Computers and Chemical Engineering 35 (2011) 595–605

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

Numerical simulation and validation of gas-particle rectangular jets in crossflow

Z.F. Tian[a,*], P.J. Witt[a], W. Yang[b], M.P. Schwarz[a]

[a] CSIRO, Mathematics, Informatics and Statistics (CMIS), Australia
[b] CSIRO, Process Science and Engineering (CPSE), Australia

ARTICLE INFO

Article history:
Received 14 October 2009
Received in revised form
17 September 2010
Accepted 19 September 2010
Available online 29 September 2010

Keywords:
Gas-particle flow
Jet in crossflow
Standard k–ε model models
SST model
Lagrangian model

ABSTRACT

This paper presents a numerical study of a gas-particle flow in three inclined rectangular jets in crossflow. The predicted gas phase velocities and particle phase velocities are validated against previously reported experimental data. Two turbulence models, the standard k–ε model and Shear Stress Transfer (SST) model, are used to model the gas phase turbulence. This work shows that both models provide acceptable predictions of the gas flow and mixing generated by the three jets. Neither model could accurately reproduce the jet core and the flow near bottom wall. The particle phase in this flow comprises a large number of small particles. Thus particles follow the gas phase flow closely and any errors in the turbulence model and gas flow predictions are passed on to the particle phase simulation. This paper also includes a literature review on rectangular jets in crossflow and gas-particle laden jets in crossflow.

1. Introduction

Brown coal production from the Latrobe Valley in Victoria, Australia is over 60 millions tonnes per year. About 97% of the brown coal is burnt by power stations in the Latrobe Valley region, producing over 85% of the Victoria's electricity supply (Allardice, 2000). Victorian brown coal, on a mass basis, has a typical moisture content of 50–66% (Li, 2004). Burning of the Victorian brown coal thus contributes significantly to the generation of greenhouse gases by the Latrobe Valley power plants. New pre-drying technologies, for example steam fluidised bed drying, are proposed as short-term solutions for meeting the greenhouse gas emission targets for the Latrobe Valley power generators.

Department of Primary Industries for the State of Victoria has commissioned CSIRO Mathematics, Informatics and Statistics (CMIS) to assess the future use of pre-drying technology in existing Victorian brown coal fired power plants. The associated research program involves the application of Computational Fluid Dynamics (CFDs), Particle Image Velocimetry (PIV), and Laser Doppler Anemometry (LDA) techniques.

To establish confidence in the CFD model that is being developed, validation of the model predictions is required. This work aims to validate the model by comparing simulation results for gas-particle isothermal jets in three inclined rectangular ducts in crossflow (for geometry see Fig. 1a) against measurements taken in CSIRO laser diagnostic lab (Ahmed, 2005; Ahmed et al., 2007). The model of gas-particle jets in crossflow (JICF) has been developed both experimentally and numerically to represent air-coal flow through slot-burner in a tangentially fired furnace, which is widely used in power plants in Latrobe Valley.

This paper reports on the numerical simulation of the gas-particle JICF using the commercial CFD code ANSYS/CFX 11.0. Two turbulence models for the gas phase simulation are compared, the standard k–ε model and the Shear Stress Transport (SST) model. A Lagrangian particle tracking model is used for the particle phase simulation. Accuracy of the results is assessed by comparing predictions to the measured gas phase and particle phase velocities obtained by Ahmed (2005) and Ahmed et al. (2007). The layout of this paper is as follows. Section 2 presents a brief literature review that is focused on single-phase rectangular JICF and gas-particle JICF. CFD modelling details are introduced in Section 3, including turbulence models, Lagrangian particle tracking model, boundary conditions, and other numerical details. Results are presented and discussed in Section 4, followed by conclusions in Section 5.

2. Literature review

This literature review considers two specific flow conditions: (i) single-phase rectangular JICF and (ii) gas-particle JICF. More comprehensive and general reviews of JICF can be found in Sherif and Pletcher (1990), Margason (1993), and Holdeman (1993).

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* Corresponding author at: School of Mechanical Engineering, The University of Adelaide, SA 5005, Australia. Tel.: +61 8 83131125; fax: +61 8 83034367.
E-mail address: zhao.tian@adelaide.edu.au (Z.F. Tian).

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doi:10.1016/j.compchemeng.2010.09.007

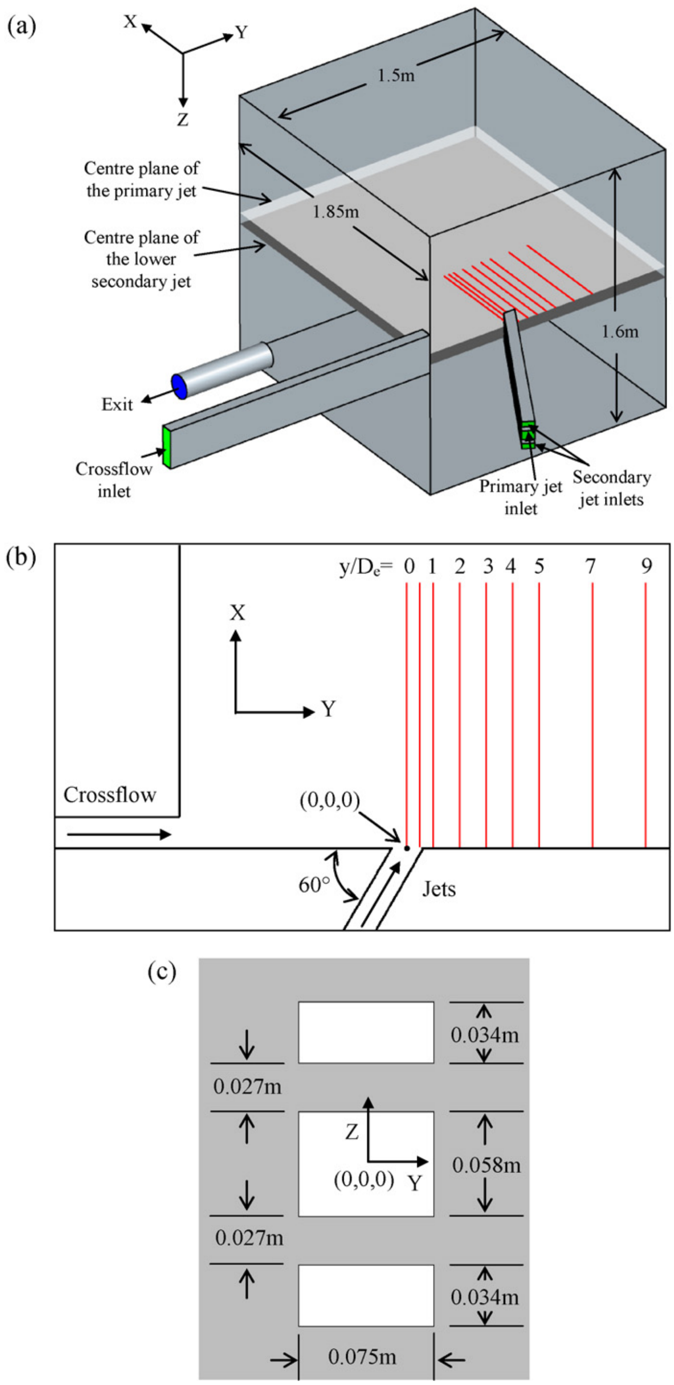

Fig. 1. (a) Computational geometry of the slot-burner and the test chamber; (b) The lines downstream the jet in the centre plane of the primary jet; (c) details of the jet inlets.

2.1. Single-phase rectangular jets in crossflow

Single-phase flow through a rectangular JICF has been studied experimentally by Kavsaoglu, Schetz, and Jakubowski (1989), Krothapalli and Lourenco (1990), Haven and Kurosaka (1997), Plesniak and Cusano (2005) and Salewski, Stankovic, and Fuchs (2006). Through these studies, some characteristic features of the rectangular JICF are identified, namely, the horseshoe vortices, the counter-rotating vortex pair (CRVP) and the reverse flow in the wake of jet. The horseshoe vortices in the near field upstream of the jet exit is a result of the deceleration of crossflow stream fluid as it approaches the obstructing jet, which acts like a solid bluff body in the crossflow (Ajersch, Zhou, Ketler, Salcudean, & Gartshore, 1997). The CRVP is the downstream manifestation of vorticity initially arising from within the sidewall boundary layer of the jet passage (Scorer, 1958). The reverse flow in the jet could be induced by the upward tilting of the trailing edge vortex near its centre and the lower pressure in the wake, which is present to balance the centrifugal force acting on the curved jet (Haven & Kurosaka, 1997). In addition, other vortical structures are also observed in the JICF, such as the jet shear layer and the wake structures (Fric & Roshko, 1994). Nevertheless, weak jets (e.g. the jet-to-crossflow ratio, R, is about 1) may not exhibit all the above characteristics (Ajersch et al., 1997). The case of JICF with an inclined jet has also been studied experimentally. Kavsaoglu et al. (1989) compared rectangular JICFs with jet injection angles of 60-degree and 90-degree to the streamwise direction. Interaction of a 60-degree jet with crossflow was found to be smoother than the 90-degree jet producing a lower magnitude negative pressure, which are distributed over a lesser area when compared to the 90-degree jets (Kavsaoglu et al., 1989).

JICF with dual and multiple jets have been experimentally investigated by Kavsaoglu, Schetz, and Jakubowski (1986), Kavsaoglu et al. (1989), Ajersch et al. (1997), Findlay, Salcudean, and Gartshore (1999) and Ahmed et al. (2007). Kavsaoglu et al. (1986, 1989) studied the flow of side-by-side dual rectangular jets in crossflow. The spacing between the jet centre lines was 4.7 times the width of one jet. The crossflow fluid between two jets and the influence of each jet on the other caused additional complications to the flow structure of the dual jets. Ajersch et al. (1997) conducted an experimental study on a row of six rectangular jets injected at 90-degree to crossflow. The CRVP structure was observed in the results for $R = 1.5$ and $R = 1.0$, but was less distinct for $R = 0.5$ case where the jet was too weak to penetrate through the turbulent boundary layer formed upstream of injection. Findlay et al. (1999) measured the flow field produced by a row of square jets injecting fluid into the crossflow in three directions: perpendicular to the crossflow, 30-degree inclination towards the streamwise direction, and 30-degree inclination towards the spanwise direction. Jet-to-crossflow velocity ratios of $R = 0.5$, 1.0, and 1.5 were investigated. The flow field at the jet exit was found to be strongly influenced by the crossflow and the inlet conditions at the jet nozzles. The strong streamline curvature which was present in the perpendicular and spanwise injection cases resulted in greater turbulence anisotropy than the streamwise injection case (Findlay et al., 1999). Ahmed et al. (2007) studied the effect of jet velocity ratio on aerodynamics of a slot-burner comprising three rectangular jets (see Fig. 1) in crossflow using LDA measurements. The three jets are at an angle of 60-degree to the crossflow. They conducted experiments for $R = 1.0$ and secondary jet to primary jet velocity ratio, ϕ, of 1.0 and 3.0. They found that for $\phi = 1.0$, the primary jet remained within the crossflow layer, while for $\phi = 3.0$, the primary jet penetrated the crossflow layer due to higher momentum of the secondary jets.

With improving computer performance and widespread availability of commercial codes, CFD techniques are gradually becoming an attractive investigative tool for studying rectangular JICF. Sau, Sheu, Hwang, & Yang (2004) and Sau, Hsu, Hwang Ou, & Hwang (2006) conducted Direct Numerical Simulation (DNS) of the square JICF with Reynolds numbers of 225, 300 and 2000 based on the jet duct length and the crossflow velocity. Yao, Petty, Barrington, Yao, and Mason (2006) carried out a DNS simulation of JICF for a flow Reynolds number of 100. Using Large Eddy Simulation (LES), Tyagi and Acharya (2000) investigated the effect of different jet inclination angles (30-degree and 90-degree) on the square JICF case of Ajersch et al. (1997). The Reynolds number was about 5000 based on the jet velocity and the spanwise dimension of the jet nozzle. The dispersion of the jet in the mainstream was found to be distinctly different for the two injection angles; significantly greater penetration and mixing of the jet with the crossflow was