

Systematic Experimental Study on the Thermal Mixing Characteristics of Parallel Twin Water Jets Using UDV

Authors: ZHANG Lingyun, Prof. Songbai Cheng, Chen, Mr. Xiaolin, LIU, Dr. Xiaoxing, Prof. Songbai Cheng

Date: 2025-03-10T21:53:24+00:00

Abstract

To obtain a comprehensive understanding of the mechanisms underlying the thermal mixing phenomenon of coolant jet flowing from the core outlet in a Lead-cooled Fast Reactor (LFR), a systematic research project has been initiated recently under the collaboration between the Sun Yat-sen University and Harbin Engineering University in China. In the first stage of the project, experiments were conducted in the Thermal-hydraulic characteristics in Liquid Jet Mixing (TLJM) apparatus. Parallel twin water jets under various thermal and hydraulic conditions were mixed in a rectangular water pool and the mixing behavior was measured by using the Ultrasonic Doppler Velocimetry (UDV). The study analyzed the transient characteristics of water jets in the thermal mixing zone, including flow velocity, temperature as well as their fluctuation intensity distributions. Additionally, the impact of experimental parameters (e.g. inlet velocity, temperature, velocity ratio, and hydraulic diameter) on the velocity field, temperature field, and their fluctuation intensity distributions were also examined in detail. The results indicate that thermal mixing occurs in specific regions and follows distinct patterns with main fluctuation frequencies up to 10 Hz. Velocity fluctuations are tightly coupled with temperature fluctuations, as turbulence enhances thermal diffusion in the mixing zone. All experimental parameters are found to have noticeable influence on the mixing patterns. The study provides valuable insights and database on the thermal mixing mechanism and also verifies the applicability of UDV in transient velocity measurement. The obtained knowledge benefits the upcoming lead-bismuth experiments and ultimately contributes to future design and safety analysis of LFRs.

Full Text

Preamble

Systematic Experimental Study on the Thermal Mixing Characteristics of Parallel Twin Water Jets Using UDV

Lingyun Zhang^{1,3}, Songbai Cheng^{2,1,*}, Xiaolin Chen³, Xiaoxing Liu¹

¹ Sino-French Institute of Nuclear Engineering & Technology, Sun Yat-Sen University, Zhuhai City, Guangdong Province 519082, China

² School of Nuclear Science and Technology, Harbin Engineering University, Harbin, Heilongjiang Province 150001, China

³ Advanced Energy and Nuclear Technology Research Center, Advanced Energy Science and Technology Guangdong Laboratory, Huizhou City, Guangdong Province 516002, China

*Corresponding author. E-mail: chengsongbai@hrbeu.edu.cn (S. Cheng).

Abstract

To obtain a comprehensive understanding of the mechanisms underlying the thermal mixing phenomenon of coolant jets flowing from the core outlet in a Lead-cooled Fast Reactor (LFR), a systematic research project has been initiated recently under collaboration between Sun Yat-sen University and Harbin Engineering University in China. In the first stage of the project, experiments were conducted in the Thermal-hydraulic characteristics in Liquid Jet Mixing (TLJM) apparatus. Parallel twin water jets under various thermal and hydraulic conditions were mixed in a rectangular water pool, and the mixing behavior was measured using Ultrasonic Doppler Velocimetry (UDV). The study analyzed the transient characteristics of water jets in the thermal mixing zone, including flow velocity, temperature, and their fluctuation intensity distributions. Additionally, the impact of experimental parameters (e.g., inlet velocity, temperature, velocity ratio, and hydraulic diameter) on the velocity field and fluctuation intensity distributions was examined in detail. The results indicate that thermal mixing occurs in specific regions and follows distinct patterns with main fluctuation frequencies up to 10 Hz. Velocity fluctuations are tightly coupled with temperature fluctuations, as turbulence enhances thermal diffusion in the mixing zone. All experimental parameters were found to have noticeable influence on the mixing patterns. The study provides valuable insights and a database on the thermal mixing mechanism and also verifies the applicability of UDV in transient velocity measurement. The obtained knowledge benefits upcoming lead-bismuth experiments and ultimately contributes to future design and safety analysis of LFRs.

Keywords: Lead-cooled Fast Reactor; Parallel jets; Thermal mixing; Water jet mixing characteristics

1. Introduction

In recent years, Sodium-cooled Fast Reactors (SFRs) and Lead-cooled Fast Reactors (LFRs) have been accepted as promising GEN-IV nuclear systems. In these Liquid Metal-cooled Fast Reactors (LMFRs), liquid metal coolant flows out from the core outlet with different temperatures due to non-uniform core power distribution. In the upper plenum, cold and hot coolant flows mix in the form of jets and plumes. Inadequate mixing could lead to temperature fluctuations that are transmitted to adjacent solid structures through convective heat transfer. This phenomenon, first observed in the 1970s, was called thermal striping in LMFRs [1-3].

Thermal striping may cause thermal fatigue in structural components and eventually lead to structural damage or failure that threatens reactor safety [4,5]. Therefore, understanding flow mixing mechanisms and accurately predicting the thermal striping characteristics of liquid metal coolant are crucial for the design and operation of LMFRs.

Previous researchers have conducted many experiments to investigate flow mixing behavior at the core outlet. Due to the complexity of the structure in the core outlet region, simplified models such as parallel jets and coaxial jets were employed. Experimental studies on mixing of different working fluids in different models are summarized in Table 1. Moriya and Ohshima [6] measured temperature in coaxial jet mixing using sodium, water, and air, and found that if the Reynolds and Peclet numbers are sufficiently large, the temperature fluctuation characteristics of sodium can be evaluated using water or air experiments. Tanchine and Moro [7] studied mixing of coaxial vertical jets using sodium and air, indicating that temperature fluctuations of air and sodium agree well when the air Reynolds number is sufficiently high. Ahmed and Sharma [8] investigated turbulent mixing of confined coaxial air jets, suggesting that the mixing process depends on the velocity ratio as well as interactions between the boundary layer, mixing layer, and main flow. Wakamatsu et al. [9] analyzed attenuation of temperature fluctuations from parallel impinging jets to the structure surface using sodium and water, obtaining attenuation ratios of temperature fluctuations in both water and sodium tests. Tokuhiro and Kimura [10] investigated thermal-hydraulic mixing of triple water jets and described characteristics of the convective mixing region between jets by estimating turbulent heat flux. In a parallel triple sodium jets experiment, Kimura et al. [11] evaluated transfer characteristics of temperature fluctuations from fluid to structures and proposed a method to evaluate heat transfer coefficients. Lu et al. [12] revealed three-dimensional characteristics of transient temperature fluctuations caused by coaxial water jet flow. Cao et al. [13] observed an axisymmetric distribution of time-averaged temperatures when the velocity ratio of coaxial water jet flow exceeded 1, and verified that the region and intensity of temperature fluctuations differ from those with velocity ratio equal to 1. Kok et al. [14] obtained a dominant temperature fluctuation frequency of 5 Hz in a coaxial water jets experiment, finding that thermal mixing efficiency was enhanced with increasing

temperature difference between jets. In their subsequent mixing experiment of parallel twin water jets [15], they concluded that sequential obstacles increase thermal mixing efficiency.

Although more detailed data and characteristics of thermal mixing would be preferable, these experimental investigations provide a valuable benchmark database for validation and verification of numerical simulation.

Computational Fluid Dynamics (CFD) simulation has been widely applied in the thermal-hydraulics design and analysis of LMFBRs in recent years [16]. Yu et al. [17] employed both Reynolds-Averaged Navier-Stokes (RANS) and Unsteady Reynolds-Averaged Navier-Stokes (URANS) methods in simulation of parallel triple sodium jets mixing, and found that RANS models are unable to accurately predict temperature fluctuations. Large Eddy Simulation (LES) has been considered a promising approach to describe instantaneous temperature fluctuations since most eddies are computed instead of modeled. For this reason, LES method is applied in benchmark simulation of jet mixing experiments [14,15,17,18,19,20] and also in simulation of jet mixing at realistic core outlets [21,22,23].

Due to the low Prandtl number property, the thermal mixing behavior of liquid metal shows significant differences compared with water or air. To the authors' knowledge, there is no experiment on thermal mixing of lead or lead-based alloy jets so far. The similarity criteria obtained in water or air experiments [6,7] to predict sodium temperature fluctuations may not be directly applicable to LFRs. Additionally, Particle Image Velocimetry (PIV) employed in previous water experiments cannot be applied to opaque fluids, meaning that a reliable method for velocity measurement in liquid metal is necessary. Therefore, more effort, including instrument improvement, is needed to investigate thermal mixing of liquid lead or lead-based alloy in LFRs.

Motivated by the need to achieve a more comprehensive understanding of the thermal mixing mechanism of liquid lead-bismuth and accurately predict thermal mixing phenomena in LFRs, a systematic research project consisting of three well-organized stages has been launched under collaboration between Sun Yat-sen University and Harbin Engineering University. In the first stage, an experimental apparatus was established to study mixing of parallel twin jets using water, employing Ultrasonic Doppler Velocimetry (UDV) for velocity measurement to verify its applicability and performance. In parallel, numerical simulation using LES method was performed for validation against experimental data. This more comprehensive dataset is expected to enable in-depth analysis of the thermal mixing phenomenon. In the second stage, a lead-bismuth test loop will be established, in which thermal mixing experiments of lead-bismuth jets will be carried out. Validation and verification of LES numerical simulation are also expected to provide better understanding of thermal mixing characteristics of liquid lead-bismuth. In the third stage, numerical simulation of thermal mixing characteristics of jets from the core outlet of a realistic LFR model and conditions will be performed. The results and data will provide important values and

evidence for future industrial design and improvement of LFRs.

This paper focuses on experimental activities in the first stage of the project. A series of water experiments in parallel twin jet flow were performed under various inlet conditions. Velocity and temperature fluctuations in the mixing zone were measured and analyzed. The knowledge and favorable experimental data obtained from this study will soon be employed for validation of numerical simulation and will provide reference and guidance for liquid lead-bismuth experiments in the following stage of the project.

2.1. Facility Description

The experimental facility consists of a loop system and test section. The loop system contains cold and hot fluid loops. In each loop, water in the storage tank is heated to the desired temperature by a heating rod. Pumps then drive the fluid at controlled flow rates. Cold water and hot water flow into a jet generator and are injected into the test section. After mixing in the test section, water flows back to the tanks via drains. The schematic of the loop system including connecting piping, flowmeters, and valves is given in Fig. 1 [Figure 1: see original paper].

The test section is a rectangular transparent water tank with length of 400 mm, width of 60 mm, and height of 800 mm, as shown in Fig. 2 [Figure 2: see original paper]. Two rectangular injection nozzles are set parallel at the central bottom of the test section without level difference. The nozzles have the same length as the width of the test section (see Fig. 2), while their widths can be adjusted to various sizes. Cold fluid and hot fluid are injected through the nozzles, mix in the form of parallel twin jets, and flow out of the test section through drain piping at the top. A Cartesian coordinate system is adopted to analyze flow velocity and temperature distribution in the mixing zone. As shown in Fig. 2, the x-axis is defined along the length direction, the z-axis as the vertical direction, and the y-axis along the test section width. The origin of the coordinates is set at the center of the bottom of the test section.

2.2. Experimental Measurements

The velocity field of the mixing zone in the test section is measured using UDV. Based on the Doppler effect, UDV measures fluid velocity by emitting ultrasonic signals and receiving reflected signals from tracer particles inside the fluid. UDV can provide detailed information on the fluid velocity field without interfering with the fluid. The UDV DOP5000, manufactured by Signal Processing SA, is used in this study. In the measurement process, an appropriate amount of tracer particles with density close to water is added to ensure the intensity and effectiveness of the echo signal. The position of the UDV probe in the test section is shown in Fig. 2, primarily measuring the velocity component along the x-axis to derive turbulence distribution and fluctuation frequencies in the mixing zone.

Temperature in the mixing zone is measured by a thermocouple system arranged as shown in Fig. 3 [Figure 3: see original paper]. K-type armored thermocouples are chosen, with outer diameter of 1 mm and measurement accuracy of $\pm 0.4\%$. The integrated signal acquisition frequency can reach 64 Hz. Twenty thermocouple probes are arranged at intervals of 5 mm on a support that is movable in the vertical direction.

2.3. Inlet Conditions and Data Processing Method

The inlet conditions of the parallel twin water jets in experiments are given in Table 2 . The temperature of the cold water jet is set at 35°C while the temperature difference between hot and cold jets varies from 10 to 20°C. The experiments include cases of injection velocity ratios (R) from 0.5 to 2 and inlet hydraulic diameters (D^*) from 5.71 mm to 18.59 mm.

In data processing, to better compare temperature fluctuations across different cases, the normalized temperature T^* is defined as:

$$T^* = \frac{T - T_c}{\Delta T}$$

where T is the measured temperature, T_c is the cold fluid temperature, and ΔT is the temperature difference between cold and hot fluids. The average temperature \bar{T} and its normalized value are expressed as:

$$\bar{T} = \frac{1}{N} \sum_{i=1}^N T_i \quad \text{and} \quad \bar{T}^* = \frac{\bar{T} - T_c}{\Delta T}$$

where N is the number of measurements within a certain time period. The normalized root-mean-square (RMS) temperature is defined to describe the intensity of temperature fluctuations:

$$T_{RMS}^* = \sqrt{\frac{1}{N} \sum_{i=1}^N (T_i^* - \bar{T}^*)^2}$$

The normalized amplitude and frequency of temperature fluctuations are obtained by Fast Fourier Transform (FFT). The dimensionless distances x^* and z^* are defined as:

$$x^* = \frac{x}{D^*} \quad \text{and} \quad z^* = \frac{z}{D^*}$$

where D^* is the inlet hydraulic diameter of the jets. The intensity of velocity fluctuation in the x-axis at a certain position is defined by standard deviation as:

$$\sigma_{v_x} = \sqrt{\frac{1}{N} \sum_{i=1}^N (v_{x,i} - \bar{v}_x)^2}$$

where $v_{x,i}$ is the measured transient velocity component in the x-axis during the time period and \bar{v}_x is the average of $v_{x,i}$:

$$\bar{v}_x = \frac{1}{N} \sum_{i=1}^N v_{x,i}$$

3.1. Flow Field Analysis

The thermal mixing process between hot and cold jets under Case 1 boundary conditions is illustrated in Fig. 4 [Figure 4: see original paper], effectively showcasing the interaction of these flows. The use of colorants as visualization agents permits clear observation of the jet mixing phenomenon without modifying the physical properties of the working fluid (water). The figures display a sequence of images taken at specific time intervals (0 s, 0.2 s, 0.4 s, 0.6 s, 0.8 s, and 1.0 s) using a high-speed camera, offering a dynamic view of the evolving mixing region. The figure clearly illustrates that the zone of thermal commingling is largely circumscribed within a defined rectangular volume, extending 250 millimeters vertically and 100 millimeters laterally. This volume, distinguished as the “Main Thermal Mixing Area,” is of paramount importance for empirical measurement collection. Given that the D^* value for Case 1 is 12.54, the spatial dimensions of the critical region are presented in normalized form, with the x-axis spanning from -4.0 to 4.0 (x) and the z-axis ranging from approximately 0 to 20 (z). These specifications establish a standardized framework for evaluating thermal mixing behavior.

Fig. 5 [Figure 5: see original paper] presents time-domain plots that capture the fluctuating nature of the instantaneous velocity component along the x-axis at four specific locations ($x^* = -3, -1, 1, 3$), recorded at various vertical levels throughout a contiguous 3-second interval during the stable jet mixing phase under Case 1 boundary conditions. The plots delineate the velocity component's directional variability, with positive and negative values denoting movement in respective positive and negative x-directions. Fig. 5 reveals that the velocity component's amplitude spans approximately from -0.15 m/s to 0.15 m/s. The figure also highlights significant variability in velocity direction across different x positions, providing compelling evidence of intense and chaotic recirculation turbulent activity. This observation suggests complex fluid dynamics occurring within the mixing zone.

While time-domain plots of the x-axis velocity component offer valuable insights, they fall short of providing a comprehensive depiction of the velocity field within the mixing zone. To address this limitation, we conducted further examination of the velocity component along the z-axis. Fig. 6 [Figure 6: see original paper]

portrays transient velocity components in the z-axis at various vertical positions throughout a selected 1-second period during the stable mixing phase of Case 1. Positive transient velocity values denote movement in the positive z-axis direction. The figure primarily illustrates upward velocity aligned with the jet's initial trajectory, with only isolated occurrences of local backflow manifesting as velocity values contrary to the jet direction. Scrutiny of velocities at four distinct points along the x-axis reveals that with increasing height (z^*), both the breadth of the main flow region and the intensity of velocity oscillations exhibit a tendency to rise initially, followed by a subsequent decrease, thereby characterizing the complex interplay of flow dynamics within the mixing zone.

The evidence presented in Figs. 5 and 6 permits nuanced characterization of the transient flow field associated with thermal mixing of parallel twin jets. The mingling of twin jets is largely localized to a defined area remotely positioned from the jet inlets. In the vertical plane of development, the main flow exhibits not only upward progression but also inherent lateral instability, manifesting as x-axis left-right oscillation. This dynamic behavior underscores the complex three-dimensional nature of flow interactions within the mixing zone.

The jet mixing process is a perpetual continuum inherently marked by turbulence. While the transient flow field diagram affords qualitative appreciation of flow dynamics, deeper quantitative understanding necessitates more rigorous examination. To ascertain the magnitude and characteristics of velocity pulsations at various points and elucidate the internal governing mechanisms, thorough analysis of velocity statistics is indispensable. This involves meticulous assessment of mean velocity values and standard deviation, which together provide more profound insight into complex flow behavior.

Fig. 7 Figure 7: see original paper illustrates the distribution of average and extreme values of 128 experimentally collected data points over a randomly selected two-second interval during the stable mixing phase, showing average velocity along the z-axis. Fig. 7(b) presents the corresponding standard deviation measurements. Analysis reveals that velocity oscillations at various transverse positions and ascending through different stratifications in the wake of the twin jets' intersection exhibit a nearly bilateral distribution, indicating commensurate extent of extremity between left and right velocity components. Furthermore, the mean velocity on the x-axis remains near zero throughout the interval under scrutiny. It is thus inferred that the mixing zone contains disordered turbulent flow, engendering multiple directional changes within the flow field's velocity vector. When jets have equal initial impact velocities of 0.5 m/s, lateral velocity deviations are constrained to less than 0.25 m/s, highlighting nuanced force interplay within the flow. Fig. 7(b) illustrates that the standard deviation of x-axis velocity components in the mixing zone generally exhibits symmetric distribution, indicating uniform turbulence mixing intensity on both sides. As height increases, the width of the region with higher standard deviation values in the x-axis expands significantly near the jet inlet, though the turbulence mixing zone does not widen continuously with z^* .

The insights presented above are based on empirical data collected under Case 1 parameters. Starting from Case 1, we systematically undertook a series of experiments, rigorously maintaining the control variable principle. Each experiment was carefully designed to modify only one parameter—temperature, velocity, velocity ratio, or inlet hydraulic diameter—while holding all other factors constant, enabling nuanced observation of each parameter’s effect on experimental results. This methodological approach aimed to systematically explore and elucidate the influence of various factors on jet mixing distribution characteristics.

Fig. 8 [Figure 8: see original paper] depicts a comparison of the standard deviation of x-axis velocity components across varying initial velocities for equivalent cold and hot flow velocities. The standard deviation typically exhibits symmetric distribution, indicating uniform turbulence mixing intensity on both sides. As inlet velocity increases, the overall standard deviation escalates, suggesting intensification of turbulence mixing in the x-axis direction. For inlet velocities of $v_c=v_h=0.5$ m/s and $v_c=v_h=1.0$ m/s, the strongest velocity fluctuations occur at higher z^* positions (approximately 19.9 and 22.3). However, at $v_c=v_h=1.5$ m/s, the strongest velocity fluctuation shifts significantly to $z^* = 11.2$, suggesting that higher initial inlet velocities may reduce the vertical extent of the thermal mixing region, leading to earlier completion of mixing. Furthermore, from the perspective of the x-axis gradient of velocity fluctuation intensity, regions with greater velocity fluctuations under all three inlet velocity conditions are primarily concentrated within the range $-2 < x^* < 2$, indicating that the strongest velocity fluctuations occur near the centerline.

Fig. 9 [Figure 9: see original paper] presents a comparative analysis of the standard deviation of x-axis velocity components within the thermal mixing zone for temperature differences of 10 K and 20 K. Initial observations reveal that the distribution form of the standard deviation for both $\Delta T = 10$ K and $\Delta T = 20$ K are strikingly similar. As the inlet jet temperature difference increases from 10 K to 20 K, a pronounced increase in peak values of the standard deviation of x-axis velocity is evident at central positions within the thermal mixing zone, specifically at $z^* = 2.8$ and $z^* = 6.8$. This trend suggests that a higher temperature differential induces enhanced x-axis velocity fluctuations, which may facilitate earlier onset of vigorous turbulent mixing. Notably, beyond $z^* \geq 10.8$, the reduction in peak standard deviation observed for the larger temperature difference indicates that mixing is essentially complete. Regardless of temperature difference ($\Delta T = 10$ K or $\Delta T = 20$ K), velocity fluctuation intensity before mixing completion ($z^* < 6.8$) exhibits clear left-right symmetry. However, after mixing completion, the velocity fluctuation distribution becomes asymmetric, particularly under larger temperature differences. For instance, the intensity difference between the two sides at $z^* = 16.7$ is more pronounced under $\Delta T = 20$ K than at $z^* = 16.0$ under $\Delta T = 10$ K, indicating that higher temperature differences amplify asymmetry in velocity fluctuations after mixing is complete.

Fig. 10 [Figure 10: see original paper] provides the standard deviation of the x-axis velocity component under different velocity ratios. Across all cases, the

standard deviation first increases and then decreases with height. Under $R = 0.5$, velocity pulsation intensity is significantly higher on the hot jet side, while on the cold jet side it is almost negligible. Conversely, under $R = 2$, pulsation intensity shifts to the cold jet side. The peak values are also influenced by velocity ratio: when $R = 0.5$, the peak ranges between 0.08 and 0.1 m/s, while for $R = 2$ it stabilizes between 0.06 and 0.08 m/s. This discrepancy arises from stronger momentum of the hot jet under $R = 0.5$, resulting in more intense turbulent mixing.

Fig. 11 [Figure 11: see original paper] illustrates the distribution of the standard deviation of x-axis velocity within the thermal mixing zone for three inlet hydraulic diameters: $D^* = 5.71, 12.54, \text{ and } 18.59$. The figure shows that as hydraulic diameter increases, the peak standard deviation of x-axis velocity also increases, indicating more intense turbulent mixing. For the smallest hydraulic diameter ($D^* = 5.71$), velocity fluctuations are relatively less intense and distributed over a wider downstream region. The standard deviation peaks at a higher axial location, suggesting slower mixing and reduced efficiency. As hydraulic diameter increases to $D^* = 12.54$ or 18.59 , there is noticeable increase in velocity fluctuation intensity, with the peak shifting closer to the inlet region. This indicates that larger hydraulic diameter generates more intense turbulence, leading to faster and more localized mixing in the thermal zone. The more intense velocity fluctuations likely enhance heat exchange, promoting more effective thermal mixing.

3.2. Temperature Field Analysis

Fig. 12 [Figure 12: see original paper] elaborates on the intricate distribution of temperature fluctuations for Case 1 across various x-axis positions at $z^* = 6.4$, where substantial velocity fluctuations are discernible (Fig. 5). Specifically, Fig. 12(a) unveils the temporal evolution of normalized temperature T^* in the time domain, while Fig. 12(b) meticulously portrays the amplitude (A) of normalized RMS temperature (T RMS) as a function of frequency, derived via FFT analysis. In terms of time-domain characteristics, the data reveal that temperature fluctuations exhibit distinct amplitudes and patterns at varying x-axis positions. Notably, positions within the range $x^* = -1.8$ to 1.0 exhibit relatively smaller temperature fluctuation amplitudes, whereas other positions demonstrate larger amplitudes. The trend of temperature fluctuations over time varies across positions, with some locations showing relatively stable fluctuations and others displaying significant variability. In the frequency domain, A^* is higher in the low-frequency region, indicating that temperature fluctuation frequencies at most positions are primarily concentrated below 10 Hz. In the high-frequency region, although amplitudes are small at most positions, a few notable A^* values appear at certain specific positions (such as $x^* = 1.0$ and $x^* = 1.8$), indicating the presence of higher frequencies.

Fig. 13 Figure 13: see original paper presents time-domain profiles of temperature fluctuations for Case 1 at various z-axis positions at $x^* = -0.2$, where

significant velocity fluctuations are observed (Fig. 6). Fig. 13(b) displays the corresponding frequency-domain spectra. In the time domain, distinct temporal behaviors are observed at different vertical positions. At low z^* values (e.g., $z^* = 0$), temperature fluctuations are characterized by minimal temporal variation and small oscillation amplitudes. As z^* increases, fluctuation amplitudes progressively enlarge. Notably, within the range $z^* = 6.4$ to 15.9 , fluctuations are more pronounced with larger amplitudes. However, further increase to $z^* = 19.1$ results in amplitude decrease. In the frequency domain, overall spectral content remains below approximately 10 Hz. The spectral characteristics vary across positions: at low z^* values (e.g., $z^* = 0$), the spectrum remains relatively stable with uniform frequency components. As z^* increases, the spectrum becomes increasingly complex, exhibiting a rise in high-frequency components indicative of broader temperature fluctuation distribution. Particularly at $z^* = 12.8$ and $z^* = 15.9$, the spectra display more pronounced peaks, indicating significant energy concentration at specific frequencies.

Fig. 14 [Figure 14: see original paper] presents datasets from Case 1 for the same time period as Figs. 12 and 13, after averaging and normalization processes. Specifically, Fig. 14(a) illustrates the spatial distribution of average temperature (T_{avg}) within the mixing zone. Influenced by the initial water temperature in the test tank (25°C , below T_c), the vertical average temperature starts with a maximum temperature difference of approximately $\Delta T = 10$ K at the lowest position ($z^* = 0$) and diminishes to around $\Delta T = 4$ K in the region $z^* = 12$ to 14 , maintaining this temperature difference thereafter. Fig. 14(b) displays the normalized average temperature (T^*_{avg}) distribution, offering clearer visualization of temperature gradient distribution in both vertical and x-axis directions.

The aforementioned temperature field conclusions were derived under Case 1 conditions. To elucidate the influence of diverse factors on thermal mixing characteristics, boundary conditions were varied systematically. Specifically, we altered velocity, temperature, velocity ratio, and inlet hydraulic diameter to obtain temperature data under different conditions for subsequent analysis.

Under conditions of equal initial velocities in both cold and hot jets, a comparative analysis examined T^* RMS variation along the z -axis at inlet velocities of 1.0 m/s and 1.5 m/s, as shown in Fig. 15 [Figure 15: see original paper]. In terms of vertical distribution, at $v_c = v_h = 1.0$ m/s, temperature fluctuation intensity peaks at $z^* = 19.1$. In contrast, at $v_c = v_h = 1.5$ m/s, regions with higher temperature fluctuation intensity are concentrated within $z^* = 6.4$ to 12.8 . These observations clearly indicate that as inlet velocity increases, the region of intense thermal mixing does not shift upward. Instead, the height of the most vigorous mixing region decreases, suggesting that higher inlet velocities lead to downward shift of the thermal mixing zone and earlier completion of mixing. Furthermore, the maximum normalized root mean square value in Fig. 15(b) is smaller than in Fig. 15(a). Combined with the velocity fluctuation distribution shown in Fig. 8, this suggests that as turbulence intensifies (i.e.,

with increased velocity fluctuations), thermal mixing becomes more effective, leading to quicker equilibration of local temperature differences and relatively reduced temperature fluctuations.

The relationship between velocity and temperature fluctuations reveals clear coupling influenced by inlet velocity. As observed in Figs. 8 and 15, higher inlet velocities not only intensify velocity fluctuations but also significantly alter the vertical extent of both velocity and temperature fluctuation regions. For example, at $v_c = v_h = 1.5$ m/s, peak velocity fluctuations occur at $z^* = 11.2$, significantly lower than peaks observed at $z^* > 19$ for lower velocities ($v_c = v_h = 0.5$ m/s or 1.0 m/s). A similar trend is evident in temperature fluctuations: under $v_c = v_h = 1.5$ m/s, regions of higher temperature fluctuation intensity are concentrated within $z^* = 6.4$ to 12.8, whereas at $v_c = v_h = 1.0$ m/s, temperature fluctuation intensity peaks at $z^* = 22.3$. These findings suggest that higher inlet velocities enhance turbulence intensity, thereby accelerating the mixing process and compressing regions of both velocity and temperature fluctuations to lower vertical positions. The alignment of peak velocity and temperature fluctuation regions at higher velocities highlights strong coupling between momentum-driven turbulence and thermal mixing, implying that redistribution of velocity fluctuations due to increased jet momentum directly facilitates faster thermal diffusion, leading to earlier mixing completion and downward shift of the thermal mixing zone.

Fig. 16 [Figure 16: see original paper] compares T^* RMS distributions within the mixing zone under ΔT values of 15 K and 20 K. Regardless of temperature difference, T^* RMS distributions exhibit similar patterns along the x-axis. Within the mixing zone ($z^* < 14$), temperature fluctuations are pronounced, while downstream regions ($z^* > 17$) show significantly reduced fluctuations. Elevated temperature fluctuation intensity is observed near the left wall. This behavior arises from two primary factors: first, the asymmetry in velocity fluctuations described in Fig. 9, where the hot jet demonstrates higher velocity fluctuation intensity; and second, localized mixing between the high-temperature jet and surrounding static water in the tank. The increased temperature fluctuations near the wall suggest that the mixing mechanism in this area is influenced by interactions between the jet and ambient water, rather than being solely driven by turbulence associated with velocity fluctuations.

The relationship between velocity and temperature fluctuations reveals strong coupling influenced by inlet temperature difference (ΔT). As described in Fig. 9, higher temperature differences ($\Delta T = 20$ K) result in amplified x-axis velocity fluctuations, particularly at central positions within the mixing zone ($z^* = 2.8$ and $z^* = 6.8$). This intensification of velocity fluctuations directly contributes to enhanced turbulence, which facilitates more vigorous thermal mixing. Similarly, as shown in Fig. 16, elevated temperature fluctuations (T^* RMS) are observed near the same vertical positions within the mixing zone ($z^* < 14$) under higher temperature differences, reflecting the impact of intensified turbulence on thermal diffusion. Furthermore, after mixing completion ($z^* > 10.8$ in

Fig. 9 and $z^* > 14$ in Fig. 16), asymmetry becomes evident in both velocity and temperature fluctuations. For instance, pronounced asymmetry in velocity fluctuations at $z^* = 16.7$ under $\Delta T = 20$ K aligns with elevated temperature fluctuations observed near the left wall in Fig. 16. This asymmetry arises from stronger momentum and mixing effects of the hot jet, as well as its interaction with surrounding static water.

Fig. 17 [Figure 17: see original paper] shows T^* RMS distributions in the thermal mixing zone under different velocity ratios. When $R = 1$, temperature fluctuation distribution is generally symmetric around the central x-axis, except for localized regions on the hot jet side where elevated fluctuations are observed, attributed to the hot jet's higher momentum and interaction with ambient-temperature water. When $R = 0.5$ or $R = 2$, temperature fluctuation distribution becomes asymmetric, consistently favoring the side with higher inlet velocity. Under varying velocity ratios, the side with higher jet velocity exhibits more intense temperature fluctuations due to enhanced turbulent mixing and shear forces, resulting in more vigorous interaction between high-velocity fluid and surrounding fluid. The intensified mixing leads to greater local temperature variations, as increased frequency and intensity of interactions amplify thermal fluctuations.

The relationship between velocity and temperature fluctuations under varying velocity ratios demonstrates strong coupling influenced by jet dynamics and turbulent mixing. As shown in Fig. 10, velocity fluctuation distribution becomes asymmetric when $R = 0.5$ (faster hot jet) or $R = 2$ (faster cold jet), with higher standard deviation observed on the side of the faster jet. This asymmetry reflects dominance of the jet with greater momentum, which drives stronger turbulence and improves mixing efficiency. Similarly, Fig. 17 shows corresponding asymmetry in temperature fluctuations (T^* RMS), with elevated fluctuations on the faster jet side. This alignment highlights the role of velocity fluctuations in enhancing turbulence, which accelerates thermal diffusion and amplifies temperature variations due to intensified shear forces and frequent fluid interactions. Variations in velocity ratio directly influence spatial distribution and intensity of both velocity and temperature fluctuations, underscoring the interplay between momentum-driven turbulence and thermal diffusion. The results indicate that efficient thermal mixing is largely governed by the strength and asymmetry of velocity fluctuations, which drive the rate of thermal energy transfer and ultimately determine mixing dynamics.

Fig. 18 [Figure 18: see original paper] compares T^* RMS values under different inlet hydraulic diameters of 5.71, 12.54, and 18.59. With increasing D , *the intensity of temperature fluctuations in the central region significantly enhances. The peak location shifts to lower z values as D^* increases: $z^* = 28$ for $D^* = 5.71$, $z^* = 12.8$ for $D^* = 12.54$, and $z^* = 4.3$ for $D^* = 18.59$. This trend demonstrates that as D^* grows, the region with most pronounced temperature fluctuations moves closer to the inlet.*

The relationship between velocity and temperature fluctuations in the thermal

mixing zone is strongly coupled and significantly influenced by inlet hydraulic diameter (D). As illustrated in Fig. 11, an increase in D (from 5.71 to 18.59) amplifies the peak standard deviation of the x-axis velocity component, indicating enhanced turbulent mixing intensity. For smaller diameters ($D^* = 5.71$), weaker velocity fluctuations are distributed over a broader downstream region, with peak turbulence occurring farther from the inlet. This spatial separation correlates with delayed and less efficient mixing. Conversely, larger diameters ($D^* \geq 12.54$) generate stronger velocity fluctuations localized near the inlet, accelerating turbulent energy dissipation and promoting rapid, localized mixing. With increasing D , T RMS peaks shift significantly toward the inlet ($z^* = 28 \rightarrow 4.3$), accompanied by notable rise in temperature fluctuation intensity. This behavior aligns with enhanced turbulent kinetic energy associated with larger hydraulic diameters, which promotes more vigorous mixing and heat transfer. The shift in peak locations indicates that larger D^* values not only intensify velocity fluctuations but also bring regions of maximum temperature fluctuations closer to the inlet, reducing the characteristic length scale over which mixing occurs. Thus, hydraulic diameter plays a critical role in governing the spatial and temporal coupling of velocity and temperature fluctuations, with larger diameters fostering concurrent, high-intensity fluctuations that optimize thermal mixing efficiency by aligning regions of maximum momentum and thermal activity.

4. Conclusions

In this study, an experimental investigation on thermal mixing characteristics of parallel twin water jets was conducted using UDV. The effects of inlet velocity, temperature difference, velocity ratio, and hydraulic diameter were systematically analyzed. The key conclusions are as follows:

- (1) **Flow field characteristics:** Thermal mixing predominantly occurs within a confined rectangular zone near the jet inlets (Fig. 4), characterized by intense turbulence with recirculation phenomena (Figs. 5-7). Transient velocity fluctuations in the x-axis exhibit symmetric distributions (Fig. 7b), and their intensity scales with inlet velocity (Fig. 8). These observations align with UDV-measured velocity profiles and turbulence statistics.
- (2) **Temperature field characteristics:** Temperature fluctuations exhibit significant spatial variations along both x- and z-axes (Figs. 12-14), with dominant frequencies below 10 Hz (Fig. 12b). The T^* RMS peaks within the mixing zone ($z^* < 14$) and diminishes downstream (Fig. 14), confirming localized thermal mixing followed by stabilized temperature distributions.
- (3) **Impact of inlet conditions:**
 - **Velocity and temperature difference:** Increased inlet velocity (Figs. 8, 15) and temperature difference (Figs. 9, 16) enhance turbulence in-

tensity, accelerating thermal diffusion and compressing the mixing region vertically.

- **Velocity ratio asymmetry:** Velocity ratios $R \neq 1$ induce asymmetric velocity (Fig. 10) and temperature fluctuations (Fig. 17), with higher turbulence intensity on the faster jet side due to momentum dominance.
 - **Hydraulic diameter:** Larger diameters ($D^* \geq 12.54$ mm) intensify velocity fluctuations near the inlet (Fig. 11) and shift temperature fluctuation peaks closer to the jet source (Fig. 18), indicating enhanced mixing efficiency.
- (4) **Velocity-temperature coupling:** Velocity fluctuations directly govern turbulence intensity, which amplifies thermal diffusion (Figs. 8 vs. 15, 9 vs. 16). Regions of high velocity pulsations (e.g., $z^* = 11.2$ for $v = 1.5$ m/s) coincide with elevated T^* RMS values, demonstrating spatiotemporal coupling between momentum and thermal fields.

This study validates the applicability of UDV for transient velocity measurements in jet mixing, providing critical insights for subsequent lead-bismuth experiments. The experimental database supports future numerical simulations and safety analyses of Lead-cooled Fast Reactors (LFRs).

Acknowledgments

This work was supported and funded by the Fundamental Research Funds for the Central Universities (No. 3072024CFJ1506).

References

- [1] Ohshima, H., Muramatsu, T., Kobayashi, J., et al., 1994. Current status of studies on temperature fluctuation phenomena in LMFRs. In: IAEA/IWGFR Specialist Meeting on Thermohydraulics and Correlation between Material Properties and Conditions in Liquid Metal-cooled Fast Reactors (LMFRs), Aix-en-Provence, France, 22-24 November.
- [2] Choi, S.K., Han, J.W., Kim, D., et al., 2015. The present state-of-the-art in thermal striping studies for sodium-cooled fast reactors. In: Proceedings of the 16th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-16), Chicago, USA, August 30-September 4, pp. 6614-6624.
- [3] Brunings, J.E., 1982. LMFBR Thermal-Striping Evaluation. Electric Power Research Institute, Report No. EPRI-NP-2672.
- [4] Chellapandi, P., Chetal, S.C., Raj, B., 2009. Thermal striping limits for components of sodium-cooled fast spectrum reactors. Nucl. Eng. Des. 239 (12), 2850-2862.
- [5] Tenchine, D., 2010. Some thermal hydraulic challenges in sodium cooled fast reactors. Nucl. Eng. Des. 240 (5), 1195-1217.

- [6] Moriya, S., Ohshima, I., 1990. Hydraulic similarity in the temperature fluctuation phenomena of non-isothermal coaxial jets. *Nucl. Eng. Des.* 120 (2-3), 385-393.
- [7] Tenchine, D., Moro, J.P., 1997. Experimental and numerical study of coaxial jets. In: *Proceedings of the 8th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-8)*, Kyoto, Japan, pp. 1381-1387.
- [8] Ahmed, M.R., Sharma, S.D., 2000. Effect of velocity ratio on the turbulent mixing of confined, co-axial jets. *Exp. Therm. Fluid Sci.* 22 (1-2), 19-33.
- [9] Wakamatsu, M., Nei, H., Hashiguchi, K., 1995. Attenuation of temperature fluctuations in thermal striping. *J. Nucl. Sci. Technol.* 32 (8), 752-762.
- [10] Tokuhiko, A., Kimura, N., 1999. An experimental investigation on thermal striping: mixing phenomena of a vertical non-buoyant jet with two adjacent buoyant jets as measured by ultrasound Doppler velocimetry. *Nucl. Eng. Des.* 188 (1), 43-73.
- [11] Kimura, N., Miyakoshi, H., Kamide, H., 2007. Experimental investigation on transfer characteristics of temperature fluctuation from liquid sodium to wall in parallel triple-jet. *Int. J. Heat Mass Transf.* 50 (9-10), 2024-2036.
- [12] Lu, D., Cao, Q., Lv, J., et al., 2012. Experimental study on three-dimensional temperature fluctuation caused by coaxial-jet flows. *Nucl. Eng. Des.* 242, 234-242.
- [13] Cao, Q., Li, H., Lu, D., et al., 2017. Temperature fluctuation caused by coaxial-jet flow: experiments on the effect of the velocity ratio $R\$\ \1 . *Nucl. Eng. Des.* 314, 142-149.
- [14] Kok, B., Varol, Y., Ayhan, H., et al., 2017. Experimental and computational analysis of thermal mixing characteristics of a coaxial jet. *Exp. Therm. Fluid Sci.* 82, 215-227.
- [15] Kok, B., Varol, Y., Ayhan, H., et al., 2020. Experimental and LES simulation of thermal mixing behavior of a twin-jet flow with sequential cylindrical obstacles. *Int. Commun. Heat Mass Transf.* 114, 104576.
- [16] Roelofs, F., 2020. Liquid metal thermal hydraulics: state-of-the-art and future perspectives. *Nucl. Eng. Des.* 362, 110590.
- [17] Yu, Y.Q., Merzari, M., Thomas, J.W., et al., 2017. Steady and unsteady calculations on thermal striping phenomena in triple-parallel jet. *Nucl. Eng. Des.* 312, 260-270.
- [18] Tenchine, D., Vandroux, S., Barthel, V., et al., 2013. Experimental and numerical studies on mixing jets for sodium-cooled fast reactors. *Nucl. Eng. Des.* 263, 263-274.
- [19] Chacko, S., Chung, Y.M., Choi, S.K., et al., 2011. Large-eddy simulation of thermal striping in unsteady non-isothermal triple jet. *Int. J. Heat Mass*

Transf. 54 (19-20), 4400-4409.

[20] Angeli, P.E., 2019. Verification and validation of LES of a triple parallel jet flow in the context of a thermal striping investigation. Nucl. Eng. Des. 353, 110210.

[21] Cao, Q., Liu, S., Lu, D., et al., 2018. Numerical study on temperature fluctuation of upper plenum in FBR with a more realistic model. Ann. Nucl. Energy 114, 455-464.

[22] Wang, Y., Wang, M., Zhang, J., et al., 2021. Large eddy simulation on the mixing characteristics of liquid sodium at the core outlet of sodium-cooled fast reactors (SFR). Ann. Nucl. Energy 159, 108347.

[23] Jung, Y., Choi, S.R., Hong, J., 2022. Numerical analysis of temperature fluctuation characteristics associated with thermal striping phenomena in the PG-SFR. Nucl. Eng. Technol. 54 (10), 3928-3942.

Nomenclature

Abbreviations - LES: Large Eddy Simulation - LMFR: Liquid Metal Fast Reactor - LFR: Lead-cooled Fast Reactor - PIV: Particle Image Velocimetry - RMS: Root-mean-square - RANS: Reynolds-Averaged Navier-Stokes - SFR: Sodium-cooled Fast Reactor - Std. Dev.: Standard deviation - UDV: Ultrasonic Doppler Velocimetry - URANS: Unsteady Reynolds-Averaged Navier-Stokes

Symbols - A : Amplitude of normalized RMS temperature - D : Hydraulic diameter of inlet nozzles (mm) - N : Number of measurements - R : Velocity ratio - T : Fluid temperature ($^{\circ}\text{C}$) - T : Normalized temperature - T RMS: Normalized root-mean-square temperature - T_{avg} : Average temperature - T_c : Inlet cold fluid temperature ($^{\circ}\text{C}$) - T_h : Inlet hot fluid temperature ($^{\circ}\text{C}$) - ΔT : Inlet cold and hot temperature difference ($^{\circ}\text{C}/\text{K}$) - v : Velocity (m/s) - v_c : Cold jet velocity (m/s) - v_h : Hot jet velocity (m/s) - v_x : Velocity component in the x-direction - \bar{v}_x : Average velocity in x-direction - x : X-axis position (mm) - x : Normalized x-axis position - z : Vertical position (mm) - z : Normalized vertical position - σ_{v_x} : Standard deviation of velocity in x-direction

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv – Machine translation. Verify with original.