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Journal of Hydro-environment Research 9 (2015) 482–495

Journal of
Hydro-environment
Research

www.elsevier.com/locate/jher

Research paper

Numerical study of turbulent round jet in a uniform counterflow using a second order Reynolds Stress Model

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Received 22 July 2014; revised 18 April 2015; accepted 27 April 2015

Abstract

A turbulent round jet issuing into a uniform counterflow stream is computationally investigated together with comparison with earlier experiments data, including velocity component along the jet axis and the radial direction. The simulation is carried out using the Reynolds Stress Model (RSM). Numerical results agree well with experimental results and the penetration and spreading of the jet are studied. The turbulence feature of the counterflowing jet indicates that the root-mean-square (rms) of axial velocity fluctuation ($\sqrt{\overline{u'^2}}$) has two distinct peaks whose the second is a specificity of the jet into a counterflow, located within the region near the stagnation point. As the centerline velocity, the centerline temperature is found to decay more rapid when the jet-to-current velocity ratio is smaller. The spreading of the jet is also interpreted by the growth of both momentum width and temperature width of the counterflowing jet leading to that the presence of a counterflow enhances the mixing of the jet.

Keywords: Turbulent jet; Counterflow; Velocity; Temperature; Mixing

1. Introduction

Turbulent jets are perhaps the most studied shear flow whose different geometries have been involved. In fact, the behavior of the jet becomes very different from that in a quiescent ambient since the presence of a moving ambient can modify significantly the flow structure and the mixing characteristics (Wood et al., 1993). Depending on the direction of the surrounding fluid relative to the jet exit direction, three possible configurations are encountered; jet in a coflow, jet in a crossflow and jet in counterflow. While the jet and the external flow are parallel, we are in the coflow situation, once the angle between them increases, crossflow situation is promoted and finally the counterflow configuration is established when the jet and the main flow directions are opposed. Within this group of geometries, jet in uniform counterflow stream has been the subject of relatively few investigations due to the experimental and theoretical difficulties related to flow reversal and to the instability of the flow. Nevertheless, the same characteristics that are responsible for the strong flow complexity also contribute to enhance its dilution and mixing efficiency, making this flow configuration interesting for many engineering applications, especially for environmental (Lam and Chan, 1995, 1997), chemical or process engineering.

The counterflowing configuration can be classified as a free jet in counterflow or a buoyant jet in counterflow which their spread behavior can be explained using the Lagrangian jet spreading hypothesis (Lam et al., 2006). The non-buoyant free jet discharged into a uniform counterflow stream may be

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http://dx.doi.org/10.1016/j.jher.2015.04.004
1570-6443/

divided on two distinct regions (Yoda and Fiedler, 1996); the first is the region just downstream the jet exit which is called the zone of flow establishment (ZFE), also known as the potential core. It represents the initial region of jet development in which jet flow is dominant and its behavior is similar to that of a free jet. The second region or the far field of the jet is termed the zone of established flow (ZEF) where the counterflow dominates. In this zone, as the jet interacts with the counterflow stream, it will be decelerated and deflected backwards. After reaching the stagnation point where the jet is stopped, the jet is reversed and approached asymptotically the counterflow velocity. The distance from the jet exit to the stagnation point is called jet penetration length (L_p) and it depends on the jet-to-counterflow velocity ratios (Arendt et al., 1956).Based on several experimental studies, Rajaratnam (1976) reported that the penetration length normalized by the jet diameter was proportional to jet-to-counterflow velocity ratio R (R is defined as the ratio between the jet exit velocity and the velocity of counterflow stream), described by two empirical relationships $L_p/D = 2.7R$ or $L_p/D = 2.4R$. Similarly, König and Fiedler (1991) and Yoda and Fiedler (1996) concluded from flow visualization that $L_p/D = 2.8R$. However, Morgan and Brinkworth (1976) clarified that we can consider this linear relationship valid only when the momentum flux jet-to-current ratio was less than 0.25. Recently, in the case of unconfined jet discharged in a counterflow, Saghravani and Ramamurthy (2010) confirmed that the relationship $L_p/D = 2.7R$ is also applicable.

Traditional studies of counterflowing jet used to involve velocity and concentration measurements of the flow in order to investigate the mixing features of the jet with its opposing fluid. The Laser Doppler Anemometry (LDA) technique was used by Lam (1991) to report velocity data of a counterflowing jet in a laboratory flume. He found that spreading of the jet is enhanced by the counterflow. Lam and Chan (1995, 1997) determined the penetration and spreading of a round jet issuing into an ambient counterflow stream over a range of jet-to-current velocity ratios, using the laser-induced fluorescence (LIF) technique. This technique was used also by Yoda and Fiedler (1996) to study the structure and concentration field of counterflowing jet. They concluded that the penetration distance increases with the velocity ratio.

Chan and Lam (1998) derived an analytical expression for the centerline velocity decay which predicted well available LDA measurements. These measurements data were made by two research groups; one at the Technical University of Berlin (Yoda and Fiedler (1996) and later Bernero (2000) and Bernero and Fiedler (2000)) and the other at the University of Hong Kong (Lam and Chan (1995, 1997) and later Lam and Chan (2002)). As a result of collaboration between these two groups, Chan et al. (1999) summarized experimental results of the jet discharged in counterflow stream. Lam and Chan (2002) focused their research on both velocity and concentration fields, which have been obtained with LDA and LIF techniques respectively, and on the mixing behavior of a counterflowing round jet at different jet-to-current velocity ratios ranging from 3 to 15.

In an approach to a better understanding of the interaction between the jet flow and its surrounding flow, dynamical behavior of the jet was investigated using digital imaging techniques such as Particle Imaging Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF). Bernero and Fiedler (1999) performed simultaneous PIV and PLIF experiments on a circular jet in a uniform counterflow and they suggested a relationship between velocity and concentration fields (Bernero, 2000). Proper Orthogonal Decomposition (POD) analyses were carried out by Bernero and Fiedler (2000) at high velocity ratios to investigate the fluctuations appearing in the far field of the jet. Among investigators who used PIV and PLIF techniques for studying round jet in a uniform counterflow, that may be mentioned Tsunoda and Saruta (2003), Tsunoda and Takei (2006) and Tsunoda (2010) who exhibited experimental results employing flow visualization methods. Tsunoda and Saruta (2003) showed that the rms velocity fluctuation as well as fluctuation of the rms concentration had a noticeable local maximum within the stagnant region. Tsunoda (2010) found that experimental data could be approximated more accurately by the linear relation between penetration length and jet-to-counterflow velocity ratio $L_p/D = 2.4R$. Or et al. (2011) examined experimentally the mean flow fields of round jet discharged in stagnant and moving ambient measured with PIV and LIF techniques. For the counterflow configuration, they concluded that the *1/x* decay relationship for the jet centerline velocity and concentration was valid only in the initial region of jet development.

The scarcity of experimental researches on counterflowing jet, caused by the instability and the complexity of the flow, limited the reliable data for validation of numerical experiments. Sivapragasam et al. (2009) reported some preliminary computational results for an incompressible turbulent jet issuing into annular counterflow, by varying both annular-to-jet diameter ratios and jet-to-counterflow velocity ratios. However, Sivapragasam et al. (2010) investigated experimentally and computationally turbulent jet in annular counterflow stream for a given annular-to-jet diameter ratio and various jet-to-counterflow mass flow ratios. More recently, Li et al. (2013) used large eddy simulation (LES) to investigate round jet discharging in counterflow. They derived from instantaneous vortex and streamlines, taken at several times, that there existed many vortices near the stagnation point owing to the presence of counterflow stream.

From the available literature, it can be seen that the investigation of the isothermal jet stream in a counterflow has been studied in greater detail earlier, however very few researches have been interested to the thermal character of the flow. For example, Timma (1962) studied the velocity and temperature fields of a slightly heated circular and flat jet developing in a counterflow. Elghobashi et al. (1981) provided predictions and measurements of velocity, temperature and concentration in a turbulent jet of air issuing into an opposing stream. They found that the recirculation zone is longer for the case of heated jet than for the cold one.

In this investigation, a momentum jet flowing into a counterflow where buoyancy effect can be neglected is