Journal Name: *Nuclear Engineering and Design*

Article Title: Particle Image Velocimetry Measurements of the Flow in the Converging Region of Two Parallel Jets

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Acknowledgement

The authors would like to thank Nuclear Energy Advanced Modeling and Simulation (MEMS) under Department of Energy (DOE) for their financial supports.

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Abstract

The interaction between parallel jets plays a critical role in determining the characteristics of the momentum and heat transfer in the flow. Specifically for next generation VHTR, the output temperature will be about 900 °C, and any thermal oscillations will create safety issues. The mixing variations of the coolants in the reactor core may influence these power oscillations. Numerous numerical tools such as computational fluid dynamics (CFD) simulations have been used to support the reactor design. The validation of CFD method is important to ensure the fidelity of the calculations. This requires high-fidelity, qualified benchmark data. Particle image velocimetry (PIV), a non-intrusive measuring technique, was used to provide benchmark data for resolving a simultaneous flow field in the converging region of two submerged parallel jets issued from rectangular channels. The jets studied in this work had an equal discharge velocity at room temperature. The turbulent characteristics including the distributions of mean velocities, turbulence intensities, Reynolds stresses and Z-component vorticity were studied. The streamwise mean velocity measured by PIV and LDV were compared, and they agreed very well.

Keywords

CFD Validation, Parallel Jets, PIV, Experimental Study

Nomenclature

U	streamwise velocity
V	lateral velocity
a	jet width
S	jet spacing, the distance between the centers of two jets
l	jet length
x	x axis which is perpendicular to the direction of main stream
y	y axis which is parallel to the direction of main stream
U_{max}	maximum value of U
ω	Z-component vorticity

1. Introduction

Parallel jets are important shear flows widely existing in nuclear reactors. For example, in Gen. IV conceptual nuclear reactors, the coolants merge in the upper or lower plenum depending on the specific reactor types after passing through the reactor core. The velocity and temperature distributions of the coolant are heavily influenced by the mixing condition of these jets. Studying the interaction of two parallel jets or twin jets will pave the way for better understanding of the flow behaviors of multiple jets, which is a more complex flow phenomenon. Numerical experiments such as CFD simulations are massively involved in the design process. However, the results cannot be trusted until they are validated. Thus, obtaining high-fidelity experimental data sets for benchmarking the numerical models has become an important subject.

The flow structure of parallel rectangular jets is typically divided into three regions. These regions are the converging region, merging region and combined region as demonstrated in Fig.1. The converging region starts from the jet's exiting point and ends at the merging point (MP). U is equal to zero at MP. Another important point is the combining point (CP), which is defined as the position where U reaches its maximum. The region between the MP and the CP is called the merging region. The region after the CP is the combined region, in which the two jets develop and form a single jet. Due to the entrainment of the two jets in the converging region, the jets are deflected, and a recirculating zone is formed.

Table 1 summarizes the previous studies of the parallel jets under varied experimental conditions. It was reported that the velocity field and the turbulence characteristics were functions of the spacing ratio S/a and the aspect ratio l/a [2]. Previous works have mainly focused on large spacing ratios and aspect ratios. However, these ratios are relatively small in nuclear reactors. Moreover, the working fluid reported was mainly air, and the measuring technique used was a hot-wire anemometer (HWA). Although the governing equations are the same for water and air, the type of working fluids will introduce different measurement

uncertainties and challenges into the specific experiments. Compared to HWA, PIV is superior in handling the reversed flows, which exist in the recirculating zone of the parallel jets.

Thus, the purpose of this study is to evaluate the flow behaviours in the converging regions of parallel rectangular jets with a small spacing ratio of 3.07 and an aspect ratio of 15.1 using PIV. This study will help enlarge the experimental database of this specific flow. It can also serve as a benchmark for the data sets to validate related numerical models.

2. Experimental Apparatus and Procedure

The setup of the PIV system is shown in Fig. 2. The water flow was driven by two 0.5 horsepower pumps. The rectangular nozzle had a width of 5.8mm and length of 87.6mm. The spacing ratio S was 17.8mm. The height of the slots was 279.4 mm, which was long enough to ensure that the turbulent flow was fully developed. The flow passed a stagnation box before entering the channels to dampen the undesired fluctuations in the flow. The exit Reynolds number was 9,100 based on the average discharge velocity, which was 0.75 m/s. The acrylic tank had a capacity of 0.76 m³. The flow rate was controlled by two valves and monitored using two GPI TM100 flow meters with an accuracy of 97% and repeatability of 95%. The channels were located at the center of the tank as illustrated in Fig. 3 with detailed dimensions presented. The jets could develop freely without being disturbed by the walls. The two jets had the same discharge velocity and were at room temperature.

The PIV system used to measure the velocity field consisted of a high-power Nd:YAG dual-head laser (Beamtech PIV200) with a wavelength of 527 nm and a high speed camera (GX3 V-190-B/W) equipped with a 1.3 Mega pixel sensor. The maximum laser energy was 100 mJ per head, and the maximum shooting frequency was 15 Hz, which was employed in this study. The maximum frame rate of the camera was 198,000 fps. 4G memories enabled a longer period of measurements with respect to a fast transportation speed of the data. The maximum resolution was 1280 x 1014, which was used in this work. The high speed camera and the laser were

synchronized by a high accuracy pulse generator. The time period between each pair of images in this experiment was 500 μ s.

The high speed camera was sitting on a 3-D traversing system from Dantec with an accuracy of 0.01 mm so that the camera could be able to move accurately to investigate different regions of the jets. The seeding particles used in this experiment were hollow glass spheres from TSI centered at 10 μ m with a refractive index of 1.5. The density ranged from 1.05 g/cc to 1.15 g/cc. The Stokes number, an indication of the tracer fidelity, calculated using Eq. (1) was 0.0009 implying that the particles could follow the fluid very well [15].

$$Sk = \frac{\tau U}{L} = \frac{D_p^2 \rho_p C_c u_o}{18 \mu L} \quad (1)$$

where τ is the relaxation time of the particle, u_o is fluid velocity, L is the characteristic length of the fluid, D_p is particle diameter, ρ_p is particle density, and C_c is the slip correction factor which is equal to 1.017 for the particle with a diameter of 10 μ m.

The particles were injected into the system from two water reservoirs under the water tank, and the system ran long enough before the measurements were taken to minimize any unstable effects. The laser was operated at the pulse mode with a frequency of 15 Hz. The full 4 Gb memory was used for each measurement generating about 812 pairs of images. Two measuring scales were employed to study the mixing condition in and above the converging region. The camera was moved closer to the target area after completing the measurements of the two regions together. These two cross-validated data sets helped reveal the uncertainties introduced by the enlargement factor, which was a common uncertainty that existed in any PIV measurements [16]. The images were then analysed using an open-source code PIVlab V. 1.2. Pre-processing techniques of contrast limited adaptive histogram equalization (CLAHE) and a high-pass filter were employed to enhance the quality of the raw images [17]. A comparison of original raw image and the enhanced one is shown in Fig. 4.

3. Results and Discussion

As stated in section 2, the measurements were carried out using two scales, scale M1 and scale M2. Scale M1 corresponded to the area ranging from $y/a = 0$ to 12 while scale M2 was from $y/a = 0$ to 3. The purpose of running an extra measurement with scale B was to evaluate the enlargement effect of PIV. So the results reported in this work are based on scale A. Results from both scales will be compared and discussed. Measurements using scale M1 were repeated three times to evaluate the uncertainties. These three measurements A, B and C were carried out at different times and independently. The system was cleaned and resampled before any new measurements started to ensure the independence of each measurements. The results from three measurements were then ensemble-averaged to evaluate the mean streamwise velocity U , mean lateral velocity V and other turbulence quantities, such as turbulence intensity, Reynolds stress and Z-vorticity.

3.1 Mean Velocity

The mean velocities U and V were calculated by time-averaging over 800 frames or pairs of images. Then, as mentioned above, these three averaged mean velocities were ensemble-averaged again to obtain the final mean values. Fig. 5 presents distribution of U with streamlines. The two jets were symmetrical about the center axis. Obviously, the jets had not combined at $y/a = 12.3$, the highest elevation in this measurement. Streamlines clearly indicate the entrainment of surrounding fluid. In the recirculating zone, reversed flows were observed. One interesting phenomenon captured in this zone is that the flow, let's call it flow A, moved upward first from $y/a = 0$ then "met" another stream of flow B coming downward at about $y = 1.4$. Due to mutual forces from these two flows, flow B started to recirculate while flow A moved to the lateral direction. In addition, the flow, let's call it flow C, at some distance above flow B had an opposite moving direction. The point separating flow C and B is MP, where U is zero. The location of MP was found to be at about $y/a = 3.45$. In order for other researchers to compare with results in this

work, U distribution at four different elevations are plotted in Fig. 6. The errors bars were the standard deviations from three independent measurements.

The distribution of V is shown in Fig. 7, and Fig. 8 presents the plots of V at different locations. Strong lateral movements of the flow were observed in the region between $y/a = 2$ and $y/a = 5$. This is the region that two jets were converging on. Lateral movements of the surrounding fluid were also significant near the outer edge of each jet. This implies that a low pressure region was formed due to the fast moving jets near the exit. In order to find the exact location of MP, the mean vector field, as shown in Fig. 9, was calculated using U and V . The mean vectors were highly symmetrical along the center line. The zoomed-in view of the region circled in Fig. 9 clearly confirmed the location of the MP, which was at about $y/a = 3.45$. This value is close to what was found in previous LDA measurements performed by the authors, which was located between $y/a = 1.72$ and 3.45 as there were no measurement points available inside this range [18]. As a comparison, U profiles at $y = 1.74$ (1.72) measured by LDV [18] and PIV are presented at Fig. 10. Results based on both scales M1 and M2 are shown. Obviously, M2 had many more points than the other two scales due to its high resolution. These three data sets agree very well with the majority of the zones, with the exception of the recirculating zone in which the flow behaviours were complex. Uncertainties of PIV_M1 were calculated using standard deviations based on the three measurements. The errors of PIV_M1 were less than 3% except for those points of velocities close to zero.

3.2 Mean z-vorticity

With known U and V , z-component vorticity, an indication of the rotation speed of fluid particles in the x-y plane, can be computed by Eq. (2).

$$\vec{\omega}_z = \left(\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y} \right) \vec{e}_z \quad (2)$$

The mean z-vorticity distribution is shown in Fig. 11. The positive direction is pointed out of the x-y plane. Strong vortices were located at the edges of the jets. These vortices died out along the positive y direction. No strong vorticities were found at locations above $y/a = 10$. The friction forces between the moving jets and static surrounding them generated these vortices. Vortices in the inner edge area started moving closer around the MP indicating a strong combination of activities.

3.3 Turbulence Intensity

The power of turbulence can be evaluated by computing turbulence intensity, or put more simply, root mean square (R.M.S.) velocities. It represents the degree of fluctuations of fluid particles. The turbulence intensity near the jet nozzles determines the position of MP and the mixing condition in the converging region. Fig. 12 shows the profile of streamwise turbulence intensity U_{rms} , and Fig. 13 presents the values at four elevations. The two potential cores near the jet nozzles could be clearly observed, in which the turbulence intensities were close to zero. Due to the shear force, turbulence intensity was higher at the edges of the jets. A long and narrow low-fluctuation region was found in the space between the two jets. It was noticeable that the turbulence intensity was low in the recirculating zone although flow behaviors in that zone were complicated. Lateral turbulence intensity V_{rms} and the detailed values at different locations are presented in Fig. 14 and 15, respectively. Strong fluctuations existed in the merging region after the MP implying that the main momentum transfer happened in the merging region. The lateral fluctuations were not strong in the recirculating zone either. A relative low-intensity region was found around $y/a = 11$. This is because the major momentum transfer happened around $y/a = 7$, and energy exchange in the lateral direction was weak.

3.4 Reynolds Stress

Reynolds stress is a measure of momentum flux in the flow. Fig. 16 shows the Reynolds stress component distribution. It shows that the strongest momentum transfer happened not in the converging region but in the merging region, specifically the region between $y/a = 3.5$ and $y/a = 8.5$. It is interesting to see that $y/a = 3.5$ is the exact location of MP. That is, the effective momentum transfer started right after the MP. Another region with significant momentum flux was the outer edge of the jet which ranged from $y/a = 1.5$ to $y/a = 12$, which is the maximum value that this measurement could reach with respect to the satisfying resolution. Again, the majority of the momentum transfer happened in the merging region.

3.5 Instantaneous Vector Field

One of the benefits of using PIV compared to LDA is that the full field instantaneous velocity profile can be captured simultaneously. Different from averaged quantities, instantaneous velocities enable us to better understand the evolution of the flow in the time domain. Because of the nature of turbulence, the flow pattern changes with time. Thus, studying the instantaneous velocities measured at different frames can help us reconstruct some meaningful information that is lost in the mean quantities. For example, as shown in Fig. 17, the movement of vortex A could be clearly identified. Since vortex A emerged periodically, the time period between these two frames might be necessarily equal to the real length of time that vortex A needed to travel to the position of A'. Similarly, the growth of the vortex could be clearly revealed.

Another interesting phenomenon found by analyzing the instantaneous vector field was how the two jets interacted with each other. Two characteristic interacting patterns were observed repeatedly as presented in Fig. 18. In the left picture, the two jets diverged immediately after hitting each other. However, as shown in the right-side image, the two jets rejoined and separated a few times before they fully merged. These vector profiles are useful for better understanding the behaviors of twin jets. This information was totally lost in the averaged quantities.

4. Conclusions

PIV measurements of turbulence mixing in the converging region and partial merging region of two parallel rectangular jets were carried out. The jets were of equal discharge velocity, and were at room temperature. The frame rate of the PIV measurement was 15 Hz, and the time interval between each pair of images was 0.5 ms. The particle used was hollow glasses centered at 10 μm . The study of mean velocities revealed interesting flow behaviors in the circulating zone. Three parts of flow moved at totally opposite directions generating a significant amount of recirculations. The lateral movements of the jets were found to be significant at the inner edges of the jets located between $y/a = 1.5$ and 6. The MP was located at $y/a = 3.5$ at which U was equal to zero. Two scales of PIV measurements, scale M1 and M2, were employed. By comparing the mean U profiles measured from two scales of PIV measurements and previous LDA results, it was shown that they agreed very well. The standard deviation of the measurement PIV_M1 was less than 3%. Turbulence studies implied that strong momentum transfer happened in the region ranging from $y/a = 3.5$ to 8.5. That is, the momentum started to be transferred significantly after the MP. Instantaneous vector fields were evaluated to identify the displacements and growth of vortices as well as their interaction patterns. Future work may include but not limited to the study of coherent turbulence structures using high-frequency PIV systems and evaluation of the uncertainties in the measurements of turbulence quantities resulted from the change of measurement resolutions.

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Table 1 Summary of the literature review

Year	Authors	Working fluid	Spacing ratio (S/a)	Aspect ratio (l/a)	Re	Measuring tools	Contributions
1959 [1]	Miller and Comings	Air	6	very large	17,800	Hot-wire anemometer	Symmetry, Merging into single jet, MP = 7
1970 [2]	E. Tanaka	Air	8.5 - 26.3	very large	4,290 - 8,750	Hot-wire anemometer	Negative pressure region, Independence of Re
1974 [3]	E. Tanaka	Air	8.5 - 26.3	very large	4,290 - 8,751	Hot-wire anemometer	For S/a = 20, MP = 13~15a, CP=30a
1977 [4]	G.F. Marsters	Air	17.25	40	12,000	Hot-wire anemometer	Proposed a crude integral model
1983 [5]	H. Elbanna and S. Gahin	Air	12.5	40.8	20,000	Hot-wire anemometer	Half-width of the combined flow grew linearly
1987 [6]	H. Elbanna and S. Gahin	Air	27.64	89	n/a	Hot-wire anemometer	CP = 60 for equal velocity, studied uneven jets
1989 [7]	N.W.M. Ko and K.K. Lau	Air	2.5	5.6	10,000	Hot-wire anemometer	MP = 2.5a, CP = 10.5a
1990 [8]	Y.F. Lin and M.J. Sheu	Air	30 & 40	90	9,000	Hot-wire anemometer	For S/a=30a, MP = 40, CP = 60a
1997 [9]	A. Nasr and J.C.S. Lai	Air	4.25	24	11,000	LDA (using frog fluids)	MP = 4a, CP = 8a
1998 [10]	P. Behrouzi and J. J. McGuirk	Water	13	n/a	37,500	LDA	Flow Impingement
2001 [11]	E. A. Anderson and R. E. Spall	Air	9 - 18.25	32	5,900 - 6,100	Hot-wire anemometer	For S/a = 9, MP = 12a, CP = 19a
2007 [12]	Z. Q. Yin et. al	Air	1.5, 1.75, 1.89	6.8	33,300 - 83,300	Hot-wire anemometer	U was independent of Reynolds number
2011 [13]	A. Nasr and J. Lai	Air	2.5	n/a		LDA & Numerical	MP = 1.75a, CP = 4.4a, the proposed model didn't work for small S/a

Figure

Fig. 1. The flow structure of parallel rectangular jets

Fig. 2. PIV setup

Fig. 3. Illustration of the parallel jets system

A

Fig. 4.

comparison of original raw image and the one enhanced by pre-processing techniques of CLAHE and a high-pass filter

Fig. 5. Streamwise average velocity U profile and streamlines

Fig. 6. Streamwise average velocity U at different elevations

Fig. 7. Lateral average velocity V distribution

Fig. 8. Lateral average velocity V at different elevations

Fig.9. Mean vector field and identification of the MP location where $U = 0$

Fig. 10. U profile at $y/a = 1.74$ (1.72) measured by LDV [18] and PIV (scale of M1 and M2). M1 and M2 refer to different measuring scales. Scale M2 had a higher resolution than that of M1. Error bars of PIV_M1 is the standard deviation of three independent measurements.

Fig. 11. Z-vorticity distribution

Fig. 12. U_{rms} profile

Fig. 13. Streamwise average R.M.S. velocity $U_{r.m.s.}$ at different elevations

Fig. 14. V_{rms} profile

Fig. 15. Lateral average R.M.S. velocity $V_{r.m.s.}$ at different elevations

Fig. 16. Reynolds stress distribution

Fig. 17. Instantaneous vector field obtained at $t = 5.226 \text{ s}$ (left) and $t = 51.054 \text{ s}$ (right) showing the growing and movement of vertexes A and B (not within one period).

Fig. 18. Two characteristic and repeated patterns observed