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A numerical study of a plane turbulent wall jet in a coflow stream

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Abstract

This work is a numerical study of an isothermal and a non-isothermal turbulent plane wall jet emerging in a coflow stream with different velocity ratios ranging from 0 to 0.2. Turbulence modeling is performed by using a modified low-Reynolds number k–ε model. The numerical resolution of the governing equations was carried out via finite difference method. The present predictions are compared with those suggested in the literature. It was found that the studied model reasonably predicts the mean flow proprieties of the flow field. The main purpose of this work is to determine the influence of the velocity ratio on the dynamic, thermal and turbulent characteristics of the flow. A comparison with a simple wall jet is made. Besides, the influence of Reynolds and Richardson numbers on the wall jet emerging in a coflowing stream is examined. As far as the isothermal flow is concerned, results show that the potential core length decreases in accordance with the velocity ratio. It was also found that, downstream from the jet exit (in the established region), the longitudinal distributions of the normalized forms of the excess maximum x-velocity and the turbulent maximum kinetic energy converge to a single curve at different velocity ratios. The present investigation suggests that the effect of coflowing jet on the dynamic, thermal and turbulent parameters is negligible in the potential core area (ZFE) and the jet is similar to that of a simple jet. Further downstream of this region, the velocity ratio affects the flow as far as the high coflow streams are concerned.

Keywords: Wall jet; Turbulent; Coflow stream; Velocity ratio; Isothermal flow; Mixed convection

1. Introduction

A turbulent wall jet is formed when a fluid is discharged through a rectangular slot at a high velocity into a medium of the same fluid that is either stagnant or moving. This type of flow has been extensively studied not only because it is very interesting but also due to its considerable practical importance in the fields of hydraulics and environment such as: wall jets issued from storage tanks or basins (Naser et al., 2005; Rossman and Grayman, 1999; Rostamy et al., 2009). Wall jets are widely used for film-cooling, evaporation enhancement, and boundary layer control. They are applied to windshields and windows as defrosters in order to enhance evaporation. They are also present in aircraft slotted flaps and leading edge slats, enabling increased lift and delayed flow separation. Wall jets are also applied to turbine blades and rocket nozzles, for example, in order to shield them against heat flow and corrosive environment. Recently, the theory of turbulent wall jets and their practical applications has gained special interest in many research fields (Afzal, 2005; Matthew, 2010; Tachie et al., 2004).

The development of the wall jet in a stagnant environment (simple jet) is found to resemble a free jet. This type of flow is characterized by three main regions: a Zone of the Flow Establishment (ZFE), in the vicinity of the ejection nozzle, followed by a transition area and a third region of established flow (ZEF). In accordance with the standard, two regions can be identified: one similar to a plane free jet and the other one similar to a boundary layer. Downstream the interaction between these two regions, a mixed or third region is created (Kechiche, 2006).

The turbulent plane wall jet in the absence of coflow stream is a prototypical configuration whose characteristics have been investigated in every detail. Many of these investigations focused on the scaling laws for the mean velocity and the turbulence properties and examined the limitation of the self-similarity assumptions (Ahlmen et al., 2007; Barenblatt et al.,

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2005; Eriksson et al., 1998; George et al., 2000; Rostamy et al., 2009). The flow was traditionally scaled in a way that made its rate of spread and the decay of its maximum x-velocity in the direction of streaming dependent on the nozzle Reynolds number (Tailland and Mathieu, 1967). Narasimha et al. (1973) proposed that the mean flow parameters should scale with the jet momentum-viscosity scaling. It was determined that the bulk of the flow is self-similar and it depends on the momentum flux at the nozzle and on the viscosity of the fluid. Zhou and Wygnanski (1993) proposed a scaling based on the work of Narasimha et al. (1973) for the wall jet in an external stream. These authors extended the notion of self-similarity to a wall jet in a uniform stream provided $u_m / u_{co} \geq 2$, where u_m and u_{co} are the maximum and free stream x-velocities respectively.

The behavior of a jet is affected by the presence of a main flow in the ambient fluid. The plane jet discharging into a quiescent atmosphere always behaves as a strong jet, whereas the plane jet with co-flow can behave as a strong jet near the exit and, due to the decrease of the mean velocity on the centerline, behaves as a weak jet farther downstream (Davidson and Wang, 2002; Nickels and Perry, 1996; Rajaratnam, 1976). The behavior of the "far field" of the jet or the Zone of the Established Flow (ZEF) has been the subject of several studies. In this region, the self-similarity behavior is observed on the spreading of the jet as measured by various mean flow properties including the growth of the jet width, the decay of the jet centerline properties with an axial distance, and the radial profiles of velocity and concentration (Fischer et al., 1979; Jirka, 2004). Youssef (2012) has generated a database on the plane jet with co-flow for a wide range of Reynolds number and velocity ratio. These authors showed that the plane jet behaves as a strong jet in the self-similar region explored within 37.5 jet exit width. In this region, the decay rate of the centerline mean velocity and the jet spreading rate depend slightly on the Reynolds number but strongly on the velocity ratio. Xia and Lam (2009) measured the velocity and concentration fields of round jets submerged in a stagnant environment and in coflow. They showed that the centerline mean flow quantities collapse onto an asymptotic curve at different coflow strengths, through the use of the jet excess velocity and the normalization of downstream distances with a length scale of l_m. Turbulence proprieties inside a jet are increased by the presence of a strong coflow.

A buoyant jet ejected in medium at rest or in moving stream has been the subject of several investigations (Gazzah and Belmabrouk, 2014; Lam et al., 2006; Sini and Dekeyser, 1987). For instance, Habli et al. (2008) investigated a turbulent buoyant axisymmetric jet in a coflowing ambient stream. It was found that the increase of the coflow could slow the development of the jet to the state of similarity of mean characteristic profiles. In buoyant jets, only a flow with ($r = u_{co} / u_0 \leq 0.05$) reaches a similar state. Buoyancy ensures that the similarity region begins at a distance closer to the nozzle exit than in the case when the medium is stagnant. In laminar regime, Ben Haj Ayech et al. (2014) conducted a numerical study on the dynamic and thermal characteristics of isothermal and non-isothermal wall jet in a coflowing stream at jet Reynolds number (Re < 2000). They found that, for low Grashof numbers (forced convection), the results are similar to the isothermal flow. For a mixed convection, when both natural convection and forced convection heat transfer mechanisms interact, they noticed the absence of the influence of the coflow velocity on most parameters.

From the available literature, it can be seen that the investigation of the turbulent buoyant jet ejected horizontally and tangentially to a plate has been studied; however, no available studies on a buoyant vertical plane wall jet are found. For example, Huai et al. (2010) conducted a numerical simulation on a three-dimensional horizontal buoyant jet ejected tangentially to an adiabatic plate in medium at rest. The horizontal buoyant wall jet can be divided into three regions: initial region, wall jet region and free jet region. The initial region is the region where the maximum x-velocity keeps constant, and the one behind the wall jet region is the free jet region. The centerline trajectory given at the central plane in the free jet region indicates that the wall buoyant jet clings to the floor and slips for some distance before it lifts off, and the position that the centerline leaves wall is closer to the nozzle.

In the current study, we used a configuration of a turbulent plane jet ejected vertically and tangentially to a heated plate subjected to a constant temperature. The aim of this work is to predict the spreading and mixing behavior of isothermal and non-isothermal turbulent wall jet with coflowing stream, using a modified low-Reynolds number k–ε model. A comparison between Eriksson et al.'s (1998) and Rostamy et al.'s (2009) experimental results and numerical findings is conducted. The dependence of Reynolds number on the isothermal turbulent wall jet in coflowing stream is analyzed together with the effect of velocity ratio. Also, the effect of Richardson number on the maximum x-velocity of the jet and its half width is studied in order to understand the relative importance of buoyancy and inertia forces on a turbulent wall jet in parallel coflowing stream. Various physical parameters such as mean and turbulent quantities of the coflowing wall jet are examined and compared with those of the simple jet case (jet evolving in a medium at rest). The effect of free stream on the heat transfer between the jet and the heated wall is also studied. Results are presented for velocity ratios varying between 0 and 0.2.

2. Problem formulation

2.1. Assumptions

An incompressible flow jet issuing with a constant velocity u_0 and temperature $T_\infty$from a rectangular nozzle, with a slot width b, tangentially to an infinite flat plate subjected to a constant temperature T_p is considered (Fig. 1). The jet is discharging into an ambient medium with a temperature T_∞ and a uniform velocity u_{co}. In this figure, x and y denote the longitudinal and the transverse distances, respectively. The problem is valid for a two-dimensional boundary layer flow. The turbulent flow is steady and satisfies the Boussinesq approximation.

2.2. Governing equations

The time averaging of the conservation equations can be expressed as follows (Kechiche, 2006):