NUMERICAL INVESTIGATION ON TURBULENT CHARACTERISTICS OF DOWNSTREAM OF THE U-BEND OPEN CHANNEL FOR DIFFERENT FROUDE NUMBERS

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ABSTRACT

The turbulent fluctuation intensity, during to the effect of the bend, enhances in downstream of the bend, however, most of the experimental and numerical analyzes are investigated on the flow phenomena in a bend and only limited articles have focused on the flow properties in the downstream of the bend. Combined with the volume of fluid (VOF) method, renormalization group (RNG) k-ε turbulence model was employed to numerically investigate the turbulent properties in the downstream of the U-bend open channel with various Froude numbers (Fr). A comparison was carried out between the numerical simulation and experiment, and then detailed investigations have been performed from the turbulent kinetic energy (TKE) and turbulent dissipation rate (ε) with varying Froude numbers to investigate the turbulent characteristics. The calculated results suggested that TKE and ε were conspicuously influenced by Fr. The average turbulent kinetic energy (TKE-A) and turbulent dissipation rate (ε-A) decreased along the downstream of the bend. The intensity of the TKE and ε increased with the increasing Froude numbers, however, the rate of variation with the TKE-A and ε-A declined as the Froude number increased.

Keywords: Downstream of the U-bend; Hydraulic characteristics; Froude number; RNG K-ε

1 INTRODUCTION

The turbulent flow becomes more violent when the fluid pass through the bend, which can remain for a period of time, causing certain impact on the downstream, after it comes out of the bend. It is particularly evident in the heat exchange of pipelines. Ohadi (Ohadi & Sparrow 1988) carried out experimental studies on the heat exchange in the downstream of the bend with three different angles and varying Reynolds Numbers, and found that the heat exchange in the downstream increased with the increase of degree. PIV was used by Hellstrom (Hellstrom 2013) to study the downstream turbulent structure of a 90 degree bend. Scholars (Arvanitis 2018) had studied other characteristics downstream of the bend in pipe.

With the development of computers and algorithms, numerical simulation was gradually used to conduct the related investigation. Standard k-ε turbulence model was adopted by Chowdhury (Chowdhury 2016) to analyze the velocity and turbulent intensity in the downstream of the bend with various curvature ratio. The influence of the bend on the downstream was not only reflected in the pipeline, but also noticeable for the open channel. Ma (Ma 2017) employed RNG k-ε turbulence model and VOF method discussed the variation law of water surface in the downstream of the 90 degree bend. Ghobadian (Ghobadian 2011) applied SSIM 3-D model compared lengthwise stream lines in bend and downstream at diverse levels.

It is of great significance to study turbulent kinetic energy and turbulent dissipation rate, important characters in turbulence structure, in the downstream of open channel bend, however, the paper concentrated upon which are very limited. And Froude number is an indispensable parameter in open channel bend (Farhadi 2018). Based on previous research, RNG k-ε turbulence model and VOF method were employed to investigate the variation law of the turbulent kinetic energy and turbulent dissipation rate in downstream of the U-bend.

2 Numerical Model

The numerical investigations were carried out in an U-bend open channel of rectangular cross-section consisted of a half circle bend of 180° with centerline radius of 0.8m and two straight cross-sections up and down the bend of 6m in length. The channel was 0.4m wide and 0.203m and 0.190m were employed in water depth of the inlet and outlet, respectively. Simultaneously, six Froude numbers (Fr) of 0.16, 0.25, 0.29, 0.33, 0.37 and 0.49 were analyzed. A 3D view of the numerical model and the vertical view was respectively shown in Figure 1(a) and (b) and the relevant parameter was shown in Table 1.
Figure 1. U-bend open channel. (a) 3D view, (b) vertical view.

Table 1. Relevant parameter in different series.

<table>
<thead>
<tr>
<th>Series</th>
<th>Q (m³/s)</th>
<th>v (m/s)</th>
<th>Fr</th>
<th>Re</th>
<th>R (m)</th>
<th>R₁ (m)</th>
<th>R₂ (m)</th>
<th>B/H₀</th>
<th>cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>case1</td>
<td>0.019</td>
<td>0.231</td>
<td>0.16</td>
<td>1.63×10⁴</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>case2</td>
<td>0.028</td>
<td>0.347</td>
<td>0.25</td>
<td>2.45×10⁴</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>case3</td>
<td>0.033</td>
<td>0.404</td>
<td>0.29</td>
<td>2.85×10⁴</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>case4</td>
<td>0.038</td>
<td>0.462</td>
<td>0.33</td>
<td>3.26×10⁴</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>case5</td>
<td>0.042</td>
<td>0.520</td>
<td>0.37</td>
<td>3.67×10⁴</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>case6</td>
<td>0.057</td>
<td>0.693</td>
<td>0.49</td>
<td>4.89×10⁴</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Q = discharge  
B = width of channel  
R = centerline radius  
v = velocity of the inlet  
R₁ = inner radius  
R₂ = outer radius  
Fr = Froude number  
H₀ = depth of the inlet  
Re = Reynolds number  
Cells = numbers of the element

2.1 Numerical Methods  
Renormalization group (RNG) k-ε turbulence model originated by Yakhot and Orszag (Yakhot & Orszag 1986) was adopted with the CFD software Fluent. The volume of fluid (VOF) method (Hirt 1981) was adopted.
in order to track the air-water interface and the PISO algorithm, pressure-based calculation and transient time was employed in the solver. Number of the channel was $30 \times 28 \times 504$, which is shown in Figure 2.

![Figure 2. Meshing pattern of the channel.](image)

2.2 Governing Equations

The equation of continuity, momentum, turbulent kinetic energy (TKE) and turbulent dissipation rate ($\varepsilon$) are shown below:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0$$  \[1\]

Momentum equation:

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \frac{\partial}{\partial x_j}(-\rho u_i u_j) \right]$$  \[2\]

Turbulent kinetic energy equation:

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ (\mu + \mu_t) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon$$  \[3\]

Turbulent dissipation rate equation:

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ (\mu + \frac{\mu_t}{\sigma_k}) \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{C_{1e} \varepsilon}{K} G_k - C_{2e} \rho \frac{\varepsilon^2}{K}$$  \[4\]

where,

$$\mu_t = \mu_C \frac{\varepsilon}{K}$$  \[5\]

$$G_k = \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_i}$$  \[6\]

$$C_{1e} = C_{1e} = \frac{1 - \eta}{1 + \beta \eta^3}$$  \[7\]

$$\eta = \frac{\alpha_{w} \rho_w + (1 - \alpha_{w}) \rho_a}{\rho \mu_e}$$  \[8\]

$$\rho = \alpha_{w} \rho_w + (1 - \alpha_{w}) \rho_a$$  \[9\]

$$\mu = \alpha_{w} \mu_w + (1 - \alpha_{w}) \mu_a$$  \[10\]

$\mu$ is the dynamic viscosity; $\mu_t$ is the turbulence viscosity; $\mu_w$ and $\mu_a$ is the viscosities of water and air, respectively; $\rho$ is the density; $\rho_w$ and $\rho_a$ is the density of water and air, respectively; $u_i$ is the velocity component in the $i$th direction; $t$ is the time; and $c_{1}, c_{2}, \beta$, and $\eta_0$ are empirical constants; $\alpha_{w}$ is the volume fraction of water. In the RNG $k$-$\varepsilon$ model, the empirical constants are given as $C_{1} = 0.0845$, $c_{2} = 0.7179$, $C_{1e} = 1.42$, $C_{2e} = 1.68$, $\beta = 0.012$, and $\eta_0 = 4.38$ (Han 1995).

2.3 Boundary Conditions

Standard atmospheric pressure and pressure-inlet were adopted for the air-water interface. Velocity-inlet and pressure-outlet were employed in the inlet and outlet of the U-bend channel, respectively. Standard wall function approach was used for the bed and sidewalls, which were stationary wall.

2.4 Model Verification
Longitudinal velocity of the entrance of bend in the concave bank, center line, convex bank were chosen to validate the accuracy of the numerical method. Data calculated by numerical model were compared with the experimental data from Ma (Ma 2017), which were shown in Figure 3. The maximum relative error for (a), (b) and (c) was 12%, 10.8%, 13.9%, respectively. Consequently, the RNG k-ε model could be employed for the numerical investigation.

3 Results and Discussion

The turbulence in the bend was more intense and it would last for a period of time in the downstream. Turbulent kinetic energy and turbulent dissipation rate were the characteristic quantity reflecting the turbulence. The calculation results were discussed as follows.

3.1 Variation of turbulent kinetic energy

A numerical analysis was performed from a U-bend open channel with varying Froude numbers. In this study, the equation of TKE calculation was as follows:

\[ K = \frac{1}{2}(u'^{2} + v'^{2} + \omega'^{2}) \]  \[11\]

where, \( K \) presents the TKE, \( u' \), \( v' \), \( \omega' \) are the streamwise, spanwise and vertical fluctuating velocity, respectively.

The average turbulent kinetic energy (TKE-A) and maximum turbulent kinetic energy (TKE-M) of seven sections, i.e. U1.5, D0, D1, D2, D3, D4, D5 were plotted for varying Froude numbers and analyzed to study the influence of Froude number on downstream. Variation of TKE-A and TKE-M in U1.5 and along the downstream of the channel was shown in Figure 4 and Figure 5, respectively. The value of TKE-M and TKE-A increased with the increasing Froude numbers and the law of variation was consistent with the distribution of power functions, as shown in Figure 4 (a) and (b).

TKE-A-N was the dimensionless TKE-A, which was non-dimensionalized via the corresponding value of U1.5 with maximum Froude number, and the calculation of TKE-M-N was similar to TKE-A-N. Figure 5 (a) and (b) showed the variation of TKE-M-N and TKE-A-N along the downstream, respectively. TKE-M-N increased firstly and then decreased for increasing distance to the exit of bend, and the maximum TKE-M-N was shown in 1.0m away from the exit of bend. TKE-M-N increased with increasing Froude numbers in the same position. The variation trend of TKE-A-N was different from TKE-M-N. The TKE-A-N decreased for increasing distance to the exit of bend with smaller Froude numbers. However, the TKE-A-N decreased firstly, then increased and decreased finally with the Froude number of 0.37 and 0.49. The decreasing rate (RD) with \( \Psi-A \) and \( \Psi-M \) was calculated by equation (12) and equation (13), respectively. As shown in Figure 6, the decreasing rate of TKE-M fluctuated around 0.37 except that the Froude number was 0.49 and decreasing rate of TKE-A gradually declined with the increase of Froude number.

\[ RD-A = \frac{\Psi_{DS} - \Psi_{DS}}{\Psi_{U1.5}} \]  \[12\]

\[ RD-M = \frac{\Psi_{DS} - \Psi_{DS}}{\Psi_{U1.5}} \]  \[13\]

where, \( RD-A \) and \( RD-M \) presents the decreasing rate with \( \Psi-A \) and \( \Psi-M \), respectively; \( \Psi_{DS}, \Psi_{U1.5} \) are the \( \Psi \) in the sections of U1.5, D0, D1, D5, respectively; TKE and \( \epsilon \) can be employed to express the \( \Psi \) in this paper.
3.2 Variation of turbulent dissipation rate ($\epsilon$)

The variation of the turbulent dissipation rate along the downstream with the varying Froude numbers was discussed next. The $\epsilon$-M and $\epsilon$-A was the maximum and average turbulent dissipation rate in a section respectively. The variation of $\epsilon$-A and $\epsilon$-M in U1.5 and along the downstream of the channel was shown in Figure 7 and Figure 8, respectively. It was similar to the variation law of turbulent kinetic energy that turbulent dissipation rate increased for increasing Froude numbers and the law of variation with $\epsilon$ was also consistent with the distribution of power functions, as shown in Figure 7(a) and (b).

TKE-M-N increased firstly and then decreased for increasing distance to the exit of bend, and the maximum TKE-M-N was shown in 1.0m away from the exit of bend. The variation law of $\epsilon$-M-N was increase firstly and then decrease for increasing distance to the exit of bend for all six Froude numbers and the maximum $\epsilon$-M-N were captured in 1.0m away from the exit of bend, as showed in Figure 8 (a). The distribution of $\epsilon$-A-N along the downstream of the channel was similar to the variation of TKE-A-N. RD-M and RD-A with $\epsilon$ was calculated by equation (12) and equation (13), respectively. The decreasing rate of $\epsilon$-M fluctuated around 0.73, except that the Froude number was 0.49. The decreasing rate of TKE-A, also gradually decreased with the increase of the Froude number.
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4 CONCLUSIONS

From the results of variation of turbulent kinetic energy and turbulent dissipation rate for the varying Froude numbers, it could be concluded that TKE-M and $\varepsilon$-M increased firstly and decreased then for increasing distance from the exit of the bend in the downstream and enhanced for the increasing Froude numbers. The TKE-A and $\varepsilon$-A were all decreased along the downstream of the channel, the RD of which were reduced as Froude number improved. More information will be presented at the conference.

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REFERENCES


