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Laser-Doppler measurements of the turbulent mixing of two rectangular water jets impinging on a stationary pool

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ABSTRACT

Turbulent mixing of parallel jet flows has broad engineering applications. For example, in Gen. IV conceptual nuclear reactors, high-temperature flows mix in the lower plenum before entering the secondary cooling system. The mixing condition needs to be accurately estimated and fully understood. In addition, massive computational works involved in the design process necessitate high-fidelity experimental data sets for benchmarking simulation results.

The purpose of this study is to use laser Doppler anemometry, a non-intrusive measuring technique, to evaluate the mixing characteristics of two submerged parallel jets issuing from two rectangular channels. The jets with a small spacing ratio of 3.1 were at room temperature. Flow characteristics including distributions of mean velocities, turbulence intensities, and Reynolds stresses were studied for the cases with equal and non-equal discharge velocities. The merging point (MP) was found to be between $y/a = 1.72$ and $y/a = 3.45$. The combining point (CP) was at $y/a = 15.52$. The Reynolds shear stress, a measure of the intensity of momentum transfer, reached its maximum after the merging point. An uncertainty analysis indicated that the average standard deviations of the streamwise mean velocity U and turbulence intensity U_{rms} at all locations in the five days' measurements were 1.5% and 1.6%, respectively. Spectral analyses including fast Fourier transform, power spectral density estimation and continuous wavelet transform revealed the scale and the evolution in time of varied-size eddies in the mixing region of the flow. Repeating flow structures were observed in different time segments.

The experimental data obtained from the LDA measurements of the averaged quantities and transient are not only valid for benchmarking steady-state numerical simulations using turbulence models to solve RANS equations but they also enlarge the database of the experimental data for twin jets.

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1. Introduction

High temperature gas-cooled and sodium-cooled reactors have been designated as two of the six candidate reactors for next generation, also Generation IV, (Gen. IV) nuclear power plants. The design process needs a large amount of numerical simulations such as computational fluid dynamics (CFD) computations and, as any large-scale experiments requires significant amount of money and time. However, the inherent uncertainties existing in the turbulent models and wall functions of any CFD codes solving Reynolds-averaged Navier–Stokes (RANS) equations negatively influence the credibility of the CFD simulation results. This necessitates high-fidelity experimental data sets for benchmarking these results.

In Gen. IV reactors, mixings of high-temperature flows appear in the lower plenum. The spacing ratio of the jets is relatively small, for instance, in the sodium-cooled reactor, compared to those in the external aerodynamics applications. The mixing condition and the mixing length are of great importance to the reactor safety because of the existence of thermal stresses and possible temperature oscillations induced by the turbulent mixing. These temperature oscillations will further result in output power instabilities. In this work, two submerged parallel waters jets issuing from two rectangular channels, also known as twin-jet flow, were selected to study the turbulent mixing phenomenon.

Different from a single jet flow, twin jets issuing from two adjacent rectangular slots are characterized by the formation of a subatmospheric pressure region due to the mutual entrainment of the two jets. This negative-pressure region deflects the jets, causing

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them to move towards each other and form a converging region. Inside this region, strong recirculations near the slots area create a flow reversed with respect to the direction of the main flow. The converging region ends at the merging point (MP) which is defined as the point at which the mean velocity is zero along the symmetry axis [1]. Beyond this point the jets start to combine until they form a single jet at the combining point (CP). The region between the MP and the CP is called the merging region. The combined jet then behaves as a single jet and analytical solutions derived for a single jet hold in this combined region. The mixing does not only happen between the jets themselves but also between the jets and the static surrounding fluid that was entrained as a result of the shear force created. In engineering applications, knowing the length of the mixing region and the locations of the CP and MP are often important to ensure a good mix. The schematic structure of a typical twin jet is shown in Fig. 1.

In 1959 Miller and Comings [2] made the first measurements of the 2-D twin jets using a constant temperature hot-wire anemometer (HWA). The non-dimensional jet spacing ratio, the ratio between the jet spacing *S* and the jet diameter *a*, was 6. By measuring the mean and fluctuating velocity as well as the static pressure and comparing them to a single jet, they found that the flow of the 2-D twin jets had a high degree of symmetry about the centerline of jets. The two jets merged at certain location behaving as a single jet. This location was defined as the separating point of the converging region and the combined region. Before the MP, there was a stagnation point, also called the combining point, at which point the static pressure gradient and the turbulent shear stress force were equal but with different signs.

Tanaka [3] conducted a similar measurement using a dual jet of air issuing from parallel slot nozzles but focused on the effect of the spacing ratio ranging from 8.5 to 25. The static pressure was determined to be negative near the nozzle region but suddenly increased to atmospheric pressure or even higher after the free stagnation point [3]. The author also concluded that the streamwise velocity distribution was independent of the Reynolds number within the limits of velocity studied. An empirical equation relating the curvature of the central stream-line of the jet and the nozzle distance was proposed. In another report [4], the combined flow of the twin jets was found to have a velocity distribution similar to a single jet with its width spread linearly downstream. The decay of the center velocity was stronger than that of a single jet.

A crude integral model of two parallel jets was proposed, and the results predicted the mixing behavior surprisingly well, despite the fact that the model overpredicted the entrainment rates. The experiments revealed that the velocity distributions were self-preserved upstream and downstream of the merging region [5]. Elbanna and Gahin [6] evaluated the turbulent characteristics of the twin jets and compared with the behavior of a single jet. The spacing between the two nozzles applied was 12.5 slot widths. The results indicated that the half-width of the combined flow grew linearly in the direction of the stream but the spread angle was slightly smaller than that of a single jet.

Research on non-equal parallel jets studied shows that the slower jet was more attracted to the faster jet when the velocity ratio decreased [7]. However, the total momentum, including the velocity and pressure momentum, was still conserved. Using a similar measuring technique, the distributions of the overall Reynolds stress and the velocity fluctuations of two parallel jets with a spacing ratio of about 2.5 was evaluated, and the presence of inner and outer mixing regions in each jet was found [8]. The directions of rotation of the inner and outer vortices were opposite. The jets did not converge because side plates were not installed in the

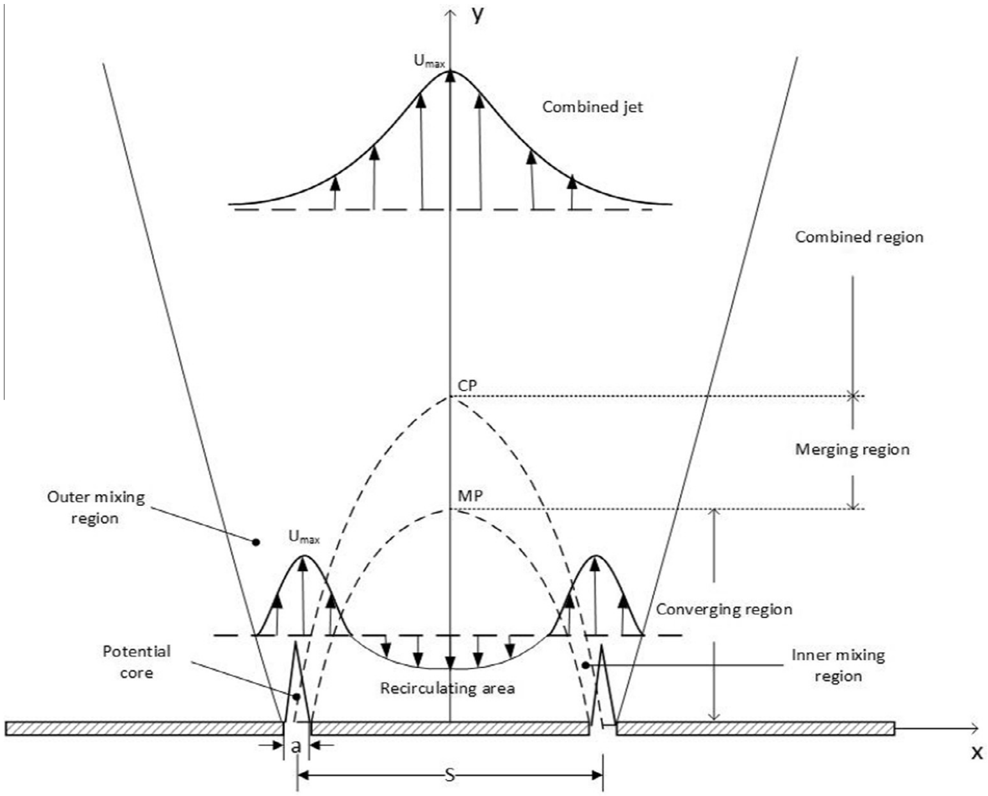

Fig. 1. Diagram of a typical twin jet system. *a* is the channel width, *S* is the distance between centers of the two jets, U_{max} is the local maximum velocity in the streamwise direction, *x* is the coordinate perpendicular to the direction of the jets, *y* is the coordinate along the streamwise direction, CP stands for the combining point, and MP is the merging point.

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