International Journal of Heat and Mass Transfer 119 (2018) 752–767

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Computational study of turbulent flow interaction between twin rectangular jets

Han Li [a], N.K. Anand [a], Yassin A. Hassan [a,b,*]

[a] Texas A&M University, Department of Mechanical Engineering, 3123 TAMU, College Station, TX 77843-3123, United States
[b] Texas A&M University, Department of Nuclear Engineering, 3133 TAMU, College Station, TX 77843-3133, United States

ARTICLE INFO

Article history:
Received 13 July 2017
Received in revised form 1 December 2017
Accepted 1 December 2017

Keywords:
Turbulent mixing
Parallel jets
Computational fluid dynamics
OpenFOAM

ABSTRACT

Turbulent jets are commonly used in engineering applications. Systems of multiple parallel jets have an important flow structure that could accomplish rapid and efficient mixing. The mixing feature of parallel jets has several engineering applications, such as its application in Generation IV very-high-temperature nuclear reactors, where the coolants merge in the upper or lower plenum after passing through the reactor core. Computational fluid dynamics (CFD) simulations are extensively employed in the study of the mixing phenomenon of parallel jets. Therefore, the validation of various turbulence models is of great importance to the process of ensuring that the numerical results are trustworthy and that they serve as a guide for future designs.

In this study, an open source CFD library, namely OpenFOAM, was utilized to conduct the numerical simulation of the twinjets. This work consists of two parts; one part focuses on steady-state simulations, and the other on transient simulations. In the first part, the Reynolds-averaged Navier–Stokes (RANS) models, such as the realizable k–ε and the shear stress transport (SST) k–ω, were used for the steady-state validation study. Steady-state simulations showed that with proper boundary conditions at the inlets, the mean velocity data agreed with the experimental data well within an engineering accuracy (14%). In the second part, the partially averaged Navier–Stokes (PANS) models were implemented in the code, and were utilized to conduct transient simulations. Experimental fluctuating inlet boundary conditions were employed. The results obtained from the PANS and the unsteady Reynolds-averaged Navier–Stokes (URANS) models were compared with the experimental data. The PANS model presented good agreement in terms of the merging point (4.3%). In addition, the k–ε PANS model was compared with the k–ε URANS model. Power spectrum density (PSD) analysis was performed based on the velocity at four sample locations to compare resolved frequencies between the PANS and the URANS models. It was observed that PANS model presented better capabilities in resolving higher turbulence flow frequencies compared with the URANS, based on the PSD analysis.

1. Introduction

A system of two or more parallel jets have an interesting flow structure, which could accomplish rapid mixing. The mixing feature of parallel jets can be found in several engineering applications (e.g., the very-high-temperature reactor (VHTR)). The coolants merge in the upper or lower plenum, after passing through the reactor core. In sodium-cooled fast reactors (SFR), the mixing of different-temperature fluids from the jets can cause thermal stresses and flow-induced vibration in a rod bundle. In cooling applications of electronic packages, jet impingement is considered as an efficient strategy for heat removal. In boiler burners, a fuel injection system with parallel jets can be an effective manner to achieve fuel mixing. Considering the importance of multiple-jet systems, a numerical simulation of two parallel turbulence jets, referred to as twinjets, was conducted. In this study, the simulation results were compared to recent experimental data [1,2] from twinjets.

A schematic of a typical structure of twinjets is shown in Fig. 1. Twinjets flows have three distinct regions: the converging region, the merging region, and the combined region. In the converging region, there is recirculation between the two jets, and the jet interactions are still at a primitive stage. At the end of the converging region, the mean velocity along the axis of symmetry is zero. This is defined as the merging point (MP). Beyond the merging

* Corresponding author at: Texas A&M University, Department of Nuclear Engineering, 3133 TAMU, College Station, TX 77843-3133, United States.

E-mail address: y-hassan@tamu.edu (Y.A. Hassan).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.12.008
0017-9310/

Nomenclature

a	jet width	PSD	power spectral density
CFD	computational fluid dynamics	RANS	Reynolds averaged Navier–Stokes equations
CP	combining point	S	jets spacing
GCI	grid convergence index	U	streamwise component of mean velocity
HWA	hot wire anemometry	u′	streamwise component of fluctuating velocity
LDA	laser Doppler anemometry	URANS	unsteady Reynolds-averaged Navier–Stokes equations
MP	merging point	V	spanwise component of mean velocity
PANS	partially averaged Navier–Stokes equations	v′	spanwise component of fluctuating velocity
PIV	particle image velocimetry		

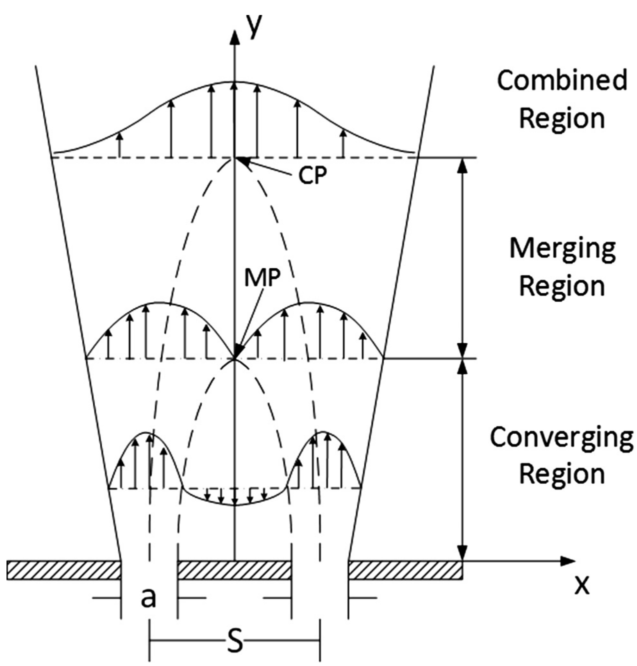

Fig. 1. A schematic of the twinjets structure.

point, twinjets start to merge into a single jet. The point at which the flow behaves as a single jet is defined as the combining point (CP); this means that the streamwise mean velocity U at the symmetry line reaches its maximum. The region between the MP and the CP is defined as the merging region. The region beyond the CP is the combined region. Two vital parameters are often used to describe the twinjets system, namely the jet width ***a*** and the jets spacing ***S***.

The history of twinjets study can be traced back to 1959. Miller and Comings [3] experimentally investigated the merging of dual-jet air flow using a hot-wire anemometer (HWA). The spacing ratio (S/a) was 6, and the aspect ratio was 40. Based on the large aspect ratio, this study was treated as a study of a two-dimensional twinjets system. The mean flow of their measurements presented symmetry on the centerline. Their study revealed that after a certain location, the two jets combined into a single jet. Tanaka [4,5] reported experimental studies on twinjets, with air issuing from parallel slot nozzles, he employed a hot-wire anemometry method. The study was focused on the effect of changing the distance between nozzles (S/a), varying from 8.5 to 26.3. In his first report [4], the author focused on the interference between the two jets, and proposed a correlation between the MP and the spacing ratio. In his second report [5], the author focused on the combined flow of the twinjets. The results confirmed that the combined flow profile agreed well with the single-jet velocity distributions. Marsters [6] introduced an integral method to predict the mixing of twinjets, and conducted experimental work on the mean flow using parallel-plane jets. The model predictions agreed well with the experimental data. Elbanna and Gahin [7] investigated twinjets with a spacing ratio of 12.5 using a hot-wire anemometry technique. The authors found that jets that spread linearly behaved in a manner similar to that of a single jet; however, the three components of the velocity fluctuations presented different behavior.

Self-preservation is a jet-flow feature that normalizes a velocity profile to be similar at different locations downstream of the jet entrance. Lin and Sheu [8] conducted experiments with parallel-plane jets, with a spacing ratio of 30 and 40. In their study, they found that the mean velocity was self-preserving in the converging region and the combined region, whereas the Reynolds stress exhibited self-preserving behavior only in the combined region.

At the early stage of the experimental research on twinjets, hot-wire anemometry, which is an intrusive measurement method, was extensively used. In 1997, the laser Doppler anemometry (LDA) measuring system, a non-intrusive measuring technique, was first used in the study of twinjets by Nasr and Lai [9]. The spacing ratio was 4.25, and the results confirmed that the development of coherent structures created from the shear layer instability was significant in controlling the dynamics of twinjets. In a different research work, Nasr and Lai [10] compared the LDA results with those of the two-dimensional simulations of the three Reynolds-averaged Navier–Stokes models (which will be further explained in Section 2.1), namely the standard k–ε, the renormalization group (RNG) k–ε, and the Reynolds stress model (RSM). The simulations overpredicted the MP from 8 to 18% compared with the LDA experimental data obtained by the authors. Anderson and Spall [11] investigated the two-dimensional simulation of the standard k–ε model and the Reynolds stress model, and compared the results with hot-wire anemometry measurements for twinjets with a spacing ratio between 9 and 18.25. The results showed that the models could predict the mean symmetry-plane velocity with satisfactory accuracy. Bunderson and Smith [12] conducted experiments on parallel-jet mixing using the Schlieren flow visualization and hot-wire anemometry. The spacing ratio was between 7 and 27. Their experiments showed that parallel jets flapped when the two jets had equal momentum flux. The oscillation frequency was similar to that of the wake of the flow over a bluff body. Moreover, the results indicated that controlling the momentum flux ratio of the jets could be an effective method for limiting or enhancing jet mixing.

As computational power developed, computational fluid dynamics (CFD) became popular as a tool for the study of turbulent jets. Durve et al. [13] performed a two-dimensional steady-state simulation on two and three jets using the FLUENT solver with the RSM model. In their simulations [13], the spacing ratios were 9, 13, and 18.25. Based on their simulation results, Durve et al.