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Performance Evaluation and Modeling of a Conical Plunging Jet Aerator

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***Abstract*—**Aeration by a plunging water jet is an energetically attractive way to effect oxygen-transfer than conventional oxygenation systems. In the present study, a new type of conical shaped plunging aeration device is fabricated to generate hollow inclined plunging jets (jet plunge angle of $\pi/3$) to investigate its oxygen transfer capacity. The results suggest that the volumetric oxygen-transfer coefficient and oxygen-transfer efficiency of the conical plunging jet aerator are competitive with other types of aeration systems. Relationships of volumetric oxygen-transfer coefficient with jet power per unit volume and jet parameters are also proposed. The suggested relationships predict the volumetric oxygen-transfer coefficient within a scatter of $\pm 15\%$. Further, the application of Support Vector Machines on the experimental data revealed its utility in the prediction of volumetric oxygen-transfer coefficient and development of conical plunging jet aerators.

***Keywords*—**Conical plunging jet, oxygen-transfer efficiency, support vector machines, volumetric oxygen-transfer coefficient.

I. INTRODUCTION

A falling water jet, when passes through the surrounding atmosphere and plunges into a pool of water, it entrains into this pool a substantial amount of air and forms a submerged two-phase region with a considerable air-water interfacial area. This process is called plunging water jet entrainment and aeration. It is basically a combination of hydrodynamic and aerodynamic forces interacting between water jet and ambient air [1]. Plunging jet applications include aeration and floatation in water and wastewater treatment, oxygenation of mammalian-cell bio-reactors, biological aerated filter, fermentation, bubble floatation of minerals, plunging columns, cooling system in power plants, stirring of chemicals as well as increasing gas-liquid transfer, plunging breakers and waterfalls [2] – [6]. Aeration by a plunging water jet is an attractive way to effect oxygen-transfer than conventional aeration systems for various reasons [2],[7] – [8]: it is energetically attractive, it does not require an air compressor; it does not require separate stirring device because the plunging jet itself achieves aeration and mixing; it is simple in design, construction and operation; and it is free from operational difficulties such as clogging in air diffusers, limitations on the installation of mechanical aerators by the tank width, etc. Supported by these potential advantages, there has been a growing interest in aeration by plunging jets in the last few years.

A substantial number of researchers have studied air-water oxygen transfer by plunging jets. Experimental studies on the oxygen transfer by plunging water jets were carried out by [9] – [17]. These and the other related studies were reviewed in detail by Bin [2]. Some of these researchers have presented their data in the form of empirical relationships. The simplest relationships for single circular water jets plunging vertically (i.e. jet plunge angle, $\theta = 90^0$) are recommended by Ahmed and Glover [19] (Eq.1), Bin and Smith [14] (Eq.2) and by Tojo and Miyanami [12] (Eq.3):

$$K_L A_{(20)} = 3.1\times 10^{-4} + 4.85\times 10^{-2}\ v_j^3\ d_j^2 \qquad (1)$$

$$K_L A_{(20)} = 9\times 10^{-5}\ P \qquad (2)$$

$$K_L a_{(20)} = 0.029\left(P/V\right)^{0.65} \qquad (3)$$

where $K_L A_{(20)}$ is volumetric oxygen transfer factor at standard conditions (m^3/h); v_j is jet velocity at exit (m/s); d_j is jet diameter (m); P is jet power (W); $K_L a_{(20)}$ is volumetric oxygen transfer coefficient at standard conditions (1/s); and P/V is jet power per unit volume (kW/m^3). Thus much useful information is available on the oxygen transfer characteristics of conventional plunging water jets.

These and other researchers have identified jet velocity, jet diameter, jet plunge angle and jet power (which is a function of jet velocity and jet diameter) as the four operating variables affecting the oxygen transfer of a plunging water jet aeration system. However, it is insufficient to investigate or discuss the oxygen transfer by plunging jet aeration system only by these four factors. An important factor that cannot be overlooked is geometry/shape of the jet in the aeration system. Reviewing existing studies on different geometries of plunging jets, most of these works were carried out on conventional shapes of plunging jets. Chanson and Brattberg [20] investigated air entrainment by two-dimensional planner plunging jet; Bagatur et al. [21] investigated entrainment by oval and rectangular (with rounded ends) plunging jets; and Emiroglu and Baylar

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[8] have reported oxygen-transfer by venturi type circular plunging jet. So far only circular, rectangular with rounded ends and oval shapes of plunging jets have been studied. In the present study, a conical shaped plunging aeration device is fabricated to generate hollow inclined plunging jets of different thicknesses (Fig. 1) to investigate oxygen transfer (in terms of volumetric oxygen-transfer coefficient at standard conditions $K_L a_{(20)}$ and oxygen-transfer efficiency OE) by a hollow inclined plunging jet. A jet plunge angle of $\theta = \pi/3$ has been selected for the hollow inclined plunging water jets in the present study. This selection of jet plunge angle is on the basis of findings of Tojo et al. [13] which revealed that the inclined jets have to be preferred to vertical jets and concluded that the optimum jet plunge angle is $\pi/3$. Relationships for conical plunging jet are also presented to predict volumetric oxygen-transfer coefficient $K_L a_{(20)}$ as a function of jet power and jet parameters.

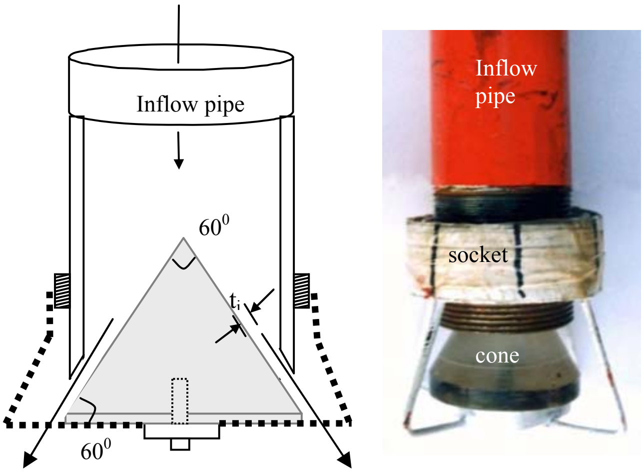

Fig. 1 Details of conical plunging jet aerator

II. OXYGEN TRANSFER BY PLUNGING JETS

In the “closed” system of the plunging liquid jet aerators [2], an oxygen balance equation relating the instantaneous rate of change in dissolved oxygen (DO) concentration (dC/dt) to the rate of oxygen mass transfer between air and water is given as:

$$\frac{dC}{dt} = K_L \frac{A}{V}\left[C_s - C\right] \tag{4}$$

where K_L is bulk liquid film coefficient.; C_s is the saturation dissolved oxygen concentration in water at prevailing ambient conditions; A is the air-water contact area; and V is the volume of water associated with this. The term A/V is called the specific surface area (a) or surface area per unit volume; while the term $K_L A$ is called the volumetric oxygen-transfer factor. Integrating Eq.4 between the limits of $C = C_0$ and $C = C$ and $t = 0$ and $t = t$ and solving, we get:

$$K_L a = \frac{1}{t}\ln\left[\frac{C_S - C_0}{C_S - C_t}\right] \tag{5}$$

where C_0 and C_t are dissolved oxygen concentrations in the water at start and at the time t of aeration respectively; and $K_L a$ is volumetric oxygen-transfer coefficient. Eq.5 shows that values of $K_L a$ can be obtained by substituting the measured values of C_S, C_0, C_t and t. In order to have a uniform basis for comparison of different systems, $K_L a$ is generally normalized at 20^{O}C standard. The temperature dependence of $K_L a$ can be expressed [22] using the following empirical equation:

$$K_L a_{(20)} = K_L a_{(T)} \times (1.024)^{(20-T)} \tag{6}$$

where $K_L a_{(20)}$ is oxygen-transfer coefficient at standard conditions (1/s); $K_L a_{(T)}$ is oxygen-transfer coefficient at T ^{O}C (1/s); and T is water temperature (^{0}C).

The oxygenation performance of plunging water jets is generally expressed in terms of the oxygen-transfer efficiency OE (kg O_2/kW.h), and give by Eq.7:

$$OE = \frac{O_R V}{P} \tag{7}$$

where O_R is oxygen-transfer rate (mg/L/h) at 20^{O}C and 1 atmosphere (standard conditions); and P is jet power (kW). O_R and P can be expressed as:

$$O_R = K_L a_{(20)} \,.\, 3600 \,.\, C_S^* \tag{8}$$

$$P\,(in\,kW) = \left(\frac{1}{2}\rho Q v_j^2\right)\frac{1}{10^3} = \left(\frac{\pi}{8}\rho\, t_j^2\, v_j^3\right)\frac{1}{10^3} \tag{9}$$

where C_S^* is saturation dissolved oxygen (DO) concentration in water at standard conditions (mg/L); ρ is density (kg/m^3); Q is discharge or jet flow rate (m^3/s); v_j is jet velocity at exit (m/s) and t_j is jet thickness (m).

III. EXPERIMENTATION

A. *Experimental Setup*

The schematic representation of the experimental set-up is shown in Fig. 2. The experimental set-up consists of a water tank, a water pump, a flow regulating valve, an orifice meter, a thermometer, a hollow inclined plunging jet device, a piezo meter and a scale. All experiments on oxygen-transfer by conical plunging jet were carried out in a water tank with dimensions of 1.02 m long x 1.02 m wide x 1.0 m deep. The water-depth in the tank was kept at 0.6 m for all experiments and measured with the help of a piezo meter fitted to the water tank alongside a scale. The water in the experimental set-up was circulated by a centrifugal pump. A flow regulating valve was provided at the location identified in Fig. 2. A pre-calibrated orifice meter was installed in the pipeline for flow measurements. A digital thermometer was used for the temperature measurement. The conical plunging jet aerator was fitted to the vertical inflow pipe and adjusted such that the jet impinges centrally in the pool. The vertical distance between exit of the jet and water surface in the pool, was kept as 0.1 m through out the experimentation.

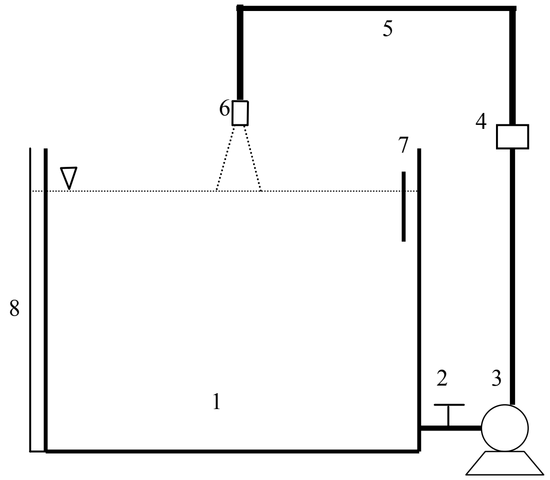

Fig. 2 Experimental set-up: (1) water tank; (2) flow regulating valve; (3) water pump; (4) orifice meter; (5) inflow pipe; (6) hollow inclined plunging jet device; (7) Thermometer probe; (8) piezo meter with scale

B. *Conical Plunging Jet Aerator*

The device has two main components, namely a solid cone and a socket. A solid cone of perspex having diameter of 64.5 mm and apex angle of 60^0 was fabricated to achieve jet plunge angle of $\pi/3$ (Fig. 1). The cone was fitted to the socket made up of cast iron as shown in the Fig. 1. The socket has internal threads so that it can be fitted/tightened to the inflow pipe and also a rack-and-pinion arrangement is obtained when the socket is rotated. When the socket is fully tightened to the inflow pipe, no flow is possible as the cone closes the exit. However, by rotating the socket (fitted with cone) anticlockwise, conical jets can be generated as water flows through the annular space between the inflow pipe and the cone. The desired thickness of hollow conical jet (t_j) can be obtained by counting the number of rotations of rack-and-pinion arrangement from the fully tightened position of the socket.

C. *Experimental Procedure*

In this study, a series of laboratory experiments were carried out on conical plunging water jet to study its volumetric oxygen-transfer coefficient ($K_L a$) and oxygen-transfer efficiency (OE). The experiments were performed on three jet thicknesses, t_j = 1.90 mm, 2.72 mm and 3.77 mm. Each of these jet thickness were tested at four different flow rates, viz., 1.33 x 10^{-3} m^3/s, 1.8 x 10^{-3} m^3/s, 2.5 x 10^{-3} m^3/s and 3.1 x 10^{-3} m^3/s. To begin with an experiment, the conical plunging jet aerator was fitted to the inflow pipe and the desired jet thickness t_j was fixed with the help of rack-and-pinion arrangement. Tap water was then filled in the water tank. The opening of the regulating valve was set at desired flow rate using the pre-calibrated orifice meter in the supply line. Water in the tank was deoxygenated by adding an estimated quantity of sodium sulfite (Na_2SO_3) and in addition cobalt chloride ($CoCl_2$) was added to act as a catalyst. A representative sample of the deoxygenated water was taken and the initial dissolved oxygen concentration (C_0) was determined by azide modification method [23]. Aeration was then carried out for a fixed duration of time (t = 60 seconds). The representative samples of the aerated/oxygenated water were taken for the determination of dissolved oxygen concentration after time t (C_t). The water temperature (T) was recorded during the course of experiment. The value of $K_L a_{(T)}$ was then calculated by using Eq.5 and volumetric oxygen-transfer coefficient at standard conditions ($K_L a_{(20)}$) was obtained by using Eq.6. The OE and P values were calculated by using Eq.7 and Eq.9 respectively.

IV. RESULTS AND DISCUSSIONS

The effect of jet velocity on volumetric oxygen-transfer coefficient is shown in Fig. 3. It is observed that $K_L a_{(20)}$ increases remarkably as v_j increases; and for a given jet velocity, the thicker jets have higher $K_L a_{(20)}$ values in all the experiments. This increase in $K_L a_{(20)}$ with increase in jet velocity may be ascribed due to increase in the momentum of the jet flow and/or increased jet power.

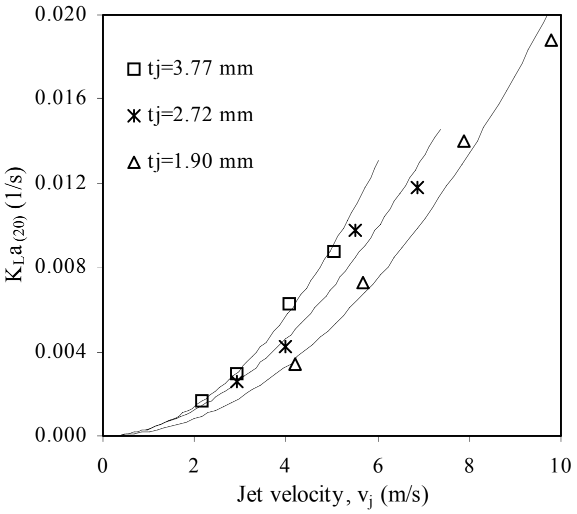

Fig. 3 Oxygen-transfer as a function of jet velocity

To study the combined effect of jet velocity (v_j) and jet thickness (t_j) on the volumetric oxygen-transfer coefficient, the $K_L a_{(20)}$ data for conical jets are compared in Fig. 4 in terms of the jet power per unit volume (P/V). It was observed that the values of $K_L a_{(20)}$ increases with the increase in jet power per unit volume over the whole range of experiments. For predicting the volumetric oxygen-transfer coefficient $K_L a_{(20)}$ by conical plunging water jets having jet plunge angle of $\theta = 60^0$, the following relationships between $K_L a_{(20)}$ and P/V was obtained from the plot between $K_L a_{(20)}$ v/s P/V (Fig. 4):

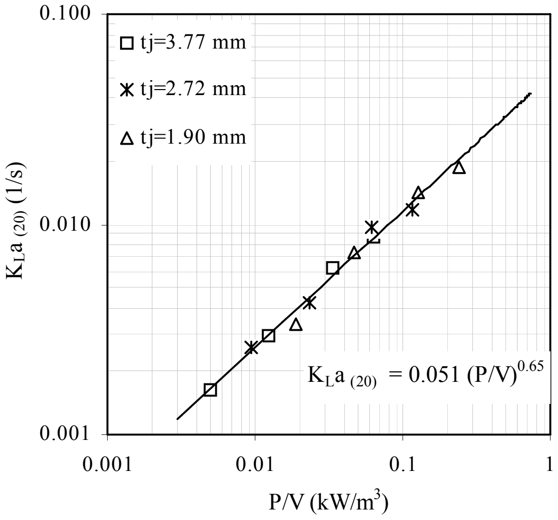

Fig. 4 Oxygen-transfer as a function of jet power

$$K_L a_{(20)} = 0.051(P/V)^{0.65} \tag{10}$$

The above relationship (Eq.10) is similar to expressions proposed by Bin and Smith [14] (Eq.2) and by Tojo and Miyanami [12] (Eq.3) for conventional vertical plunging jets having jet plunge angle of $\theta = 90^0$. The correlation coefficient between the experimental values of $K_L a_{(20)}$ and predicted values of $K_L a_{(20)}$ using Eq.12 is 0.99. Further, when a multivariate linear regression was applied to formulate an equation/relationship between $K_L a_{(20)}$ for conical water jets with jet plunge angle of $\theta = 60^0$ and jet parameters represented by P (i.e. v_j and t_j), the following relationship is developed:

$$K_L a_{(20)} = 0.023\ \ v_j^{1.98}\ t_j^{0.74} \tag{11}$$

The above relationship (Eq.11) is similar to expression proposed by Ahmed and Glover [19] (Eq.1) for conventional vertical plunging jets having jet plunge angle of $\theta = 90^0$. The correlation coefficient between the experimental values of $K_L a_{(20)}$ and predicted values of $K_L a_{(20)}$ using Eq.11 is 0.99.

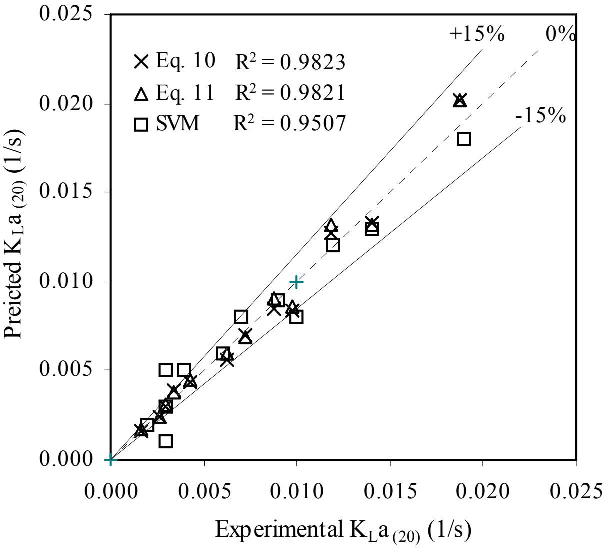

Fig. 5 Experimental $K_L a_{(20)}$ v/s predicted $K_L a_{(20)}$

Support Vector Machines (SVM)is also used for the prediction of overall volumetric oxygen transfer coefficient $K_L a$. The correlation coefficient obtained is 0.986. The predicted values of $K_L a$ by Eqs. 10 and 11 and SVM modeling technique are plotted against the observed $K_L a$ and the results are given in Fig. 5. A scatter of ± 15% to the line of perfect agreement (Fig. 5) was achieved by Eqs. 10 and 11 and SVM. Thus, Eqs. 10 and 11 along with SVM are helpful in providing information about the oxygen-transfer by conical plunging jet aerator with fair precision.

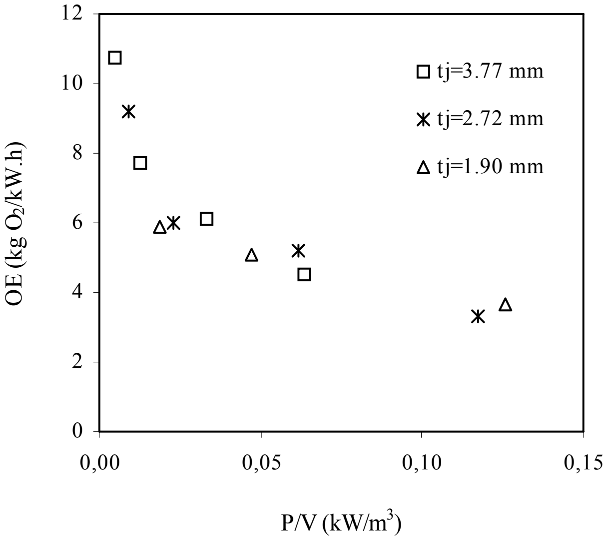

Fig. 6 Effect of jet power on oxygen-transfer efficiency

Fig. 6 shows the oxygen-transfer efficiency (OE) for conical plunging jet as a function jet power per unit volume

(P/V). It was observed that oxygen-transfer efficiency decreases as the P/V increases for conical plunging jet as in the case with all other types of aerators. Table I provides a comparison of oxygen-transfer efficiency of the conical plunging jet with other types of aeration equipments. It can be observed from this table that conical plunging jet device studied here is quite competitive with the other conventional aeration/oxygenation equipments.

TABLE I
OXYGEN-TRANSFER EFFICIENCY FOR VARIOUS TYPES OF EQUIPMENTS

S. No.	Equipment	*OE* (kg O_2/kW.h)
1*	Small bubble size disperger	1.36 – 1.8
		0.95
2*	Large bubble size disperger	0.98
		0.64
3*	Turbine agitator	1.2 – 1.38
4*	Surface aeration by mechanical agitator	1.68
5*	Deep shaft aerator	3.0 – 6.0
6*	Gas jet aerator	1.64
7*	Eddy jet mixer	4.78
8*	Plunging Jet	0.92 – 3.9
9[#]	Plunging venturi device	2.2 – 8.8
10^	Hollow inclined plunging jet (θ= $\pi/3$)	2.56 – 10.73

* Cited from Tojo and Miyanami [12]
[#] Emiroglu and Baylar [8]
^ Present study

V. CONCLUSION

Based on the findings of this study, the following conclusions can be drawn for conical plunging jet aerator:

- The volumetric oxygen-transfer coefficient increases with the increase in jet velocity. For a given jet velocity, the $K_L a_{(20)}$ values are higher for thicker jets.
- The volumetric oxygen-transfer coefficient increases with increase in the jet power per unit volume.
- The volumetric oxygen-transfer coefficient for hollow inclined plunging jets is well correlated with the jet power per unit volume and jet parameters (representing jet power). Eq.12 and Eq.13 along with SVM predicted the $K_L a_{(20)}$ from P/V and jet parameters within a scattering range of $\pm 15\%$. These relationships and SVM would be quite useful in comparing the performance of conical plunging jets of different thickness; and also in deciding the optimum thickness of conical plunging jet for given flow conditions.
- In a practical situation, involving variations/fluctuations in the inflow to the aeration unit of a wastewater treatment plant, hollow inclined plunging jet device suggested in the present study can be quite useful due to their flexibility in comparison to other aeration devices. Simply altering the thickness of the jet, by moving the cone up-and-down with the help of rack-and-pinion arrangement, can meet the changed requirement.

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