Investigating the Effect of Ramp Geometry on the Flow Characteristics Around Under Pressure Tunnel Aerator Using OpenFoam Open Source Software

Mohammad Manafpour
Department of Civil Engineering
Urmia University
Urmia, Iran
m.manafpour@urmia.ac.ir

Hamzeh Ebrahimnezhadian
Department of Civil Engineering
Urmia University
Urmia, Iran
h.ebrahimnezhadian@urmia.ac.ir

Abstract—The flow around the ramp embedded in a pressurized tunnel is divided into various zones downstream of the ramp, including the cavity and the main zone of flow above the shear layer. Ramp angle and height are parameters that affect the flow characteristics such as cavity length, velocity, and pressure coefficient immediately downstream of the ramp. In this study, OpenFOAM open source software and RNG K-ε turbulence model were used to simulate the flow around the under pressure tunnel ramp. In order to investigate the effect of the ramp geometry on the flow in various relative air discharges $0<\beta<10$, the range of height and the angle of the ramp as $5<\theta<20$ and $0.1<t_r/d<0.4$ were developed and simulated. The correlation coefficient between the numerical and experimental results for the relative cavity length is in the range of $0.9377\leq R^2\leq 0.9722$ that indicates proper agreement between results. The result of the research shows that in both cases of fixed height of ramp and increasing ramp angle, and fixed angle of the ramp and increasing ramp height, the values of the cavity length and maximum turbulence intensity increase, and the minimum pressure values at the cavity zone bed are decreased. But in both cases, the sensitivity of the three mentioned parameters is higher than the ramp height increment.

Keywords-aerator ramp; pressurized tunnel; RNG K-ε turbulence model; OpenFOAM; cavity length

I. INTRODUCTION

Aeration is known as the most efficient and economical method for prevention of cavitation in high-speed flows over chute spillways [1, 2]. With 8% air near the concrete surface the damage of cavitation attack is completely prevented [3, 4]. Surface aeration takes place in spillways but in this way usually not enough air is introduced near the concrete surface [5]. Therefore, forced aeration of flow is recommended [6]. Aerators, which locally create an air cavity at the lower boundary of the flow, have been found to be an effective and cheap way of promoting air entrainment into the flow. Aerators cause the flow to separate from the surface of the spillway and form a nappe. Flow behavior on aerator ramps in Figure 1 shows the complex interaction between flow turbulent structures, the phenomenon of cavitation, the behavior of the jet in the atmosphere, the air entering the jet, as well as the propagation of bubbles in the downstream of ramps. Air will be entrained along the lower surface as well as along the upper surface of the nappe [7]. The entrainment on the lower surface introduces air bubbles near the bed of the spillway for some distance downstream [8, 9].

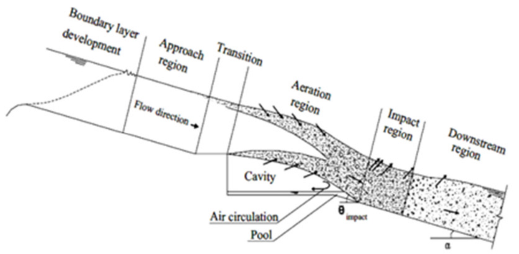

Fig. 1. Flow region over typical aerator.

In under pressure flow upon ramp aerator embedded in the tunnel floor (Figure 2), immediately downstream of the ramp, the flow is two-phased and disturbed. There is no surface aeration and it is divided into the various zones immediately downstream of the ramp, including the cavity zone and the main zone of flow above the shear layer. As flow separates from the trailing edge of the ramp, the lower layers accelerate and small intense eddies form on the lower surface of the nappe which roughens the air-water interface. As turbulence overcomes surface tension, this air will be entrained into the flow. On the other hand, the pressure distribution in the nappe rapidly adjusts itself to near atmospheric conditions, the slip velocity of air bubbles falls and the air bubbles are diffused by turbulence deeper into the core of the nappe. Further downstream, more and more air will be entrained into the flow [10]. Turbulence plays an important rule here, and higher turbulence levels cause more air entrainment [5, 11].

The introduction of forced air, especially from the bottom of the jet, will increase air concentration near the surface of the concrete. Aeration in spillways and under pressure tunnels is usually carried out by aeration systems and by using ramp, groove, and steps. The most common type of aeration can be seen in Figure 3. Bringing air to the bottom of the jet is carried

Corresponding author: Mohammad Manafpour

out by a duct from the floor. In this way, the flow is completely aerated and despite this air near the floor, the damage caused by cavitation is prevented [12].

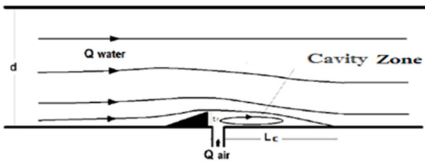

Fig. 2. Flow pattern upon under pressure tunnel ramp.

Proper recognition of the two-phase flow pattern in under pressure tunnel spillways with and without aeration system is among the studied topics, but because of the complexity of two-phase flows, there is still a need for more studies in this field. Many research works have been conducted to find the relationship between the inflows of air through aerators. Relative air discharge (β), which is defined as the ratio of air to water discharge, is a function of cavity length, Froude number and cavity subpressure. In 1990, a mathematical model based on Galzoo's work in 1984 was presented [13]. This model computed the cavity length as well as the airflow and cavity subpressure. Based on this model, cavity length directly affected airflow. Authors in [4] studied and compared VOF and mixture methods during a series of experimental and numerical studies with three-dimensional simulation of aerated flow downstream of ramp aerator in a tunnel under pressure. Comparing numerical and experimental results indicated that both methods calculated accurately free water surface and cavity length. Air concentration inside the water and the average values of pressure downstream the aerator from the mixture model have less error than the experimental results. Authors in [14] examined the effects of flow regime downstream of aerator on entering the air into the flow and preventing damage of cavitation. The results of the experiments showed that the conversion of flow regimes downstream of aerator to each other depends on aerodynamic parameters such as ramp angle, ramp height and slope of tunnel floor. Authors in [15] compared laboratory performance of two types of aerator in two different designs. It was found that for tunnel spillways, the shape and size of aerator require special design and tunnel spillways can be protected from cavitation by applying a plan of aerator that increases cavity zone length, air inflow, and the air concentration near the floor.

Authors in [16] carried out laboratory studies on measuring the pressure fluctuations in downstream of the aerator located in a circular tunnel and studied aerator performance with different geometries. It was found that the use of aerator with small heights for air supply in tunnel duct is more suitable than aerator with high heights from a hydrodynamic point of view. Authors in [17] studied the effect of geometric and hydraulic parameters on pressure, cavity length and relative air discharge in the flow around the ramp embedded at the end of the tunnel. It was found that by increasing the relative cross-section of the air inflow, which leads to an increase in the amount of air entering the flow, the cavity length downstream of the ramp and the aeration coefficient of the flow increase. The average cavity pressure also increases significantly with increasing air inflow. Authors in [18] experimented in the effect of air injection on the wall pressure in the near field of deflectors placed in a duct. Various quantities of air have been injected just downstream of the ramps to form stationary air cavities. The variation of cavity length has been studied as a function of the ratio of the volume of air flow to the water discharge. This study showed how air injection affects the wall pressure field.

The effects of aerator ramp geometry on the flow characteristics have been studied, but the effective factor between ramp height and angle is not determined on the flow characteristics. Hence, in this study, the flow near the aerator ramp embedded in a under pressure flow in various relative air discharges $0<\beta<10$, angle $5<\theta<20$ and height $0.1<t_r/d<0.4$ was developed and simulated, by the use of an open-source numerical model and appropriate turbulence model. The effect of the angle and ramp height on the characteristics of the flow, the minimum values of the pressure at the cavity zone bed, and the maximum turbulent intensity are determined immediately downstream of the ramp.

II. MATERIALS AND METHODS

A. Experimental Setup

The details of the experimental arrangement are presented in Figure 3. The experimental model consists of a horizontal pressurized duct with a square cross section that ramps of perspex of triangular cross section were glued to the duct bottom. Four ramps were used. Two heights of t_r/d=0.1 and 0.2 were used, where t_r is the height of the ramp and d is the height of the duct. For each value of t_r/d test, two slopes of 5^0 and 10^0 were used. Water supply to the duct housing the ramps was from a constant head tank located on the roof of the laboratory. A 0.1m wide and height duct was used with a tank upstream to achieve the desired flow velocities. The modeled aerator consisted of a ramp. Dimensions of the aerator are given in Table I. The aerator was installed 1m downstream of the channel entrance to allow the turbulent boundary layer to develop completely. A Pitot tube was employed to measure flow velocity. Air was introduced through nine 10mm diameter holes placed at regular intervals immediately downstream of the ramps [19].

TABLE I. CHARACTERISTICS OF THE STUDIED RAMPS

Ramp	Ramp height t_r (mm)	Ramp length L_r (mm)	Ramp angle (θ)	t_r/d
A	10	113.4	5	0.1
B	10	56.7	10	0.1
C	20	226.8	5	0.2
D	20	113.4	10	0.2

B. Numerical Model

OpenFoam software was used to simulate the flow around the aerator ramp embedded in a under pressure duct.

C. OpenFOAM

The widely known CFD-toolbox "OpenFOAM" (Open Field Operation and Manipulation) is a well-designed C++ library that allows numerical simulation of various engineering applications. Through its object-orientated structure it is very flexible and can be adjusted to very specific problems. Since the code is open source, code analysis and manipulation are possible. With its specific data types for describing the PDEs and the usage of operator overloading, OpenFOAM allows formulating equations in a way that resembles the mathematical formulation. In contrary to most CFD programs, OpenFOAM is not delivered with a graphical user interface for performing pre- and post-processing of the simulations [20].

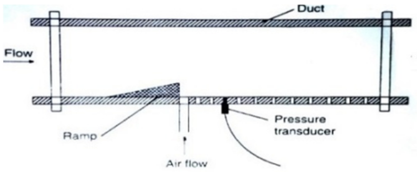

Fig. 3. Experimental apparatus.

The most important difference between OpenFOAM and other computational fluid dynamics commercial software is that in OpenFOAM to create a model in each subcategory, the user must choose a proper solver to project physics. Therefore, one of the difficulties of OpenFOAM is the choice of proportional solver. The flow around the under pressure tunnel ramp aerator has a two-phase nature. Multiphase flow modeling is performed using three views: 1) volume of fluid, 2) Eulerian-Lagrangian, and 3) Eulerian-Eulerian. In OpenFOAM, to analyze multiphase flow problems, various solvers are foreseen. The choice of a suitable solver is the most important part of the simulation in OpenFOAM. A number of multiphase solvers in the OpenFOAM are InterFoam, bubbleFoam, twoPhaseEulerFoam and multiPhaseEulerFoam. In this study, due to the two-phase nature of the flow and the importance of mixing the two phases, the Eulerian-Eulerian approach and a solver that has the basis of the twoPhaseEulerFoam solver were used. Necessary development in the solver to increase efficiency in the discussion of the two-phase mixing simulations has been done. OpenFoam was used to simulate the flow around the aerator ramp embedded in a under pressure duct.

D. Geometry, Meshing and Boundary Conditions

In order to construct the geometry of the numerical model, a code was written in Fortran. By applying the input data such as the ramp angle and height, the distance to the ramp entrance and the distance from the end of the ramp, the information necessary for constructing geometry from the Fortran code was extracted and transferred to the BlockMesh environment inside the OpenFOAM. Regarding the dimensions of the study area and air bubble diameter, a geometry grid of the numerical model with dimensions of 2mm was prepared. The meshing of the numerical model is shown in Figure 4.

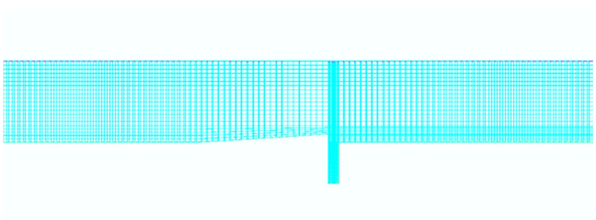

Fig. 4. Numerical model meshing.

Sensitivity analysis of the numerical model was measured relative to the mesh size, and it was found that using a smaller cell size did not affect the accuracy of the calculations. The boundary conditions in the present study include: 1) water inlet: mass flow rate, 2) air inlet: mass flow rate, and 3) outlet: pressure outlet and for all duct walls, a wall boundary condition was used.

III. RESULTS AND DISCUSSION

In order to evaluate the performance of a numerical model in the simulation of two-phase flow around an aerator ramp embedded in under pressure duct bed for 4 types of ramps that are presented in Table I, numerical and experimental results were compared. The flow near the aerator ramp embedded in a under pressure flow in various values of relative air discharge β, $0 \le \beta \le 10$, angle θ, $5^o \le \theta \le 20^o$, and height t_r, $0.1 \le t_r/d \le 0.4$ were simulated until the effect of θ and t_r on the characteristics of the flow, such as the cavity length (L_C), the minimum values of the pressure at the cavity zone bed (CP_{min}) and maximum turbulent intensity ($T.I._{max}$) were determined immediately downstream of the ramp.

A. Verification of Numerical Results

1) Cavity Length (L_c)

After the passing flow through the aerator ramp, in addition to the main zone, cavity zone is formed: two regions are separated by a shear layer between them (Figure 5). In Figure 6, the comparison between the relative cavity lengths calculated by the numerical model using the two-equation turbulence model RNG K-ε and experimental results for cavity formed immediately downstream of four different ramps in the various relative values of β are shown in which L_C and t_r are the length of the cavity zone and ramp height respectively. According to Figure 6, the two-dimensional numerical model in all ramps estimates a cavity length less than the experimental model. The correlation coefficient between the relative cavity length of the numerical and experimental models for forced relative air discharge 2%, 4%, 6% and 8% was 0.9729, 0.9371, 0.946 and 0.966 respectively, which suggests an acceptable simulation of the flow by the numerical model. Results for 2% and 8% relative air discharge are presented.

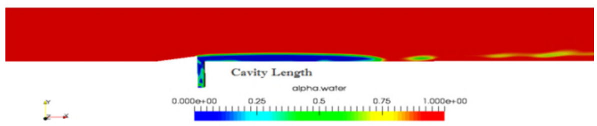

Fig. 5. Cavity in the under pressure duct due to forced air injection.

2) Flow Velocity

The comparison of average velocity distribution profiles between numerical and experimental results for ramp D ($t_r/d=0.2$, $\theta=10^o$, $\beta=2\%$) is displayed in Figure 8, where Z is the distance from the end of the ramp and U is the average velocity of the flow equal to 4.1 m/s. The adaptation of numerical and experimental results suggests the proper accuracy of the numerical model in simulating the flow velocity field near the aerator ramp. According to Figure 8, the velocity in the direction of flow at the end of the ramp due to the existence of the ramp and the decrease of the duct cross section reaches its maximum value.

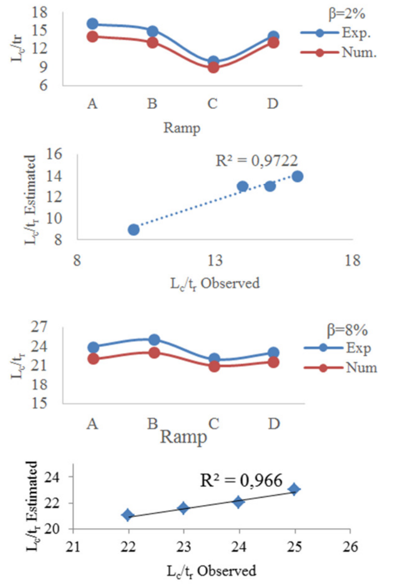

Fig. 6. Comparison of the cavity length generated by the numerical model, the experimental results, and their correlation.

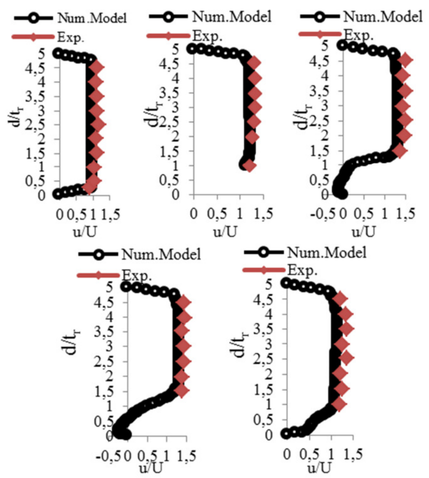

Fig. 7. Flow velocity profiles for ramp D ($t_r/d=0.2$, $\theta=10^o$), in section (Z/t_r: a=-28, b=-0.2, c=2.1, d=6.7, e=15.7).

3) *Pressure Coefficient*

The dimensionless parameter of pressure coefficient (C_p) is defined as the static pressure ratio to the dynamic pressure. In this research, the pressure coefficient is obtained from the relationship $C_P=P-P_o/0.5\rho U^2$ where P is the static pressure of the floor at the desired point, P_o is the static pressure at the reference point located at the upstream of the ramp, ρ is the water density and U is the average flow velocity. Figure 8 shows the variation of the pressure coefficient in the duct floor relative to the distance from the downstream of ramp. The correlation coefficient between the numerical and experimental results for pressure coefficient of the ramp B ($t_r/d=0.1$, $\theta=10^o$) and forced relative air discharges (β=2%,4%,6%,8%) is in the range of $0.7163<R^2<0.9167$ which emphasizes the accuracy of the numerical model in simulating the flow field.

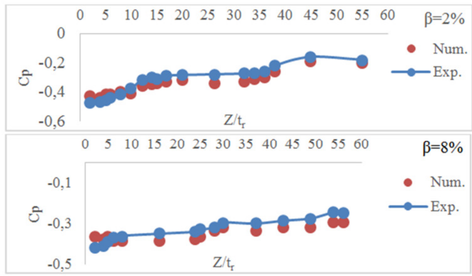

Fig. 8. Changes in the pressure coefficient in the duct floor relative to the distance from the end of the ramp A ($t_r/d=0.1$, $\theta=5^o$) and (β=2%, 8%).

B. *Effect of Ramp Angle and Height on Cavity Length*

To investigate the effect of the angle and height of ramp on the flow characteristics near the aerator ramp embedded in an under pressure flow in various β, various values of θ ($5^o\leq\theta\leq 20^o$) and t_r ($0.1\leq t_r/d\leq 0.4$) were simulated. The variation process of cavity length in aeration to flow is the same as the variations in the length of recirculation zone of the flow in a non-aeration state. Figure 9(a)-(b) shows the effect of increasing t_r relative to the fixed $\theta=5^o$ and the effect of increasing θ relative to the fixed $t_r/d=0.1$ for various β. According to Figure 9, increased intensity of cavity length (L_c) in increased t_r/d is more than the increase of θ. This suggests greater sensitivity of cavity length to the increase of the ramp's relative height. The cavity length increases with increment of relative air discharge (β) in both cases.

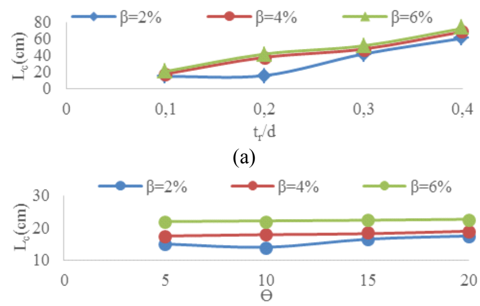

Fig. 9. Changes in cavity length: (a) Ramp height increase relative to fixed ramp angle 5^o, b) ramp angle increase relative to fixed ramp height ($t_r/d=0.1$).

In Figure 10, variations in the relative air discharges coefficient of flow are presented as a function of cavity length for different ramps. The changes in this function are very close in both quantitative and qualitative terms for ramps of the same height. In other words, the effect of the ramp angle on the aeration coefficient through the relative cavity length is very low (comparing ramp A with B and C with D). While the effect of ramp height on this relationship is high (ramp A comparison with C and B with D).

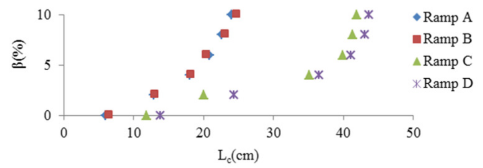

Fig. 10. Air discharges coefficient variation relative to cavity length for different ramps.

C. Effect of Ramp Angle on Minimum Pressure Coefficient of the Cavity Zone Bed

The effect of increasing relative height and ramp angle on C_{Pmin} follows [17] which showed that with increasing ramp height and angle, the local pressure in the whole tunnel, decreases. The effect of increasing relative height and ramp angle on C_{Pmin} at the cavity zone created at the downstream of the ramp is shown in Figure 12. C_{Pmin} values in both cases are reduced and the impact intensity of the C_{Pmin} of the ramp height (t_r/d) is far greater than ramp angle. Therefore, the sensitivity of the minimum pressure coefficient to increasing ramp height is higher than the ramp angle's. Also, by increasing the relative air discharge to the flow, the minimum pressure coefficient value increases, indicating the effect of flow aeration on localized pressure increase over the entire duct.

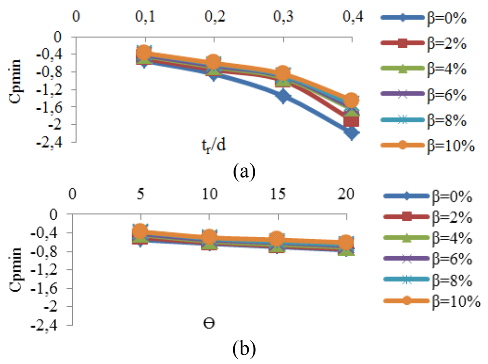

Fig. 11. Minimum floor pressure of cavity zone variations: a) Increasing ramp height for fixed ramp angle 5°, b) increasing ramp angle for fixed ramps height (t_r/d=0.1).

D. Effect of Ramp Angle on Minimum Turbulence Intensity of the Flow

The changes in turbulence intensity due to the increase in relative height and ramp angle in different relative air discharges follow the qualitative process of Figure 12. With increasing ramp angle and height, turbulence intensity increases. Figure 12 illustrates the effect of increasing height and ramp angle on the maximum turbulence intensity at the downstream of the ramp. Results indicate that increasing angle and relative height of the ramp increase the turbulence intensity with the difference that the increase in maximum turbulence rate due to ramp height (t_r/d) is higher than the ramp angle increase. Also, maximum turbulence intensity was reduced due to an increase in the air flow rate (β).

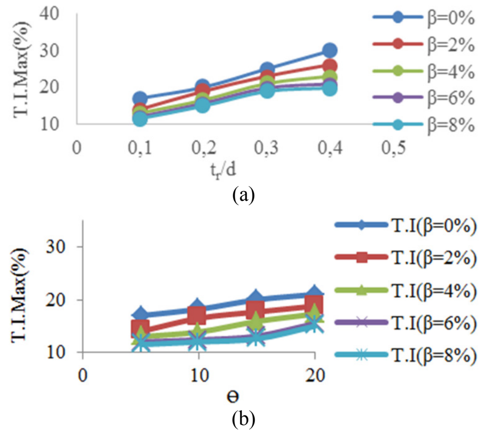

Fig. 12. Maximum turbulence intensity variation: a) Increasing ramp height for fixed ramp angle 5°, b) increasing ramp angle for fixed ramp height (t_r/d=0.1)

IV. CONCLUSIONS

This study on the flow field near the aerator ramp of a tunnel under pressure with OpenFOAM produced the following results: The correlation between numerical and experimental results for relative cavity length and relative air discharge of 2%, 4%, 6% and 8%, was 0.9722, 0.9371, 0.946 and 0.966 respectively, which indicates proper agreement between numerical and experimental results and the superiority of the TwoPhaseEulerFoam solver in the simulation of two phase flow. In both cases of fixed ramp height and increasing ramp angle and fixed ramp angle and increasing ramp height, the values of the cavity length and maximum turbulence intensity increase, and the minimum pressure values at the cavity zone bed are reduced. However, with increasing ramp height at fixed ramp angle, the intensity of the increase in the cavity length, maximum turbulence intensity and the reduction of the minimum pressure at the cavity zone bed are greater indicating higher sensitivity to ramp height. By increasing the forced relative air discharge β, minimum pressure coefficient value is increased and maximum turbulence intensity is reduced.

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