ME-NETT 24
The 24th Conference of the Mechanical Engineering Network of Thailand

The 24th Conference of the Mechanical Engineering Network of Thailand
October 20 – 22, 2010, Ubon Ratchathani

Simulation of Recirculating and Cavitation on Stepped Spillway using CFD

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Abstract

The flow over a stepped spillway is free surface, multiphase, cavitations and turbulent. Moreover, there is the recirculation region occurred at each step of the spillway. The flow characteristic is hence complicated and difficult to predict. In the previous works of the stepped spillway (Chen et al. [1] and Xiangju et al. [2]), only the linear turbulence model was applied which gave low accuracy. Furthermore, there are still no optimized model constants for this kind of flow. Since experimental investigations for marine applications are expensive, CFD simulations represent a powerful tool in order to investigate the phenomenon. The final goal of this work is to get a deeper understanding of the structure of the flow over a stepped spillway. The accurate prediction of cavitations has been found out to be intrinsically related to the accurate resolution of turbulent structures of the flow. Therefore, a thoroughly analysis of the turbulence modeling in this kind of application was performed.

***Keywords**:* Recirculating, Turbulent flow, Free surface, Cavitations and Stepped Spillway.

1. Introduction

Over the last two decades, the stepped spillways have been included in a Roller Compact Concrete Dam (RCC). Besides the ease of construction and maintenance, their advantages are to dissipate flow energy and thus reduce the size of energy dissipater and to increase the turbulent boundary layer and thus to enable free-surface air entrainment along the spillways; this air reduces the potential cavitations damage. The macro-roughness of the steps in the spillways increases the energy dissipation; this means the water depth increases and the flow velocity reduces. Consequently, the size of the energy dissipater downstream of the stepped spillways can be reduced. In 2002, Chen et al. [1] used the standard $k-\varepsilon$ turbulence model to simulate the flow over a stepped spillway. Later, Xiangju et al. [2] used the RNG (renormalization group) $k-\varepsilon$ turbulence model to simulate the same stepped spillway as Chen et al. They found that their results were more accurate than the results from Chen et al. Therefore, it can be seen that the turbulence model plays an important role on the accuracy of the flow simulation using computational fluid dynamics (CFD). Nowadays, the large eddy simulation (LES) plays an important role in the turbulent flow simulation because of its high accuracy. Nevertheless, it requires too much computational time and memory that it is not suitable for the engineering design. The conventional linear Reynolds-averaged Navier-Stokes (RANS) turbulence model uses less computational power than the LES but also gives low accuracy for complex flows. Therefore, the linear RANS turbulence model is modified by replacing the linear Reynolds-stress term with the nonlinear Reynolds-stress term. This modified model called the nonlinear RANS turbulence model has become more popular in the last decade because of its high accuracy and reasonable computational time. It has been applied to many complex flow problems successfully; for examples, compressible flow through an S-shaped diffusing ducts (Juntasaro et al. [3]), flow through a rotating square duct (Gururatana et al. [4]) and non- linear turbulence models for multiphase recirculating free-surface flow over stepped spillways (Tongkratoke et al. [5]).

It can be seen from the literature that the $k-\omega\ SST$ (shear-stress transport) turbulence models, realizable $k-\varepsilon$ turbulence model combined with the non-equilibrium wall function equations, $k-\omega$ turbulence models (standard) and RSM (Reynolds stress model) have never been applied to simulate the flow over the chute and stepped spillways before.

2. Governing Equations

The Reynolds-averaged Navier-Stokes (RANS) equations for multiphase recirculating free-surface flow over the chute and stepped spillways are written as follows:

continuity equation

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (1)$$

momentum equation

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left\{\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right\} - \frac{\partial \rho \overline{u_i' u_j'}}{\partial x_j} + \rho g_i \qquad (2)$$

where ρ is density, u_i and u_j are velocity components, P is pressure, g is gravity, μ is dynamic viscosity, $\overline{u_i' u_j'}$ is Reynolds stresses, x_i and x_j are coordinate components, and t is time. The equation for the mass fraction of air is

mass fraction equation

$$\frac{\partial}{\partial t}(\rho C) + \frac{\partial}{\partial x_j}(\rho u_j C) = \frac{\partial}{\partial x_j}\left(\Gamma_\phi \frac{\partial C}{\partial x_j}\right) \qquad (3)$$

where C is the mass fraction of air or the air concentration and Γ_ϕ represents effective diffusivity of mass

$$\Gamma_\phi = \rho D + \frac{\mu_t}{Sc} \qquad (4)$$

where D is the diffusion coefficient, μ_t is the eddy viscosity, and Sc is the turbulent Schmidt number.

3. Numerical Method

The governing equations are discretized using the finite volume method with the QUICK scheme. The coupling of the pressure and the velocity is achieved through the SIMPLEC algorithm. The calculation domain is divided into discrete control volumes by the unstructured grid, which has a high flexibility to fit the complex geometry of spillways. The grid-independent study is made for all cases as presented Figure 1 showing the grid divisions for the chute spillway with air entrainment (case 1) is presented to show the fineness of the grids.

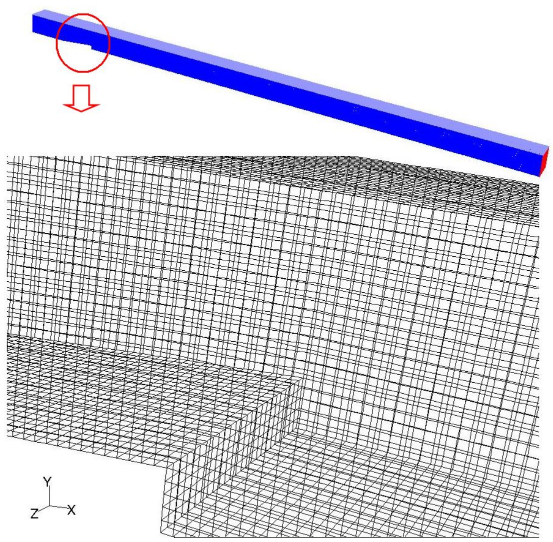

Figure 1 Grid divisions for the chute spillway with air entrainment (case 1)

4. Results and Discussions

The performance in predicting the multiphase recirculating turbulent free-surface flow over the chute spillway with air entrainment and the stepped spillways of the $k-\omega\ SST$ turbulence models, realizable $k-\varepsilon$ turbulence model combined with the non-equilibrium wall function equations, $k-\omega$ turbulence models (standard) and RSM is assessed in this section using the experimental data of Kramer et al. [6], Boes and Hager [7] and Chanson and Toombes [8]. The geometries of the considered spillways are presented in Table 1, Figures 2 and 3.

4.1 Chute spillway with air entrainment

The experimental data of Kramer et al. [6] are used for comparison in the case of the chute spillway with air entrainment. The geometry of the case study is shown in Figure 2 and case study 1 in Table 1. The comparison of the predicted air concentration distribution using the $k-\omega\ SST$ turbulence models, realizable $k-\varepsilon$ turbulence model combined with the non-equilibrium wall function equations, $k-\omega$ turbulence models (standard) and RSM is presented in Figure 4 and Figure 5 comparison of cavitations distribution of $k-\omega\ SST$ turbulence models in the case 1. It can be seen that the $k-\omega\ SST$ turbulence models, realizable $k-\varepsilon$ turbulence model combined with the non-equilibrium wall function equations, $k-\omega$ turbulence models (standard) and RSM. The $k-\omega\ SST$ turbulence models can also predict the results close to the experimental data of Kramer et al. [6].

Table 1 Geometry and water flow rate for flows over the spillways

Case	Type	Reference	Water flow rate, q_w ($m^3/s/m$)	Air flow rate, q_a ($m^3/s/m$)	Geometry: Slope (degree)	Spillway height, H (m)	Spillway length, L (m)	Spillway width, W (m)	Step height, h (m)
1	Chute spillway with air entrainment	Kramer et al. [6]	0.3682	0.0992	5.31	1.30	14.00	0.50	-
2	Stepped spillway	Boes and Hager [7]	0.0466	-	30	2.85	5.70	0.50	0.0231
3	Stepped spillway	Chanson and Toombes [8]	0.1140	-	21.8	1.00	2.70	1.00	0.1000

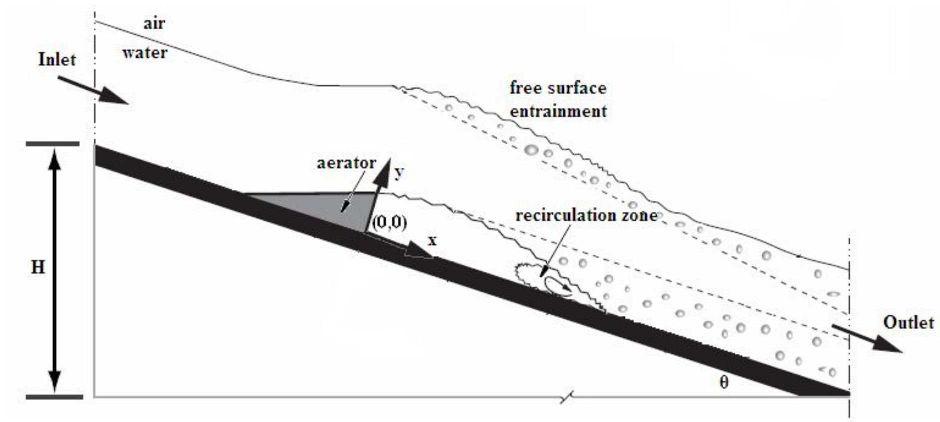

Figure 2 Geometry of the chute spillway with air entrainment (case 1)

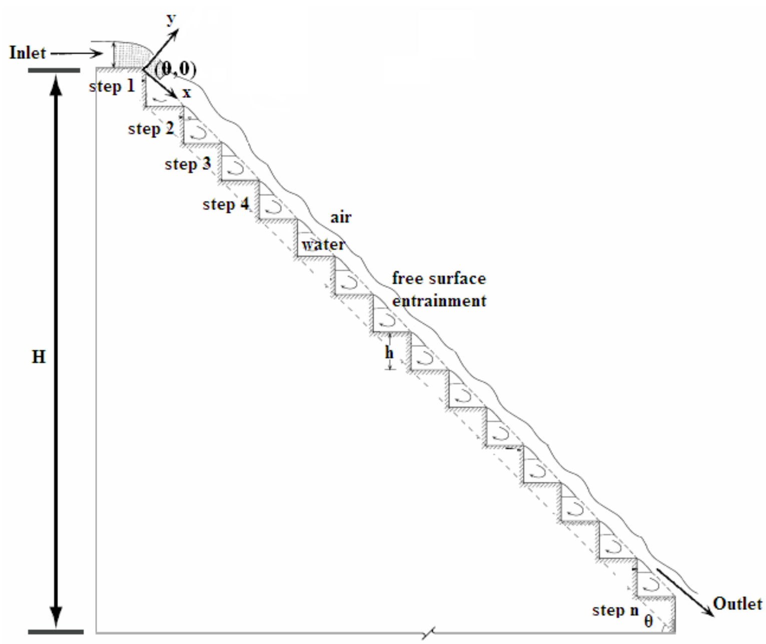

Figure 3 Geometry of the stepped spillway (cases 2 and 3)

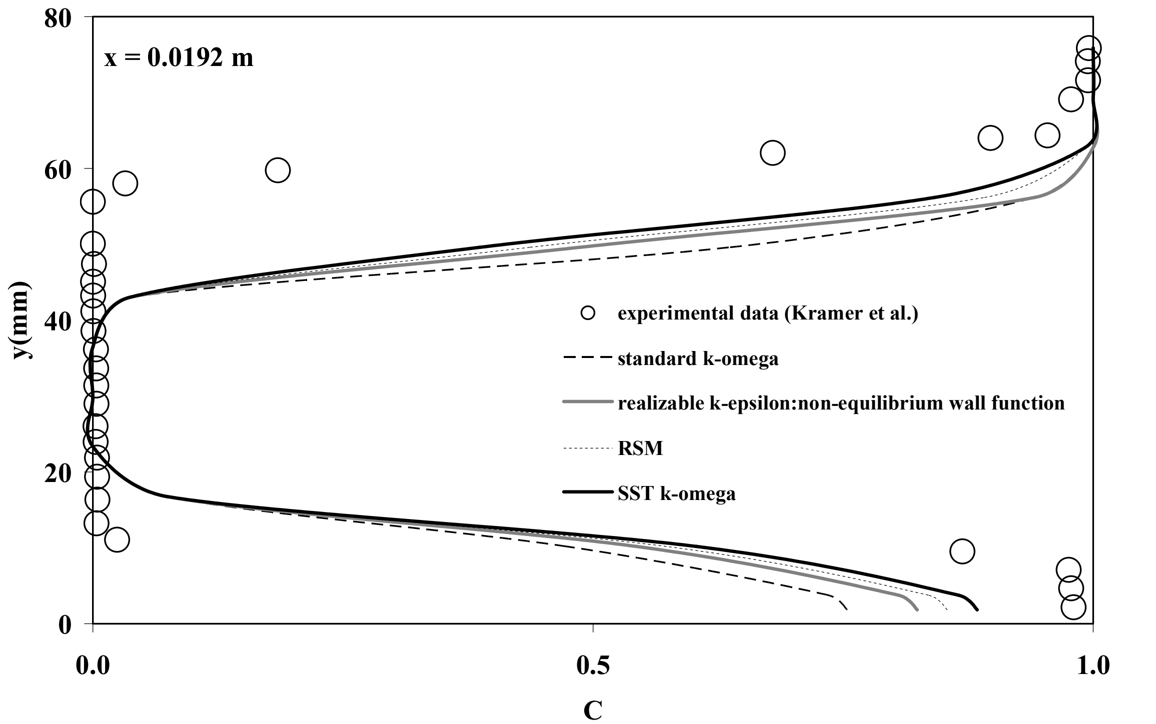

Figure 4 Comparison of air concentration distribution using the $k-\omega\ SST$, realizable $k-\varepsilon$, standard $k-\omega$ and RSM turbulence models for case 1

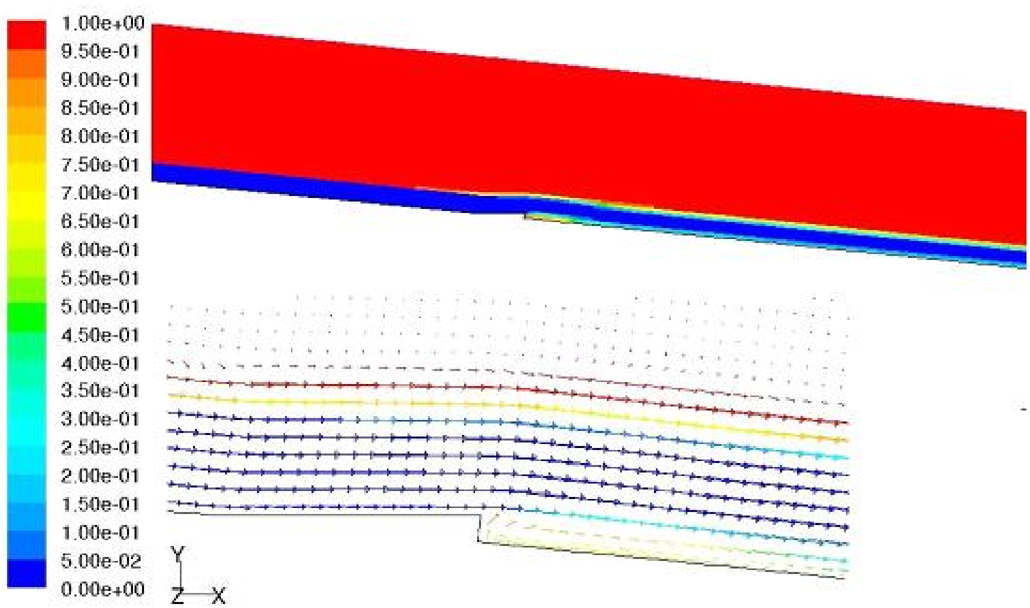

Figure 5 comparison of cavitations distribution of $k-\omega\ SST$ turbulence models in the case 1.

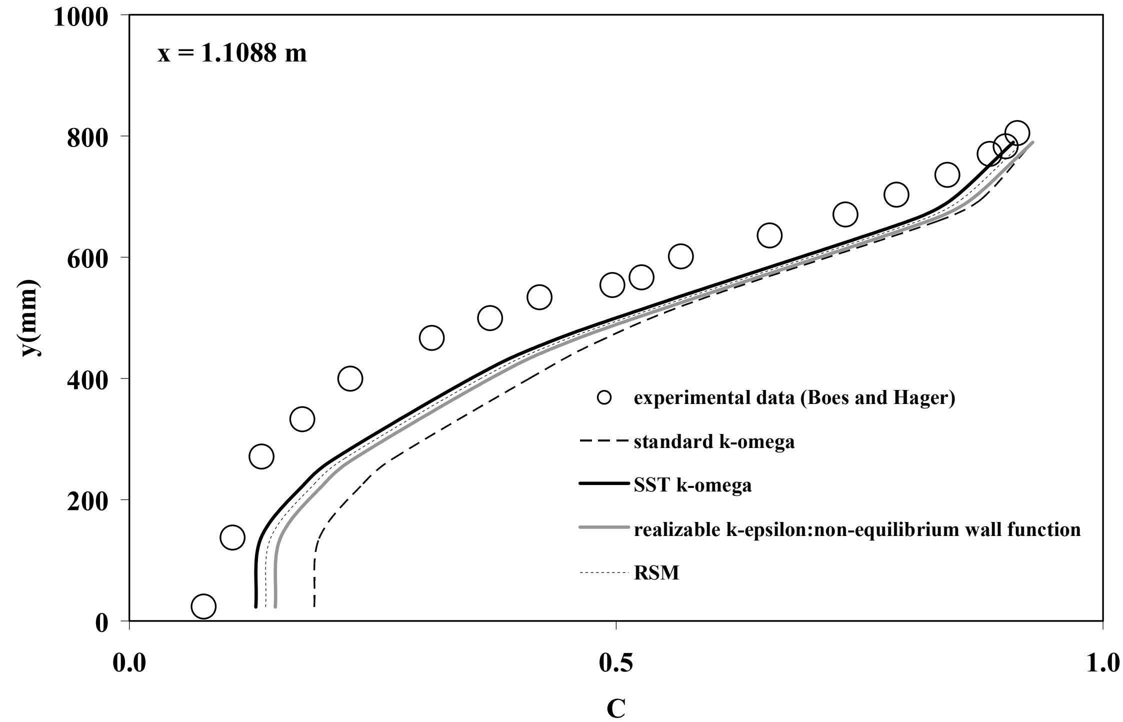

Figure 6 Comparison of air concentration distribution using the $k-\omega\ SST$, realizable $k-\varepsilon$, standard $k-\omega$ and RSM turbulence models for case 2

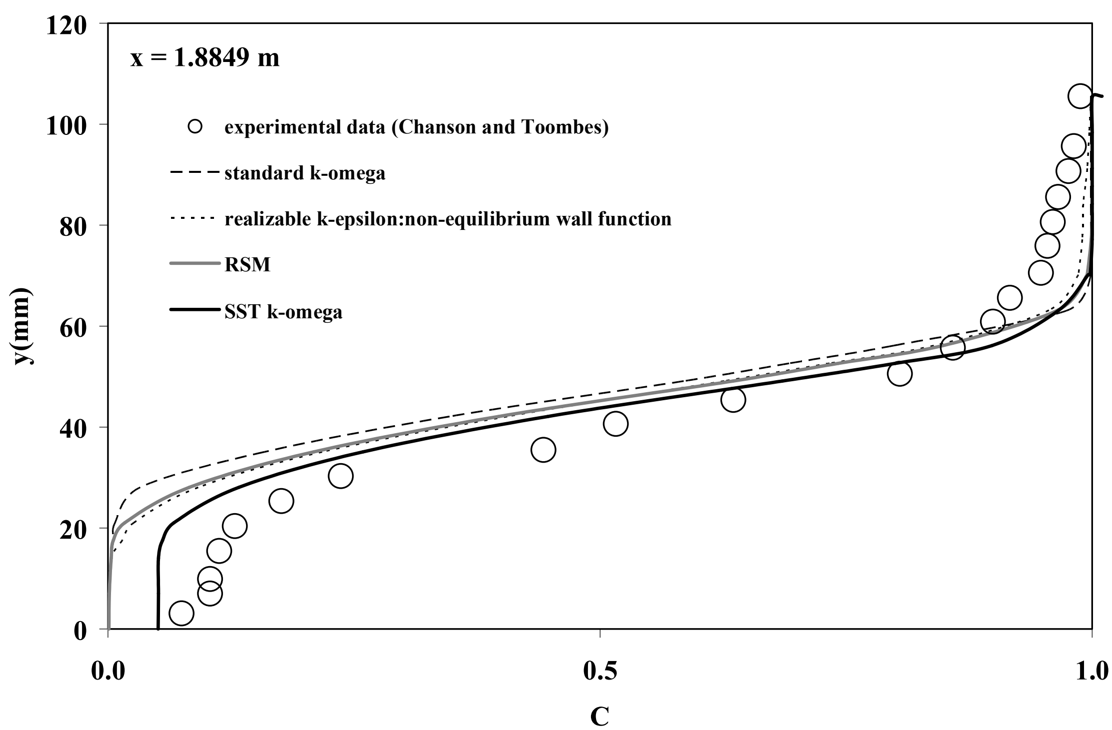

Figure 7 Comparison of air concentration distribution using the $k-\omega\ SST$, realizable $k-\varepsilon$, standard

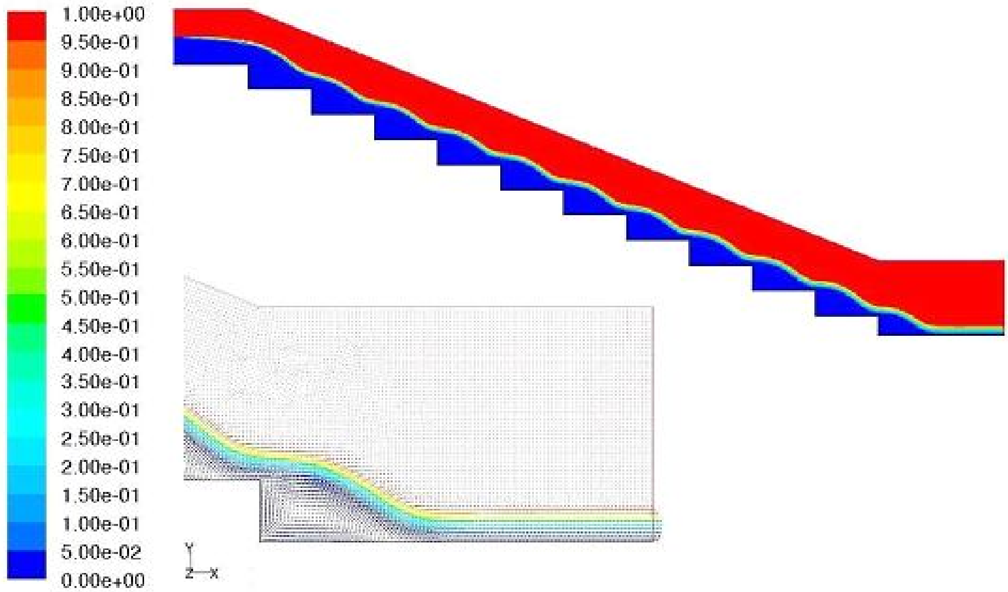

Figure 8 comparison of cavitations distribution of $k-\omega\ SST$ turbulence models in the case 3.

4.2 Stepped spillways

The experimental data of Bose and Hager [7] and Chanson and Toombes [8] are used for comparison in the case of the stepped spillways for various slopes and step heights. The geometry of the case studies is shown in Figure 3 and case studies 2 and 3 in Table 1. The comparison of predicted velocity distribution and air concentration distribution using the $k-\omega\ SST$ turbulence models can predict the flow phenomena more accurately than the realizable $k-\varepsilon$ turbulence model combined with the non-equilibrium wall function equations, $k-\omega$ turbulence models (standard) and RSM. The $k-\omega\ SST$ turbulence models can also predict the results close to the experimental data of Bose and Hager [7] and Chanson and Toombes [8] is presented in Figures 6 to 7.

The characteristic of the flow over the stepped spillway is more complicated than that over the chute spillway in the sense that there is the recirculation region at every step of the spillway. This highlights the ability of $k-\omega\ SST$ turbulence models in predicting the recirculating flow over the entire turbulence model as can be clearly seen in Figure 8.

5. Conclusions

The performance of various of the $k-\omega\ SST$ (shear-stress transport) turbulence models, realizable $k-\varepsilon$ turbulence model combined with the non-equilibrium wall function equations, $k-\omega$ turbulence models (standard) and RSM (Reynolds stress model) in predicting multiphase recirculating turbulent free-surface flows over the chute spillway with air entrainment and the stepped spillways with various slopes and step heights is assessed in details. It is found that the results predicted by the $k-\omega\ SST$ turbulence models can predict the flow phenomena more accurately than the realizable $k-\varepsilon$ turbulence model combined with the non-equilibrium wall function equations, $k-\omega$ turbulence models (standard) and RSM. Moreover, the computational results are helpful for understanding the flow phenomena over the stepped spillways and can be used as the preliminary assessment of cavitations potential.

Acknowledgement

This research work has been supported by Research and Development Institute Chalermphrakiat Sakon Nakhon Province Campus and Faculty of Science and Engineering, Kasetsart University, Chalermphrakiat Sakon Nakhon Province Campus, Thailand.

References

[1] Chen, Q., Dai, G.Q. and Liu, H.W., 2002. Volume of Fluid Model for Turbulence Numerical Simulation of Stepped Spillway Over Flow. Journal of Hydraulic Engineering, ASCE, 128 (7): 683-688.

[2] Xiangju, C., Yongcan, C. and Lin, L., 2006. Numerical Simulation of Air-Water Two-Phase Flow Over Stepped Spillway. Science in China Series E: Technological Sciences, 49 (3): 674-684.

[3] Juntasaro, V., Dechaumphai, P. and Marquis, A.J., 2005. Evaluation of the Damping Functions in Low-Reynolds-Number Non-Linear $q-\zeta$ Turbulence Model. International Journal of Computational Fluid Dynamics, 19 (3): 225-234.

[4] Gururatana, S., Juttijudata, V., Juntasaro, E. and Juntasaro, V., 2006. Prediction of 3D Turbulence Induced Secondary Flows in Rotating Square Duct. Whither Turbulence Prediction and Control, 26-29 March 2006, Seoul National University, Seoul, Korea.

[5] Tongkratoke, A., Chinnarasri, C., Pornprommin, A., Dechaumphai, P. and Juntasaro, V., 2009. Non-linear turbulence models for multiphase recirculating free-surface flow over stepped spillways. International Journal of Computational Fluid Dynamics, Volume 23, Issue 5, p.401-409.

[6] Kramer, K., Hager, H.W. and Minor H.E., 2006. Development of Air Concentration on Chute Spillways. Journal of Hydraulic Engineering, 132 (9): 908-915.

[7] Boes, R.M. and Hager, W.H., 2003. Two-Phase Flow Characteristics of Stepped Spillways. Journal of Hydraulic Engineering, 129 (9): 661-670.

[8] Chanson, H. and Toombes, L., 2002. Experimental Study of Gas-Liquid Interfacial Properties in a Stepped Cascade Flow. Environmental Fluid Mechanics, 2: 241-263.