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Experimental study of flow structures near the merging point of two parallel plane jets using PIV and POD

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ABSTRACT

The initial and interacting region near the merging point of unventilated two parallel plane jets were investigated using Particle Image Velocimetry (PIV) and Proper Orthogonal Decomposition (POD). Two parallel rectangular nozzles with an aspect ratio of 15.1 (5.8 mm in width and 87.6 mm in length with 12 mm spacing) produced the jets at $Re \approx 4900$ based on the jet width. This study collected statistically enough number of data with high spatiotemporal resolution. The experimental data was evaluated in terms of PIV uncertainty and statistical convergence. The POD analysis visualized the interaction and transportation of multi-scale vortical structures and their spectral characteristics. The experimental data also presented the characteristic parameters of the two parallel plane jets including the converging region and the location of the merging point. Two models to predict the merging point were proposed satisfying several experimental data reported.

1. Introduction

Many researchers [1–14] have investigated two parallel plane jets using pointwise measurement techniques including Hot-wire Anemometry (HWA) and Laser Doppler Anemometry (LDA) as summarized in Table 1. The pointwise data successfully provided local spectral analysis and supported Reynolds Averaged Navier-Stokes (RANS) based turbulent models. However, that data could not provide transient spatial structures of mixing jets. Although there exist recent studies on a single jet by Shim et al. [15] and two round jets by Zang and New [16], there is still a lack of transient whole-field measurement data to understand multi-dimensional flow structures in two parallel plane jets. In addition, recent Computational Fluid Dynamics (CFD) calculations using Large Eddy Simulation (LES) require high-resolution experimental data in time and space. Especially, for the design of a sodium-cooled reactor using CFD which is one of the next generation nuclear reactor designs, high-fidelity experimental benchmarking data is required in a relatively small spacing ratio of the jets. In order to satisfy the current needs, the present study employs Proper Orthogonal Decomposition (POD) using the data acquired by Particle Image Velocimetry (PIV), which allows investigating the large-scale coherent structures in the near field of the two parallel plane jets. The experimental data also presents the characteristic parameters of parallel plane jets including the converging and merging regions and the location of the mixing point shown in Fig. 1. As one of the early researchers, Tanaka [2] identified characteristic parameters to explain the structure of the two parallel jets, and other studies in Table 1 confirmed the structure of the interaction of two jets as shown in Fig. 1.

They characterized two parallel jets using Reynolds number, Re, and the spacing ratio, s/w, where s is the distance between the center of each jet, and w is the width of the jets. The interaction of two jets occurs in three regions: converging region, merging region, and combined region. There are two points of interest called the merging point, y_{mp}, and the combined point, y_{cp}. The merging point is located between the converging region and the merging region, which is one of the main targets in this study before continuing to POD analysis. The combined point places between the merging region and the combined region. Several researches [2, 7, 8, and 13] proposed empirical correlations between y_{mp} and s/w.

It would be beneficial to review the studies on a plane jet that has been one of the essential topics in turbulent study for decades. The studies on a plane jet focused on large-scale coherent structures and found that coherent structures are closely related to entrainment and mixing of jets with ambient fluid. An important characteristic of plane jets is two modes of large-scale vortex formation called the "flapping" for asymmetric structures and "puffing" for symmetric structures [17]. Sato [18], Goldschmidt & Bradshaw [19], Rockwell & Niccolls [20], and Thomas and Goldschmidt [21] demonstrated initially symmetrical streamwise evo-

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Nomenclature

A_n^i	element of eigenvector $\mathbf{A}^i$
E	two-dimensional kinetic energy (m^2/s^2)
H	water level from the top of the jet outlet (mm)
I	turbulence intensity
L	water tank length (mm)
M	number of spatial nodes in a velocity field
N	number of velocity fields
R	residual, root-mean-square value of the difference between two batches of n and n-1
Re_0	jet initial Reynolds number with jet width, w
Re_{dh}	jet initial Reynolds number with hydraulic diameter
R_{ii}	diagonal Reynolds stress terms
$St_{1,2}$	Strouhal number using $f_{1,2}$
St_v	Strouhal number using vortex shedding frequency, f_v
U	mean lateral (transverse) velocity component (mm/s)
V	mean vertical (streamwise) velocity component (mm/s)
V_{max}	maximum vertical (streamwise) velocity (mm/s)
$\overline{V_0}$	mean jet outlet velocity (mm/s)
$V_{i,j}^n$	averaged vertical velocity up to generic time snapshot n at (i, j) (mm/s)
W	water tank width (mm)
ΔX	displacement of particle images (mm)
a_i^n	time variable expansion coefficients of ith mode at generic time snapshot n
d_h	hydraulic diameter of the nozzle (mm)
f_0	initial jet shear instability frequency (s^{-1})
f_c	jet column frequency (average passage frequency) (s^{-1})
$f_{1,2}$	dominant frequency of the POD modes 1 and 2 (s^{-1})
f_v	dominant vortex shedding frequency (s^{-1})
h	channel height (mm)
l	jet length (mm)
n_{eff}	effective sample size
s	jet separation (mm)
Δt	time interval of successive images (s)
u	instantaneous lateral (transverse) velocity on x-axis (mm/s)
u'	fluctuating component of u (mm/s)
δu	information of the image differs from the flow field (mm/s)
v	instantaneous vertical (streamwise) velocity on y-axis (mm/s)
v'	fluctuating component of v (mm/s)
w	jet width (mm)
y_{cp}	combining point (mm)
y_{mp}	merging point (mm)
Ω	mean vorticity (s^{-1})
Ω_Q	rate-of-rotation tensor (s^{-1})
α	magnification factor (mm/pixel)
η	Kolmogorov length-scale (m)
λ^i	eigenvalues of $\mathbf{C}$
ν	kinematic viscosity (mm^2/s)
$\sigma_{C,PIV}$	combined uncertainty of PIV (mm/s)
σ_{Rii}	standard deviation of diagonal Reynolds stress terms
τ	Kolmogorov time-scale (s)
ω	vorticity (s^{-1})
ω'	fluctuating component of vorticity (s^{-1})
$\mathbf{A}^i$	ith eigenvector of $\mathbf{C}$
$\mathbf{C}$	auto-covariance $N \times N$ matrix of $\mathbf{U}$
$\mathbf{S}$	rate-of-strain tensor
$\mathbf{U}$	velocity matrix
$\mathbf{u}^n$	velocity column vector at generic time snapshot n
Ψ	POD mode matrix
ϕ^i	ith POD mode in space

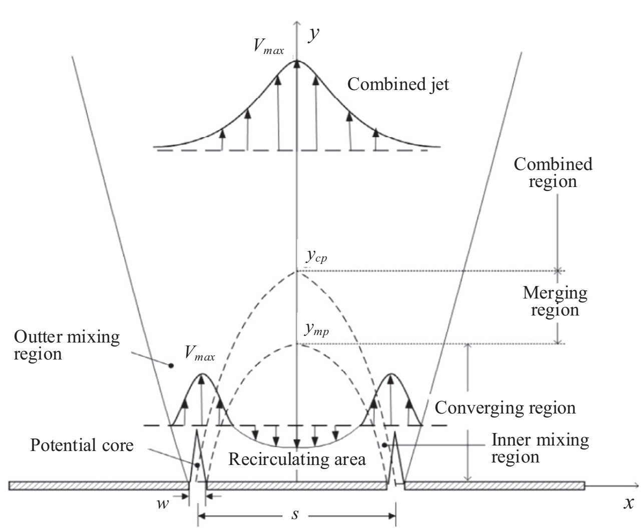

Fig. 1. Structure of plane two parallel jets.

lution of the vorticity field. Sato [18] investigated the behavior of a two-dimensional jet in the region where laminar flow becomes unstable and found two modes of velocity fluctuation; one is symmetrical and the other is asymmetrical with respect to the centerline of the jet. Sato observed that the relative intensity of two modes of fluctuation is strongly dependent on the mean-velocity distribution. When the velocity distribution was nearly parabolic, the asymmetrical fluctuation prevailed. On the other hand, when the velocity distribution was close to flat, the asymmetrical fluctuation was not observed. The current POD analysis visualizes the flow structure under a non-flat mean-velocity distribution as Sato [18] demonstrated with oscillography records. Recently, Shim et al. [15] carried out PIV measurements in a plane jet and applied POD for the study of large-scale coherent structures. Their POD analysis revealed vortex merging at the subharmonic sideband frequency, $(f_0 \pm f_c)/2$, where f_0 was the initial jet shear instability frequency, and f_c was the jet column frequency corresponding to the average passage frequency of vortical structures near the tip of the potential core (Thomas and Prakash [22]). The current study proposes two empirical correlations to predict y_{mp} for $s/w < 3$ and $3 \le s/w \le 10$ based on the models proposed by Tanaka [2] and Lin and Sheu [8]. The POD analysis reveals several significant frequency peaks related to the subharmonic sideband frequency, which explains vortex pairing between the jet nozzle outlet and the merging point. The peak frequency of the POD modes 1 and 2 which contain the largest energy is compared to an existing single plane jet experimental data in terms of Strouhal number. Also, the POD modes visualize the multi-scale vortical structures.

2. Methodology

Two parallel jets have two outer mixing layers and two inner mixing layers as shown in Fig. 1. When two jets are close to each other, the development of vortical structures should be different from a single plane jet. The present study visualizes the flow struc-