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Numerical study of a turbulent plane jet in a coflow environment

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ABSTRACT

The influence of the coflow velocity ratio on the behavior of a turbulent plane jet in forced convection was numerically investigated. A finite difference method was used to solve a system of coupled partial differential equations. A comparison was carried out between the numerical results obtained in the present work and the experimental data reported in the literature. It was found that the investigated model reasonably predicts the mean flow properties of the flow field. The present investigation suggests that the potential core length increases as the velocity ratio rises. Analyses of the mean and turbulent parameters showed that, when using a momentum length scale, parameters can reach an asymptotic curve, at different velocity ratios.

1. Introduction

The development of free turbulent jets is relatively well known and the works on this type of flow are numerous. This abundance reveals the interest it raises on researchers, both numerically and experimentally. On the other hand, the comparison of results obtained by various authors proves to be very delicate because of the exit conditions whose characteristics are not always given with enough accuracy.

Generally, the development of a free jet in a stagnant environment (simple jet) is characterized by two main regions [1]. The Zone of the Flow Establishment (ZFE) near the jet exit is the potential core where the mean centerline velocity is equal to the jet exit mean centerline velocity. This region is followed by the Zone of Established Flow (ZEF) far away where the flow becomes self-similar in both mean and turbulent properties. However, before becoming self-similar, the ZEF region is preceded by a transition one [2].

The behavior of a jet is also affected by the presence of a main flow in the ambient, especially coflow jet. The coflowing jet is accepted to be asymptotic in two limiting regions [3,4]. First, a strong jet region in the vicinity of the jet exit when the centerline velocity is much greater than the free stream. In this region, the effect of the coflow can be ignored and the jet is similar to that of a simple jet. Far from the jet exit, the second region is a weak flow when the jet centerline velocity approaches the free stream velocity. The transition occurs from the strong to the weak region.

The effect of a coflow on the jet's spreading and mixing has been investigated by several authors. Much more attention has been given to the coflowing round jet. It has been shown that the excess mean velocities are approximately self-preserving, assuming a point momentum source. However, turbulence quantities including turbulence intensity and Reynolds shear stress are not self-preserving [5,6], and this suggests that the standard entrainment constant changes whether it is relative to a strong or a weak jet [7]. Indeed, the entrainment constant relates the mass flow rate of the surrounding fluid entrained into the jet to the characteristic velocity difference between the jet and the coflow. Observation suggests that the variation in the entrainment might be explained by the incorporation of the fluid from the surroundings into the jet by turbulent eddies generated by the shear existence between the two regions.

Experimental investigations were also conducted in coflowing jets. Nickels and Perry [6], Antonia and Bilger [8], Smith and Hughes [9], made measurements in the strong region of round jets as well as in the strong-to-weak jet-transition region; Davidson and Wang data [4] extend into the weak region.

Initial jet exit conditions defined as: exit Reynolds number, mean velocity and turbulence intensity exit profiles, aspect ratio AR (for noncircular jets) (AR = w/h, where w and h are respectively the long and short sides of the slot), nozzle-exit geometric profiles, and global density ratio of the jet fluid to ambient fluid have been found to affect the development of jets. Xia and Lam [10] report experimental results for round jets in a stagnant environment

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Nomenclature

c_μ, $c_{\varepsilon 1}$, $c_{\varepsilon 2}$	coefficients in the (k–ε) model
h	slot height of the nozzle (m)
i, j	axial and lateral nodes
k_u	velocity decay rates
k_y	spreading rate (m)
k	turbulent kinetic energy ($\mathrm{m^2\,s^{-2}}$)
T	mean temperature (K)
u, v	mean axial and lateral components of velocity, respectively ($\mathrm{m\,s^{-1}}$)
x, y	longitudinal and transversal coordinate (m)
x_u, x_y	virtual origins
$y_{0.5}$	dynamic jet half-width, value of the lateral distance at which mean axial velocity is half of the centerline value (m)
$y_{0.5T}$	thermal jet half-width, value of the lateral distance at which the mean temperature is equal to half its value at the centerline (m)
Δx and Δy	axial and lateral steps (m)
r	radius of contraction of the nozzle (m)
Re	Reynolds number ($\frac{u_0 h}{\nu}$)
$R = \frac{u_{co}}{u_0}$	velocity ratio
M_e	initial excess momentum of the jet at exit
u_{ex}	$u - u_{co}$ ($\mathrm{m\,s^{-1}}$)
Greek symbols	
ε	dissipation rate ($\mathrm{m^2\,s^{-3}}$)
ν_t	kinematic eddy viscosity ($\mathrm{m^2\,s^{-1}}$)
ν	kinematic viscosity ($\mathrm{m^2\,s^{-1}}$)
σ_k, σ_ε, σ_T	turbulent Prandtl numbers
ϕ	generalized variable
subscripts	
c	centerline value
co	coflow stream
0	value at the jet exit
ex	excess
∞	ambient fluid
Superscripts	
–	average
‘	fluctuation

and in a coflow. Measurements are made in the initial region within distances of 40 jet exit diameter (in the strong jet) at a jet Reynolds number between 1000 and 5000 (laminar, transitional or turbulent jets) and a coflow-to-jet velocity ratio ($R = \frac{u_{co}}{u_0}$) from 0 to 0.43. In coflowing jets, the collapse of the centerline mean flow quantities onto an asymptotic curve at different coflow strengths can be achieved through the use of the jet excess velocity or the normalized dilution and the normalization of downstream distances with the length scale l_m.

Self-similarity of radial profiles of mean velocity or excess velocity and mean concentration are observed mainly for turbulent jets. However, for the turbulence intensities, self-similarity is not established.

Or et al. [11], performed measurements of velocity and concentration in the initial region of a round jet (15 jet exit diameter) in a stagnant fluid and in a moving environment of the coflow, counterflow or crossflow situation. In this study, the authors determined the potential core length or the Zone of the Flow Establishment (ZFE) and the decay of jet centerline properties in the Zone of the Established Flow (ZEF) where the self-similarity behavior is observed with the effect of the virtual origin. Results in coflowing jets show that the decay constant and the virtual origin are increased by the coflow.

Submerged plane jets have been studied thoroughly [12–15], and many investigations focused on the effect of initial conditions on the jets' downstream development [16–20]. Nevertheless, less work deals with coflowing plane jets [21–28].

A small coflow is often added to the inflow profile of the velocity for reasons of numerical stability. Bradbury [21] and Bradbury and Riley [22] studied experimentally a turbulent plane jet in a slow moving airstream. They found that the spread of jets could be merged, with varying coflow velocity ratio, when accounting for the effective origins. Self-similarity is observed at a distance about thirty jet widths downstream of the jet nozzle. Le Ribault et al. [25] investigated a plane turbulent jet using the large eddy simulation at both low and high values of Reynolds number. Computations have been performed in a weak coflow stream so that the flow behavior is similar to that of a jet in a medium at rest.

Reichert and Biringen's work [26,27] provides the effect of compressibility in the nearly self-preserving region of the plane jet exhausting into a parallel stream.

The present study aims to discuss the effect of a coflow velocity ratio (coflow to jet exit velocity ratio) on the behavior of a turbulent plane jet in forced convection. One of the main purposes of the investigation was to find asymptotic behaviors of a jet in a coflow which could enable a description of the flow field as much as possible independently of the details of the exit conditions. A comparison has been carried out between the numerical results obtained in the present work and the experimental data, reported in the literature, of a plane jet in a medium at rest.

2. Governing equations

A turbulent jet flowing vertically from a plane nozzle is considered. The jet is discharged into a non-turbulent coflowing air stream. We assumed the fluid to be incompressible and the ambient dynamics pressure constant. The equations are written in a steady form that is valid for a two-dimensional boundary layer flow at a high Reynolds number for a fully-developed turbulent flow so that the viscous diffusion can be neglected compared to the turbulent one. Under these assumptions, equations governing the mean velocity and temperature distribution in forced convection are reduced to:

$$\begin{aligned}
&\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \\
&u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{\partial}{\partial y}\left(-\overline{u'v'}\right) \\
&u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\partial}{\partial y}\left(-\overline{v'T'}\right)
\end{aligned} \tag{1}$$

The k–ε model is used for the closure of this problem: the equations of the kinetic energy of turbulence and its rate of dissipation can be written as:

$$\begin{aligned}
&u\frac{\partial k}{\partial x} + v\frac{\partial k}{\partial y} = \frac{1}{\sigma_k}\frac{\partial}{\partial y}\left(\frac{\partial k}{\partial y}\right) + \upsilon_T\left(\frac{\partial u}{\partial y}\right)^2 - \varepsilon \\
&u\frac{\partial \varepsilon}{\partial x} + v\frac{\partial \varepsilon}{\partial y} = \frac{1}{\sigma_\varepsilon}\frac{\partial}{\partial y}\left(\frac{\partial \varepsilon}{\partial y}\right) + c_{\varepsilon 1}\upsilon_T\frac{\varepsilon}{k}\left(\frac{\partial u}{\partial y}\right)^2 - c_{\varepsilon 2}\frac{\varepsilon}{k}
\end{aligned} \tag{2}$$