Journal of Engineering and Applied Sciences 11 (4): 884-890, 2016
ISSN: 1816-949X

Numerical Analysis of the Boundary Layer Hydraulic Jump Caused by the Damper Function in Divergent Rapids Stilling Basin

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Abstract: One of the main important goals of stilling basins is to provide a proper operation toward energy dissipation by creating hydraulic jump. Since, the experimental model usually involves spending time and money in present study numerical simulation using finite-volume software has been used to simulate Alborz dam in order to investigate the boundary layer hydraulic jump caused by the damper function in divergent rapids stilling basin of the dam. The results showed that using basin blocks have had positive effect on improvement of hydraulic jump performance and stabilized the jump in the basin. For higher values of Debi, the hydraulic jump tends to far away from the beginning of stilling basin and the flow behavior of rapids (a fast-flowing and turbulent part of the course of a river) surface affected by depth flow in stilling basin and indicate the latitudinal rapids function in the length in which the water level in the vicinity of the wall along the middle of the basin is rippling and bubbling due to the effects of turbulence and transverse waves move diagonally to the wall and boundary layer development on the side walls and too fast air entering in turbulent flows; while in the Debi, the entrance and air and water phase mixing and jump formation point is on the rapids which leads to stabilization of the submerged hydraulic jump within stilling basin in which water surface profile is concave and almost uniform.

Key words: Ansys CFX, numerical simulation, k-ε turbulence model, cavitation, Navier-stokes, hydraulic jump, dynamic pressure

INTRODUCTION

One of the main important goals of stilling basins is to provide a proper operation toward energy dissipation by creating hydraulic jump. Although, many studies have ever been carried out on hydraulic jump and practical suggestions with the right hydraulic efficiency have been recommended to design stilling basins in downstream of dams, but it is necessary to carry out further studies on the geometric change and the rate of energy dissipation. In the other side, energy dissipation in large dams causes to plan stilling basin in full length and depth which is not economically affordable. Available analytical and numerical methods and experimental relations have significant limitations due to the complexity of fluid dynamic behaviors and especially, in two-phase flow spillways. In present study, the numerical simulation of flow field on rapids and basin of Alborz dam has been performed with laboratory scales and using Ansys CFX software. The Alborz dam has been evaluated in order to investigate the boundary layer hydraulic jump caused by the damper function in divergent rapids stilling basin.

MATERIALS AND METHODS

The governing equations: In present study, the Ansys CFX Softwares have been used for simulation of flow field by considering features and abilities and limitations of available soft wares. The Volume of Fluid (VOF) method has been proposed by Hired and Nichols. The method has been designed to simulate the interface of two or more immiscible liquids in an Euler Grid. In present study, it has been used to simulate the interface between water and air. In the procedure, equations governing incompressible flow in water are firstly solved and then in each computational cell, the volume fraction of each fluid (water and air) in whole the computing field is calculated by solving the water volume transport equation. Equations governing flow include mass conservative law and conservative law of momentum in turbulent flow conditions and in time averaged form and Reynolds averaged Navier-stokes equations have been extracted as follow:

$$\frac{\partial(pu_i)}{\partial x_i} = 0 \quad (1)$$

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$$\frac{\partial(pu_i)}{\partial t}+\frac{\partial(pu_iu_j)}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\mu\left[\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right]+\frac{\partial\left(-\rho\overline{u_i^{'}u_j^{'}}\right)}{\partial x_j} \quad (2)$$

Where:

u_i = Velocity in the direction of x_i
p = Total pressure
ρ = Fluid density
$\overline{\rho u_i^{'}u_j^{'}}$ = Reynolds tention (which have been appeared due to the averaging from Navier-stokes moment equations)

Equation 1 and 2 have three unknowns including two velocity components toward two directions of (u, v) and the pressure. In the other side, the equation of momentum includes four unknown components of Reynolds tension. Therefore, the system of above equations is not closed (the number of known components is lower than unknowns) and they should be calculated by suitable semi-empirical models of turbulence and Reynolds tension which have been described in continue.

In the volume of flow method, a variable function named α is used as water volume fraction in the computational cell. If $\alpha = 1$, then the computational cell is full of water and if $\alpha = 0$, then the computational cell is full of air.

For $0<\alpha<1$, a percentage of the cell contains water and the rest of it contains air. By taking the free surface in a given volume fraction, free surface can be determined with solving Eq. 3 which is continuity equation. For volume fraction of water, the volume fraction of α is solved in total solution field:

$$\frac{\partial\alpha}{\partial t}+u\frac{\partial\alpha}{\partial x}+\frac{\partial\alpha}{\partial y}=0 \quad (3)$$

The flow passing through triangular side overflows is very turbulent the flow momentum transition occurs with a significant rate. In general, flow turbulence models are considered as empirical solutions to estimate model the Reynolds tension parameter in Eq. 2 which are created by averaging Navier-stokes equations with respect to the time parameter. One of the most common approaches for modeling this tension is Booziness Approximation method in which the term $-\rho\overline{u_i^{'}u_j^{'}}$ is related to the velocity gradients in the mean velocity field. The approximation is as follow:

$$-\rho\overline{u_i^{'}u_j^{'}}=\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\left(\rho K+\mu_t\frac{\partial u_i}{\partial x_i}\right)\delta_{ij} \quad (4)$$

where K denotes the turbulence kinetic energy expressed as velocity variance fluctuations. The turbulence models are needed to calculate turbulent viscosity of μ_t.

The numerical mode

Specifications of solving field: The present study has been carried out on Alborz dam spillway based on experimental work in the Water Research Institute. The considered field is consist of stream input from the rapids and then passing the falling stream through stilling basin with primary damper blocks and end steps. In this regard, the roughness effects on flow field, comparison of turbulence models for simulation and compare the performance of different models of multi-phase flow and optimization gridding in flow simulation have been investigated. For this purpose, the model has been validated for a number specific debby. After ensuring the accuracy of numerical model, the simulation has been performed for four different flows of 400, 600, 800 and 1050 m^3 sec^{-1} (cubic meters per second) and the effect of debby on flow field has also been studied and the hydraulic characteristics of the flow and boundary layer of hydraulic jump caused by the damper function in divergent rapids stilling basin of Alborz dam have been evaluated (Escue and Cui, 2010).

Modeling and gridding: Since in this study, the numerical model has been used to analyze the flow by ANSYS CFX computational fluid dynamics software, the biggest constraint is to create a fluid volume gridding in the numerical model and the right choice of it can increase the accuracy of calculations. The unstructured grid was used to analyze and discrete of the flow of under study model. In analytical model of the structure, sensitivity analysis was performed on grid in order to achieve a proper and optimum grid size among various grids with different sizes. Figure 1 represents the numerical model and fluid volume of Alborz dam basin (ANSYS Inc., 2009).

For each model of turbulence, different grids were used near the bottom of the channel based on the need of design in the term of reaching a pressure distribution close to the experimental data in order to investigate the accuracy of the numerical model as well as its sensitivity to the used model and finally the optimal grid in the terms of accuracy and time was used to solve the model. To quality control of the selected grid, the proposed article has been used in NASA Glenn Research Center. By reviewing the forecasted results on pressure, it was found that the results of forecasted pressure has been improved in numerical modeling with square meshed grid and has

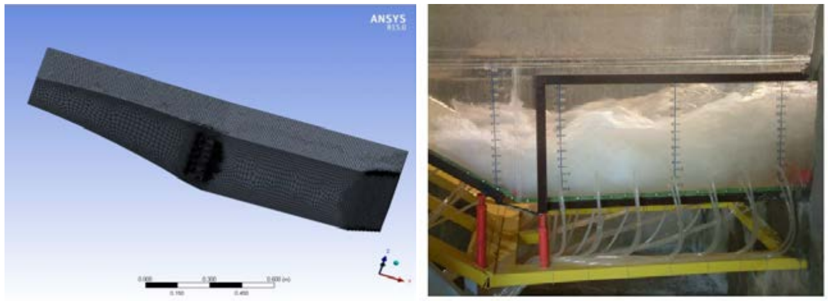

Fig. 1: View of the numerical model of Alborz dam spillway

better agreement with the experimental results which confirm the grid with its special size in the term of model's calibration.

Solution areas, fluid analysis and the boundary conditions: According to the nature of numerical modeling, it should be simulated in the form of non-permanent flow (unsteady) in present study. In numerical simulations, a coupling solution is used to solve the hydrodynamic equations (Abrishami and Husseini, 2008).

The velocity boundary condition has been used in the border flow and the measured velocity was used in vitro model as a velocity value. The inlet boundary condition was distanced from spillway, because the velocity profile is fully developed and the flow conditions are initially smooth. For outlet boundary, i.e., end of the control section, the flow depth obtained from experimental results was used as boundary condition of the pressure. In addition, smooth wall with no flow slip was considered as a boundary condition to other surfaces.

RESULTS AND DISCUSSION

As it was said before, after horizontal tunnel stilling basin and rapids were designed in Alborz dam after horizontal tunnel to flow energy dissipation. The stilling basin is type II of Standard USBR and energy buster blocks have been embedded at the beginning and end of the stilling basin. In present study after ensuring the accuracy of numerical modeling, the effects of debby on hydraulic parameters of flow field and the position of the jump and the possibility of cavitation have been investigated in order to meet the purposes of the study.

Water surface profile: In present study, the hydraulic jump in the basin was measured for different values of froude number (A dimensionless number used in hydrodynamics to indicate how well a particular model works in relation to a real system) using numerical simulation in order to evaluate the condition of boundary layer. The results analysis indicates the flow condition. The investigation of observations related to the water surface profile and changes in the distribution of water and air levels is as in Fig. 2.

For values of debby higher than design debby, the water depth is almost uniform at any point during rapids (Table 1). As a result, the procedure of rapids flow function is not affected by the water level of stilling basin. By reducing the value of debby (for design debby equal to 400 m^3 sec^{-1}), the flow depth was reduced within the length of the rapids and the function and behavior of the flow on the rapids was proportional to the hydraulic jump formed at the beginning of the basin and the flow depth was significantly increased after initial depth jump in the stilling basin. The first and last blocks of the basin had effect on formation and stabilization of submerged hydraulic jump at the level of design's debby. The levels of water surface were reduced on the bed of stilling basin with increase in the values of debby and transition of hydraulic jump to outlet section of the basin and the values of water level were increased on last stepped blocks. In lower values of debby, energy dissipation was more on the initial blocks. The initial blocks in design Debby reduced the basin length and required runoff by forced hydraulic jump and also stabilized the jump place by the effect of the last stepped block. In addition, the last stepped blocks of stilling basin had a positive effect on runoff depth increasing and stabilization of jump in the basin. By increasing the values of debby higher than design debby, the height of water surface profile was increased in the vicinity of the walls compare to the middle basin along caused by the transverse waves move diagonally to the wall and increasing local water level in the vicinity of the wall as it can be seen from the curve of flow level (Fig. 3 and 4).

Therefore as it can be seen from the results, the hydraulic jump inside the basin is formed in design debby of the basin equal to 400 m^3 sec^{-1}. As, it is clear in the

Table 1: The comprising the values of flow depth on rapids and basin (for different debby values)

			Water depht along the stilling basin and chute (center) (m) (numerical)			
Piezometers (No.)	Distance from vertical axes (m)	Elev. (m)	Q = 400 cms	Q = 600 cms	Q = 800 cms	Q = 1050 cms
I	370.21	230.00	2.75	3.84	4.55	5.25
J	390.01	227.00	1.23	3.26	3.79	4.11
K	409.03	221.50	5.48	2.48	3.22	4.21
L	427.03	221.50	8.32	2.35	2.28	2.18
M	445.03	224.30	7.97	3.92	4.01	4.43

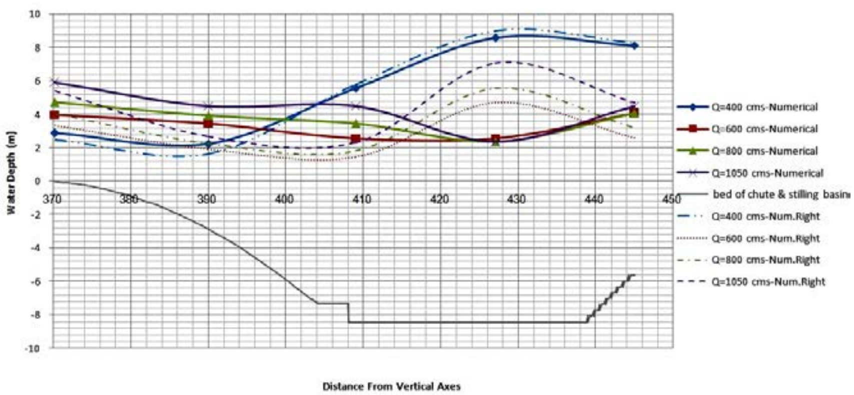

Fig. 2: The comparative curve of flow depths on rapids and basin in numerical model (for different debby values)

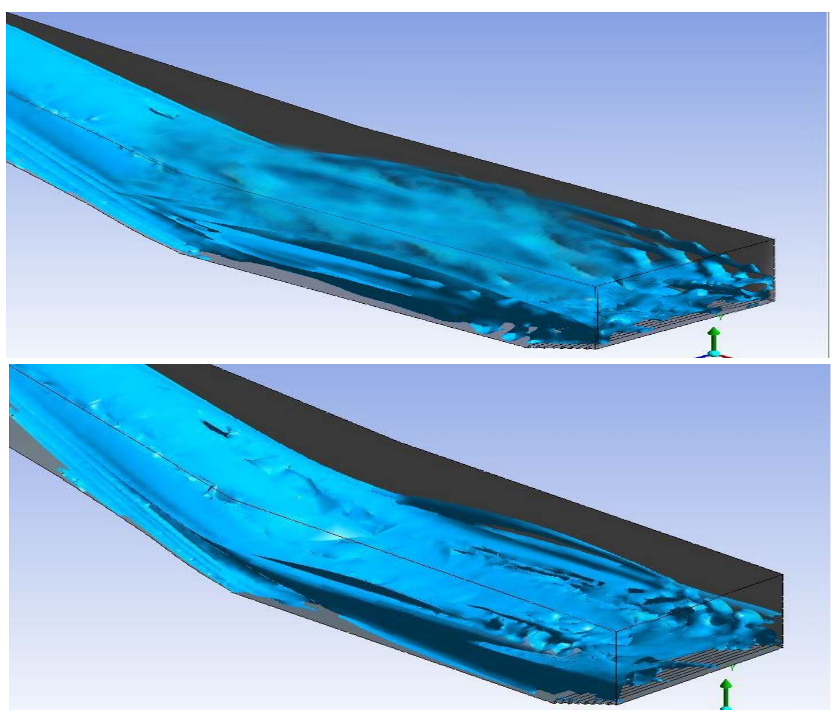

Fig. 3: Three-dimensional view of the free surface in the rapids and basin: a) For debby of 400 m^3 sec^{-1} (designed debby); b) For debby of 1050 m^3 sec^{-1} (maximum debby)

figure of flow free surface and changes of the distribution of water and air concentrations in the flow, the place of entrance and mixing the water and air phases and the formation of jump is on the rapids, but it moves toward the basin in continue and a part of jump takes place in the basin. By stabilization of hydraulic jump inside the stilling

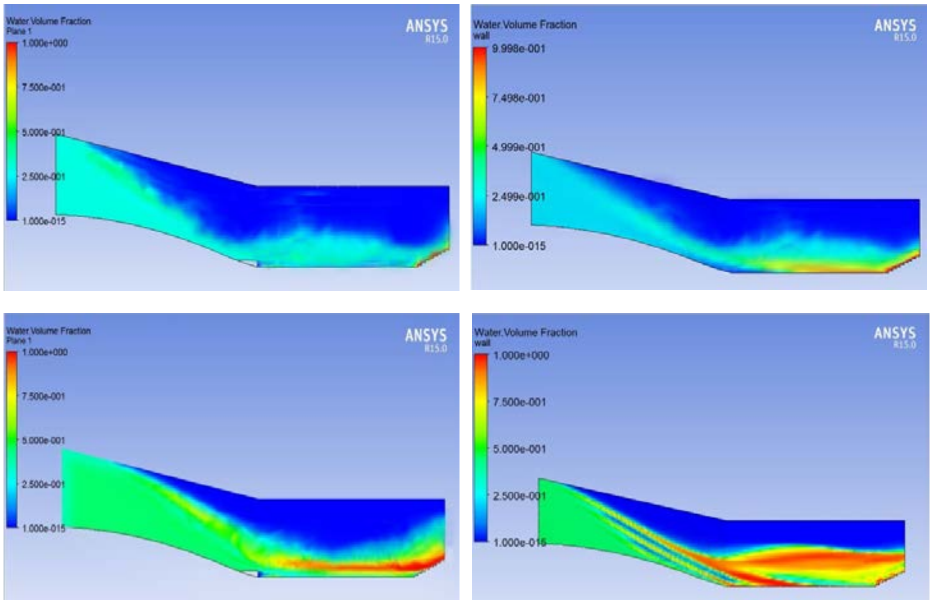

Fig. 4: Investigating the volume concentrations of water and air on rapids and basin: a) The longitudinal cross section of rapids and basin on the walls of rapids and basin. A view of flow behavior for debby of 400 m^3 sec^{-1} (designed debby); b) The longitudinal cross section of rapids and basin on the walls of rapids and basin. For debby of 1050 m^3 sec^{-1}(maximum debby)

basin and optimizing the flow behavior at outlet of the basin, the behavior and condition of the flow in the stilling basin and flow level in the rapid become almost uniformly and steady. In design debby, the water surface profile is concave and shows that the jump is created in submerged form. The shape and arrangement of initial stuck energy blocks (negative steps) and the last stepped blocks (positive steps) of the stilling basin have desirable performance and by increasing the value of debby, the hydraulic jump move toward out of the basin in which water surface is rippling and bubbling affected by hydraulic jump (Fiorotto and Rinaldo, 1992).

As it can be seen from the pattern of flow behavior by increasing the value of debby higher than designed debby, the water level profile increase in the vicinity of the wall compare to the middle of basin due to the development of boundary layer on the side walls and entering too fast air in turbulent flows, especially in the vicinity of side walls which leads to wind-up and deepening of the flow (Khatsuria, 2004).

Flow velocity rate: Investigating the curves of flow rate indicated scattered flow path, uncertain, irregular and eddy flows created due to the mixing up of water and air phases and the formation of jump from the end of the rapids to the beginning of the basin. It can be seen that the velocity rate profile has had characteristics similar to water jets within the hydraulic jump which is the combination of boundary layer and the free layer at top of it. Gradually, shape of the profile turn into usual velocity profiles in open channels by distancing from the place of jump formation and with develop of boundary layer, as well as by decreasing the velocity (Fig. 5 and 6).

According to the observations of numerical results for Debby of 400 m^3 sec^{-1}, the velocity is reduced along rapids and its procedure is suitable and the hydraulic jump formed at the beginning of the basin. After initial depth of jump, the velocity I significantly reduced. In the so mentioned debby, the flow turns from supercritical form to subcritical form by formation of the jump at the beginning of the basin and the jump type is submerged one. Therefore, it has had appropriate depreciation performance in this case and provides less erosion in downstream. By increasing the values of debby, the velocity increased along the rapids and the ascending vertical jump is not formed due to the performance of end stepped block with reverse slope and the velocity is increased by formation of hydraulic jump out of the basin. In this case, the maximum flow velocity is observable for maximum debby and it is supercritical until end of the basin and froude number increased. Therefore, hydraulic jump formed out of the basin and the flow gets out of the basin in jet form, but the velocity is dropped with positive function of end stepped blocks and the value of froude number decreased and its value reaches to <4 (Fig. 7 and 8).

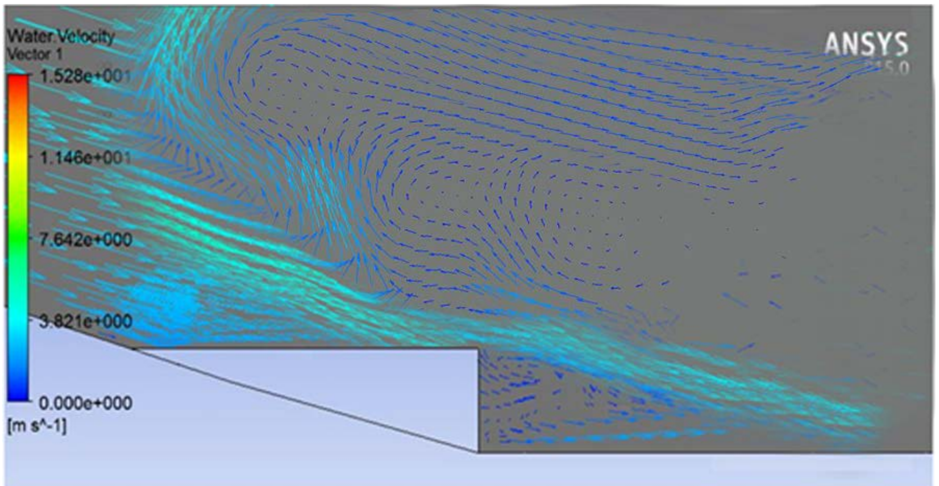

Fig. 5: A view of formed velocity vectors on the first blocks connected to the stilling basin. For debby of 400 m^3 sec^{-1}

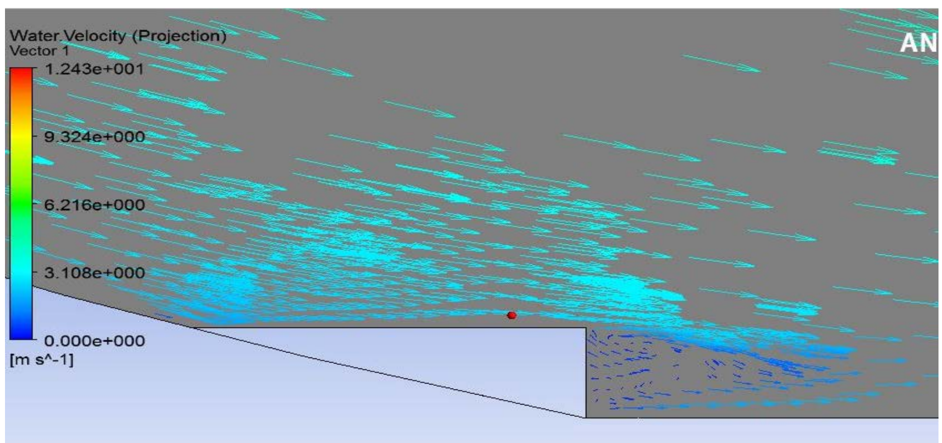

Fig. 6: A view of formed velocity vectors on the first blocks connected to the stilling basin. For debby of 1050 m^3 sec^{-1}

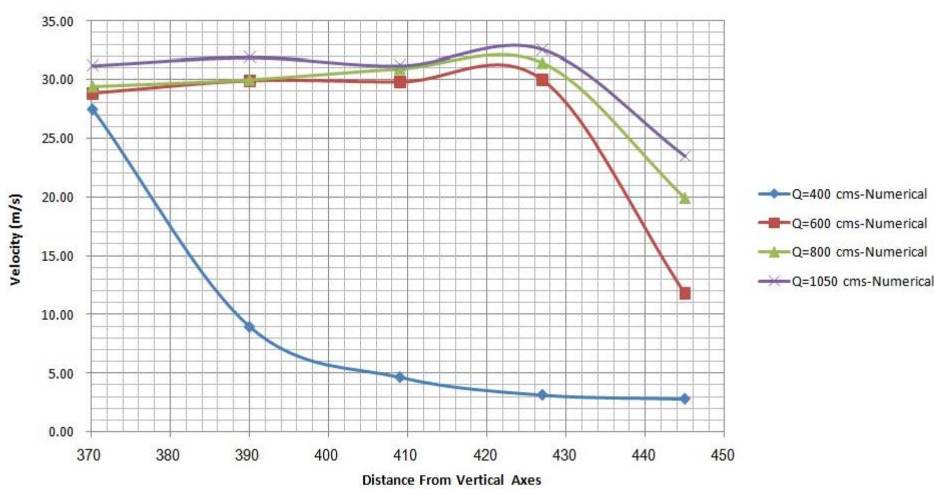

Fig. 7: Comprising the hydrograph curves of velocity parameter on rapids and basin (for different values of debby)

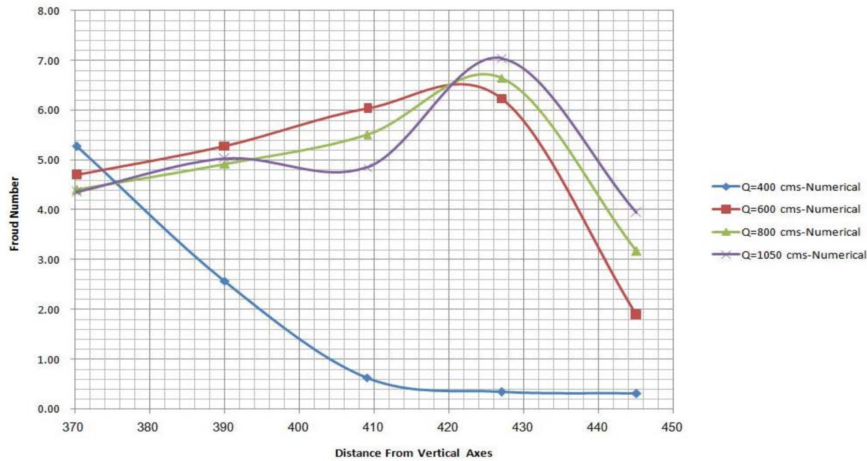

Fig. 8: Comprising the curves of froude number changing along the rapids and basin (for different values of debby)

CONCLUSION

The procedure of flow behavior is observable from each values of designed debby. It can be seen that the flooding rapids and hydraulic jump are formed at the beginning of the stilling basin. Basin's blocks have a positive effect on improvement of formed hydraulic jump, energy depreciation increasing and stabilization of the jump in the basin.

For values of debby higher than design debby, the hydraulic jump distances from beginning of the basin and the flow behavior of the rapids surface affected by flow depth in the basin which indicates the lateral divergence performance of rapids in the length. In addition, the height of water level profile is increased in the vicinity of the wall compare to the middle of basin due to the development of boundary layer on side walls and entering too fast air into in turbulent flows, especially in the vicinity of side walls which leads to wind-up and deepening of the flow.

For debby values higher than design debby and from the curve of flow level profile, it can be seen that the height of water level profile is increased in the vicinity of the wall compare to the middle of basin due to the diagonal moves of transverse waves toward the walls and locally increase of the water level in the vicinity of the walls. Fluctuations procedure of the flow velocity rate in the stilling basin is significantly affected by debby value and the place of hydraulic jump formation.

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