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Numerical Modeling of Flow in USBR II Stilling Basin with End Adverse Slope

Hamidreza Babaali, Alireza Mojtahedi, Nasim Soori, Saba Soori

***Abstract*—**Hydraulic jump is one of the effective ways of energy dissipation in stilling basins that the energy is highly dissipated by jumping. Adverse slope surface at the end stilling basin is caused to increase energy dissipation and stability of the hydraulic jump. In this study, the adverse slope has been added to end of United States Bureau of Reclamation (USBR) II stilling basin in hydraulic model of Nazloochay dam with scale 1:40, and flow simulated into stilling basin using Flow-3D software. The numerical model is verified by experimental data of water depth in stilling basin. Then, the parameters of water level profile, Froude Number, pressure, air entrainment and turbulent dissipation investigated for discharging 300 m^3/s using K-Ɛ and Re-Normalization Group (RNG) turbulence models. The results showed a good agreement between numerical and experimental model as numerical model can be used to optimize of stilling basins.

***Keywords*—**Experimental and numerical modeling, end adverse slope, flow parameters, USBR II Stilling Basin.

I. Introduction

ONE of the most important hydraulic phenomena in rapidly varied flow is the hydraulic jump that it occurs when a supercritical flow changes to subcritical flow. Stilling basin is usually built at the downstream of structures such as chutes and gates to controlling the energy dissipation of hydraulic jump [1]-[3]. With changing the effective parameters on the characteristics of hydraulic jump, the performance of stilling basin can be improved. The variant designs of stilling basins have been presented to better controlling hydraulic jump. One of these designs is the stilling basin with end adverse slope that in recent years many researches have been done about the formatting hydraulic jump in them. The first researchers who have done studies about hydraulic jump on the surface of adverse slope were Forester and Skrinde [4]. In the energy dissipater structures, baffle blocks and end still are used to prevent from the existing jump and fixing it in the stilling basin [5]. One of the first researchers who investigated the role of the baffle blocks and its effects on flow characteristics in the stilling basins was Harleman [6]. The pressure fluctuations at the bottom of hydraulic jump are studied using a negative step [7]. The hydraulic jump on adverse steps was investigated with considering the effect of tail water depth, Froude number and the height of step on the types of hydraulic jump and divided the hydraulic jump to six categories [8]. Also, various types of hydraulic jump were studied on the adverse step with a wider range of effective parameters. They proposed 11 graphs versus Froude number and tail water depth and divided the hydraulic jump into five groups [9]. Velocity and water surface profiles, kinetic energy (k) and energy loss (ε) were presented by simulating hydraulic jump [10]. The stilling basin model was designed with the impact of wall and end still. The results of this analysis showed that by suitable design of the walls size not only the efficiency of the stilling basin model increases but also the length of stilling basin decreases 29% in comparison to USBR IV stilling basin [11]. Several models of the stilling basin were studied with rectangular and circular pipe outlet based on previous researches [12]. Hydraulic jump, energy dissipation, flow characteristics were analyzed at downstream of different types of spillway with sluice gate experimentally [13]. The energy dissipation was predicted at downstream of low-head river training structures and compared two stilling basin configurations [14]. The impact of channel slope was investigated on the characteristics of hydraulic jump. The jump attributes tested in the vertical valves located in downstream of rectangular channel [15]. The impact of different shapes of stilling basin was investigated with different heights of the end steps on characteristics of submerged hydraulic jump and energy dissipation at downstream of a sluice gate [16]. The impact of tail water was studied on the designing several stilling basins in the USA [17]. Flow was simulated as 3-Dimentonal in stilling basins using VOF RNG k-ε and Mixture RNG k-ε turbulence models. Then, it was stated that the calculated parameters of water depth, velocity profile and pressure distribution are in good agreement with the experimental data. Moreover, the mixture turbulence model is better than the VOF turbulence model to calculation of the air entrainment [18]. Neural network was utilized for predicting pressure fluctuations in a sloped stilling basin and presented a formula to calculating the average pressure fluctuations based on the features with the most impact on the hydraulic jump [19]. Hydraulic jump was simulated in stilling basin with converged walls using flow-3D [20]. The performance of USBR III stilling basin was studied at downstream of the smooth and stepped spillways numerically. They employed unsteady RANS equations together with VOF method and RNG-k-ε model respectively to modeling free surface and turbulence [21]. The performance of Flow-3D and Open-FOAM was evaluated in the numerical modeling of hydraulic jump at a low Reynolds

Hamidreza Babaali is with the Islamic Azad University, Khorramabad, Iran, Islamic Republic Of (corresponding author; e-mail: ham_babaali@yahoo.com).
A. M. and N. S. are with the Department of Civil Engineering, Tabriz University, Tabriz, Iran (e-mail: mojtahedi@tabrizu.ac.ir, nasim.soori@gmail.com)
S. S. is with the Department of Civil Engineering, Semnan University, Semnan, Iran (e-mail: soori.saba@gmail.com)

number [22]. Inlet and outlet obstacles at USBR II stilling basin were studied with different height. Then, for the most optimal state, hydraulic parameters were investigated [23]. In this study, the hydraulic parameters of flow were investigated in USBR II stilling basin of Nazloochay dam model in water research institute in Iran. For this purpose with adding adverse slope (3:1, H:V) to end of stilling basin, the pressure, Froude Number, water surface profile, the air entrainment and turbulent dissipation were explored using Flow-3D software in discharging 300 m^3/s.

II. Method and Materials

A. Experimental Model

The Nazloochay reservoir dam is an earth dam with a clay core and height of 100 m which was located on Nazloochay River in northwestern Urmia-Iran. The hydraulic model of flooding discharge system was built based on Froude Number similarity with scaling 1:40. The material of bottom, walls of the weir and stilling basin are Plexiglas. USBR II stilling basin was designed for return period of 1000 years with discharging 500 m^3/s. To measuring the discharge and regulation of water surface are used respectively the rectangular weir and sluice gate at the end channel. The flooding discharge system of dam is included input channel, free-ogee weir, chutes and the USBR II stilling basin. Fig. 1 illustrates the hydraulic model of Nazloochay dam [24].

Fig. 1 Hydraulic model of Nazloochay dam

Fig. 2 and Table I present the sections to measuring hydraulic parameters in stilling basin.

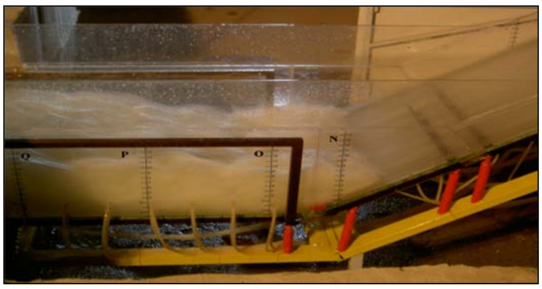

Fig. 2 The measured sections in hydraulic model

TABLE I
THE MEASURED SECTIONS IN STILLING BASIN

The measured sections	O	P	Q	R	S	T
The distance from the measured sections to weir sill (m)	285	300	315	336	366	401

B. Numerical Model

Although the flow pattern in the stilling basins is very complex, Navier-Stokes equations can present a mathematical description of stilling basins. Today, 3-D simulation of free surface flows have been become a beneficial and commodious method [25], [26]. In this study, Flow-3D software has been used to simulating the flow in the stilling basin. This software solves governing equations by the finite volume method that to accuracy in modeling the rigid bodies uses Fractional Area/ Volume Obstacle Representation (FAVOR) and employs the volume of fluid (VOF) method to the simulation of the fluid behavior. The Flow-3D software defines the equations of continuity, momentum and the free surface profile as following:

The continuity equation is defined for fluid flow at three dimensional Cartesian coordinates as (1):

$$V_F \frac{\partial P}{\partial t} + \frac{\partial (uA_x)}{\partial x} + \frac{\partial (vA_y)}{\partial y} + \frac{\partial (wA_z)}{\partial z} = \frac{R_{SOR}}{\rho} \tag{1}$$

In (1), V_F is the volume fraction of the fluid, P is the fluid pressure, ρ is the fluid density. Also, (u, v, w) and (A_x, A_y, A_z) are respectively velocity component and cross-sectional area of the flow in the (x, y, z) direction and R_{SOR} is the term of mass source.

The momentum equation is presented in x-dimensional as (2):

$$\frac{\partial u}{\partial t} + \frac{1}{V_F}\{uA_x \frac{\partial u}{\partial x} + vA_y \frac{\partial u}{\partial y} + wA_z \frac{\partial u}{\partial z}\} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + G_x + f_x \tag{2}$$

Equation (2) is written in three-dimensional (x, y, z) that G is the acceleration created by body fluids, f is viscosity acceleration and V_F is related to the VOF that is defined by (3):

$$\frac{\partial F}{\partial t} + \frac{1}{V_F}\{\frac{\partial}{\partial x}(FA_x u) + \frac{\partial}{\partial y}(FA_y v) + \frac{\partial}{\partial z}(FA_z w)\} = 0 \tag{3}$$

In (3), F is volume occupied by air in each cell and it is between [0, 1]. In addition, (A_x, A_y, A_z) are cross-sectional area and (u, v, w) are the velocity component in the directions of (x, y, z).

This software uses different turbulence models to simulating flow. In this study, Re-Normalization Group methods (RNG) and k-ε turbulent models are utilized to simulation of flow in stilling basin [27].

TABLE II
CHARACTERISTICS OF MODELS IN USBR II STILLING BASIN

	Experimental Model	Numerical Model
Basin Length(m)	70.20	
Basin Weight(m)	20	
Mesh Number		300*60*48
Initial Depth(m)	1.33	1.32
Conjugate Depth(m)	16.38	15.92
Initial Velocity(m/s)	32.46	32.36
q (m^2/s)	43.2	43.2

C. Verification of Numerical Model

To verify numerical model, the USBR II stilling basin has been modeled using Flow-3D software (Fig. 3).

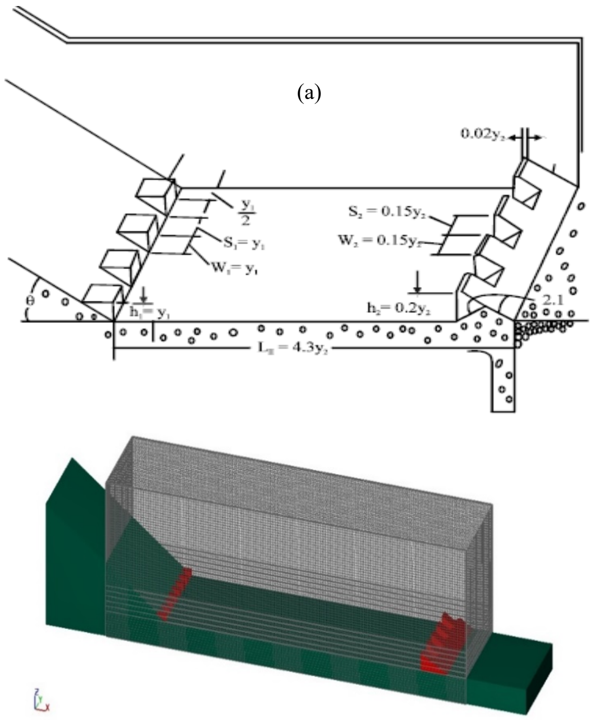

Fig. 3 Numerical model of USBR II stilling basin – (a) [28]

Table II presents the characteristics of numerical and experimental model of USBR II stilling basin.

In Fig. 4, the experimental and numerical values of water height have been illustrated for discharging 300 m^3/s in USBR II stilling basin.

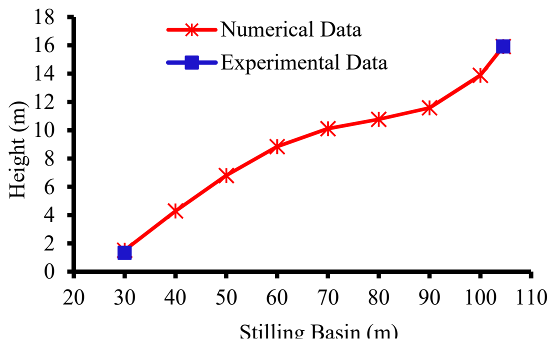

Fig. 4 Water height in length of USBR II stilling basin

According to Fig. 4, the height of water in experimental model are respectively 1.32 and 15.92 m at the inlet and outlet of stilling basin, as the difference of computational water height in comparison to experimental value is less than 3% that this represents a very accuracy of numerical model.

III. Discussion and Results

In this study, USBR II stilling basin of Nazloochay dam model was used to investigation of flow parameters. For discharges more than design discharge, the hydraulic jump forms at outlet of stilling basin as it effects on tail water waterway and river. Therefore to fixing hydraulic jump in stilling basin in discharges more than design discharge, adverse slope (3:1, H:V) was added at the end of USBR II stilling basin. Then, the parameters such as pressure, Froude Number, water level profile, air entrainment, and turbulent dissipation are investigated in discharge of 300 m^3/s. In Fig. 5, USBR II stilling basin is shown with end adverse slope.

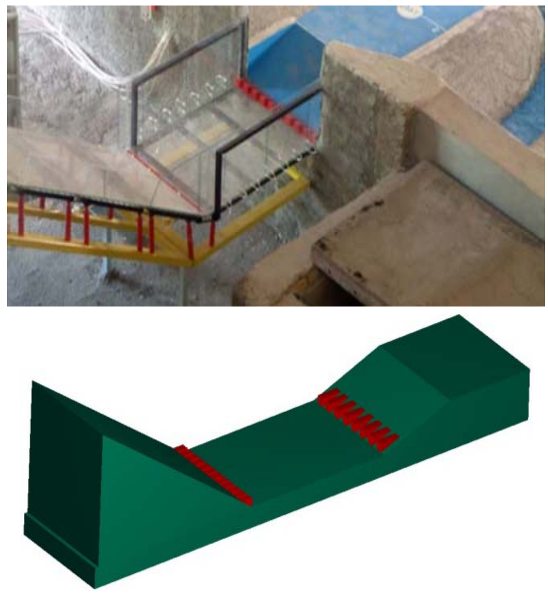

Fig. 5 USBR II stilling basin with end adverse slope

A. Pressure

Fig. 6 shows the numerical simulation of pressure in the stilling basin with the end adverse slope for discharging 300 m^3/s and k-ε and RNG turbulence models. Because of encountering flow to obstacles, the pressure in the ahead of obstacles is more as this fact can be seen truly according to Fig. 6. Also, the pressure is non-hydrostatic at the beginning stilling basin.

In Fig. 7, the variation of pressure has been presented for experimental and numerical data in discharging 300 m^3/s and turbulence models. According to Fig. 7, the comparison of the experimental and numerical values of pressure shows that RNG turbulence model has better agreement with experimental data, and this model computes more pressure into stilling basin.

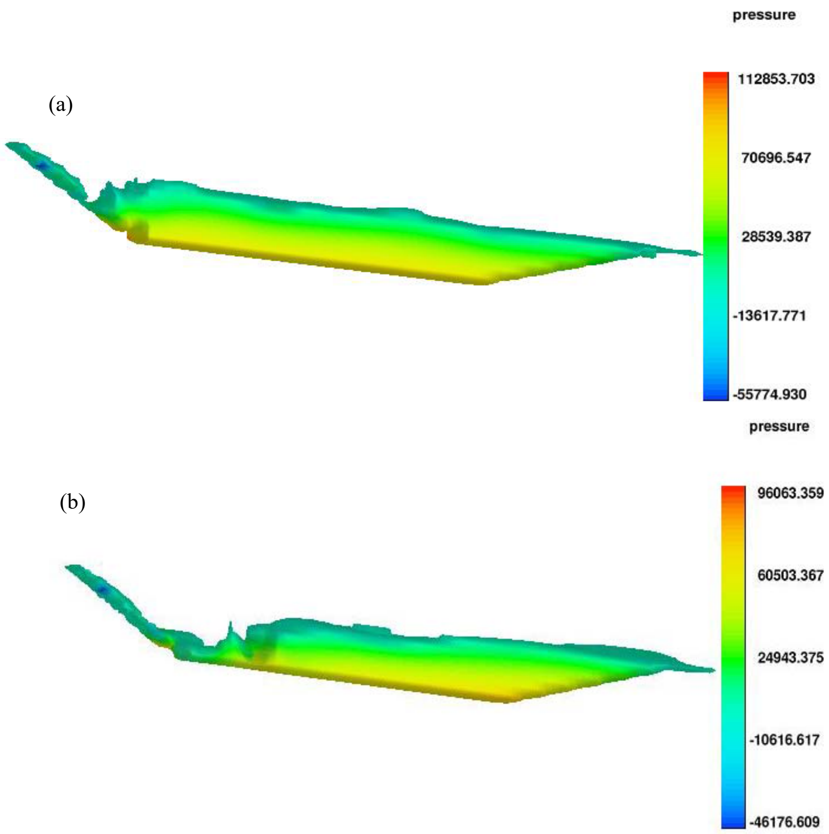

Fig. 6 Pressure distribution in USBR II stilling basin with end adverse slope – (a) RNG model, (b) k-ε model

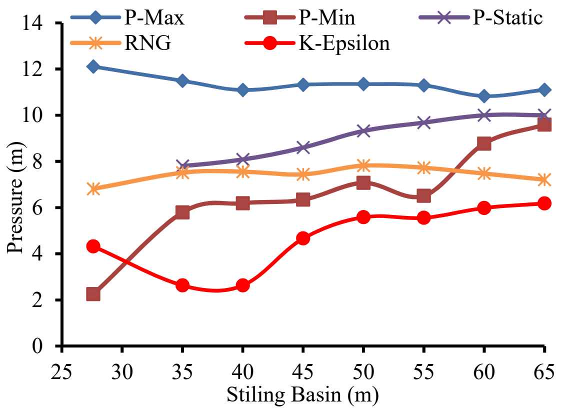

Fig. 7 Pressure in USBR II stilling basin with end adverse slope

B. Froude Number

Fig. 8 illustrates the simulation of flow for k-ε and RNG turbulence models in stilling basin.

Fig. 9 shows the comparison of Froude Number obtained from turbulence models and experimental data. According to Fig. 9, we can say that RNG method showed better results compared to k-ε method. The consistency of the lab results and numerical models namely in various aspects are interesting.

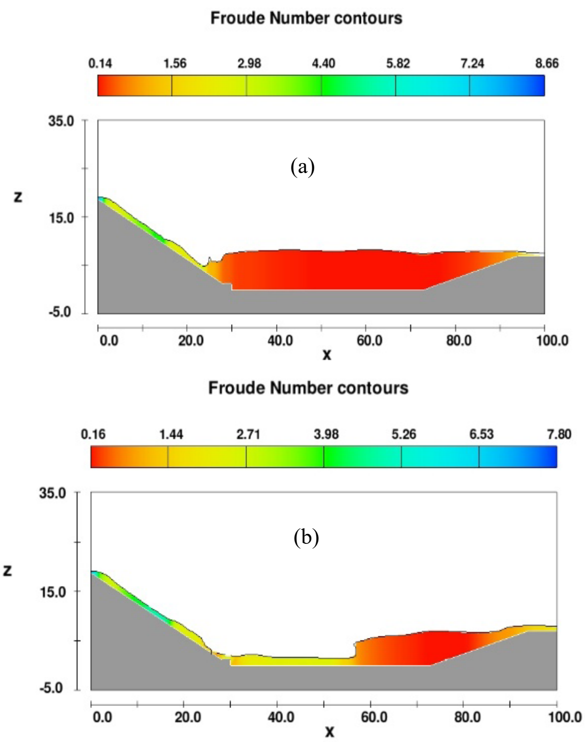

Fig. 8 Simulation of Froude number in USBR II stilling basin with end adverse slope– (a) RNG model, (b) k-ε Model

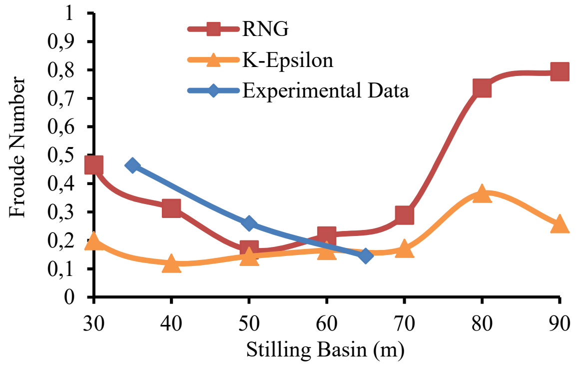

Fig. 9 Froude Number in USBR II stilling basin with end adverse slope

C. Water Surface Profile

In Fig. 10, the profile of the water surface is shown for the discharge of 300 m^3/s using RNG and k-ε turbulence models in stilling basin.

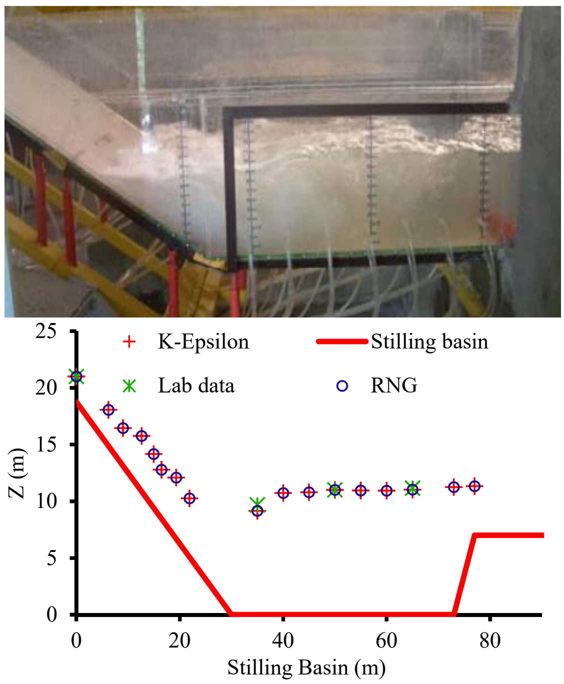

Fig. 10 Profile of water surface in USBR II stilling basin with end adverse slope

As is shown in the Fig. 10, the numerical solution predicts good results in comparison to the experimental measurements and water level inside the stilling basin has good consistency with the experimental values. In the initial region of the jump, due to the high turbulence of the flow, the calculated values are different from the measured values, but this difference at the end of jump is decreased considerably due to the reduction of turbulence. Both turbulence models k-ε and RNG showed exact results to calculate the profile of water level in discharge 300 m^3/s. The agreement is remarkable for a field situation.

D. Fraction of Entrained Air

Volume of the fraction of entrained air into the flow is shown for k-ε and RNG turbulence models for discharging 300 m^3/s in Fig. 11.

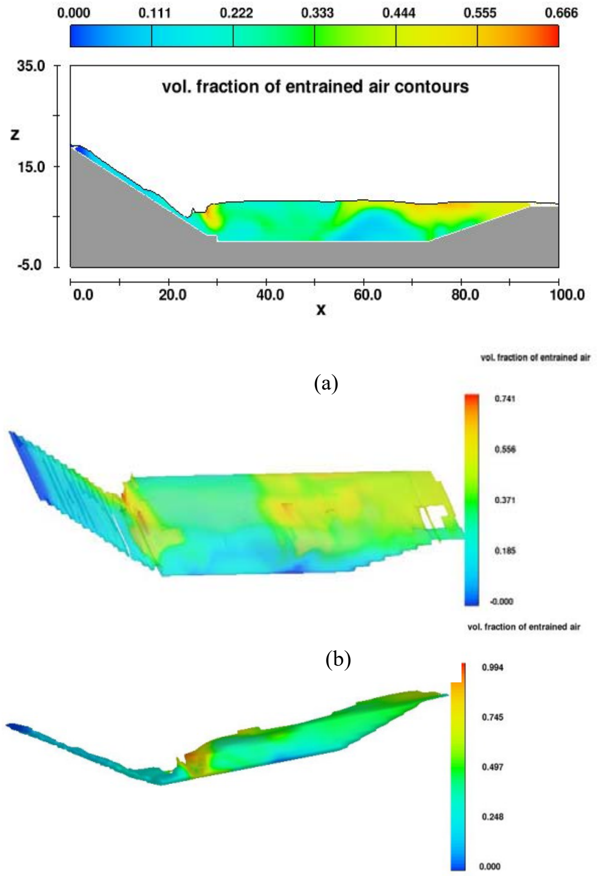

Fig. 11 Simulation of Fraction of entrained air in USBR II stilling basin with end adverse slope– (a) RNG Model, (b) k-ε Model

As is shown in Fig. 11, the inflow to the basis is as self-aerated. The more air entered the flow is from the jump toe and gradually by being far from the jump toe, the air is decreased and the calculated results prove this fact.

E. Turbulent Dissipation

One of the advantages of numerical model is measuring the parameters that user cannot measures those in laboratory such as turbulent dissipation. In Fig. 12, the turbulent dissipation has been presented at different levels in USBR II stilling basin with end adverse slope for discharge of 300 m^3/s and turbulence models.

According to Fig. 12, the maximum turbulent dissipation occurs almost in middle of stilling basin for both turbulence models, and turbulence is less at the end sections stilling basin. With approaching to the end of stilling basin, the values of turbulent dissipation reduce for both turbulence models. Also, the height different levels are uniformed.

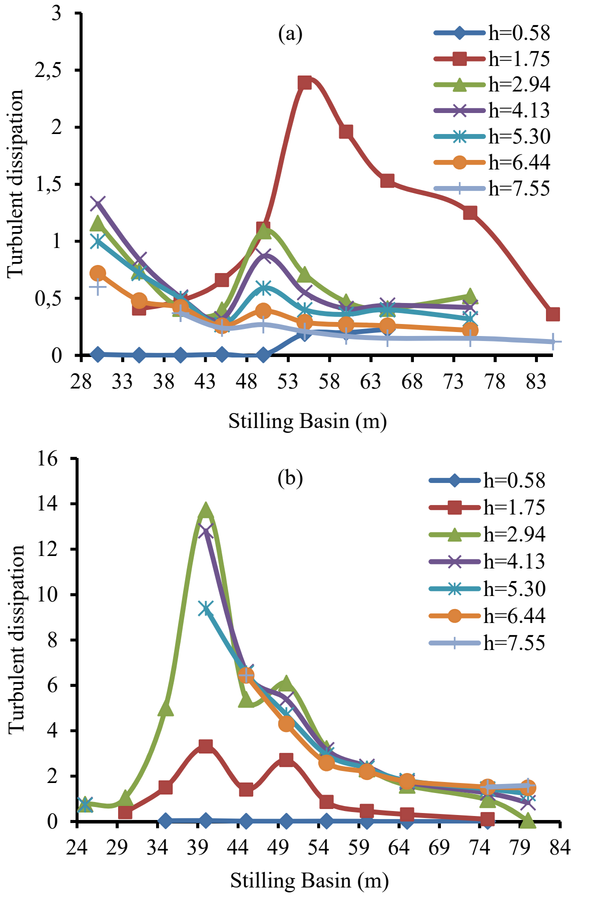

Fig. 12 Turbulent dissipation at different levels in USBR II stilling basin with end adverse slope– (a) RNG Model, (b) K-Epsilon Model

IV. Conclusion

In this study, with adding adverse slope to end of USBR II stilling basin of Nazloochay dam model in water research institute- Iran, the flow characteristics have been investigated in discharging 300 m^3/s. Then, VOF method and turbulence models have been utilized respectively to simulation of free surface and flow turbulence in stilling basin with end adverse slope. The results of pressure and Froude Number in stilling basin shown RNG turbulence model in comparison to k-ε turbulence model have more agreement with experimental results, and water surface profile for both models presents the values closer to experimental data. The agreement is remarkable for a field situation. Results are satisfactorily accurate confirming experimental findings from the physical models. Also, the values of turbulent dissipation in USBR II stilling basin with end adverse slope show that maximum turbulent dissipation occurs at 20-30% start of stilling basin that if this point of view caused to the efficiency of them is increasing.

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