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Investigation of velocity distribution and turbulence characteristics in subcritical circular open channel flows using a modified Reynolds stress model

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ABSTRACT

The velocity distribution and turbulence characteristics in circular open channel flows are investigated numerically using the commercial CFD software Fluent. The Reynolds stress model, which has been widely used in open channel flow simulation since a dissipation rate formula for the surface boundary condition was proposed by Naot and Rodi, is employed herein to model the turbulence anisotropy. To reflect the surface damping effect and the sidewall retardation effect, a reduction factor is introduced to the surface correction term in the Reynolds transport equation, and a new constant is taken in the dissipation rate formula for the surface boundary condition. The proposed model is demonstrated to be able to reproduce the secondary currents, predict the dip phenomenon well and give right level of turbulence quantities. It is found that the pattern of secondary currents is affected by both the cross-section shape and the filling ratio. The secondary motion contributes to the dip phenomenon, which occurs when the filling ratio is greater than 50%. Turbulence intensities behave differently from those in rectangular channels when the water depth is over the radius while the eddy viscosity shows a parabolic distribution approximately irrespective of the filling ratio.

1. Introduction

Circular transmission pipelines are widely used in culverts, conveyance tunnels, and municipal sewerage and drainage systems. The pipeline is termed as circular open channel, or partially-filled circular pipe if it is in a state of partially filled. For an open channel flow, stage-discharge relationship is of great practical importance, for it provides a simple way by which the discharge is reliably measured by stage gauging. The relationship is generally determined based on the Manning Equation, but a more precise one requires knowledge of the cross-sectional velocity distribution. Circular open channel flow is significantly affected by the pipe bottom slope, the flow depth and wall roughness, which make its velocity distribution entirely different from either pressurized pipe flow or rectangular open channel flow.

Circular open channel flow has a water surface that exerts a great effect on it, in contrast to pressurized pipe flow. Acting as a weak boundary, the water surface changes the velocity distribution in two ways. Firstly, the free surface damps the vertical fluctuation velocity, and redistributes it to the other two directions. As a result, the normal Reynolds stress distribution is changed, and therefore, the pattern of the anisotropy-driven secondary currents is quite different. In pressurized pipes, coherent vortices are symmetrically distributed about the horizontal axis (Duggleby et al., 2007), while in circular open channels, there is a predominant vortex on each half side (Clark and Kehler, 2011). The vortices transport low velocity flows near the upper sidewall to the center region, and high-momentum flow from the surface to below, depressing the velocity nearby the surface. Under certain operating conditions, the depression is large enough to cause the dip phenomenon where the maximum velocity lies below the surface. Secondly, the water surface reduces the turbulence length-scale near it due to geometrical restrictions. The reduction of the vertical length scale of macro-eddies, together with the damping of vertical fluctuation velocity, lead to the decrease of the eddy viscosity towards the surface.

For practical uses, various studies have been carried out to investigate the velocity distribution and turbulence characteristics in circular open channel flows. Nalluri and Novak (1973) measured the streamwise velocity and turbulence intensity in a smooth circular open channel under different filling ratio conditions. They confirmed the existence of the dip phenomenon and maintained that the shape change caused by the varying water depth result in a significant variation in the turbulence intensity distribution. Ead et al. (2000) conducted experiments in a circular corrugated metal pipe to study the velocity field, and

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proposed an empirical formula to predict the velocity profile, including the position of maximum velocity. Clark and Kehler (2011) also carried out their experiment in a circular corrugated culvert, and obtained the velocity as well as the turbulence quantities distributions. Equations were presented to describe the turbulence intensity along the centerline and to predict the streamwise velocity isovel. Yoon et al. (2012) experimentally investigated the effect of water depth on velocity distributionin a partially-filled pipe, and evaluated the difference of friction coefficient from that in pressurized pipe flows. Guo et al. (2015) proposed an analytical solution for the velocity distribution in conic open channels, based on the hypothesis that the centerline velocity profile follows the conventional log-law with a cubic deduction near the surface.

Apart from experimental and analytical studies, some numerical studies have been performed recently to investigate the circular open channel flow. Berlamont et al. (2003) used the standard k-ε turbulence model in the CFD package PHOENICS to investigate the shear stress distribution in partially filled pipes, and Clark et al. (2014) employed the RNG k-ε model in the CFD software Flow3D to study the velocity distribution in partially-filled culverts. However, both their studies took an isotropic turbulence model, thus failed to model the turbulence driven secondary currents (Rodi, 1993), which are known to affect the velocity distribution in open channel flows (Tominaga et al., 1989).

Flow characteristics in circular open channels also differ from those in rectangular ones. Specifically, the secondary currents in circular open channels are caused by the dual effect of the water surface and the inwardly curve sidewall. The damping effect of free surface is considered in numerical simulation by specifying a dissipation rate expression at the surface (Naot and Rodi, 1982), and the secondary motion can be reproduced by using an anisotropic turbulence model, such as the Reynolds stress model (RSM) and the large eddy simulation (LES) model. Since the LES model is rather time-consuming, the RSM model is preferable to investigate the secondary flow. However, despite the RSM model is successfully used in rectangular open channel flow studies, it has not yet been used in circular open channel flow simulation as the authors concerned. The RSM model was firstly put forward by Hanjatic and Launder (1972), and discussed comprehensively by Reece (1977). It was later applied to open channel flow studies by adding a surface reflection term into the Reynolds transport equation and following Naot and Rodi's treatment for the surface boundary condition (Cokljat, 1993; Cokljat and Younis, 1995; Kang and Choi, 2006a,b). This approach has been demonstrated to predict velocity distribution fairly well in rectangular channels. However, it performs poorly in circular open channel flows because the turbulence intensity distribution and the level of turbulent kinetic energy near the surface are different between circular and rectangular open channel flows, as confirmed by Clark and Kehler (2011). Such differences require a modification to the well-received numerical model for rectangular open channel flows when applied to circular open channel flow studies, which motivates this study primarily.

This paper uses a modified Reynolds stress model to study the effect of free surface on velocity distribution and turbulence characteristics in circular open channel flows, using the commercial CFD software Fluent. The model introduces a reduction factor in the Reynolds stress transport equations and uses a dissipation rate expression for the surface boundary condition in which the constant is different from that originally proposed by Naot and Rodi (1982). The model has been validated by predicting the velocity distribution well, and can reproduce secondary currents as well as the dip phenomenon. Differences of flow characteristics in rectangular and circular open channels have also been discussed.

2. Mathematical model

The Reynolds averaged continuity equation and momentum equations are used for steady incompressible turbulent flows, and are expressed as follows:

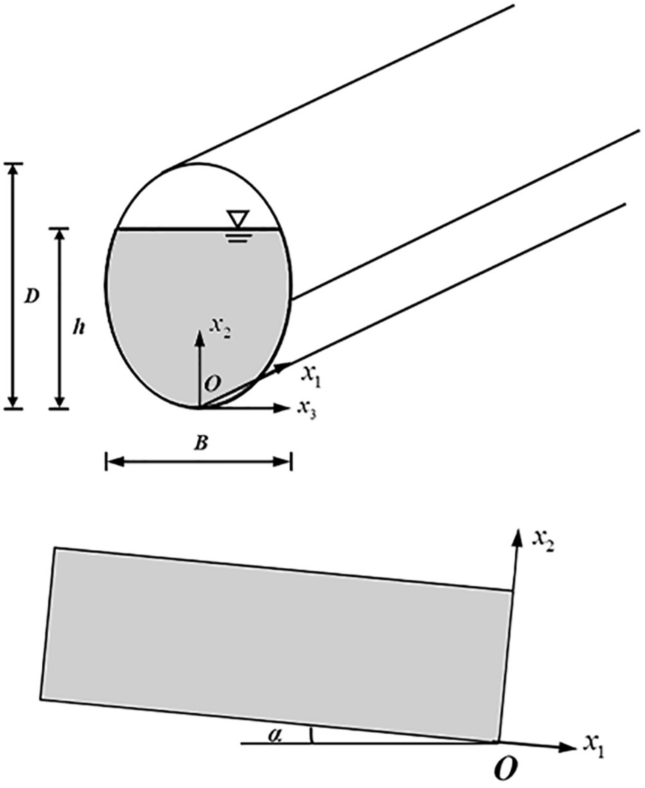

Fig. 1. Schematic sketch of the channel cross-section.

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$u_j\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{1}{\rho}\frac{\partial}{\partial x_j}\left(\mu\frac{\partial u_i}{\partial x_j} - \rho\overline{u_i' u_j'}\right) + f_i \tag{2}$$

where u_i and u'_i are the time average mean and fluctuating velocity components in the x_i direction, respectively, and the coordinate system is defined in Fig. 1. p is the mean pressure, ρ is the water density, μ is the dynamic water viscosity, and f_i is the body force. The body forces are $gsin\alpha$, $gcos\alpha$ and zero in the x_1, x_2, x_3 directions, respectively, in which α is the angle between the bed slope and the horizontal plane.

To reproduce the secondary motion driven by turbulence anisotropy, the Reynolds stress model (RSM) is employed herein (Rodi, 1993), where the Reynolds stresses in Eq. (2) are obtained by solving the following transport equations directly:

$$\frac{\partial}{\partial x_k}(\rho u_k\overline{u_i' u_j'}) = \left[\frac{\partial}{\partial x_k}\left(\frac{\mu_t}{\sigma_k}\frac{\partial\overline{u_i' u_j'}}{\partial x_k}\right) + \frac{\partial}{\partial x_k}\left(\mu\frac{\partial}{\partial x_k}(\overline{u_i' u_j'})\right)\right] - \frac{2}{3}\delta_{ij}\varepsilon - \mathrm{P_{ij}} + \varphi_{\mathrm{ij}} \tag{3}$$

where μ_t is the turbulent kinematic viscosity, δ_{ij} is the Kronecker delta, $\sigma_k = 1$ is the turbulent Prandl number for turbulent kinetic energy (TKE), P_{ij} is the stress production term and calculated as:

$$P_{ij} = \rho\left(\overline{u_i' u_k'}\frac{\partial u_j}{\partial x_k} + \overline{u_j' u_k'}\frac{\partial u_i}{\partial x_k}\right) \tag{4}$$

and ε is the TKE dissipation rate, got from the solution to the following transport equation:

$$u_j\frac{\partial\varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left(c_\mu\frac{k^2}{\varepsilon}\frac{\partial\varepsilon}{\partial x_j}\right) - c_{\varepsilon1}\frac{\varepsilon}{k}\overline{u_i' u_j'}\frac{\partial u_i}{\partial x_j} - c_{\varepsilon2}\frac{\varepsilon^2}{k} \tag{5}$$

where $c_\mu = 0019$, $c_{\varepsilon1} = 1.44$, $c_{\varepsilon2} = 1.92$ are the model constants.