Original research article

Experimental Analysis of Dependence of Aeration Efficiency on Sequent Depth Ratio and Roller Length of a Classical Hydraulic Jump

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ABSTRACT

A hydraulic jump is a phenomenon which occurs when a supercritical stream meets a subcritical stream forming large scale eddies and a reverse roller flow. The roller entrains a considerable quantity of air in it. The oxygen dissolved in this process plays a vital role in the quality of water in the stream. The overriding objective of this study is to relate roller length and sequent depth ratio of a classical hydraulic jump to the aeration efficiency on smooth horizontal rectangular channels. A series of experimental trials were conducted in a smooth rectangular channel flume with approach Froude number ranging from 2-6 and unit width discharges 0.072-0.248 m^2/s. Water samples were collected at the vena-contracta and beyond the roller of the jump in BOD bottles having 300ml capacity. The roller lengths corresponding to each observation were recorded. Dissolved oxygen in the collected samples was determined using Winkler's method. A correlation was obtained between aeration efficiency and sequent depth ratio and roller length. A good agreement was observed between observed aeration efficiency and predicted aeration efficiency. Two semi-empirical formulae were suggested between aeration efficiency with sequent depth ratio and roller length of the jump. The empirical formulae would aid the policy makers and the technocrats in designing the hydraulic structures to obtain the maximum aeration efficiency to rejuvenate polluted streams.

Keywords: Aeration efficiency; Hydraulic jump; Rectangular channel flume; Roller length; Sequent depth

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1. Introduction

In open channel flow, hydraulic structures are constructed downstream to dissipate energy by creating free and submerged jumps. The hydraulic jump occurs due to transition of flow from super-critical to sub-critical with rise in water surface with energy dissipation, large-scale turbulence and air entrainment. The energy dissipation is directly related to supercritical Froude number. Valero et al. [1] presented an overview on free hydraulic jumps and flow properties measurement using different equipment. An early study of Rajaratnam [2] explains the air entrainment in a hydraulic jump.

An important parameter that needs to be analysed in a hydraulic jump is the void fraction in the water flow [3]. Air entrainment in flowing water takes place at the toe of the free hydraulic jump that is identified by vicious amount of turbulence production. Measurement of two-phase turbulent flow depends on the good understanding of mixing, air/water exchange, diffusion, and transfer processes [4]. There are several studies concerned with the hydraulic jump flow parameters. In previous researches, less attention has been given to self-aeration of streams due to hydraulic jumps [5]. The presence of oxygen content in water is known as dissolved oxygen (DO).

An interrelation has been established between the aeration efficiency and the energy dissipation after analysing the aeration performance of boulder structure at sudden expansions and plunging jets [6]. In fish passage design standards, turbulence is indicated by amount of energy dissipation [7]. DO levels in effluent can be enhanced by using hydraulic jump for self-aeration in waste water treatment plants. The aeration efficiencies with difference in velocities were correlated to find out the interrelationship. In studies, aeration efficiency is expressed in terms of approach Froude number and Reynolds number of the flow [8]. Gualtieri and Chanson [9] showed that the void fraction in a hydraulic jump is a decay function of the distance from the toe of the jump. Mahdi E.V et. al. studied the aeration efficiency of hydraulic jumps on three slopes, 1:3, 1:5 and 1:7 with block ramps. Aeration efficiency of free jump to that of jump on block ramps was increased by 20%, 19% and 32%, respectively [10]. DO is a measure of the amount of oxygen dissolved in water which is available to aquatic organisms in a water body. Oxygen enters water streams from the atmosphere and in areas where groundwater discharges fall into streams. Oxygen deficient conditions in streams can cause water bodies to die. The concentration of dissolved oxygen is found to be inversely proportional to the water temperature. Warm water holds less oxygen than cold water. The oxygen content of normal salinity in summer is more than 8mg/l. Water is considered hypoxic when oxygen concentration is less than 2mg/l [11].

Dissolved oxygen plays a vital role in the water quality of flowing streams and stagnant water bodies. Thus, an increase in the dissolved oxygen in streams would help rejuvenate its quality to some extent. Very few studies have been done to relate the hydraulic jump parameters with the quantity of increase of dissolve oxygen during the jump. Previous studies considered Froude number to be the governing parameter for aeration efficiency. Due to turbulent conditions, this experimental study attempts to relate roller length and sequent depth ratio of a classical hydraulic jump, rather than Froude number, to the aeration efficiency and to suggest semi-empirical formulae to calculate aeration efficiencies with hydraulic jump parameters viz., sequent depth ratio, y_2/y_1 and roller length, L_{rj}.

2. Experimental Set-Up and Methodology

Experimental observations were performed in a plexiglass walled, 16.0 m long, 0.60 m wide and 0.80m deep, smooth horizontal rectangular channel flume in the Hydraulics Laboratory, National Institute of Technology, Manipur, India. A sluice gate was used to create the supercritical flow. Gate openings ranging from 4cm to 10cm with an increase of 1cm in each run were provided and unit width discharges of 0.072-0.248 m2/s were considered to record the hydraulic jump parameters. A pitot tube was used to record the flow velocities and sequent depths were measured using point gauges having precision of ±0.1mm. Water samples prior to and after the jump were collected using BOD bottles having 300ml capacity. The dissolved oxygen was decreased after saturation by using sodium sulphide and cobalt chloride in the water tank of the flume. The average temperature of the water in the flume was recorded to be 23.6°C during the collection of the data. A gate present at the flume end was used to create the hydraulic jump. A typical schematic diagram of a classical hydraulic jump is shown in Fig. 1.
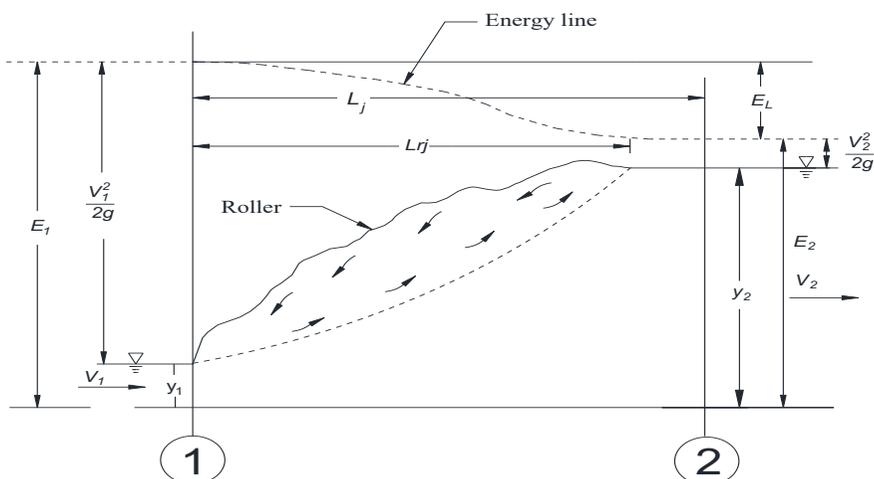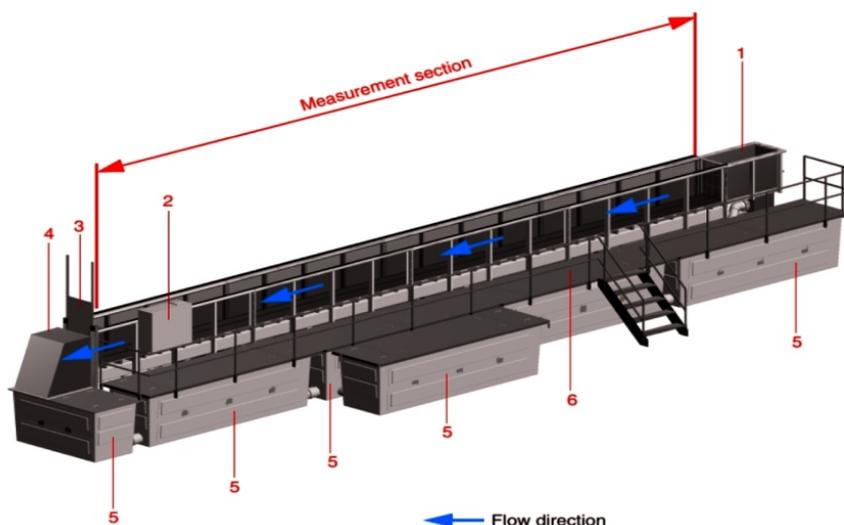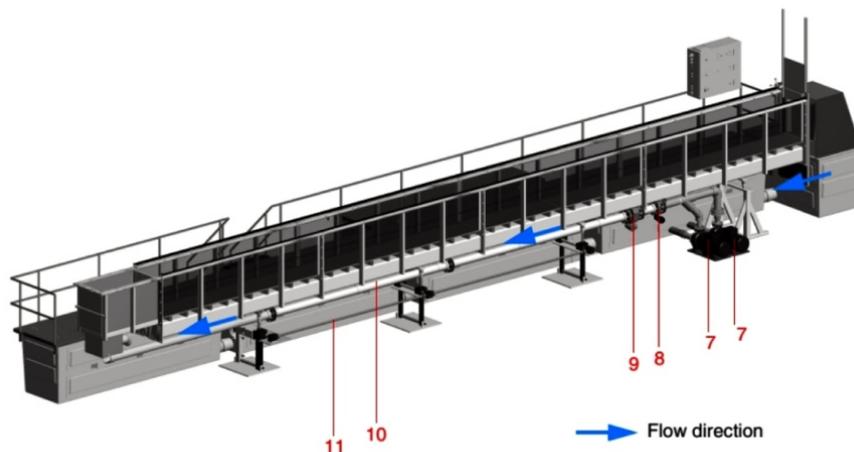

Fig. 1. Schematic diagram of classical hydraulic jump.

S.No.	Description	S.No.	Description
1	Inlet section	7	Pump
2	Control cabinet	8	Butterfly valve
3	Plate weir	9	Electromagnetic flow meter
4	Outlet section	10	Pipe
5	Water tank	11	Inclination adjustment
6	Gallery		

Fig. 2. Schematic diagram of HM 161 experimental flume and description of components (Source: HM 161 Experimental Flume Manual).

The hydraulic jump parameters were recorded at Froude numbers ranging from 2-6. The water samples were collected at vena contracta and beyond the roller of the jump at the same point of time. The supercritical velocities were recorded using a pitot tube. Fig. 2 shows the schematic diagram of the HM 161 experimental flume.

The term self-aeration has been used to denote the discharge of oxygen from the atmosphere into water [12]. Gameson [13] suggested a formula for calculation of aeration efficiency as shown in Eq. (2.1).

$$E = \frac{C_d - C_u}{C_s - C_u} = \frac{\text{total oxygen transfer}}{\text{Potential maximum oxygen transfer}},$$
(2.1)

where E represents aeration efficiency ranging from 0 to 1, C_u and C_d are upstream and downstream oxygen concentration and C_s is concentration under saturated condition.

Eq. (2.2) shows the mass transfer rate as given by Fick's law [6].

$$\frac{dC}{dt} = Ka(C_s - C),$$
(2.2)

in which, $\frac{dC}{dt}$ is mass transfer rate, K is mass transfer coefficient, molecular diffusion coefficient which is a function of transferred gas [14] and turbulent flow structure [15], 'a' denotes ratio of total bubble surface area to the total water-air mixture volume, and C is the mass concentration of gas dissolved. The upstream (C_u) and downstream (C_d) dissolved oxygen concentrations were estimated using Winkler's method for Froude numbers ranging from 2-6 to study weak, oscillating and steady type of hydraulic jumps and unit discharges, 0.072-0.248 m²/s. The standard procedure for computation of dissolved oxygen by

Winkler's method can be found in the literature [16]. The Froude number is the ratio of inertial force to the gravitational force of the flow. The unit width discharge can be calculated as the ratio of discharge of the channel to the width of the channel.

3. Results and Discussion

The experimental observations obtained from classical hydraulic jump parameters, namely sequent depth ratio (y_2 / y_1) and length of the roller jump (L_{rj}), are correlated with aeration efficiencies (E) for different unit width discharges obtained for different sluice gate openings which were used to create the supercritical depth of flow. The nonlinear regression analysis was performed to obtain the interrelationship between aeration efficiency and roller length, and aeration efficiency and sequent depth ratio using curve fitting based optimization. The nonlinear regression analysis of the experimental values showed that the aeration efficiency and roller length were significantly related by exponential growth relation with high correlation coefficient for different gate openings of sluice gate with corresponding unit discharges as shown in Fig. 3 and Table 1.

Table 1. Non-linear regression analysis results on aeration efficiency (E) and roller length (L_{rj}).

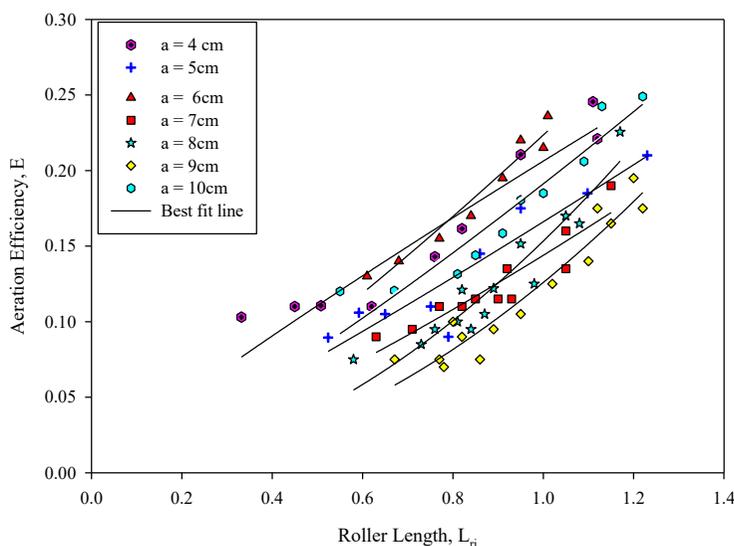| Gate opening (a) cm	Coefficient of determination R^2	Power law coefficient K_1	Power law coefficient K_2
4	0.90	0.4124	0.8987
5	0.86	0.3321	1.1235
6	0.95	0.4470	1.2362
7	0.85	0.2878	1.2827
8	0.89	0.3066	1.8891
9	0.91	0.2518	1.9446
10	0.90	0.3824	1.2235

Fig. 3. Aeration efficiency (E) as a function of roller Length (L_{rj}).

The power law relation coefficients for different unit width discharges K_1=0.014 and K_2=2.2 were obtained by optimization from the range of coefficients using the curve fitting method to obtained the best fit power law equation which could represent a general empirical relationship between aeration efficiency and roller length for a classical hydraulic jump given by Eq. (2.3).

$$E = 0.014\, L_{rj}^{2.2}, \qquad (2.3)$$

where $K_1 = 0.014$ and $K_2 = 2.2$.

From Fig. 4 it can be seen that the empirical formula suggested could predict well within an error band of $\pm$ 10% with very few data points outside the confidence interval lines.
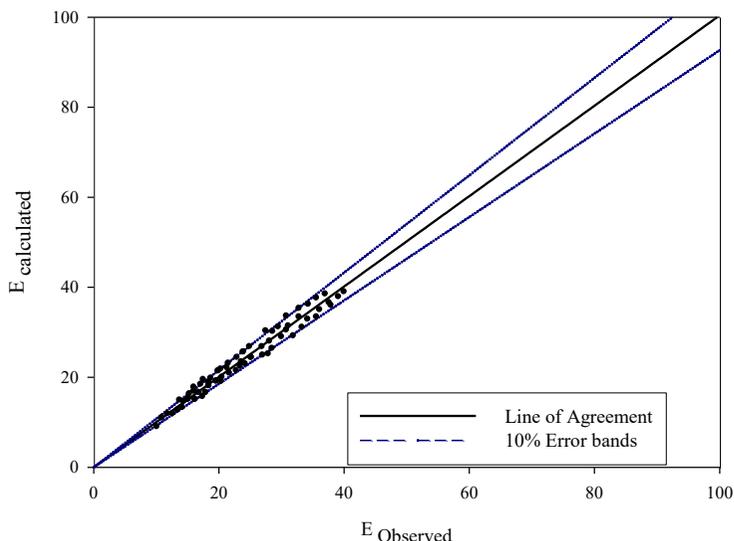

Fig. 4. Agreement of observed and calculated aeration efficiencies (E).

Similarly, the nonlinear regression analysis of the experimental values showed that the aeration efficiency and sequent depths were significantly related by power law with high coefficient of determination for different gate openings of the sluice gate with corresponding unit discharges as shown in Fig. 5 and Table 2.

Table 2. Non-linear regression analysis results on aeration efficiency and sequent depth.

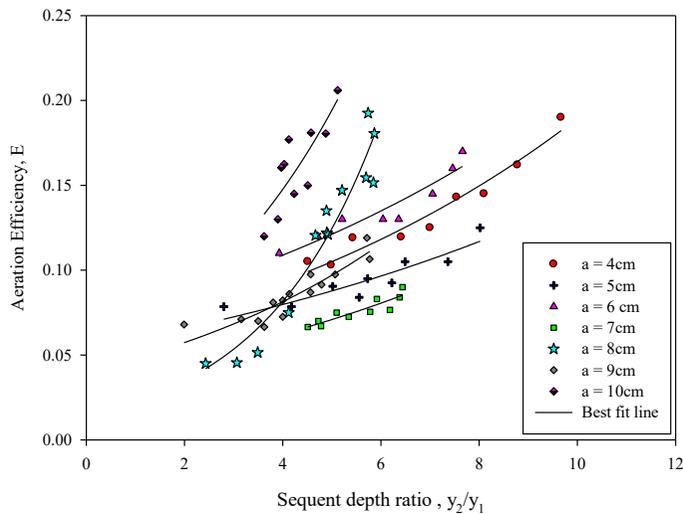| Gate opening (a) cm	Coefficient of determination R^2	Exponential Growth coefficient X_1	Exponential Growth coefficient X_2
4	0.95	0.1163	0.1181
5	0.84	0.1089	0.0955
6	0.89	0.1418	0.1072
7	0.92	0.0300	0.4229
8	0.84	0.0808	0.1752
9	0.84	0.0808	0.2745
10	0.67	0.9840	0.2745

Fig. 5. Aeration efficiency (E) as a function of Sequent depth ratio (y₂/y₁).

Similarly, from the results obtained from the experimental data, the relationship of aeration efficiency and sequent depth ratio is best fitted by an exponential function as given by Eq. (2.4)

$$E = 0.15e^{0.092\frac{y_2}{y_1}},\qquad (2.4)$$

where $X_1 = 0.15$ and $X_2 = 0.092$.

From Fig. 6 it can be seen that the empirical formula suggested could predict well within an error band of ± 10% with very few data points outside the confidence interval lines.

Thus, roller length, L_{rj} and sequent depth ratio, y_2/y_1 can be taken as important parameters in estimation of the aeration efficiency, E of hydraulic jumps.
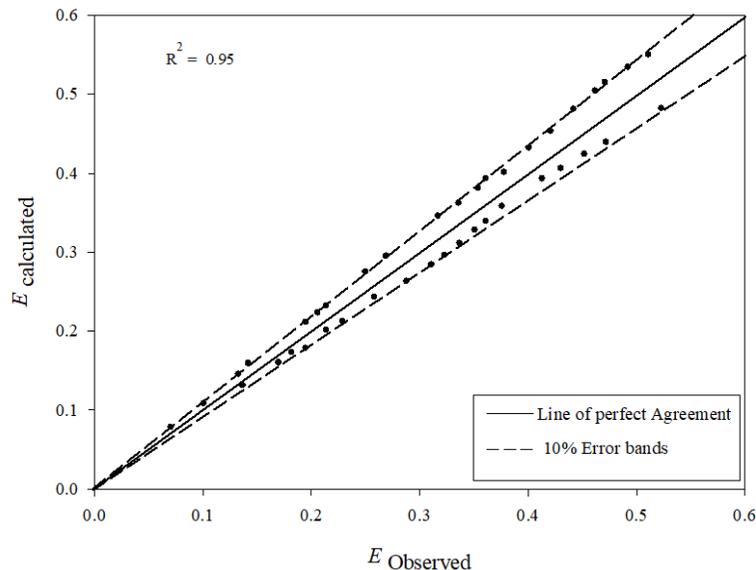

Fig. 6. Agreement of observed and calculated aeration efficiencies (E).

4. Conclusion

The aim of the study was to find out the relationship between aeration and the sequent depth ratio and length of the roller of a classical hydraulic jump. The experimental data were recorded in the range of Froude number (Fr) 2-6 and unit width discharge 0.072-0.248 m2/s.

From the experimental data collected in laboratory conditions it has been found that re-aeration of water due to hydraulic jump is related to the jump parameters, sequent depth ratio and roller length. The aeration efficiency achieved in the experimental runs was within the range of 15% to 20%. Thus, the following conclusions could be made:

1. Aeration efficiency E, is directly related to the length of the roller Lrj having a power law relation

2. Aeration efficiency E, is directly related to the sequent depth ratio y2/y1 by an exponential growth relationship.

In order to achieve the conditions for aeration in field without the adverse affect of erosion, hydraulic structures with precisely designed stilling basins could be constructed to force the hydraulic jump so that the energy is dissipated. These suggested empirical formulae are expected to perform on physical environment in calculation of the increase of the aeration capacities of hydraulic jumps so as to rejuvenate polluted streams and to aid the self-purification capacity of the streams. It is also believed that these relationships would help decision makers and engineers to design hydraulic structures in polluted streams to create the necessary jump parameters to obtain maximum aeration efficiency.

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