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Free surface and velocity field in a circular channel along the side weir in supercritical flow conditions

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ABSTRACT

A side weir is a kind of flow regulator hydraulic structure which is used in drainage systems, irrigation and sewage disposal network. The passing flow over side weir is a spatial variability flow with discharge reduction. Circular channels with side weir have been used widely for regulating runoff and flood. In this research the flow free surface and the passing flow field through a circular channel with side weir is simulated by commercial software. In this CFD analysis, the RNG k–ε turbulence model is used for simulating the turbulence of the flow field and the free surface changes are modeled using VOF model. Comparison between changes in the free surface, the passing discharge over the weir, the discharge coefficient and the specific energy at the beginning section of side weir obtained from the numerical simulation and experimental results indicates acceptable accuracy of the CFD model in the supercritical regime. Given that most previous numerical studies have been focused on the rectangular channel with side weir and in the subcritical flow condition, the main purpose of this simulation is study of the free surface changes and the velocity field along a side weir located on a circular channel in the supercritical regime.

1. Introduction

Side weirs have many applications in hydraulic and environment engineering. A side weir is used to control the balance of passing flow through main channel and divert excess water into side channel. The side channel may be installed parallel to the main channel or perpendicular to it. Side weir has many applications in water transmission systems, drainage and irrigation systems, and waste water treatment stations, disposal of sewage and hydraulic facilities of dams. Flow passing over the side weirs consider as spatial variable flow (SVF) with discharge reduction. A side weir usually installs on the channel side wall to divert excess flows. The importance of channels with side weir and the passing flow over weir has led to many theoretical and numerical studies. Spatial variable flow theory with discharge reduction has been tested for the first time on side weirs by Engels (1917) and later Coleman and Smith (1923) [1,2]. Forchheimer (1930) with the assumption of being parallel of the energy line with the weir's crest and the channel bed and also being linear of the water surface profile provided an analytical solution for this type of flow [3]. De Marchi (1934) was one of the first who solved the governing equation on spatial variable flows with discharge reduction. He showed in his research that energy along the weir is constant and the water surface profile has curvature. So that, the water surface profile slope in subcritical flows is increasing and in supercritical flows is decreasing [4]. The most important theoretical and experimental carried out studies on rectangular channels with side weir are as follows:

Frazer, 1954; Collinge, 1957; Chow, 1959; Subramanya and Awasthy, 1972; El-kashab, 1975; Ranga Raju, et al. 1979; Ramamurthy et al., 1980; Hager, 1987; Delo and Saul, 1989; Uyumaz and Smith, 1991; Singh et al., 1994; Swamee et al., 1994; Bruce, 1995; Swamee et al., 1995; Jalili and Borghei, 1996; Huagao et al., 2007; Venutelli, 2008; Vatankhah and Bijankhan, 2009; Emiroglu et al., 2010; Emiroglu et al., 2011; Bagheri and Heidarpour, 2012; Novak et al., 2013; [5–26].

Aghayari et al. (2009) and Mwafaq and Ahmed (2011) performed experimental studies on the discharge coefficient of inclined side weirs located on rectangular channels [27,28].

The most important theoretical and experimental studies on the passing flow over oblique side weir located on rectangular channel were performed by Samani (2010), Swamee et al. (2011), Borghei and Parvaneh (2011), Azza and Al-Talib (2012) [29–35].

Several theoretical and experimental studies on non-rectangular side weir located on rectangular channels have been performed. Rahimpour et al. (2011) and Haddadi and Rahimpour (2012) have

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Nomenclature

a	local speed of the flow (m/s)
C_d	discharge coefficient (dimensionless)
C_u	constant coefficient (dimensionless)
D	channel diameter (m)
E_1	specific energy in Section 1 in the main channel (m)
F	fluid volume fraction in a cell (dimensionless)
F_1	Froude number at beginning of side weir on axis of main channel
g	acceleration gravity (m/s^2)
J	any quantity at out of the boundary (dimensionless)
k_t	turbulence kinetic energy (m^2/s^2)
L	side weir length (m)
P	side weir height (m)
p	pressure (N/m^2)
Q_1	discharge in Section 1 in the main channel (m^3/s)
Q_w	discharge over the side weir (m^3/s)
q	discharge per unit length of the side weir (m^2/s)
S_0	bed slope of the main channel (dimensionless)
T_{len}	turbulent length scale (m)
T	width of the channel at the water surface (m)
t	time (s)
$U_{i,j}$	velocity components (m/s)
u_*	wall shear velocity (m/s)
$x_{i,j}$	direction of cartesian coordinates (m)
x	distance from upstream of the weir (m)
y_1	distance of the cell center from the solid wall (m)
y^+	non-dimensional parameter (dimensionless)
z	depth of the flow (m)
z_1	depth of the flow in Section 1 in the main channel (m)
z_2	depth of the flow in Section 2 in the main channel (m)
ε_t	turbulence dissipation rate (m^2/s^3)
ν	kinematic viscosity (m^2/s)
ν_t	turbulent eddy-viscosity (m^2/s)
ρ	fluid density (kg/m^3)

reported their investigations on the passing flow over the broad crested trapezoidal weir located in rectangular ducts [36,37].

Kumar and Pathak (1987), Ghodsian (2004), Yahya (2011) have provided their investigations on the broad crested and sharp crested triangular side weir located on triangular channels [38–40].

Many experimental and theoretical studies have been conducted in the field of the passing flow over side weirs located on non-rectangular ducts. Uyumaz (1992) and Vatankhah (2012) on triangular channels with side weir [41,42], Cheong (1991) and Vatankhah (2012) in regard with trapezoidal channels with side weir [43,44], Uyumaz (1997) and Vatankhah (2013) on the U-shape channel with side weir [45,46] and Vatankhah (2013) on the parabolic-shape channel with side weir have provided their theoretical, analytical and experimental studies [47].

Circular channels have wide application in sewage disposal system and considerable length of sewage disposal system consisting of circular channels. Circular channels have side weir in order to control the runoff and flood level that enter into the sewage disposal system. Side weir installs on the wall of circular channel and when the flow level is higher than the weir crest the additional flow directs into the side channel and the remaining flow continues into the main channel.

In association with circular channel with side weir Allen (1957) was the first one who conducted a laboratory study on the passing discharge over a rectangular side weir that placed on a circular channel [48]. Uyumaz and Muslu (1985) performed some experiments on the passing flow over side weirs located on circular channels in both supercritical and subcritical flow conditions. They using energy principles and the finite element method provided an analytical method for predicting the passing flow over side weir and flow free surface.

They also provided some relationships for calculating the discharge coefficient of the side weir that located on circular channels in both supercritical and sub-critical flow conditions [49]. Vatankhah (2010) using incomplete elliptic integrals method and the specific energy principle introduced an analytical solution to predict the longitude profile of the flow free surface along the side weir that placed on a circular channel [50]. As mentioned, the passing flow over side weirs is a spatial variable flow. Because of produced side flow by side weir, hydraulic behavior of such structures is quite different in comparison with common weirs. Furthermore, the flow along the side weir could be subcritical or supercritical. Several theoretical and experimental investigations in connection with supercritical flows through the channels with side weir have been conducted. Hager (1994) provided an analytical method to solve the dynamic equation governing on the passing flow over the side weir located in a circular channel in supercritical flow conditions. His method is used in both flow condition of with hydraulic jump and without hydraulic jump along the side weir [51]. Oliveto et al. (2001) investigated the characteristics of supercritical flow condition along the side weir located in a circular channel. In the experimental study that conducted by Oliveto et al. (2001) flow at the side weir's upstream is subcritical [52]. Ghodsian (2003) investigated the supercritical passing flow over the side weir located in a circular channel. He has provided a relationship for calculating the elementary discharge coefficient [53]. Coonrod et al. (2009) investigated the effect of guide vanes on the passing flow over the side weir located in a rectangular channel in the supercritical regime. They found that these guide vanes increase the amount of side flow [54].

Today with increasing of computational power of computers and high power of flow simulation software, numerical methods and computational fluid dynamic (CFD) have been known as reliable tools in modeling of complicated and three dimensional flows.

Mangarulkar (2010) using ANSYS ICEM CFD software and the k–ε (RNG) turbulence model simulated the free surface of a side weir with crest height of zero and compared the location of the stagnation point obtained through analytical investigation with the results of numerical simulations [55]. Mahmodinia et al. (2012) using FLUENT modeled the effect of the Froude number on the passing flow over side weir located in a rectangular channel [56]. Aydin (2012) using VOF model simulated the free surface profile of a flow on a rectangular channel with triangular labyrinth side weir for different Freud numbers [57]. Aydin and Emiroglu (2013) using FLUENT-ANSYS software and VOF model simulated the conduit capacity of the labyrinth side weir regarding different flow parameters [58]. Ahmed et al. (2013) using Simulink programming simulated the flow free surface profile of the passing flow over weir and the discharge coefficient of side weir [59]. Mohammed using programming and Euler numerical model on oblique weir with different installation angles provided a relationship for the elementary discharge coefficient [60].

As can be seen, by reviewing of experimental and numerical studies in the field of channels with side weir, numerical modeling of circular channels with side weir in the supercritical flow conditions has not been performed so far. The main purpose of this numerical study is simulating of the free surface and velocity field of the passing flow through a circular channel with side weir