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Assessment of Aeration Capacity of Stepped Cascade System for Selected Geometry

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Abstract: Interphase transport between atmospheric gases and water surface is achieved economically achieved through mass transfer principles. It also establishes a solid relationship between oxygen saturation concentration of liquid and oxygen concentration of gas. The concentration of dissolved oxygen (DO) is one of the important parameter used to assess the quality of water. Improvement of DO concentration in polluted water bodies ensures the endurance of aquatic organisms. In addition to it, Oxygen is important for all algae, macrophytes and also for abundant chemical reactions that are important to stream and lake for its effective functioning. Aeration process is possible in the open channel by providing suitable stepped cascade system, which is possible based on prevailing site conditions. Substantial air entrainment is promising in the air – water interphase due to the plentiful of turbulence creamed in it. This paper illustrates the experimental investigation of Potable water (PW) with and without deoxygenation of water. The experiment was conducted for seven different flow rates and in stepped cascade aeration system constructed for 1.80 m height. This work was carried by varying the tread dimensions of the step by keeping constant channel width and step height. A regression equation using dimension-less parameters was developed based on the results from the experiments.
Keywords: Aeration; stepped cascade aerator; dissolved oxygen; turbulence.

Introduction

Aeration of water by stepped cascade system is continued to be one of simplest method if natural slope is available in the stream and also in the water and waste treatment process. Stepped cascades are considered as a very efficient means of aeration because of its strong turbulent mixing characteristic, making the large residence time and the substantial air bubble entrainment. The performance of such a system depends on the selected geometry of cascade system for particular hydraulic loading. The performance of cascade aeration has been studied experimentally by a number of investigators[1-6]. Most of these literature highlights the geometry of cascade system is prime predominant governing factor in order to enhance the aeration. Cascade aeration may also be used to remove chlorine and to reduce obnoxious taste and odour[7]. In the present work, geometry of the stepped cascade is selected in such a way to produce nappe flow over the steps while the slope of the chute and width of the channel as constant. By varying the flow rate and changing the tread length, the aeration efficiency of the system was evaluated. It is common practice that aeration efficiency of water is determined after deoxygenating (ie, from reduced level of oxygen from its naturally available level). In the present work, the performance of the selected geometry of stepped cascade system was evaluated with and without deoxygenating the water.

Previous research

Hydraulic aspects of cascade system of aerators have been investigated extensively and it is shown that existence of strong relationship between flow rate and step geometries about its performance on aeration and energy dissipation[8-21.] It is to be noted that from the results of their experiments, stepped cascade is characterized by a succession of nappe flow at at lower flow rates and skimming flow at higher flow rates. In between nappe and skimming flow, there is possibility of transition flow to occur due to instability in hydrodynamics and unsuitable wave phenomena on stepped cascade. Chanson, 1994 observed a change from aerated to non-aerated nappe in the transition regime[9]. Baylar, 2000 found that the length of non-aerated flow region decreased when the step height was increased and also for all l/h (length of the step / height of the step) ratios the aeration efficiency increased with increase in step height[19]. Chanson and Toombes, 1997 concluded that aeration in the nappe flow is more efficient than the skimming flow[15] and similar observation is made latter by Emiroglu et. al., 2003[3]. Baylar et. al., 2007 reconfirmed through further investigation that nappe flow provides effective aeration when it compared with skimming flow[22]. Moulick et. al., 2010 conducted experimental study on aeration performance of a rectangular stepped channel system with a height of 3.00 m. The study provides that 90 % of aeration is achievable if cascade system consists of 14 steps for a hydraulic loading 0.009 $m^3/s/m^2$ with a slope of 0.351[18]. Another study by Baylar et. al., 2011 indicated increased aeration efficiency with increased energy-loss ratio in both skimming and nappe flow regimes and also the study indicates that nappe flow enables more energy dissipation and greater aeration efficiency than skimming flow [6]. Stepped cascade systems become very versatile in recent years because of appreciable low cost and speedy construction. The paper presents the results of experimental investigation made in a rectangular stepped channel of height 1.80m to identify the effect of the tread length on aeration and its performance on flow was evaluated with and without deoxygenating the water.

Aeration efficiency

Self aeration is a natural phenomenon of transfer of oxygen from air to the water across a free surface. The aeration efficiency depends on the quantity of air intake at hydraulic structure. Gameson, 1957 suggested an equation for finding aeration efficiency as given below[23]:

$$E = \frac{C_d - C_u}{C_s - C_u} \tag{1}$$

Where C_d – Concentration of dissolved oxygen in the downstream of hydraulic structure

C_u - Concentration of dissolved oxygen in the upstream of hydraulic structure

C_s – Saturated level of dissolved oxygen for a given ambient conditions.

Aeration efficiency of one indicates full transfer of oxygen in the water. Since the temperature plays a vital role in mass transfer mechanism, aeration efficiency needs to be converted based on standard temperature. Gulliver et. al., 1990 developed the relationship based on mass transfer similitude to adjust aeration efficiency to 20^0C and denoted as E_{20}[25] .

$$E_{20} = 1 - (1 - E)^{\frac{1}{f}} \tag{2}$$

Where f is an exponent

$$f = 1 + 0.02103(T - 20) + 8.261x10^{-5}(T - 20)^2 \tag{3}$$

If the efficiency value is ‘zero’ means, aeration process not occurred and if it is ‘1’ means 100% aeration process occurred in the system. The saturation concentrations at various temperatures were obtained from the charts. Suitable methods should be identified to eradicate the effect of salinity from the water. In this study the saturation concentration were determined by the chart by McGhee, 1991[24]**.**

Experimental Set-up

Fig.1 shows the experimental set up, which consists of a stepped cascade of 0.6 m wide and 1.8 m height. A series of precast concrete slabs was laid over the waist slab which was fabricated using steel ‘L’ section angles. The waist steel section provides a link between stilling tank and supply reservoir with an angle 14^o. The steps were constructed over the precast slabs in CM 1:5 and it was plastered to provide a smooth surface. The size of the tread ranges from 0.40 m to 0.60 m with an increment of 0.05 m was constructed in sequence. The water was pumped from the supply reservoir to the stilling tank, from which water flown over the series of steps through an approach channel, The first step level with respect to top of collecting tank was made as 1.8 m. Discharge was measured using electromagnetic flow-meter provided at the inlet pipe. The experiment was conducted to identify the effect of aeration with and without addition of sodium sulfite (Na_2SO_3) and cobalt chlorite ($CoCl_2$). During each trial of experiment, the walls of the tanks were completely cleaned with clean whip to remove the contaminant residues that get build up due to the addition of the salts. Each experiment was started by filling the storage tank with Potable water (PW) which was collected from Reverse Osmosis (RO) water purification plant. The water quality was monitored periodically during the investigation to minimize the effect of repetition in experiments. Hence a constant water quality was maintained through out the experiment. Flow rate was controlled by a valve available next to the pump and slope of the channel was kept constant. DO was measured simultaneously both in upstream side and also in downstream side using hand held DO meter. Temperature was measured in degree Celsius.

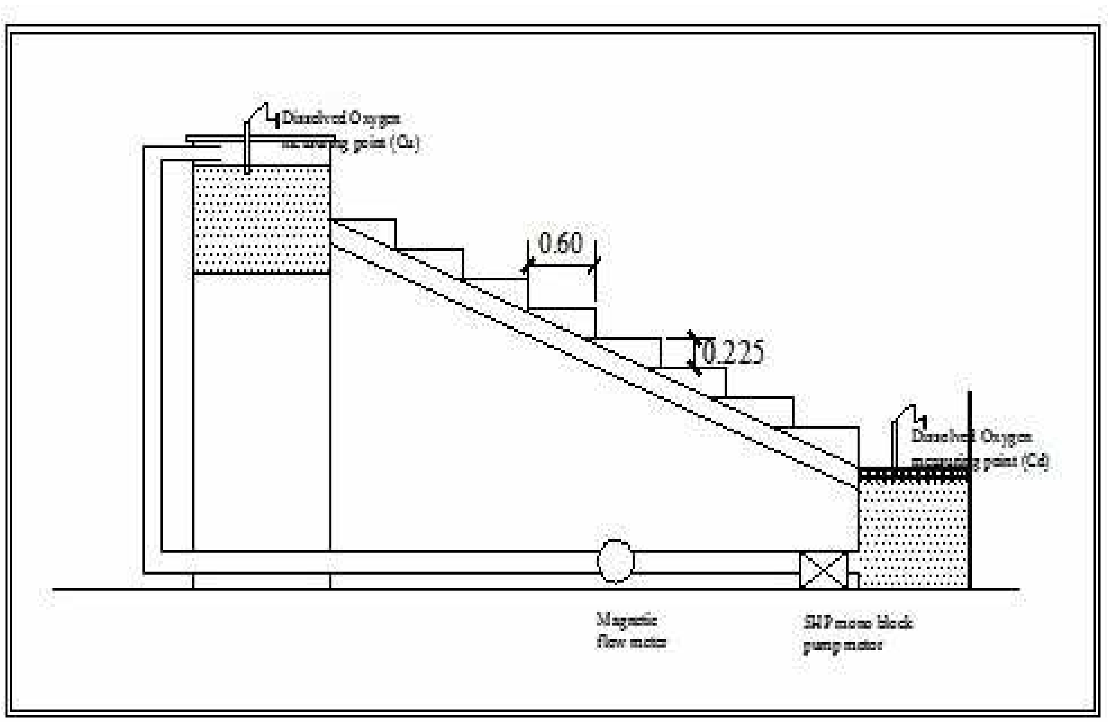

Fig 1 Sketch of experimental set up

In the present study, investigation on the aeration performance with different water quality and flow rates was conducted on nappe flow condition only. The conditions given by Chanson, 2002 for a nappe flow over the stepped cascades are presented as follows [16]:

$$d_c/h \leq 0.89 - (h/l);\ 0.06 \leq (h/l) \leq 1.8 \text{ and } \ > 0.02 \text{ m} \qquad (4)$$

Where, $d_c = (q_w^2/g)^{1/3}$ = critical depth in a rectangular prismatic channel (m), q_w is hydraulic loading rate (m^3/ m of width /day); h is step height (m); l is step length (m). Therefore, the specification, along with their ranges (agreeable the above mentioned conditions), were identified and presented in Table 1.

Table 1 Design Parameters along with their ranges

S. No.	Parameters	Ranges
i)	Hydraulic loading rate (q_w) (To be varied at 10 levels)	0.015 – 0.105 $m^3/s/m^2$ at an interval of 0.02 $m^3/m^2/s$
ii)	Step Height (rise) (h)	0.225 m
iii)	Step length (t)	0.60 m, 0.55 m, 0.50 m, 0.45 m and 0.40 m
iv)	Step Width (W)	0.60m
v)	Over all height of the stepped cascade (H)	1.8 m
vi)	Steps Number	8

The various ranges of the variables are shown in Table 1 and these values closely matches with the typical design information for a cascade type aeration system given in equation 4. Also the cascade geometry (i.e., length and height of the steps) and the flow rate were selected to be nearly full-scale to minimize the potential scale effects.

Result and discussion

In this research work, the efficiency of aeration of a stepped cascade channel was obtained for varying value of tread of the step (t) and unit discharge (q) keeping constant step height (h). Potable drinking water was used for the entire experiment and the results were correlated with the same quality of water after deoxygenation. The following segment presents and discusses the results for aeration efficiency, E_{20}.

(i) Effect of non – dimensional parameters in aeration efficiency

Results from experiment shows that efficiency of aeration was improved based on the type of flow regime, which is the function of step geometry and flow rate. Generally nappe flow was observed at the decreasing unit discharge and increasing step height. Based on the experimental results a transition flow regimes was found in increased flow rates which resulted in reduction in aeration efficiency.

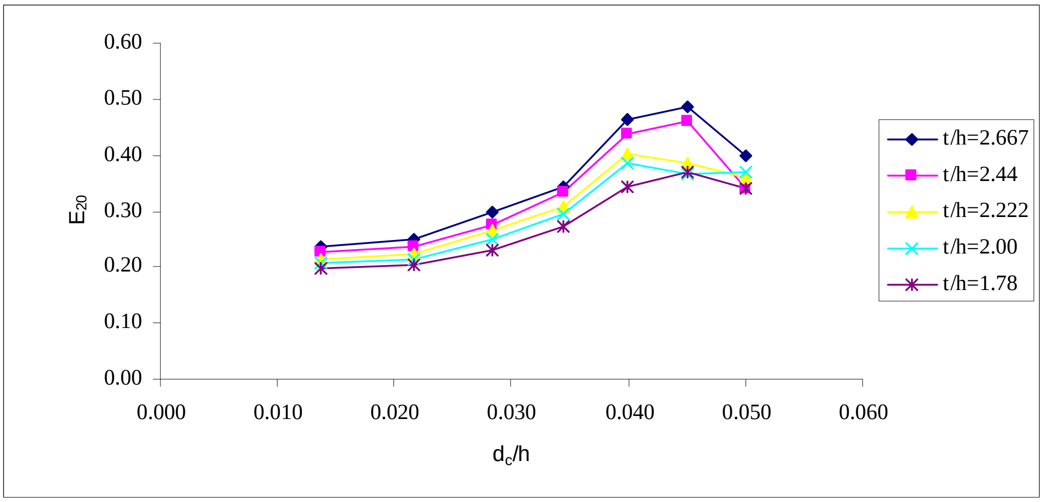

Fig.2 Graph showing variation in aeration efficiency with d_c/h for PWWC

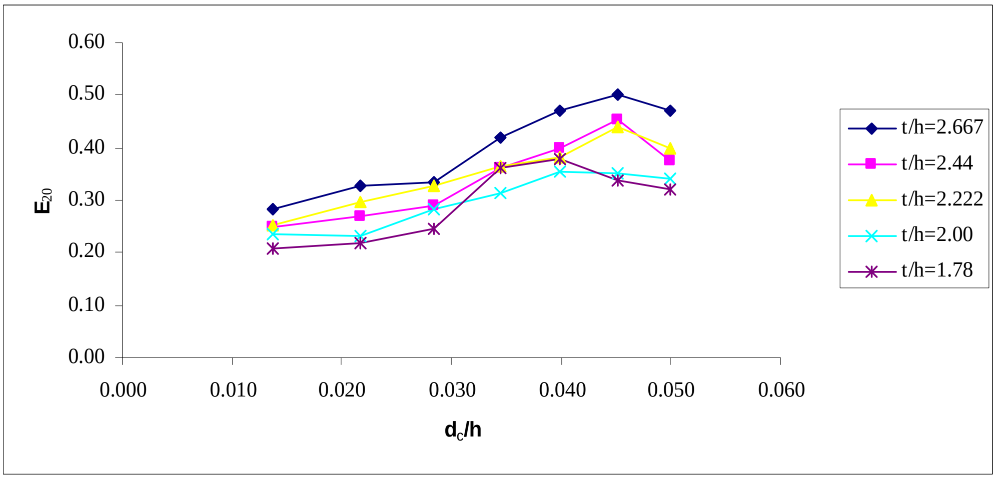

Fig.3 Graph showing variation in aeration efficiency with d_c/h for PWWOC

Fig.1 and 2 show the relationship between non-dimensional parameters (d_c/h) with aeration efficiency. It was found that aeration improvement is directly proportional to the unit discharges (m^2/s), however a tendency of the decrement was witnessed at the highest flow rates ($0.021 m^3/s$) . In higher flow rates, the residence time of water in the steps was decreased because the interphase transport of gas and water is not established. Improvement in the results especially in higher flow rates will be possible if the channel width is increased. The ratio of critical water depth to height of the water (d_c/h) which is an important non-dimensional parameter has a strong influence in the aeration improvement. Similar type of trend was observed in both the cases; in the first case PWWC (Potable water with chemical) shows 31% of aeration improvement whereas the PWWOC (Potable water without chemicals) yields 34% which is slightly greater than the previous quality of water. This difference in efficiency might have been resulted due to the presence of residues that develops during deoxygenation process. Experiments were conducted for seven different flow rates, so obviously the results were analyzed for seven different non – dimensional parameters. Among various (d_c/h) values, 0.045 found to be better in both cases as it is received 41% improvement in the first case and 42% in the second case. Overall results shows that performance of PWWOC is found slightly better than PWWC, it may be due to concentration of reactive salty agreement on the water surface which the affects the diffusion process.

(ii) Effect of ratio of tread and height of the step to aeration efficiency

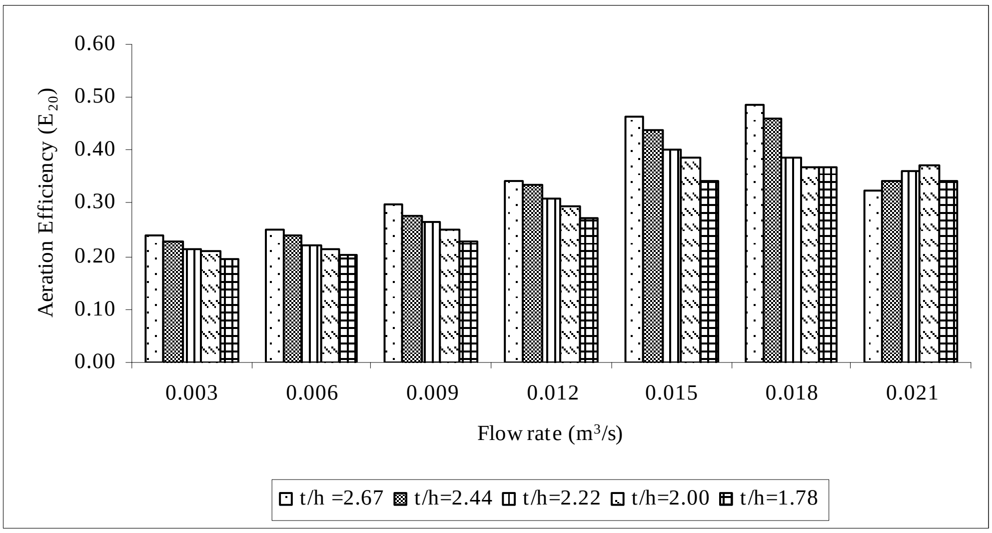

Fig. 4 Graph showing the effect of t/h on aeration efficiency for PWWC

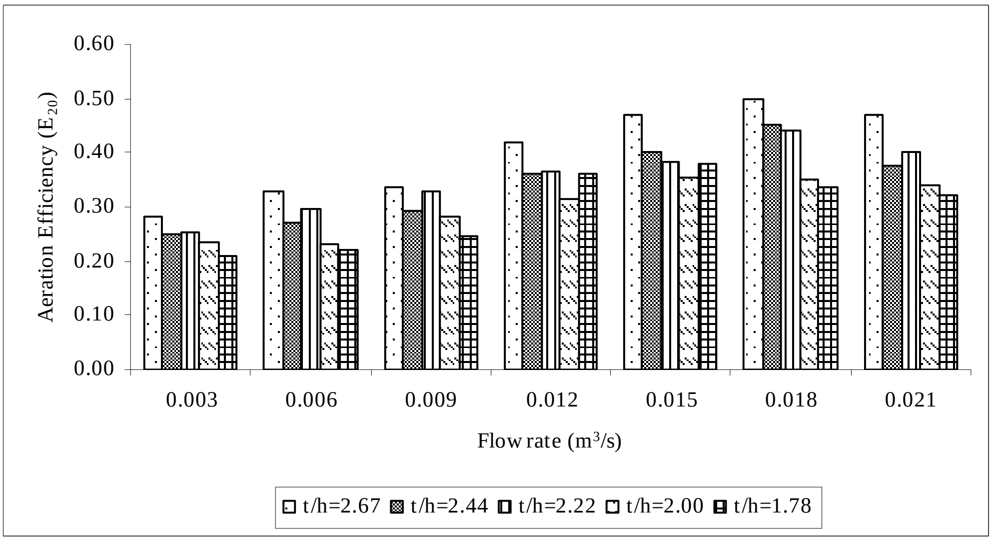

Fig. 5 Graph showing the effect of t/h on aeration efficiency for PWWOC

Fig. 3 and 4 shows the effect of tread and height of the steps in different flow rates in aeration efficiency. The present work is investigated for a single step height (0.225 m) with a combination of 5 different tread, 0.60 m, 0.55 m, 0.50 m, 0.45 m and 0.40 m. The notation (t/h) represents the ratio of tread of the step to height of the step.

Experiment result indicates that the aeration efficiency is strongly affected by t/h which in turn a function of step geometry. Observed result shows that the increment in dimensions of tread leads to good aeration improvement in all kinds of flow rates. Even the same trend was found in both qualities of water. Comparatively better aeration efficiency is found out with 0.6 m tread length then the water treated with lesser treads. The range of average aeration efficiencies for different t/h combination varies from 0.28 to 0.34 and 0.30 to 0.40 for PWWC and PWWOC respectively.

Regarding flow rates, the experiments was conducted for seven different flow rates which starts from 0.003 m^3/s to $0.021 m^3/s$ which have an equal increment of 0.003 m^3/s. In lower flow rates where the water spread over the surface of the step like a sheet which enable to produces a least aeration efficiency because of lower turbulence and increased step width. Observation announces that the increase in flow rate is directly proportional to the aeration improvement. It also indicates that higher flow rates able to generate good results when the step width is increased. In the present study, aeration improvement was found increased when the flow rates increased up to $0.018 m^3/s$ and then a small downturn was witnessed in the next higher flow rate $0.021 m^3/s$. For same geometry of cascade, increase in flow rate above 0.018 m^3/s brings transition state of flow regime Despite good turbulence in higher flow rates the smaller width of channel, tread length and step height causes the water to flow over to next steps without absorbs sufficient quantity of oxygen from the atmosphere. Present study resolutely shows the accord between flow rate and channel width.

(iii) Effect of water quality on Aeration efficiency

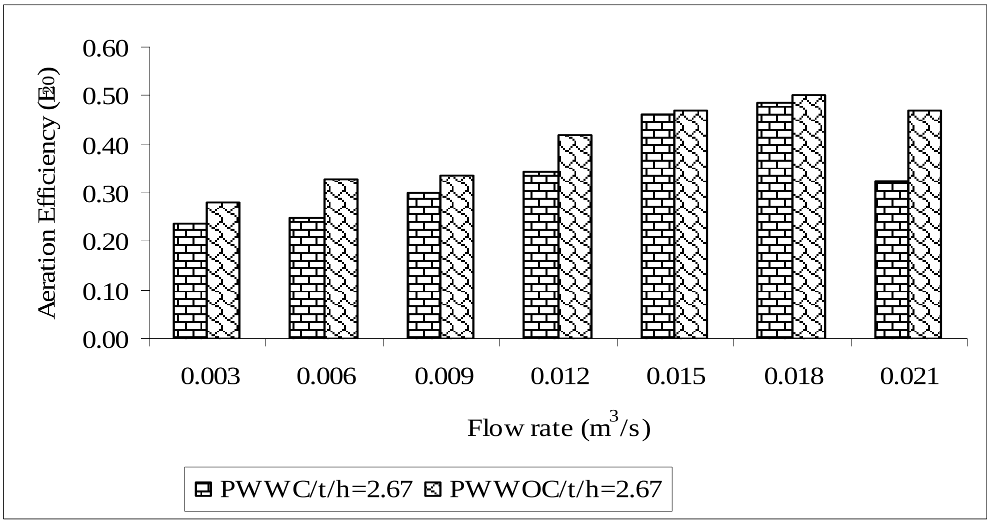

Fig 6 Graph showing the effect of water quality on aeration efficiency

Fig. 6 clearly indicates the existence of variation in aeration efficiency of water with deoxgenation and without deoxygenation. Plot evidently proves that PWWOC has shown good results when it is compared PWWC. Potable water collected from RO plant is completely free from any contaminants able to snap a minimum quantity of oxygen. In addition of sodium sulfite chemical used for deoxygenation the original DO concentration is completely is reduced. Reverse Osmosis process is capable of removing up to 99% of the dissolved salts (ions), particles and colloids from the feed water. So addition of Sodium sulfite (Na_2SO_3) in the RO water leads to stagnation of reactive salt agents on the surface of water which retards the diffusion process. But the mean difference between two qualities of water is low, as it shows an average of 34% for PWWC whereas it shows 40% for PWWOC.

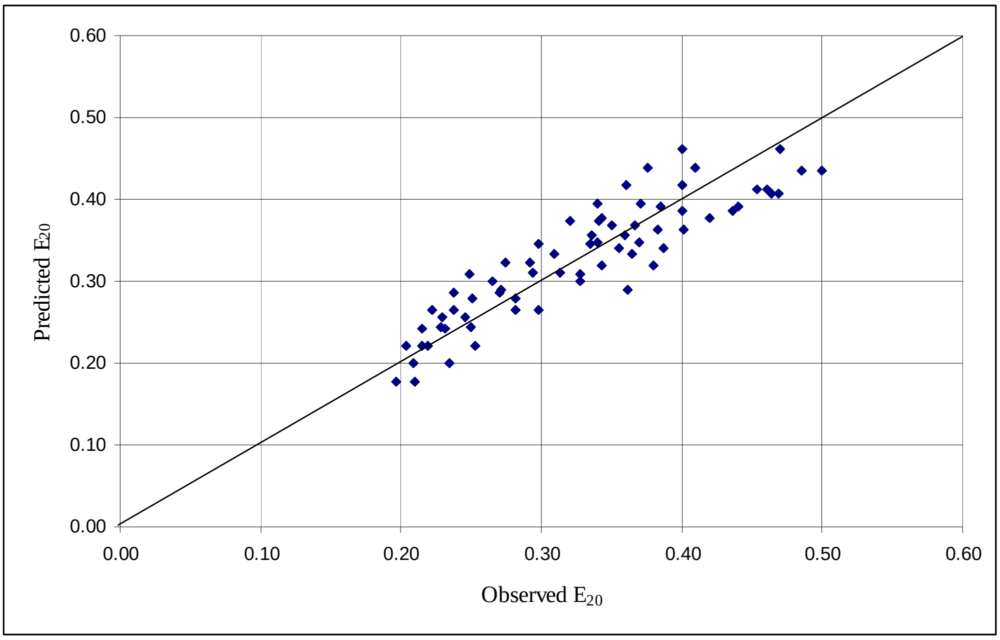

Fig. 7 Comparison of measured and predicted values of oxygen transfer efficiency

A regression was generated from the data collected from our experiment to predict the efficiency of oxygen transfer as follow

$$E_{20} = - 0.0730 + 5.40 [d_c/h] + 0.0992 [t/h] \qquad (5)$$

$R^2 = 0.81$

Where d_c is the critical depth in meters, h is height of the step and t is tread of the step

The observed efficiencies were compared with this predicted equation. Good agreement between observed and predicted values was obtained. This expression can be used for finding aeration efficiency of cascade system having different geometry.

Conclusion

In the present experimental study, aeration performance of stepped cascade system of selected geometry was investigated for water with and without deoxygenation. The result of the study confirms that when the flow through cascade increases from the threshold value, the performance of cascade decreases since time of exposure decreases. Further, it is to be noted that, though the turbulent mixing of water appears at the top surface level, but the width of the channel restricts the improvement of aeration efficiency. Result of the study indicates that selected geometry of cascade system shows better performance with PWWOC when compared with PWWC. It could be due to logging of surface reactive salts on the water surface which minimally reduces the aeration process. Further, it was found from the study that positive influence of tread length on the aeration enhancement of flow. The non – dimensional parameters (t/h) shows that steps with increased tread length depicts increased performance when compared with the other combinations.

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Notations

C_d	-	Concentration of DO in downstream (mg/l)
C_u	-	Concentration of DO in upstream (mg/l)
C_s	-	Saturation concentration (mg/l)
d_c	-	Critical flow depth (m)
d_c/h	-	Dimensionless discharges
DO	-	Dissolved Oxygen (mg/l)
E	-	Transfer efficiency at the water temperature
E_{20}	-	oxygen transfer efficiency at the 20˚C
f	-	Correction factor for temperature
g	-	Acceleration due to gravity (m^2/s)
HP	-	Horse Power
PW	-	Potable water
PWWC	-	Potable water with chemicals
PWWOC	-	Potable water without chemicals
Q	-	Flow rate in (m^3/s)
q_w	-	Hydraulic loading rate (m^2/s)
r	-	Rise of the step
t	-	Tread of the step
T	-	Temperature

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