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PIV Study of Aeration Efficient of Stepped Spillway System

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Abstract. This paper investigates the three-dimensional (3D) simulation of Cascade aerator system using Lattice Boltzmann simulation and laboratory experiment was carried out to investigate the flow, aeration and cavitation in the spillway. Different configurations of stepped spillway are designed in this project in order to investigate the relationship between the configurations of stepped spillway and cavitation in the flow. The aeration in the stepped spillway will also be investigated. The experimental result will be compared with the simulated result at the end of this project. The figure of flow pattern at the 3rd step in simulation and experiment for Set 1 and Set 2 are look similar between LBM simulation and the experiment findings. This will provide a better understanding of the cavitation, aeration and flow in different configurations of the stepped spillway. In addition the occurrence of negative pressure region in the stepped spillway, increases the possibility of cavitation to occur. The cavitation will damage the structure of the stepped spillway. Furthermore, it also founds that increasing in barrier thickness of the stepped spillway will improve the aeration efficiency and reduce the cavitation in stepped spillway.

1. Introduction

In the late 1980s, Lattice Gas Automata method is invented. It able to solve the Navier- Stokes equations of fluid motion. The evolution of lattice gas model proceeds in two steps that take place during each time step, which are collision and streaming steps. For the streaming step, the particles move to new sites relative to their previous positions and velocities. In contrast, the collision step means that the particles collide and scatter according to collision rules specified in the formulation. In the lattice gas, all particles momentum conservation of the particles is reduced to conservation of the vector sum of the velocities. However, the Lattice Gas Automata is difficult to solve complex collision in 3D and it consists of statistical noise. Therefore, the Lattice Boltzmann Method LBM is introduced. The LBM is able to solve the statistical noise.

Lattice Boltzmann Method, LBM is a computational simulation method used for simulation of fluid flow. The fundamental idea of the LBM is to create a simplified kinetic model that incorporates the essential physics of microscopic processes. Thus, the macroscopic averaged properties obey the desired macroscopic equations [1]. Besides, LBM also is a simulation technique that utlizes the distribution function to replace tagging of each particle as applied in molecular dynamic simulations. The distribution function acts as a representative for collection of particles. This is the so-called mesoscale formulation. In addition, LBM is able to recover the Navier-Stokes equation with a proper choice of collision operator [2].

The main idea of Boltzmann is to bridge the gap between micro-scale and macro-scale. LBM has advantages of both macroscopic and microscopic approaches. LBM is easy to treat multi-phase and multi-component flows because it does not need to trace the interfaces between different phases. In additional, LBM can be applied to parallel processes computing. Thus, LBM can save the computer resources significantly. Figure 1 shows the technique of simulation.

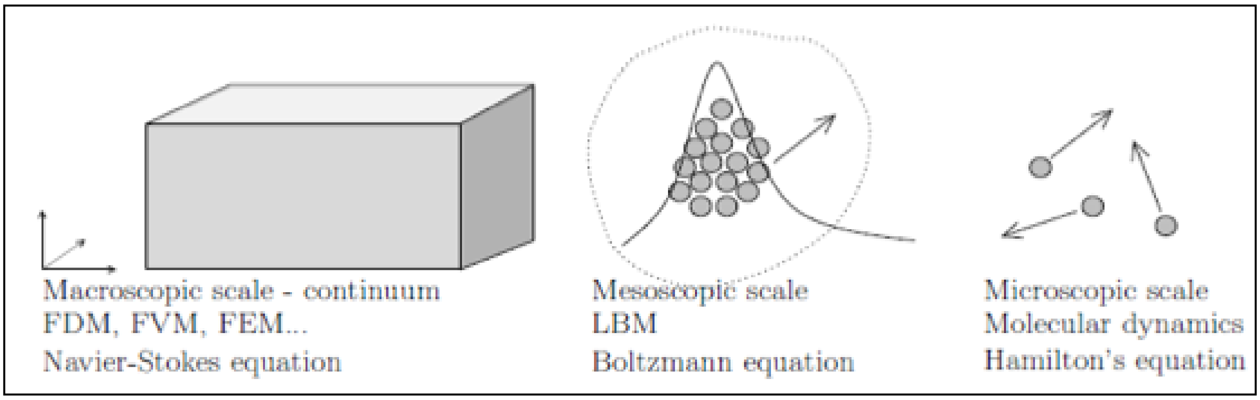

Figure 1. Techniques of simulations [2].

In this project, Lattice Boltzmann Method Simulation and laboratory experiment are carried out to investigate the flow, aeration and cavitation in the spillway. Different configurations of stepped spillway are designed in this project in order to investigate the relationship between the configurations of stepped spillway and cavitation in the flow. The aeration in the stepped spillway will also be investigated. The experimental result will be compared with the simulated result at the end of this project. This will provide a better understanding of the cavitation, aeration and flow in different configurations of the stepped spillway.

In the laboratory experiment, different configurations of stepped spillway are built. The 3mm thickness of Perspex is selected in this project. The Perspex is cut to certain dimension based on the configuration of the stepped spillway. Then, the Perspex plates are connected in order to build the stepped spillway. The model of the stepped spillway is shown in the figure 2. After the stepped spillway is built, the experiment will be carried out. Firstly, the water is poured into the water tank. Then, the water will flow down the stepped spillway. The velocity and pressure on the barrier of the step edges located in the non-aerated and aerated flow region are determined in order to investigate the aeration. Besides, the flow of the stepped spillway is observed.

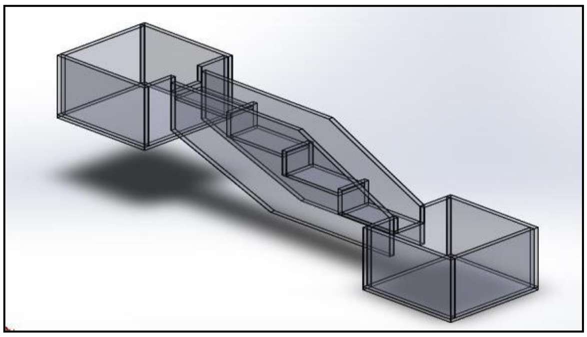

Figure 2. Schematic diagram of stepped spillway.

The Lattice Boltzmann Method (LBM) based solver is selected to simulate the flow in the stepped spillway. The LBM solver has been found effective for simulation of fluid with high accuracy on the computed solution [1,2]. Afterwards, the Paraview software is used to post-process the resultsand then analyzed.

2. Multiphase Equation

Multiphase system in water will consist of both liquid and vapour of water. Multiphase is selected because the cavitation and aeration are investigated in this project. The cavitation and aeration involve both the liquid and vapour of the water. Thus, multiphase is selected in LBM. Besides, since only water is used a medium in this project so single component is selected.

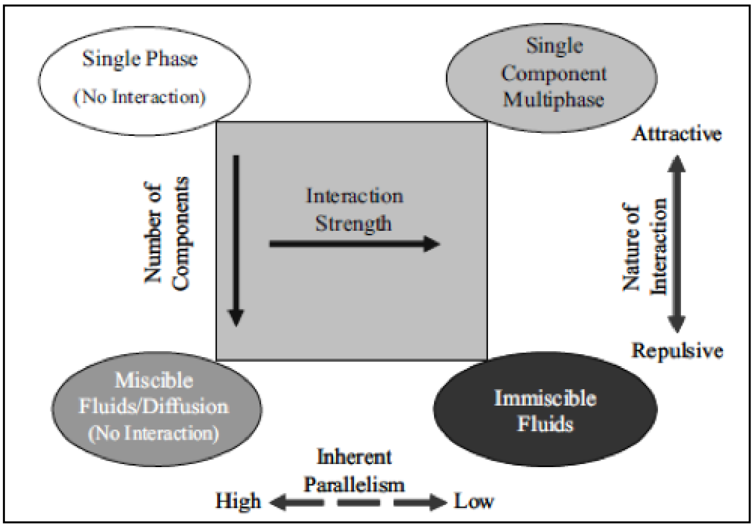

Figure 3. Conceptual framework for LBM models [4].

2.1. Cavitation

Cavitation can be defined as a phenomenon of catastrophic transition from liquid to vapor. If the cavitation is happened at the limit of pure liquid's tensile strength, the cavitation will be called as homogeneous cavitation. In contrast, if the preexisting bubbles in the structure of the liquid cause the cavitation, the cavitation will be called as heterogeneous cavitation. The total energy to create a vapour bubble can be written as:

$$\Delta E = 2\ \pi r \sigma + \pi r 2 \Delta P \tag{1}$$

Where σ is surface tension, ΔP is pressure and r = bubble radius. When the pressure is negative, it will show the possibility of cavitation. [6] Thus, when the negative value of the pressure is increased, the possibility of the cavitation is increased too.

2.1.1. Pressure in LBM. The inter-particle forces from equation of state (EOS) [4,7] are used to described the pressure, P:

$$\boldsymbol{P} = \boldsymbol{\rho R T} + \frac{\boldsymbol{GRT}}{\boldsymbol{2}}[\boldsymbol{\psi}(\boldsymbol{\rho})]^2 \tag{2}$$

where T is the temperature, R is the universal gas constant, G is the interaction strength and ψ is the interaction potential. ψ can be expressed as:

$$\psi(\rho) = \psi_0 \, exp\left(-\frac{\rho_0}{\rho}\right) \tag{3}$$

2.1.2. D3Q19

2.1.2.1 Boundary Conditions. There are three types boundaries in the LBM method:
1) Periodic boundary condition
2) No-slip boundary condition
3) Free slip boundary condition

Periodic boundary condition is the phenomena where the f leave the domain and it i will re-enter on the opposite side. It happened during the steaming phase. Periodic boundary condition can be applied to the bulk phenomena. Besides, no slip boundary condition is the phenomena that no slip and bounce back is occurred. It means that the component is in rest at the boundary. The free slip boundary condition is applied to compute the wall that does not contain any friction. Thus, the tangential velocity will be remained the same.

The velocity vector of the D3Q19 consists x, y and z components. The velocity vector is specified from which density/pressure. Density/pressure is computed on the basis of conditions inside the domain.

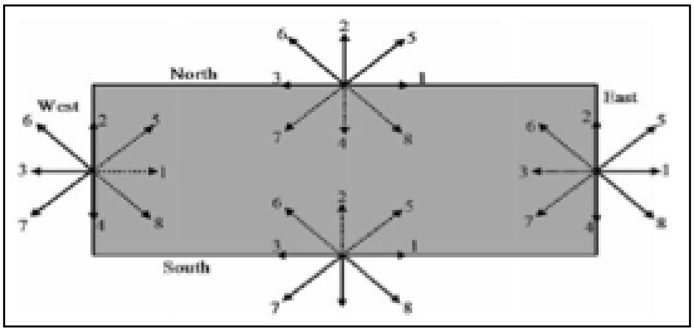

Figure 4. No-slip boundary condition.

2.2. Aeration Equation

In cascade aerator, the water falls down the steps. It is utilizing the potential energy of water in order to create interfaces for efficient gas transfer. Besides, the splashing of the water will create the turbulence in the water. The transfer of gases will be occurred when the entrained air is dispersed in the form of bubbles throughout the receiving body of water. The amount of the air entrained will be depended on velocity of the water.

The equation of the power dissipation rate in the stepped spillway will be expressed as:

$$P = \rho g Q \Delta H \tag{4}$$

Where ρ = density of water, g =gravity, Q = flow rate of water and ΔH = velocity head.

Thus, the equation of the power dissipation rate per unit width can be expressed as

$$\omega = \frac{P}{m} \tag{5}$$

Where m is the width of the step in the stepped spillway. The positive linear relationship between the aeration efficiency and energy dissipation rate is expressed as the equation below [5].

$$E20 = 0.0015\,\omega + 0.01 \tag{6}$$

the velocity head can be expressed as;

$$\Delta H = \frac{V^2}{2g} \tag{7}$$

in which V is the velocity of the water.

3. Results and discussions

3.1. Validation

The configurations of the stepped spillway are shown in table 1. There are two sets of experiments and three set of simulation in this project. The relationship between the configuration of stepped spillway and the aeration in the water of the stepped spillway is investigated in this project using both LBM simulation and PIV experiment. Additionally, the cavitation phenomenon in the stepped spillway is also investigated in this project. The velocity results are determined from both the simulation and experiment in order to study the aeration phenomena in the stepped spillways the pressure results are also determined using the simulation to investigate the cavitation phenomena.

Table 1. Dimension of the prototype of stepped spillway for Set 1, Set 2 and Set 3.

Set	Dimension of Prototype of Stepped Spillway (mm)		
	Length of Step (include Barrier)	Height of Step (include barrier)	Thickness of Barrier
1	130	70	3
2	130	70	9
3	260	70	3

The velocity result for the simulation is extracted using Paraview software. The velocity results that obtained from the Paraview are shown in three directions (x-direction, y- direction and z-direction). The total magnitude of the velocity can be obtained using formula of;

$$\sqrt{(x-direction)^2 + (y-direction)^2 + (z-direction)^2} \tag{8}$$

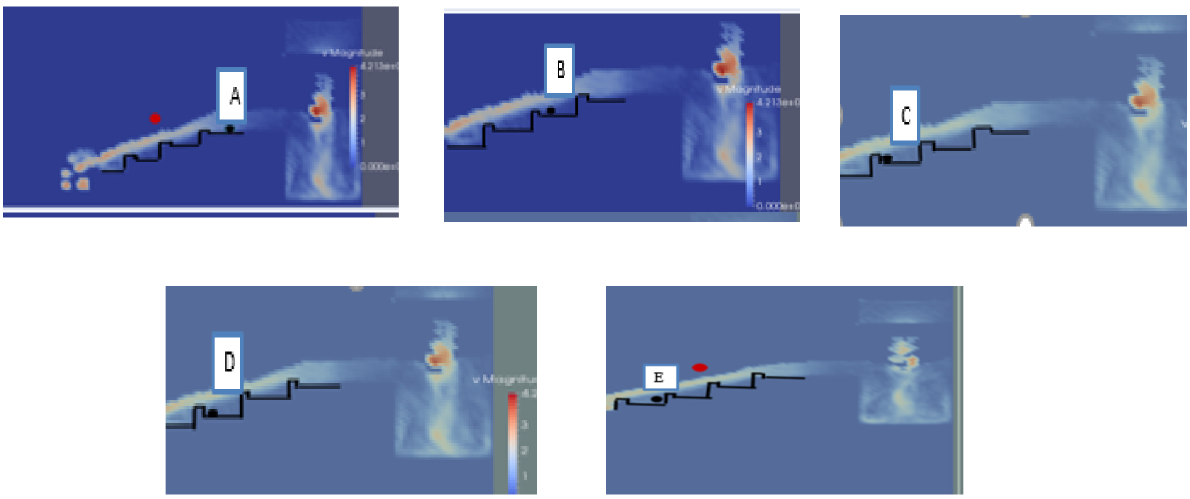

Figure 5. Point A, B, C, D and E at (1st, 2nd, 3rd and 4th) of the stepped spillway (Black point)

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The velocity results are obtained from four different points of the stepped spillway to validate the simulation and experimental findings. One point was selected at the 1st step (highest step), one point at the 2nd step and two points at the 3rd step. The locations of these points are shown in figure 5. The graph of the velocity results for Set 1 and Set 2 are plotted as shown in figure 6 and figure 7.

Based on the figure 6 and figure 7, it was shown that the flow velocity of the water increases along the main flow direction of the water. The velocity is increased due to the slop change along the main flow direction of the water. The highest velocity is located at the point D of the stepped spillway. From figure 6 and figure 7, the result of simulation and experiment for Set 1 and Set 2 show good conformity in the velocity results obtained. Both the simulation and experiment velocity result show the same trend as demonstrated figure 6 and figure 7 respectively. The percentage error between the simulation and experiment result is less than 11 percent. Given the high conformity of results between the simulation and experiment velocity, this proof that LBM simulation's capability to determine the velocity of the water on the stepped spillway with accuracy. The use of pure simulation will eliminate the need for an expensive experimental procedure of stepped spillway design in the future.

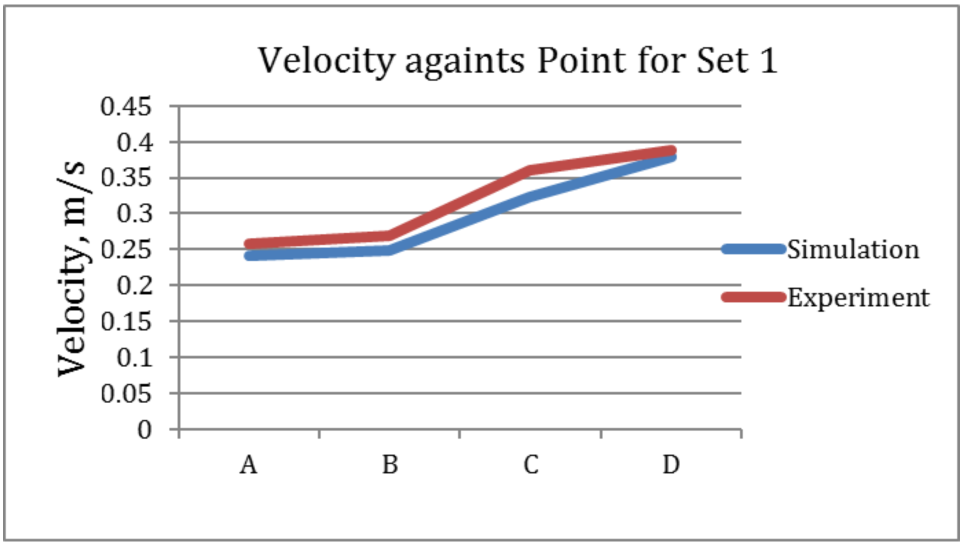

Figure 6. Graph of Velocity against Point for Set 1.

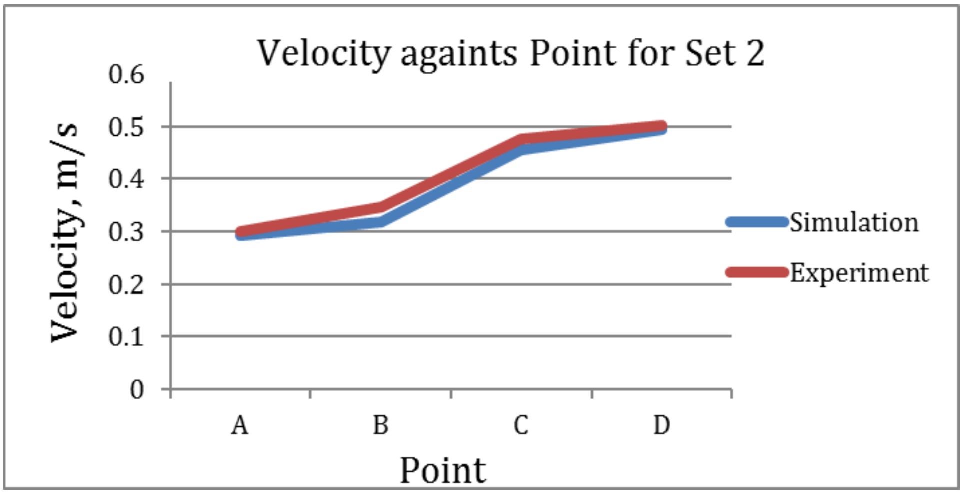

Figure 7. Graph of Velocity against Point for Set 2.

Table 2. Percentage error of velocity between simulation and experiment.

Point	Percentage Error (%)	
	Set 1	Set 2
A	6.20	2.66
B	8.15	8.096
C	10.53	4.00
D	2.83	1.20

The figure of flow pattern at the 3rd step in simulation and experiment for Set 1 and Set 2 are shown in figure 8 and figure 9. It founds that the flow pattern of the LBM simulation look similar to the experiment findings. In Figure 8, it was shown that some of the water would flow back to the reserved direction when the water is hit the 3rd step's barrier.

In figure 9, it shows that the recirculation phenomena happened at the location where near to the 3rd step's barrier. Some air is trapped into the recirculation causing small aeration be developed. Most of the aeration can be seen occuring at the final step of the stepped spillway. This observation demonstrates the high conformity of both simulation and experimental data in the flow pattern for Set 1and Set 2. Again, this will proof that the LBM simulation can be used to accurately predict the result for the stepped spillway design.

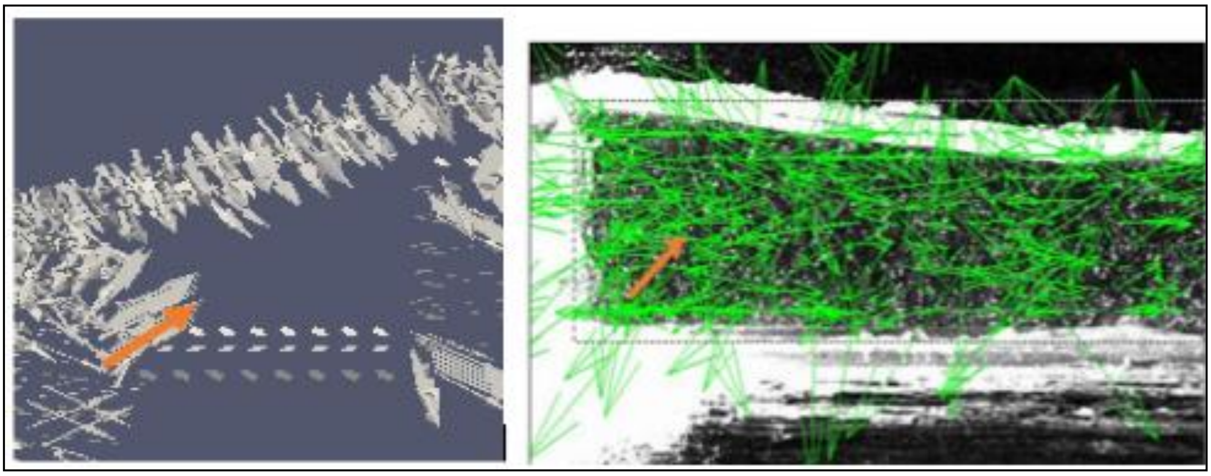

Figure 8. Flow pattern in 3rd step of the stepped spillway for Set 1.

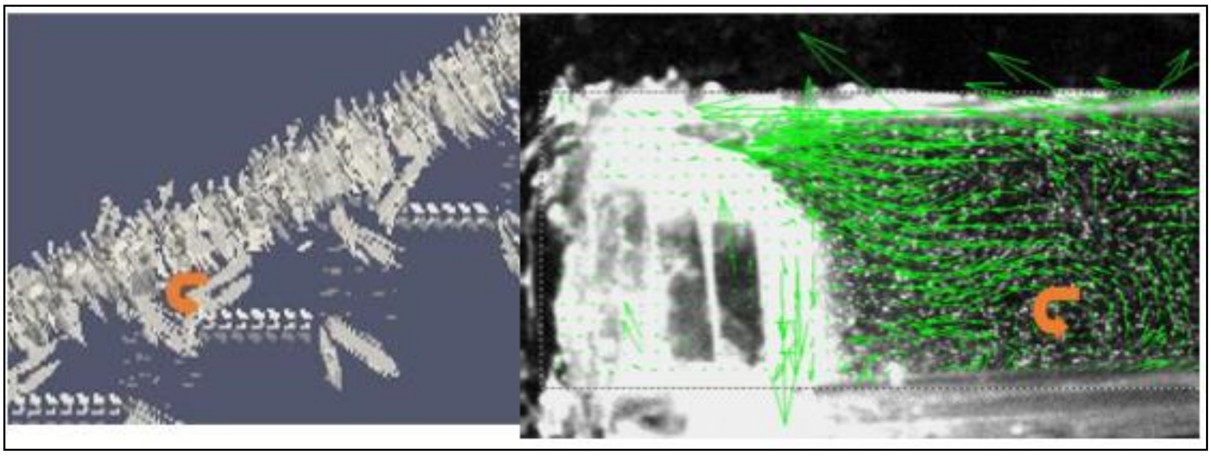

Figure 9. Flow pattern in 3rd step of the stepped spillway for Set 2.

3.2. Aeration Efficiency

Aeration process is used to remove the constituents in water in this project. Aeration will raise the dissolved oxygen content of the water. The turbulence of aeration process will cause the scrubbing process, which will help to remove the dissolved gases from the water. Then, the dissolved gas will escape into the surrounding air. The recirculating proses in the water will help to trap the air in the water.

The aeration efficiency is expressed as shown in Equation (9).

$$E20 = 0.0015\ \omega + 0.01 \tag{9}$$

This equation is created by the positive linear relationship between the aeration efficiency and the energy dissipation rate. [5] From the equation (9), it shows that the aeration efficiency is dependent on the energy dissipation rate. When the energy dissipation rate is increased, the aeration efficiency is increased. It means that the velocity of the water flow will affect the aeration efficiency. The faster the water velocity, the higher the aeration efficiency. Thus, the better aeration result will be obtained if the water velocity is higher.

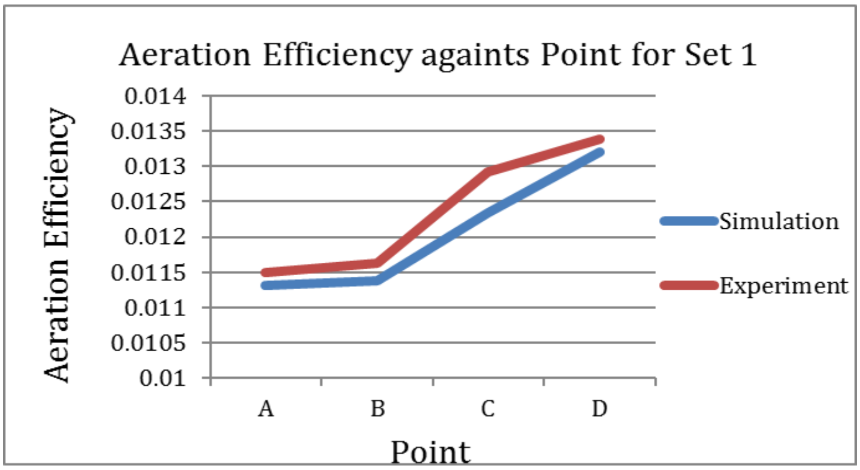

Figure 10. Bar chart of aeration efficiency against point for Set 1.

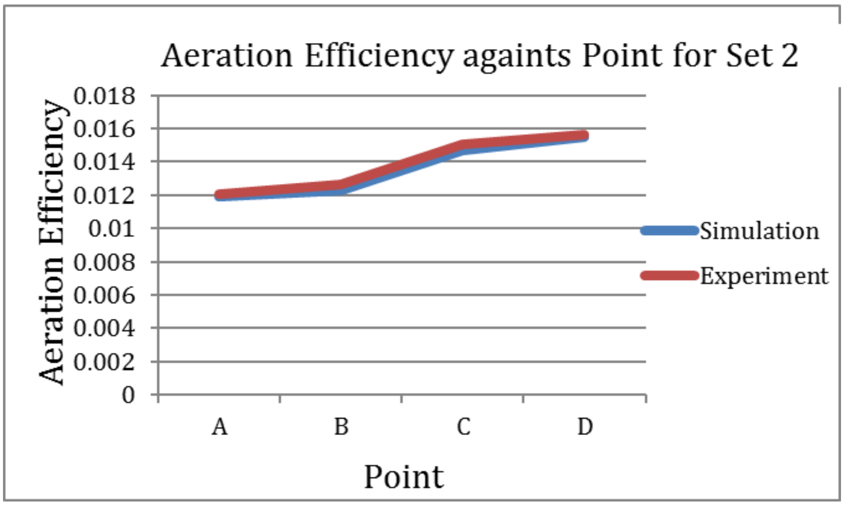

Figure 11. Bar chart of aeration efficiency against point for Set 2.

The aeration efficiency along the points is tabulated and plotted in Table 5 and 6. Based on the figure 10 and figure 11, the aeration efficiency increases along the points. The location point D has the highest aeration efficiency for both Set 1 and Set 2. Thus, when the velocity increases, the energy dissipation rate and aeration efficiency also increase. Set 2 has a better aeration efficiency than Set 1.

4. Conclusions

The velocity of the water will gradually increase along the main flow of the water over the stepped spillway. Additionally, it is also shown that the pressure decreased along the stepped spillway due to the increase in velocity of the water. As the pressure of the water is negative there is a great possibility for the cavitation to occur at the vicinity of the region. In this project, it was shown that the velocity of the water would influence the energy dissipation rate per unit width and the aeration efficiency for the stepped spillway. It was found also that as the velocity increases, the energy dissipation rate per unit width would also increase.

According to equation (3), it was found that as the energy dissipation rate per unit width is increased, the aeration efficiency of the stepped spillway would be increased. The maximum aeration efficiency is located at the 4th step of the stepped spillway. From the water flow pattern figure, it was found that there exist substantial air trapped region at the 4th step of the stepped spillway. This is the main reason the higher accumulation of aeration efficiency at the 4th step of the stepped spillway.

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