NUMERICAL STUDY OF FLOW AND DILUTION BEHAVIOR OF RADIAL WALL JET*

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Abstract: The radial wall jet is a flow configuration that combines the radial jet and the wall jet. This article presents a simulation of the radial wall jet by applying the transition Shear-Stress Transport (SST) model. Tanaka’s experimental data are used for validation. The computed velocity profiles agree well with the experimental ones. The distributions of the velocity on cross-sections show a similarity in the main region and the profiles are different with those of the free radial jet or the wall jet, because the presence of the wall limits the expansion of the jet. By introducing the equivalent nozzle width, the maximum velocity decays and the half-width distributions are normalized, respectively. In addition to compare the flow field with experiments, this paper also analyzes the dilution effect of radial wall jets in terms of the concentration distributions. The concentrations on the wall keep constant within a certain distance from the nozzle. And the concentration distributions also show a similarity in the main region. Both the decays of the maximum concentration and the distributions of the concentration half-width fall into a single curve, respectively. The dilution effect of radial wall jets is thus verified.

Key words: radial wall jet, velocity profile, concentration distribution, concentration half-width

1. Introduction

The jet is a fluxion that flows from one region to another in specific export forms and has wide applications in hydraulic and hydro-power engineering, aerospace engineering, environment engineering and other related fields. It can make fluid mix with each other substantially, especially, the radial jet and the wall jet, whose dilution effect is more effective. The radial jet is a flow directed along the radial direction after discharging from an exit, while the wall jet is a jet spreading out over a plane or curved surface. There are quite a number of studies in this field. For the radial jet, we may quote Tanaka and Tanaka[1], Guo and Sharp[2], Hunt and Ingham[3], Song and Abraham[4], Krejci and Kosner[5], and Li et al.[6], for the wall jet, we have Law and Herlina[7], Fureby and Grinstein[8], Dejoan and Leschziner[9], Fan et al.[10], Huai et al.[11]. However, the radial wall jet, as a flow configuration that combines the above two jets, has not been well investigated. Tanaka and Tanaka[12] studied it through changing the nozzle opening and discharge velocity by experiments. In this article, a comprehensive numerical simulation of the radial wall jet is carried out, covering most cases of the conditions in Tanaka’s research, and the calculated results of the velocity field are in good agreement with those in their experiments. Furthermore, a species transport equation is added to the model and the dilution effect of the radial wall jet is analyzed in terms of spreading of tracer substance. Subsequently, it is found that the concentration distributions and the concentration half-width are related with the distance from the wall or the jet exit, and the corresponding relationships are obtained.

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2. Mathematical model and calculation method

2.1 Coordinates and governing equations

The sketch of the model and the coordinate system are shown in Fig.1. Three types of nozzles are used for simulations, the same as those used in literature\cite{1}. \( y \) is the axis-direction, \( r \) is the radial-direction, \( x \) is the distance from the nozzle outlet, \( u \), \( v \) are the axial velocity and the radial velocity, respectively, \( v_y \) is the velocity of the nozzle inlet, \( U_0 \) is the velocity at the nozzle exit, \( D \) is the diameter of the nozzle, and \( b \) is the nozzle width. The diameter of the wall is 830 mm, and \( b \) is the maximum velocity on a certain cross-section and \( b \) is the half-width (i.e., the distance from the wall to the point of \( u = U_w / 2 \)) of the same cross-section. In this article, the governing equations are the steady-state Reynolds-averaged incompressible Navier-Stokes equations. The Reynolds stress terms in the momentum equations are treated with the transition SST model based on intermittency theory. Based on the SST \( k-\omega \) model, in the transition SST model, two transition equations are added, one for the intermittency and the other for the transition onset criteria in terms of the momentum-thickness Reynolds number. This model is applicable to wall-bounded flows and behaves properly in both the near-wall and far-field zones. The governing equations in the cylindrical coordinates are as follows

1. Continuous equation:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \rho u r \right) + \frac{\partial}{\partial y} \left( r \rho v y \right) = 0
\]  

2. Momentum equations:

(a) In radial-direction

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \rho u r \right) + \frac{\partial}{\partial y} = 2 \frac{\partial}{\partial r} \left( \mu_r \frac{\partial u}{\partial r} \right) + \frac{\partial}{\partial y} \left( \mu_y \frac{\partial v}{\partial y} \right) \]


(b) In axial direction

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \rho u r \right) + \frac{\partial}{\partial y} = 2 \frac{\partial}{\partial r} \left( \mu_r \frac{\partial v}{\partial r} \right) + \frac{\partial}{\partial y} \left( \mu_y \frac{\partial u}{\partial y} \right) - \rho g
\]

3. \( k \)-equation:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \rho u k \right) + \frac{\partial}{\partial y} = \frac{1}{r} \frac{\partial}{\partial r} \left( \left( \mu + \sigma_k \mu_t \right) \frac{\partial k}{\partial r} \right) + \left( \mu + \sigma_k \mu_t \right) \frac{\partial b}{\partial y} \]

4. \( \omega \)-equation:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \rho u \omega \right) + \frac{\partial}{\partial y} = \frac{1}{r} \frac{\partial}{\partial r} \left( \left( \mu + \mu_\omega \sigma_\omega \right) \frac{\partial \omega}{\partial r} \right)
\]

5. Transport equations

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \rho u \gamma \right) + \frac{\partial}{\partial y} = \frac{1}{r} \frac{\partial}{\partial r} \left( \left( \mu + \mu_\gamma \sigma_\gamma \right) \frac{\partial \gamma}{\partial r} \right) + P_{\gamma 1} - E_{\gamma 1}
\]