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Interaction between Wall Jet and Offset Jet with Different Velocity and Offset Ratio

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Abstract

Realizable *k*-*ε* model was used to study the flow and mixing characteristics of the interaction between wall jet and offset jet with different combination of offset ratio and velocity ratio. As the velocity ratio (U_w/U_o) increasing, the flow pattern shifts from offset jet to wall jet and the decay of maximum velocity gradually becomes slowly. The maximum concentration (C_m/C_0) decreases with the downstream distance increasing and the decay rate correlates with the difference of two jet velocities. These results can be employed in the engineering application for wastewater discharge.

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Keywords: wall jet; offset jet; velocity ratio; offset ratio; dilute characteristic

1. Introduction

In the engineering applications, the behaviors of wall jet or offset jet are often encountered. A wall jet is generated when a flow is injected to a region near the wall with initial momentum. The mechanism of wall jet has been studied by many researchers in the past few years. Kechiche et al. [1] demonstrated that the inlet conditions only affected the region near the nozzle rather than the self-similarity region. In the wall shear layer, streaks occurred because of the roughness geometry boundary and played an impartment role in the breakdown process. Due to these streaks, a pairing of span-wise vortices that was suppressed and breakdown to turbulence was enhanced [2]. On the other hand, a turbulent plane jet that is discharged parallel to a bottom wall with an offset distance is known as the offset jet. An offset jet will deflect to the wall on account of the presence of sub-atmospheric pressure region and then attach to the wall at an

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impingement point [3]. The flow will develop into the wall jet [3, 4] downstream the attachment region. However, the attachment region changes with the offset height deviated from the wall [5]. And the offset height (or offset ratio) may also influence the heat transfer in the cooling systems [6]. Yoon et al. [7] compared the characteristics of the wall jet and offset jet, including mean velocity, Reynolds shear stress and triple products. And they found that their mean velocities were similar in wall region, while triple products were different between them. From the above, both the wall jet and offset jet have been studied by using either experiment or numerical simulation, respectively. For the parallel jets, Ko and Lau [8] described the flow structures in the initial region. Fujisawa et al. [9] investigated the parallel with different velocity and found that the trajectory will shift to the high velocity side. However, a configuration combining the two jets has received few attentions. Hitherto, Wang and Tan [10] researched the interaction of the dual-jet created by a wall jet and an offset jet by depicting the mean velocity, Reynolds stresses and series of instantaneous vorticity fields. Vishnuvardhanarao and Das [11] studied the characteristics of heat transfer using the streamline curvature (SC) modified k-ε model.

This paper reports a numerical study on the interaction between a wall jet and an offset jet. Firstly, five turbulent models were used to simulate the case with offset ratio 1.0 and both jets initial velocity 1.0 m/s. Comparisons of simulation results with experimental data of Wang and Tan [10] to explore the best method for this flow. Secondly, the selected model was used to compute the cases with different offset ratio and velocity ratio. Further results for dilution were also discussed.

2. Computational procedure

2.1. Turbulent models

In this paper, Realizable k-ε model[12], SST k-ω model[13], k-kl-ω model[14], transition SST model[15] and v^2-f model[16] were used to select the best one for predicting the interaction of wall jet and offset jet.

In order to show the dilution of this flow pattern, the species transport equation is introduced:

$$\frac{\partial(\rho C)}{\partial t}+\nabla\cdot(\rho\boldsymbol{u}C)=\nabla\cdot\left[\left(\mu+\frac{\mu_t}{S_c}\right)\nabla C\right] \tag{1}$$

Where, C is the concentration of the tracer and ρ is the density of the field fluid. Because the species is only regard as tracer, the density is set equal to the water. μ is the molecular viscosity and μ_t is the turbulent viscosity. S_c is the turbulent Schmidt number, and in the plane jet S_c=0.7.

2.2. Boundary condition

The computational domain adopted in this study is $200w\times35w$ (x, y, direction, respectively) as shown in the Fig.1, where w is the jet height: w=10mm. The offset ratio d/w=0.5, 1, 2, 3.25, 5, 8. For obtaining a fully developed nozzle exit, the inlet is set $10w$ upstream.

Velocity inlet is enforced on the inlet condition. The velocities of wall jet and offset jet are set as: when U_w=1m/s, U_o=0.25, 0.5, 0.75, 1m/s; or when U_o=1m/s, U_w=0.25, 0.5, 0.75m/s. These totally have seven velocity combinations and have 49 cases under the different combination of offset ratio (d/w) and velocity ratio ($V_r=U_w/U_o$).

No slip and stationary wall is adopted for nozzle wall and floor plane, while slip wall condition is used for water surface. For the species boundary condition, a zero diffusive flux condition is adopted.

At the outlet plane, the normal gradients of all the dependent variables are set to be zero for the outlet boundary.

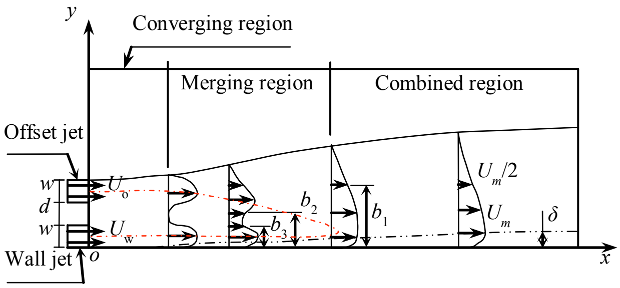

Fig.1 Schematic diagram of the computational domain

2.3. The numerical method

The incompressible transient flow is considered in this study. Finite Volume Method (FVM) is used to generate discrete governing equation. The gradient, which used to discretize the convection and diffusion terms in the flow conservation equations, is computed according to the Least Squares Cell Based methods. The SIMPLEC scheme is applied for the pressure-velocity coupling. The second upwind scheme is used to solve the convection term and diffusion term.

3. Results and Discussions

3.1. Model Comparison and Selection

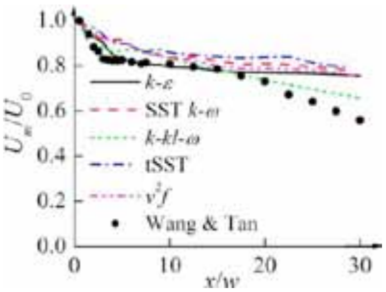

Fig. 2 Decay of U_m/U_0 downstream

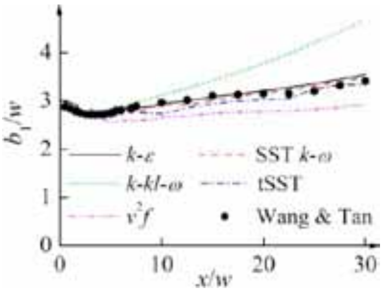

Fig. 3 Chang of b_1 downstream

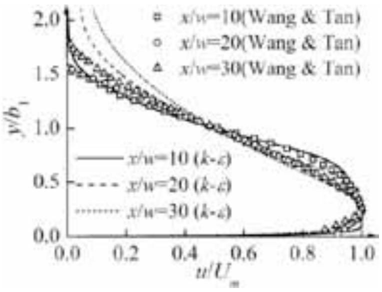

Fig. 4 Profiles of u/U_m

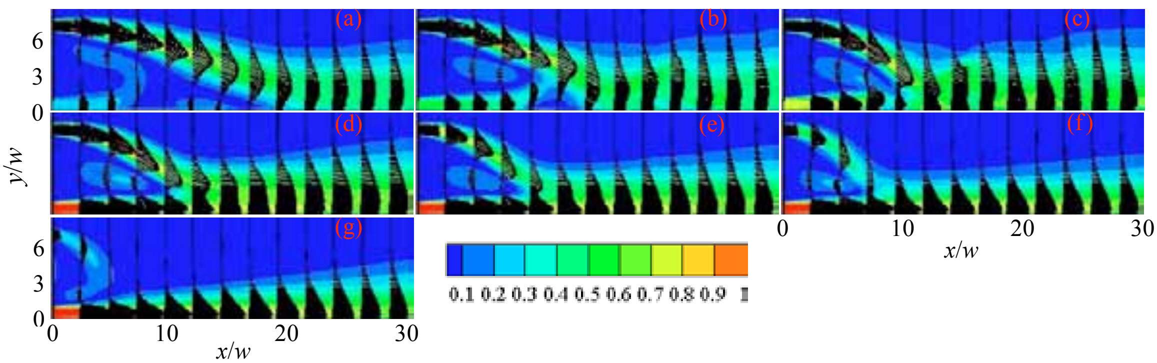

Fig.5 Contours of velocity magnitude and velocity vectors

To compare the computed results with that of the measurement, the results presented in this section is the case of offset ratio d/w=1.0 and both jet velocity U_w=U_o=1.0m/s. The results of the maximum velocity (U_m), characteristic-length and velocity distributions computed using five turbulent models, including Realizable k-ε model, SST k-ω model, k-kl-ω model, transition SST model and v^2-f model, are compared with experiment data of Wang and Tan[10]. In predicting decays of maximum velocity (U_m/U_0) along the stream-wise direction, the Realizable k-ε model has advantage near jet exit while k-kl-ω model exhibits more effective in far field (x/w>20). The half-width of velocity b_1, which defined as the vertical distance from the wall to the position where the velocity decreases to a half of the local maximum velocity (U_m) in the upper shear layer, computed by the k-kl-ω model shows wider than measurement while the one calculated by using v^2-f model presents narrower than experimental data. However, the results computed by the three other models exhibit good agreement with experimental data. From above comparing, the Realizable k-ε model, in which includes the rotation tensor, shows good performance in predicting the interaction of the wall jet and offset jet. The Realizable k-ε model is also effective in forecasting the velocity distribution, especially in the region $0<y/b_1<1$ as shown in Fig.4. Because of the restriction of map space, the velocity distributions computed by other model are not shown in Fig.4.

3.2. Velocity characteristics

In order to show the influence of the interaction between the wall jet and offset jet, the velocity characteristics will be analyze in terms of velocity changes.

The contours of velocity magnitude ($\sqrt{u^2+v^2}$) and velocity vectors are shown in Fig.5 (a), (b), (c), (d), (e), (f) and (g) for U_w/U_o=0.25/1, 0.5/1, 0.75/1, 1/1, 1/0.75, 1/0.5 and 1/0.25, respectively. As the velocity ratio U_w/U_o increasing, the flow pattern shifts from offset jet to wall jet and the recirculating region of offset jet gradually diminishes. When U_w/U_o=0.25 (Fig.5(a)), the wall jet is dragged into offset jet by the entrainment of offset jet and the back flow in the recirculating region of offset jet. When velocity ratio increasing to U_w/U_o=0.5(Fig. 5(b)), the wall jet remove longer distance before inclining to the offset jet due to the entrainment of offset jet. When U_w/U_o=1 (Fig. 5(d)), although the velocity is equal, the entrainment effect of wall jet is more intensity due to the presence of the wall. So the offset jet incline to wall jet and the wall jet almost has no bend. When U_w=1m/s and U_o gradually decreasing, the offset jet inclines more severely and shifts into wall jet eventually.

Fig.6 shows the decay of maximum velocity for d/w=8 with different velocity ratio. The maximum velocities decay more rapidly with velocity ratio V_r<1 than that of V_r>1. For V_r<1, the flow is similar with offset jet and the maximum velocity exists in the offset jet region. The decay rate of maximum velocity increases with the velocity of wall jet increasing because the entrainment of wall jet becomes stronger. On the country, for V_r>1, the characteristics of wall jet is evident. The decay rate of velocity decreases with the velocity ratio increasing in the region x<35w because the entrainment of offset jet becomes weaker. When x>35w, the maximum velocity increases with V_r increasing for V_r<1, while decreases with V_r increasing for V_r>1. Those demonstrate that the change of maximum velocity correlates with the initial total momentum.

The changes of half-width in outer shear layer b_1 are shown in Fig.7. In the region x<25w, the decreased rate of b_1 gradually increases with velocity ratio (V_r<1) increasing because of the severe entrainment. When V_r>1, the b_1 mostly exhibits the characteristics of the wall jet. The jet center line shows the same change characteristic as shown in Fig.8. Because the maximum velocity exists near wall when V_r>1, the jet center line is not presented in the Fig.8.

The decay of maximum velocity with different offset ratio for U_w/U_o=0.25/1 and U_w/U_o=1/0.25 are shown in Fig.9 and Fig.10, respectively. For U_w/U_o=0.25/1, the decay rate increase with the offset ratio increasing. However, the decay rate almost does not change for U_w/U_o=1/0.25, especially when d/w>1.

The other offset ratio cases have the same characteristics, so not all cases are exhibited due to the restriction of the paper space.

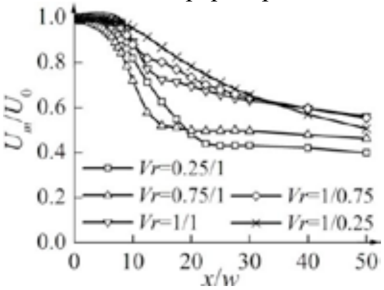

Fig. 6 U_m/U_0 downstream

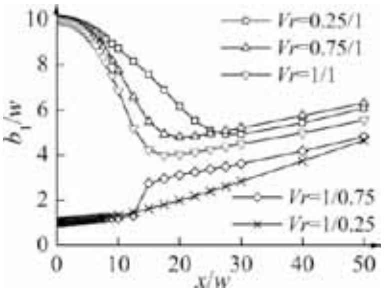

Fig.7 Half-width b_1 downstream

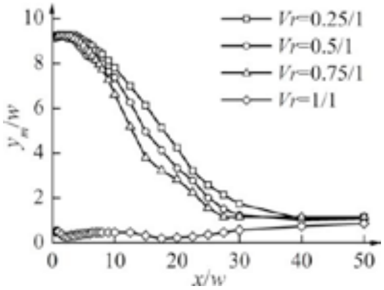

Fig. 8 y_m/w downstream

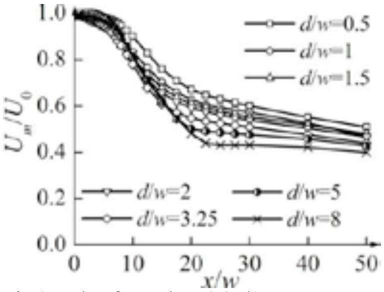

Fig.9 U_m/U_0 for U_w/U_o=0.25/1

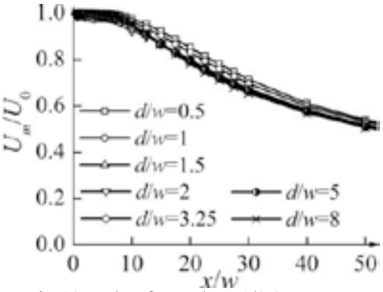

Fig.10 U_m/U_0 for U_w/U_o=1/0.25

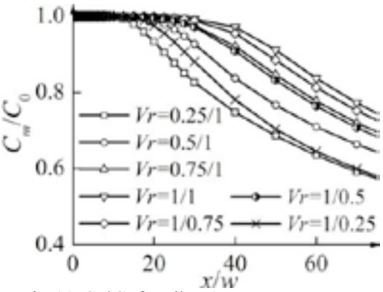

Fig.11 C_m/C_0 for d/w=1

3.3. Dilution Characteristics

In this section, the dilution characteristics are analyzed in terms of tracer concentration. The decay of maximum concentration for d/w=1 with different velocity ratio along the stream-wise direction is captured as shown in Fig.11. The maximum value gradually decreases with the distance increasing after a certain distance. The decay of maximum concentration for V_r=1 is the slowest while that of V_r=0.25/1, 1/0.25 are the rapidest. The decay rates correlate with the difference of two jet velocity. Those demonstrate that the dilution of V_r=1 is smallest.

4. Conclusion

In this paper, the interaction between a plane wall jet and a parallel offset jet was studied using five turbulent models, including Realizable k-ε model, SST k-ω model, k-kl-ω model, transition SST model, v^2-f model, and the computed results were compared with the relevant experiment data. The comparison showed that the Realizable k-ε model is the most effective one in predicting this flow pattern. And then the Realizable k-ε model was used to numerically study the other cases interaction of a wall jet and an offset jet with different velocity ratio and offset ratio.

For the same offset ratio, as the velocity ratio U_w/U_o increasing, the flow pattern shifts from offset jet to wall jet. When the velocity of offset jet keep a constant (U_o =1m/s), the decay rate of maximum velocity increases with the increasing of wall jet velocity. However, When the velocity of offset jet keep a constant (U_o =1m/s), the decay of maximum velocity becomes slower when the offset jet velocity increasing and the velocity of wall jet keeps a constant (U_w =1m/s). When the velocity ratio keeps constant, the decay rate of maximum velocity increases with the offset ratio increasing. When the wall jet velocity is seriously greater than the offset jet velocity (e. g. U_w/U_o =4), the decay of maximum almost keeps a constant, especially when d/w>1.

Finally, the dilution effect of the dual-jet is demonstrated in terms of tracer characteristics. The maximum concentration keeps constant near the exit. After a certain distance, the maximum value decay linearly along the stream-wise direction and the decay rate change with relation to the difference of the velocity of two jets.

This study on the mixing and dilution of the interaction between a wall jet and an offset jet with different velocity and offset ratio are believed to be useful in the sewage disposal and the design or management of outfalls in rivers.

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