

Experimental investigation of mixing interface fluctuation in non-isothermal flows

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ABSTRACT

In this study, the two streams mixing flow with large temperature difference is investigated. An integrated Focused Laser Differential Interferometric (FLDI) system is established to characterize the high-frequency fluctuations. The Particle Image Velocimetry (PIV) is induced to further gain the velocity distribution. A small CO₂ jet is used to probe the optical path sensitivity length, which is 50 mm approximately in this study. The resulting high-frequency density gradient fluctuations are captured by an FLDI system sampling at 5 MHz with two closely spaced beam pairs (streamwise separation 1.38 mm, spatial resolution 117 μm). Cross-correlation of the probe signals yields a convective velocity of approximately 96 m/s, consistent with PIV data. Fast Fourier transform identifies a dominant frequency, corresponding to a characteristic convective structure length of 16 mm. This length is confirmed by instantaneous vorticity interface detection and proper orthogonal decomposition analysis. High-resolution measurements at 330 locations across the mixing section reveal a deflection in the expansion angle of the mixing interface velocity distribution, indicating that the heat and mass transfer development can be divided into two distinct stages. The density gradient distributions measured by FLDI showed good consistency with mixing interface velocity distribution, which is consistent with related research results. The results demonstrate the capability of FLDI to study high-frequency mixing interface instabilities under large temperature gradients and offer a new perspective for modeling heat and mass transfer in non-isothermal mixing flows.

1. Introduction

Two streams mixing with significant temperature difference is a pivotal process in various engineering flows. In the mixing process, the rapid heat transfer driven by the evolution of mixing interface induced by turbulent motions primarily determines the mixing intensity and the uniformity of the flow field (Zecchetto et al., 2021). Furthermore, the mixing intensity exhibits increasing and then decreasing under the effect of temperature difference (Jahanbakhshi et al., 2021). Therefore, investigating this mixing process is essential for modeling and controlling mixing intensity in practical applications. The flow measurement by laser interferometry was first proposed by Smeets et al. (2007) in the 1970s for wind tunnel

experiments. Recent advancements have evolved this technique into Focused Laser Differential Interferometry (FLDI), which promotes a higher spatial resolution. Therefore, FLDI has been widely used in hypersonic aerodynamic research which carries high density gradient.

Recent studies (Huang et al., 2022) reported the high frequency (exceeding 2000 Hz) fluctuations of mixing interface, which poses a challenge for traditional measurement methods. It is necessary to apply a new method with superior spatial and temporal resolution. Given the successful application of FLDI in measuring the density fluctuations in hypersonic flow, characterizing the density gradient in mixing flow has become feasible. This study aims to verifying the feasibility of the FLDI method in non-isothermal mixing flow problems.

2. Facility and Experimental Setup

All experiments in this study were conducted at the advance combustion and heat transfer laboratory at Xiamen University. Figure. 1 illustrates the air supply design diagram of experiment system clearly. The system comprises an air compressor and an storage tank with a maximum pressure of 20 MPa and volume of 5 m³ as the air supply. This configuration allows the tests to be carried out for at least 60 s with a constant mass flow rate.

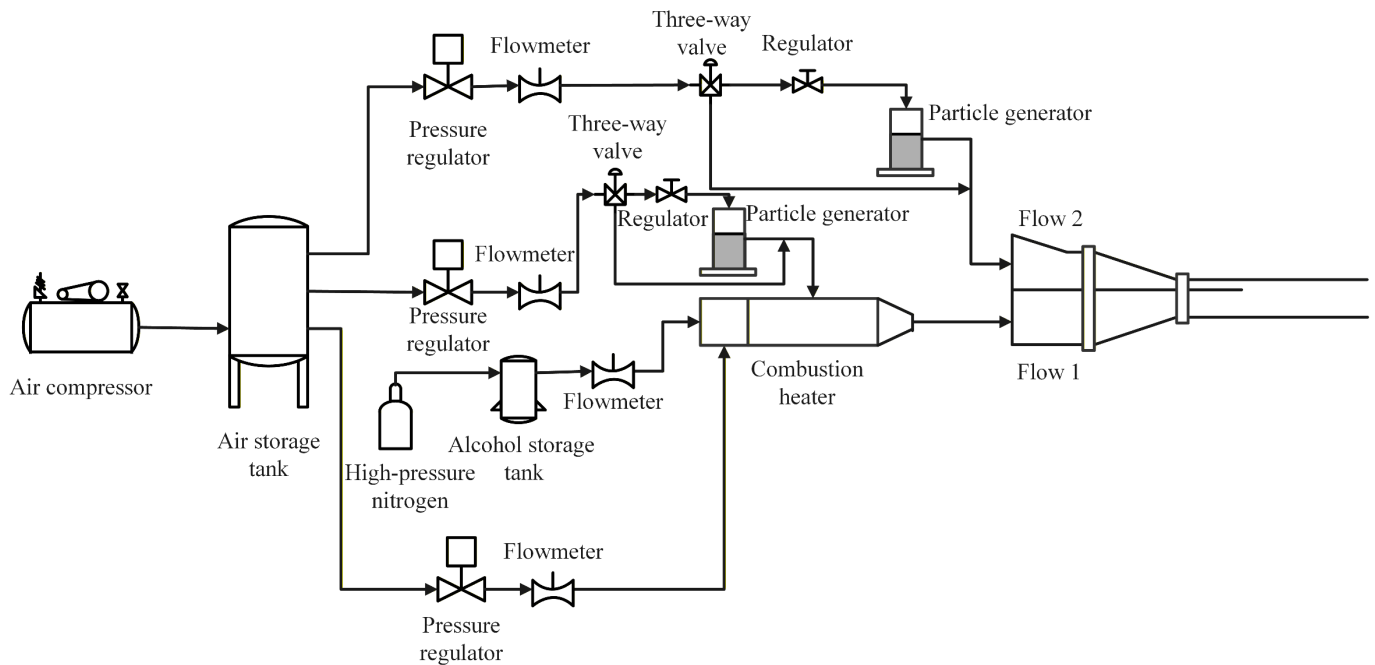


Figure. 1 The air supply design diagram of experiment system.

The experiment system delivers two streams air with different velocity and temperature to mixing at the mixing section as shown in Figure. 2. Considering the significant difference of the velocity and the temperature between two streams, the flow is divided into two flow paths before entering the mixing section. Furthermore, the high-temperature flow is generated by a combustion heater burning alcohol. Therefore, this experiment system enables the establishment of the velocity and temperature difference between two streams.

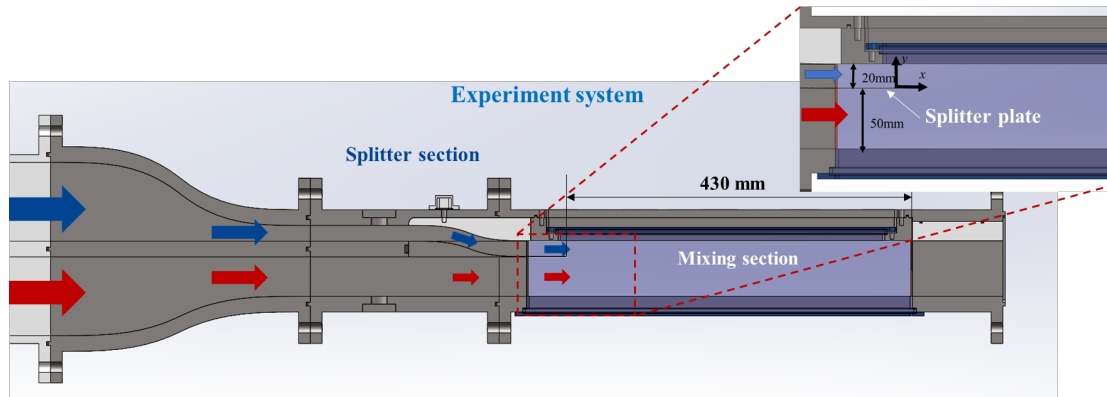


Figure. 2 Schematic of the experiment system.

The experimental conditions are shown in Table 1. Here, the m and T represent the mass flow rate and the temperature of two flows respectively. And the subscripts 1 and 2 indicate the different streams.

Table 1 Experimental conditions

m_1 (g/s)	m_2 (g/s)	T_1 (K)	T_2 (K)
303	139	1050	300

The mass flow rates measured by flowmeters and the temperature of main stream inlet measured by K-type thermocouple are shown in the Figure. 3. The uncertainties of the K-type thermocouple is 0.1 %, and the flowmeters are 0.5 %. Considering the temperature needs a few time to be stable, the testing started during the stable period to maintain the reproducibility of different cases. Therefore, the maximum temperature difference is lower than 2 % during the testing period. While the average mass flow rate difference is lower than 0.5 % and the temperature difference between different cases is lower than 3 %.

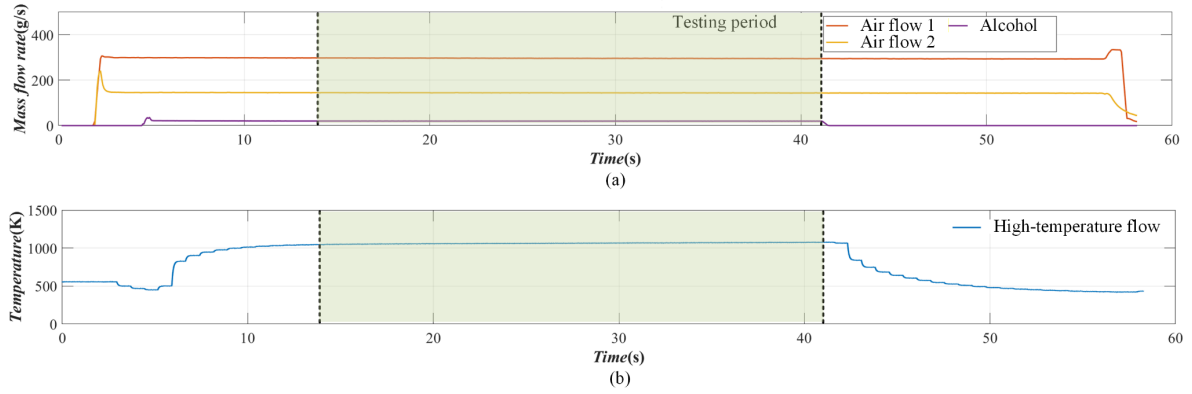


Figure. 3 Temporal variation of the mass flow rates and total temperature during the testing period.

A schematic of the FLDI system is shown in Figure. 4. The system comprises transmitting and receiving optics paths. A 633 nm He-Ne laser with a maximum output power of 5 mW is used as the light source for the FLDI. The FLDI system established in this study use a Wollaston prism with a divergence angle 1° (W1) to generate two probes, each probe is further split by a second Wollaston prism with a divergence angle $1'$ (W2). At down beam of the optics path, a complementary Wollaston prism with a divergence angle $1'$ is used to recombine the beams.

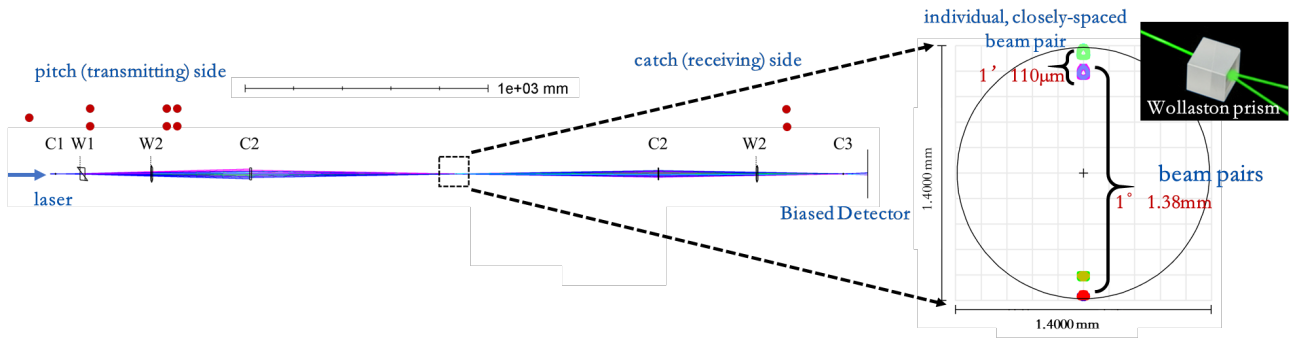


Figure. 4 Schematic of the FLDI system. Red dots represent the number of beams.

Furthermore, C1 is a convex lens with a focal length of 10mm, C2 is a convex lens with a focal length of 400mm that converges the light beam near the measurement point, and C3 is a concave lens that spreads the two light beams to facilitate collection. To improve the interference effect of the beam, a quarter-wave plate P1 is placed upstream of C2 at the transmitting side, and a polarizer P2 is placed downstream. Correspondingly, a polarizer is placed downstream of C2 at the receiving side.

The use of focused lasers implies a common path of laser, the interference between a pair of beams can be considered as confined to the focus point only as shown in Figure. 5. The area between the focus point can be considered as the sensitivity range of the FLDI system.

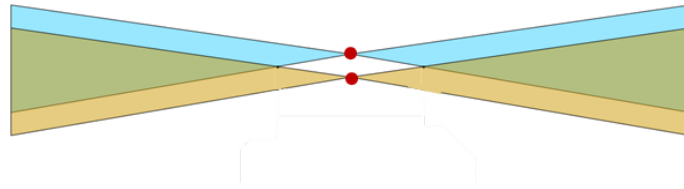


Figure. 5 Schematic of the focus point in a FLDI system.

Therefore, the FLDI system used in this study contains the two closely-spaced beam-pairs, ever beam-pair is a testing probe. The streamwise separation between each probe is 1.38 mm, while the beam separation within each pairs can be considered as the spatial resolution is 117 μm on vertical direction as shown in Figure. 6. Considering the close space between two beam pairs, it is necessary to expand and spatially separate the recombined beams to facilitate signal detection. The different optical path lengths between individual beams within a probe generates interference and manifests as fluctuations in intensity of the recombined beams, these phase shifts can be measured as changes in voltage by detectors. And two biased silicon (Si) photodetectors are used for measurement in receiving side.



Figure. 6 Picture of the positioning of FLDI beam pairs. The beams are located approximately 3 mm downstream of the splitter plate.

The principle of FLDI is that the spatial refractive index changes with density, causing an optical path difference between the two light paths, which in turn generates a phase difference $\Delta\phi$ that affects the intensity of light. Therefore, FLDI system measures the change in laser light intensity to reflect changes in refractive index at the focal point, obtaining density fluctuations,

achieving non-intrusive, high time-resolution measurements with frequencies reaching the MHz level.

The relationship between the refractive index n of a gas and its density ρ can be expressed using the Gladstone–Dale formula:

$$n = K\rho + 1 \quad (1)$$

For a laser with a wavelength of 633 nm propagating in air, the constant $K = 2.257 \times 10^{-4} \text{ m}^3/\text{kg}$.

The phase difference can be described as:

$$\Delta\phi = \frac{2\pi K}{\lambda} (\int_{c_1} \rho(s_1) ds_1 - \int_{c_2} \rho(s_2) ds_2) \quad (2)$$

Considering that the optical paths basically overlap, with differences in optical path only near the sensitive range, the phase difference can be simplified to:

$$\Delta\phi = \frac{2\pi K}{\lambda} L\Delta\rho \quad (3)$$

In the formula, λ is the laser wavelength, and L is the spatial range corresponding to the system response. According to the interference light intensity formula and the design of the polarizer and quarter-wave plate in the optical path, the light intensity I of the combined light after passing through the polarizer P2 satisfies:

$$I = I_0(1 + \sin \Delta\phi) \quad (4)$$

I_0 is constant when the laser power is stable. The light intensity will be measured as changes in voltage U by detectors, and the voltage is linearly related to the light intensity. Therefore, the relationship between density difference and measured voltage is:

$$\Delta\rho = \frac{\lambda}{2\pi LK} \arcsin \left(\frac{U}{U_0} - 1 \right) \quad (5)$$

In the formula, U_0 is the voltage when the phase difference caused by flow is 0.

Considering the significant density gradient induced by temperature difference in the incompressible flow conditions, the density gradient can be employed to investigate the mixing interface as shown in Figure. 7. Here, u represent the velocity of flows. In this paper, the mixing characteristics of the two streams mixing with large temperature difference are investigated using FLDI.

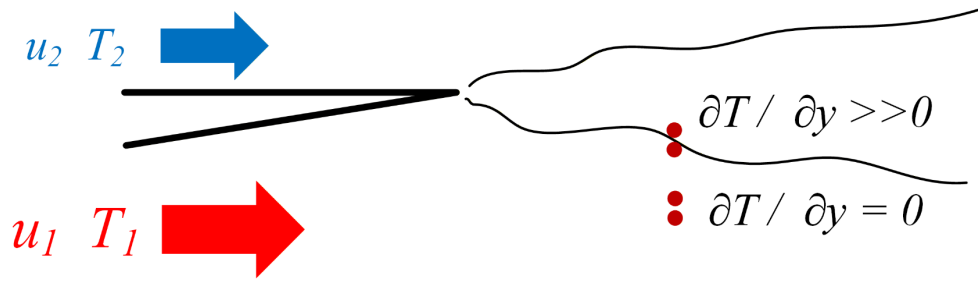


Figure. 7 Schematic of the relationship between density gradient and mixing interface under large temperature difference. Black lines represent the mixing interface, while red dots represent the beams of FLDI.

The mixing section is designed to characterize the mixing process over an extended domain, and the length is 430 mm. However, the large aspect ratio necessitates numerous measurement points, which poses challenges for the high spatial resolution measurements. Therefore, the high-accuracy three-dimensional coordinate frames can move synchronously are induced, which enabling high-resolution measurements across the entire mixing length. The integrated experimental assembly is illustrated in Figure. 8. With those carefully designed experimental facilities, the measurement can be carried out at several positions within a single test. A minimum of 11 target locations were sampled with at least 1 s respectively in this study. Considering the flow velocity and the testing time, the sampling frequency of the fluctuations measured by photodetectors is $F = 5$ MHz.

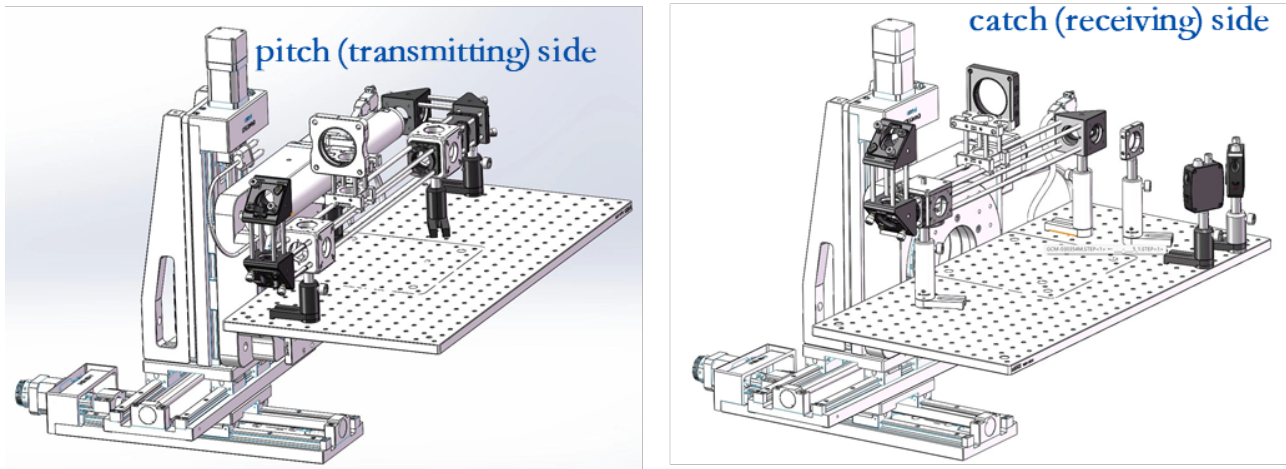


Figure. 8 Schematic of the integrated FLDI system applied in this study.

Considering the FLDI system has spatial filtering characteristics, so it is necessary to calibrate the spatial range corresponding to the optical system response. According to Parziale et al.(2012) and Tao et al. (2019), this study used a small CO_2 jet to probe the optical path

sensitivity length. By moving the small nozzle along the optical propagation direction, the responses of the FLDI system at different positions were recorded as shown in Figure. 9. The vertical axis represents the standard deviation of laser intensity (std). When the response drops to $1/e^2$ of the maximum value (at the focus), it is considered that the system has reached the non-responsive region. It can be confirmed that the sensitivity range of this FLDI system is 50 mm approximately.

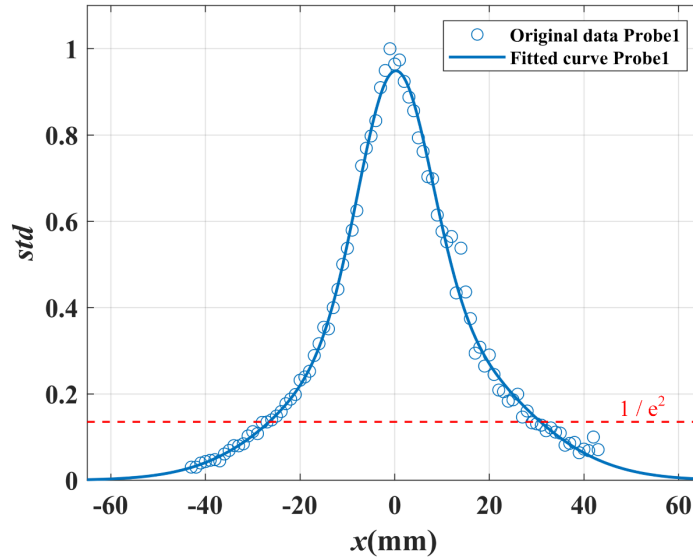


Figure. 9 Result of the FLDI sensitivity test at probe 1.

In order to evaluate the evolution of flow structures in the mixing process, Particle Image Velocimetry (PIV) measurements are applied to obtain the velocity distribution. In PIV experiments, the laser sheet produced by the Beamtech Vlite-Hi-527-20 Nd: YAG dual-cavity laser, using a Photron Mini AX200 (1024×1024 pixels) CMOS camera and LAOWA 100 mm lens to capture particle images. Under this situation, the image resolution is 0.08 mm/pixel in this study. Furthermore, the sampling frequency of the velocity field is 2000 Hz.

3. Results and Discussion

In order to facilitate the ultra-high frequency of FLDI, it is necessary to reduce the noise in the data. The wavelet-based denoising method is used by wavedec function in MATLAB, and the results with the center of two probes at $x = 20$ mm $y = 0$ mm are shown in Figure. 10. Notably, the signals within two probes both exhibit distinct periodic fluctuations during all the testing

period. Within the box with red dashed line, considering the time interval Δt , the frequency during this period is determined to be 6400 Hz. As highlighted by the green points, considering the distance Δs between two probes and Δt between correlated signal features, the velocity of mixing interface between two probes at that time can be calculated. These results demonstrate the feasibility of FLDI method for investigating the mixing interface with large temperature difference.

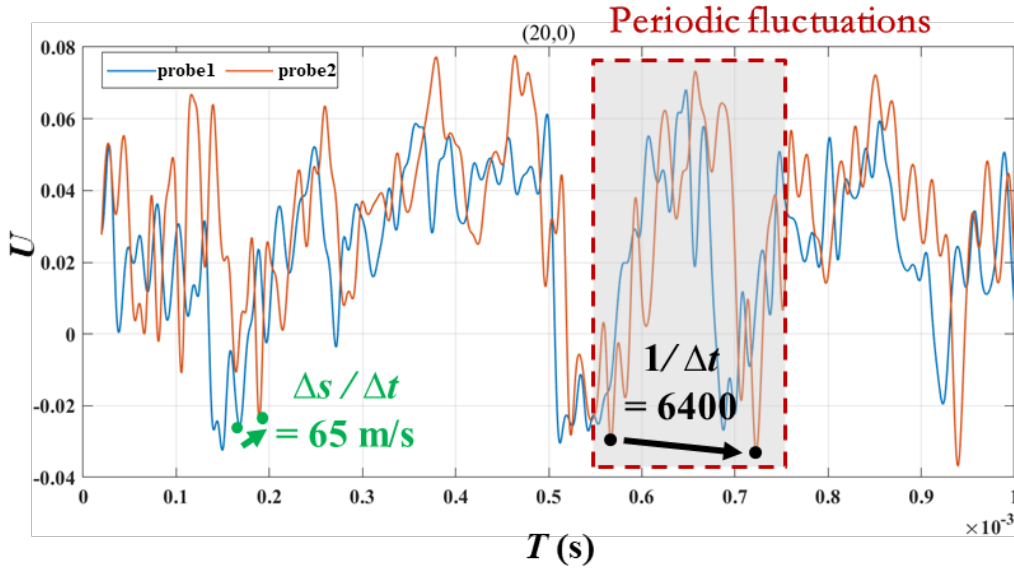


Figure. 10 The FLDI data at (20,0).

Furthermore, the MATLAB's xcorr function (Jewell et al., 2019) is used to determine the peak lag between signals. As shown in Figure. 11 (a), the correlation peak for the entire sampling duration occurs at a lag of 72 points, which corresponds to 14.4 μ s at a sampling rate of 5 MHz. Considering the Δs , the velocity of mixing interface is estimated at approximately $u = 96$ m/s, which aligns well with the PIV results. Fast Fourier Transform (FFT) is performed for frequency domain analysis as shown in Figure. 11 (b). The spectra reveal a dominant mixing interface instability frequency at approximately $f = 6200$ Hz. Therefore, the characteristic length scale of the interface structures is calculated as $d = u/f$, which is 16 mm under this testing condition.

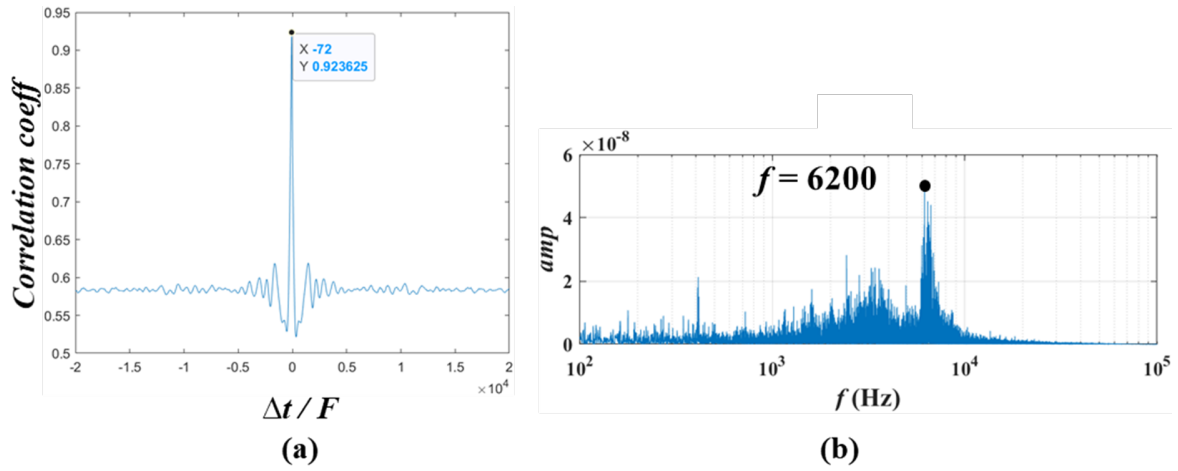


Figure. 11 (a) The correlation between two probes signal at a random sampling point. (b) The FFT results based on the signal data.

The vorticity distribution is shown in Figure. 12 (a), the black line represents the detected instantaneous vorticity interface with threshold $w = 10^4 \text{ s}^{-1}$ in this study. This interface exhibits significant similarity with the development of mixing process. And the periodic distribution of the peak shown in Figure. 12 (b) confirms the spatial correlation of structures along the mixing interface. Which also indicates the convective structures in the mixing process is primary with length of 16 mm and frequency of 6200 Hz.

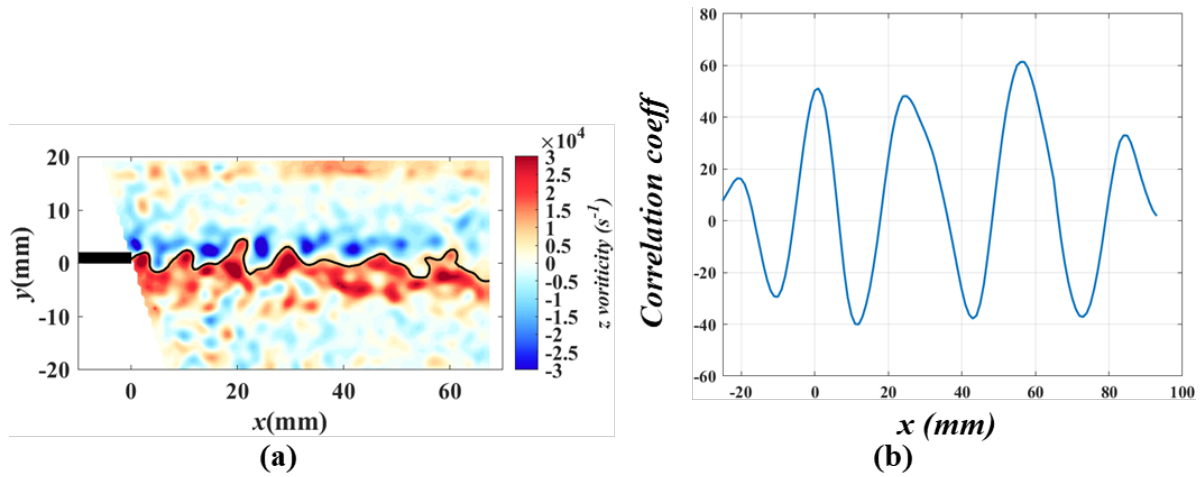


Figure. 12 (a) The vorticity distribution with instantaneous vorticity interface detected in this study. (b) The correlation of the y -position on this interface at different streamwise position with the window size is $d = 16 \text{ mm}$.

Furthermore, the proper orthogonal decomposition (POD) modes as shown in Figure. 13, reveal increasingly fragmented and smaller-scale structures in higher-order modes. Which

also proves the convective structures on mixing interface distributes with a highly periodic characteristic.

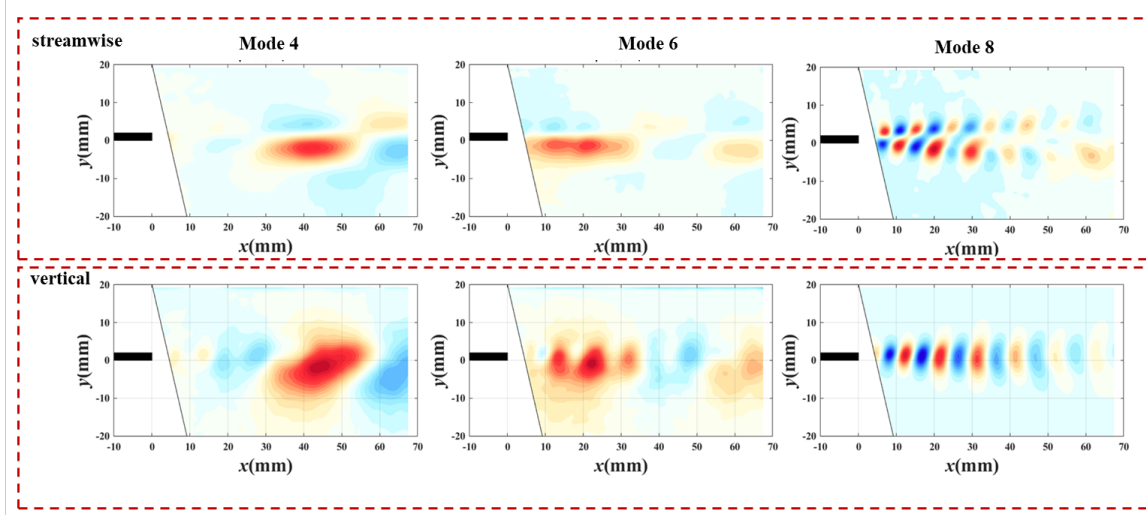


Figure. 13 The POD modes based on velocity field in streamwise and vertical direction.

With the help of the high-accuracy three-dimensional coordinate frames, there are 330 points over the mixing section are measured, and the local convective velocities of the interface were derived accordingly. Therefore, with the high density of data, Figure. 14 shows the distribution of mixing interface velocity. Recent studies (Zhang et al, 2024) reported the heat and mass transfer primarily through the mixing interface. In this study, the distribution of mixing interface velocity exhibits deflection in the expansion angle, suggesting that heat and mass transfer proceeds via two distinct stages.

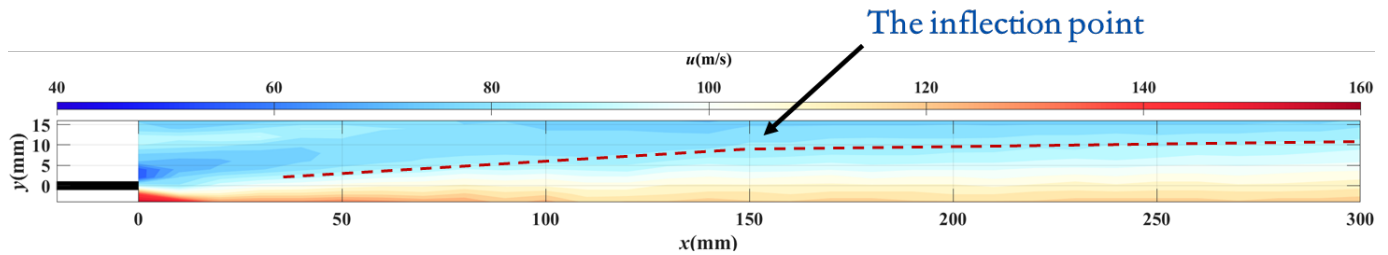


Figure. 14 The distribution of mixing interface velocity in the mixing section.

The std of laser intensity is associated with the density gradient in mixing process. As shown in Figure. 15, it can be found that the density difference also divided into two stages from about 150 mm. The mixing interface velocity distribution and density gradient changes measured by FLDI showed good consistency. This is consistent with related research results and further

demonstrates the feasibility of the FLDI method in measuring the mixing process of non-isothermal mixing flows.

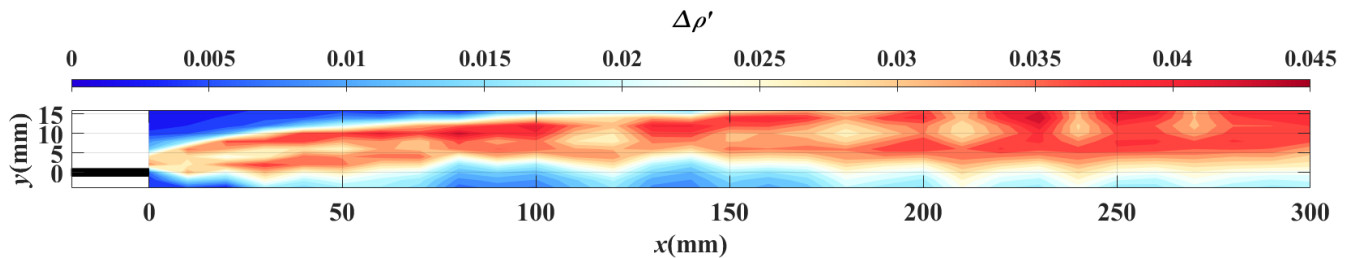


Figure. 15 The distribution of laser intensity std in the mixing section.

4. Conclusions

With the high frequency resolution of FLDI, we effectively captured the mixing interface instabilities at higher than 6000 Hz, and proved the feasibility of FLDI method for investigating the mixing interface with large temperature difference. Through the cross-correlation, the convective velocity can be determined. Furthermore, the convective structure length can be measured with the FFT analysis. Combined with the PIV results, this structure length can be proved by instantaneous vorticity interface. Meanwhile, the global distribution of mixing interface velocity and density gradient reveals a deflection in the expansion angle. This suggests that the development of the heat transfer during the mixing process can be categorized into two stages, providing a new perspective on modelling heat and mass transfer in non-isothermal mixing flow.

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