	
TR	Thermal Runaway	
WIDIM	Window Deformation Iterative Multi-grid	
Symbol	Description	Unit
d_p	Particle diameter	pixels
E_{RMS}	Root mean square error value	pixels
G	Gaussian low-pass filter kernel	–
I_0	Peak intensity of a particle	–
I_{CLAHE}	Image intensity after CLAHE processing	–
I_{HP}	Image intensity after high-pass filtering	–
I_n	Intensity of superimposed Gaussian white noise	–
N	Total number of vectors/samples	–
R	Radius of the vortex core	pixels
r	Radial distance from the vortex center	pixels
u_{meas}, v_{meas}	Measured velocity components in x and y directions	pixels/frame
u_{real}, v_{real}	Real (theoretical) velocity components in x and y directions	pixels/frame
u_θ	Tangential velocity of the Rankine vortex	pixels/frame
x_0, y_0	Coordinates of the particle center	pixels
$\Delta x, \Delta y$	Integer pixel offset for the interrogation window	pixels
ρ	Seeding density of particles	particles/IW
σ	Standard deviation of the Gaussian filter	pixels
ω	Angular velocity of the vortex core	rad/s

References

1. Zhang P, Lu J, Yang K, Chen H, Huang Y. A 3D simulation model of thermal runaway in Li-ion batteries coupled particles ejection and jet flow. *J Power Sources*. 2023;580:233357. doi:10.1016/j.jpowsour.2023.233357.
2. Gupta V, Dunn MJ, MacFarlane ARW, Xiao T, Farooq A, Masri AR. Analysis of ejecta ignition and velocity from 18650 Li-ion battery cells during thermal runaway. *J Power Sources*. 2025;653:237697. doi:10.1016/j.jpowsour.2025.237697.
3. Chai Z, Li J, Liu Z, Liu Z, Jin X. Experimental analysis and safety assessment of thermal runaway behavior in lithium iron phosphate batteries under mechanical abuse. *Sci Rep*. 2024;14(1):8673. doi:10.1038/s41598-024-58891-1.
4. Dong Y, Meng J, Sun X, Zhao P, Sun P, Zheng B. Experimental study on effects of triggering modes on thermal runaway characteristics of lithium-ion battery. *World Electr Veh J*. 2023;14(10):270. doi:10.3390/wevj14100270.
5. Kong D, Wang G, Ping P, Wen J. A coupled conjugate heat transfer and CFD model for the thermal runaway evolution and jet fire of 18650 lithium-ion battery under thermal abuse. *eTransportation*. 2022;12(7):100157. doi:10.1016/j.etrans.2022.100157.
6. Chen S, Wang Z, Liu J. A semi-quantitative analysis of infrared characteristics of thermal runaway ejection behaviour of lithium-ion battery. *J Energy Storage*. 2023;71:108166. doi:10.1016/j.est.2023.108166.
7. Wang H, Yang Z, Jiang C, Ji Z, Zhu Z. Internal temperature and flame jet characteristics during thermal runaway triggered by nail penetration for NCM811 lithium-ion battery. *J Therm Anal Calorim*. 2022;147(24):14925–38. doi:10.1007/s10973-022-11677-x.
8. Chen H, Buston JEH, Gill J, Howard D, Williams RCE, Rao Vendra CM, et al. An experimental study on thermal runaway characteristics of lithium-ion batteries with high specific energy and prediction of heat release rate. *J Power Sources*. 2020;472:228585. doi:10.1016/j.jpowsour.2020.228585.
9. García A, Zhao P, Monsalve-Serrano J, Villalta D, Martinez-Boggio S. Optical diagnostics of the venting spray and combustion behaviour during Li-ion battery thermal runaway induced by ramp heating. *Appl Therm Eng*. 2023;218:119308. doi:10.1016/j.applthermaleng.2022.119308.
10. Zhou Z, Zhou X, Wang D, Li M, Wang B, Yang L, et al. Experimental analysis of lengthwise/transversal thermal characteristics and jet flow of large-format prismatic lithium-ion battery. *Appl Therm Eng*. 2021;195:117244. doi:10.1016/j.applthermaleng.2021.117244.
11. Huang Z, Yu Y, Duan Q, Qin P, Sun J, Wang Q. Heating position effect on internal thermal runaway propagation in large-format lithium iron phosphate battery. *Appl Energy*. 2022;325:119778. doi:10.1016/j.apenergy.2022.119778.
12. Zou K, Chen X, Ding Z, Gu J, Lu S. Jet behavior of prismatic lithium-ion batteries during thermal runaway. *Appl Therm Eng*. 2020;179(7):115745. doi:10.1016/j.applthermaleng.2020.115745.
13. Mao B, Chen H, Jiang L, Zhao C, Sun J, Wang Q. Refined study on lithium ion battery combustion in open space and a combustion chamber. *Process Saf Environ Prot*. 2020;139:133–46. doi:10.1016/j.psep.2020.03.037.
14. Qin P, Jia Z, Wu J, Jin K, Duan Q, Jiang L, et al. The thermal runaway analysis on LiFePO₄ electrical energy storage packs with different venting areas and void volumes. *Appl Energy*. 2022;313(1):118767. doi:10.1016/j.apenergy.2022.118767.
15. Wang G, Kong D, Ping P, Wen J, He X, Zhao H, et al. Revealing particle venting of lithium-ion batteries during thermal runaway: a multi-scale model toward multiphase process. *eTransportation*. 2023;16:100237. doi:10.1016/j.etrans.2023.100237.
16. Jia Z, Min Y, Qin P, Mei W, Meng X, Jin K, et al. Effect of safety valve types on the gas venting behavior and thermal runaway hazard severity of large-format prismatic lithium iron phosphate batteries. *J Energy Chem*. 2024;89:195–207. doi:10.1016/j.jechem.2023.09.052.
17. Li W, León Quiroga V, Crompton KR, Ostanek JK. High resolution 3-D simulations of venting in 18650 lithium-ion cells. *Front Energy Res*. 2021;9:788239. doi:10.3389/fenrg.2021.788239.
18. Poelma C. Measurement in opaque flows: a review of measurement techniques for dispersed multiphase flows. *Acta Mech*. 2020;231(6):2089–111. doi:10.1007/s00707-020-02683-x.
19. Raffel M, Willert CE, Scarano F, Kähler CJ, Wereley ST, Kompenhans J. Particle image velocimetry: a practical guide. Cham: Springer International Publishing; 2018. doi:10.1007/978-3-319-68852-7.

20. Scarano F. Iterative image deformation methods in PIV. *Meas Sci Technol.* 2002;13(1):R1–19. doi:10.1088/0957-0233/13/1/201.
21. Becker F, Wieneke B, Petra S, Schroder A, Schnorr C. Variational adaptive correlation method for flow estimation. *IEEE Trans Image Process.* 2012;21(6):3053–65. doi:10.1109/TIP.2011.2181524.
22. Maceas M, Osorio AF, Bolanos F. A methodology for improving both performance and measurement errors in PIV. *Flow Meas Instrum.* 2021;77(3):101846. doi:10.1016/j.flowmeasinst.2020.101846.
23. Yu C, Bi X, Fan Y. Deep learning for fluid velocity field estimation: a review. *Ocean Eng.* 2023;271(4):113693. doi:10.1016/j.oceaneng.2023.113693.
24. Ruhnau P, Kohlberger T, Schnörr C, Nobach H. Variational optical flow estimation for particle image velocimetry. *Exp Fluids.* 2005;38(1):21–32. doi:10.1007/s00348-004-0880-5.
25. Bruhn A, Weickert J, Schnörr C. Lucas/Kanade meets Horn/Schunck: combining local and global optic flow methods. *Int J Comput Vis.* 2005;61(3):211–31. doi:10.1023/B:VISI.0000045324.43199.43.
26. Hui TW, Tang X, Loy CC. LiteFlowNet: a lightweight convolutional neural network for optical flow estimation. In: *Proceedings of the 2018 IEEE/CVF Conference on Computer Vision and Pattern Recognition*; 2018 Jun 18–23; Salt Lake City, UT, USA. doi:10.1109/CVPR.2018.00936.
27. Yang Z, Johnson M. Hybrid particle image velocimetry with the combination of cross-correlation and optical flow method. *J Vis.* 2017;20(3):625–38. doi:10.1007/s12650-017-0417-7.