Multiple plunging jet aeration system and parameter modelling by neural network and support vector machines

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Abstract

Plunging jet aeration systems provide a simple and inexpensive method of supplying oxygen for wastewater treatment. Though numerous studies have been reported on aeration with a single plunging jet, very few studies are available in open literature on multiple plunging jet aeration systems. The present work is the result of an extensive laboratory study carried out on single and multiple water jets in vertical and inclined orientations, and different possible configurations of the number and diameter of jets. The effect of single and multiple jets on overall volumetric mass transfer coefficient (K_La) is studied by correlating it with kinetic jet power per unit volume (P/V). It was found that K_La increases with an increase in the number of jets, and also the performance of multiple jets improves with increasing kinetic jet power per unit volume. Neural Network and Support Vector Machine modelling techniques have been applied on the experimental data to determine the significant jet parameters that govern the performance of multiple plunging jets aeration system. Based on these parameters, an empirical relationship for predicting the K_La has been proposed for which the correlation coefficient and root mean square error are 0.96 and 3.27 respectively. Both the modelling techniques have also been used for the prediction of K_La and have been found to work well. The findings of these modelling techniques and empirical relationship are expected to be quite useful in the development of an efficient multiple plunging jets aeration system.
Keywords: aeration, multiple plunging jets, overall volumetric mass transfer coefficient, kinetic jet power neural network, support vector machines.

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1 Introduction

When a water jet impinges on the surface of a pool of water at rest, a large amount of air from the surrounding atmosphere may be entrained and carried below the free surface thus forming a large submerged contacting area between water and air. This process is called plunging jet entrainment. Plunging jet applications include aeration and floatation in water and wastewater treatment, bubble floatation of minerals, cooling system in power plants, plunging columns, breakers and waterfalls (Bin [1]; Cummings and Chanson [2]). For aerobic treatment processes, such as activated sludge process, plunging jet aeration systems provide a simple and inexpensive method of supplying oxygen for wastewater treatment (Bin [1]; Tojo et al [3]).

Bin [1] has comprehensively reviewed gas entrainment by plunging liquid jets. Numerous studies are reported in his review on single plunging jets which reveal that gas entrainment by a plunging liquid jet is a complex process, largely controlled by kinetic jet power 'P' (= $\frac{\pi}{8} \rho\, d_j^2\, v_j^3$), which is further a function of jet velocity (v_j) and diameter (d_j) only. On inclined jets, Tojo et al [3] have concluded in their study that maximum oxygen transfer occur at jet impact angle of 60^0. Some researchers (Bin [1]; Tojo et al [3]; Swigget [4]; Ahmed [5]; Van de Sande and Smith [6]) have also suggested empirical relationships for predicting overall volumetric mass transfer coefficient (K_La) for single plunging jets. To the best of the knowledge of authors, very few studies have been reported on the use of multiple plunging jets till date. However, Van de Sande and Smith [6] opined that the use of several jets instead of one is probably better.

In an effort to develop an efficient aeration system to reduce the operating costs of wastewater treatment and other related processes, experiments were carried out on multiple plunging water jets impinging vertically ($\theta=90^O$) and inclined at a jet impact angle of $\theta=60^0$ in a pool of water for varying jet diameters, number of jets and jet discharges. The overall volumetric oxygen transfer coefficient (K_La) was measured for both, multiple vertical and multiple inclined plunging jets. Neural Network and Support Vector Machines modelling techniques were then applied on the experimental data to study the effects of various jet parameters on the performance of multiple plunging jets. The experimental data and the findings of the modelling techniques were then utilized to develop a simple empirical relationship between 'K_La' and the jet parameters.

2 Experimentation

A "closed" system with a complete recirculation of the water and a constant water hold-up was used in the present study (Figure 1). A flat-bottomed square tank of 1.02 m x 1.02 m x 1.0 m deep was used to create a pool of water. The water-depth in the tank was kept at 0.595 m. The vertical distance between the exit end of aerating device and the water-surface in the tank, which corresponds to the jet length, was kept as 0.1 m. A centrifugal pump was used to recirculate the flow and a pre-calibrated orifice meter was installed in the pipeline for flow measurements. The aerating device was fitted and tightened to the vertical inflow pipe of 53.34 mm internal diameter and adjusted such that the jet(s) impinged centrally on the pool. A digital thermometer, having an accuracy of ± $0.1^{O}C$, was used for monitoring the temperature of the water in the tank. The atmospheric pressure was measured with a mercury barometer with an accuracy of ± 0.05mm.

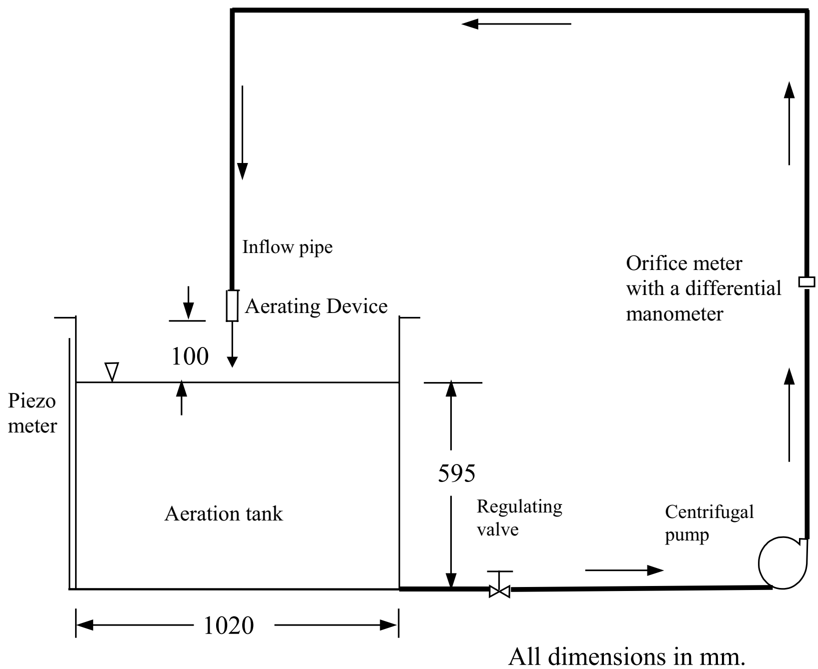

Figure 1: Experimental set-up.

2.1 Multiple plunging jets aeration device

The multiple plunging jets were produced by allowing the flow of water through circular holes (of different configurations in terms of d_j, n and θ) drilled in a 6mm thick Perspex disc of 56mm diameter. The circular holes of desired configurations were drilled perpendicular to the diameter of the disc for vertical jets (VJs); while for inclined jets (IJs) the circular holes were drilled at such an inclination so as to generate a jet impact angle of 60^0. For experimentation, a disc of desired configuration was placed in the aerating device along with other accessories and then the aerating device was fitted at the end of the vertical inflow pipe. Figure 2 shows the photograph of aerating device fitted with a Perspex disc having 16 numbers of inclined multiple jets along with other accessories.

Figure 2: Photographs of aerating device showing fitting arrangements of 16 number of inclined multiple jets.

Experiments were carried out at three different flow areas of 615.752 mm^2, 452.389 mm^2 and 314.160 mm^2, designated as series A, B and C respectively. For each flow area (or series), 1, 4, 8, 16 and 32 number of jets were used. The different configurations of circular holes used in a disc for creating multiple jets have been presented in Table 1 along with nomenclature of the multiple jets.

Table 1: Jet configurations and nomenclature.

Series	**Jet diameter** d_j **mm**	**No. of jets N**	**Total cross-sectional area** $\left[=\frac{\pi}{4}(\sqrt{n}d)^2\right]$ **mm²**	**Jet type and their nomenclature**		**Total circumference** $[=n\pi d]$ **mm**
				Vertical jets (θ=90^0)	**Solid inclined jets (θ=60^0)**	
A	28	1	615.752	VJA2801	IJA2801	88.00
	14	4	615.752	VJA1404	IJA1404	176.00
	10*	8	615.752	VJA1008	IJA1008	251.43
	7	16	615.752	VJA0716	IJA0716	352.00
	5*	32	615.752	VJA0532	IJA0532	502.86
B	24	1	452.389	VJB2401	IJB2401	75.43
	12	4	452.389	VJB1204	IJB1204	150.86
	8.5	8	452.389	VJB8.508	IJB8.508	213.71
	6	16	452.389	VJB0616	IJB0616	301.71
	4.24*	32	452.389	VJB4.232	IJB4.232	426.42
C	20	1	314.160	VJC2001	IJC2001	62.86
	10	4	314.160	VJC1004	IJC1004	125.71
	7	8	314.160	VJC0708	IJC0708	176.00
	5	16	314.160	VJC0516	IJC0516	251.43
	3.5*	32	314.160	VJC3.532	IJC3.532	352.00

*The diameter of 1 or 2 holes was adjusted so as to keep the total cross-sectional area constant.

2.2 Experimental procedure

A Perspex disc of desired configuration of jets was fitted with suitable rubber seals and fixing arrangements. The aerating device was then tightened to the vertical flow pipe. Water was filled in the tank to a depth of 0.595m.The desired flow rate was set with the help of the pre-calibrated orifice meter and a regulating valve. Water in the tank was deoxygenated by adding estimated quantity of sodium sulphite (Na_2SO_3) with cobalt chloride ($CoCl_2$) added to act as a catalyst. A representative sample of the deoxygenated water was taken and the initial dissolved oxygen concentration was determined by azide modification method (APHA [7]). Throughout the present experiments, the initial dissolved oxygen concentration was mostly kept in the range of 0.3 to 1.0 mg/l. Aeration was then carried out for a fixed duration of sixty seconds and three representative samples of the aerated water were taken for the determination of dissolved oxygen concentration. Observations of temperature, the atmospheric pressure and aeration time were recorded during the course of experiment.

The experiments were carried out for each of the configuration at four different discharges, viz., 1.33, 1.8, 2.5 and 3.1 l/s. The overall volumetric oxygen transfer coefficient 'K_La' at standard conditions of 20^0C and one atmospheric pressure was then determined for each observation.

3 Analysis

In the "closed" system of the plunging liquid jet absorbers, perfect mixing for the liquid phase in the pool and plug flow in the circulation pipe can be assumed (Bin [1]). In this case, an oxygen balance in the liquid phase yields:

$$\frac{dC(t)}{dt} = K_L A \frac{1}{V_T}\left[C_s - C(t)\right] - \frac{Q}{V_T}\left[C(t) - C\left(t - \frac{V_P}{Q}\right)\right] \tag{1}$$

where C_S is the saturation (equilibrium) dissolved oxygen concentration, Q is flow rate, V_T and V_P are the volumes of water in the tank and in the circulation pipes respectively and KLA is the overall oxygen transfer factor.

The effect due to V_P in the flow system can be significantly reduced by aerating the deoxygenated water for 2-3 seconds before taking the samples for initial dissolved oxygen concentration. Further, when V_T is much larger in comparison to V_P, the eqn (1) can be simplified as:

$$\frac{K_L A}{V} = \frac{1}{C_S - C}\frac{dC}{dt} \tag{2}$$

where V is the volume of water in the system, and is practically equal to the volume of water in the tank. Integration of eqn (2) gives:

$$\frac{K_L A}{V} = \frac{1}{t}\ln\left[\frac{C_S - C_0}{C_S - C_t}\right] \tag{3}$$

where C_0 is the initial dissolved oxygen concentration at time t=0.

Since the experiments were carried out at non-standard conditions of temperature and pressure, values of K_LA were first determined at test conditions by using equation (3) as per the procedure laid down in Standard Methods (APHA [7]) and then the values of K_LA, in m^3/sec., were estimated at standard conditions of 20^0C and 1 atmospheric pressure by using the relationship:

$$\left[K_L A\right]_{\text{at std. conds.}} = \frac{K_L A}{(1.024)^{(T-20)}} \tag{4}$$

where 'T' is temperature of pool water in ^{0}C at test conditions. The values of overall volumetric oxygen transfer coefficient K_La (in per sec.) at standard conditions were obtained by dividing the values of $[K_L A]$ $_{\text{at std. conds}}$. by volume of the water in the tank, i.e.,

$$K_L a \quad = \quad \frac{K_L A}{V} \tag{5}$$

While the kinetic jet power per unit volume P/V (in kW/m^3) for multiple plunging jets was calculated by using the relationship:

$$\frac{P}{V} \quad = \quad \frac{\pi \rho (\sqrt{n}\, d_j)^2 v_j^{\,3}}{8 B^2 Z} \tag{6}$$

4 Results and discussion

The effect of multiple jets, both vertical and inclined, on the oxygen transfer rate was studied as a relationship between the overall volumetric mass transfer coefficient K_La and the kinetic jet power per unit volume P/V of the plunging jet aeration system. The results of present study indicate that a multiple jets aerating device shows better performance in terms of oxygen transfer rate than a single jet aerating device at higher P/V values. Figure 3 shows that the aerating device with n=4 multiple vertical jets performs better in comparison to a single jet (n=1) in the entire experimental range of present study. The K_La for n=8 is higher than the device with n=1 and n=4 values when P/V exceeds 0.0028 kW/m^3 and 0.007 kW/m^3 respectively. In case of devices with n=16 it starts performing better than the devices with n=1, n=4 and n=8 when values of P/V exceeds 0.01, 0.02 and 0.05 kW/m^3 respectively. Multiple jet devices with n=32 starts performing better than devices with n=1 when P/V exceeds 0.05 kW/m^3. The trend line of aerating device with n=32 indicate that they might out-perform other multiple jets (n=4, 8 and 16) at higher P/V values.

Similar observations can be made for inclined multiple jets (Figure 4). Further, inclined jets ($\theta = 60^{\text{O}}$) have higher K_La as compared to vertical jets at a given jet power for same conditions and configurations.

The neural network and support vector machine modelling techniques are then applied independently on experimental data of vertical and inclined multiple jets.

Various parameters and their combinations are selected and ten-fold cross-validation is carried out. The test results in the form of correlation coefficient and root mean square error for different combinations of parameters, obtained from the application of these modelling techniques, are plotted on a classic combination chart – Line-Column on Two Axis (Figure 5).

From this figure, it can be interpreted that the highest correlation with lowest root mean square errors is obtained with combination code **V** by using both of the modelling techniques. From these considerations, the overall volumetric oxygen transfer coefficient K_La was correlated with parameters - velocity of jet v_j (m/s), diameter or thickness of jet d_j (m), umber of jets n, impact angle θ (degree) and geometry of the multiple jets (represented by A). Based on selected parameters following empirical relation is proposed:

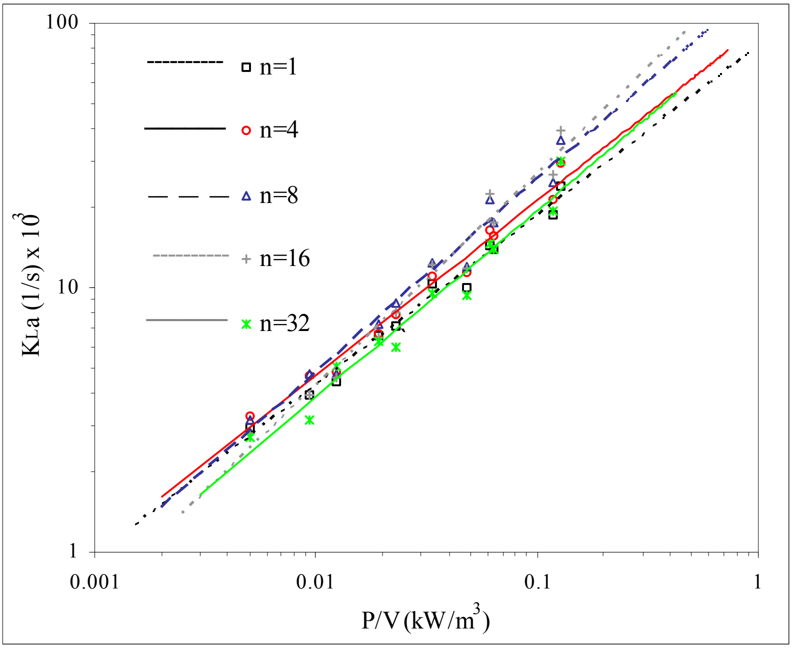

Figure 3: K_La vs. P/V for multiple vertical jets (VJs).

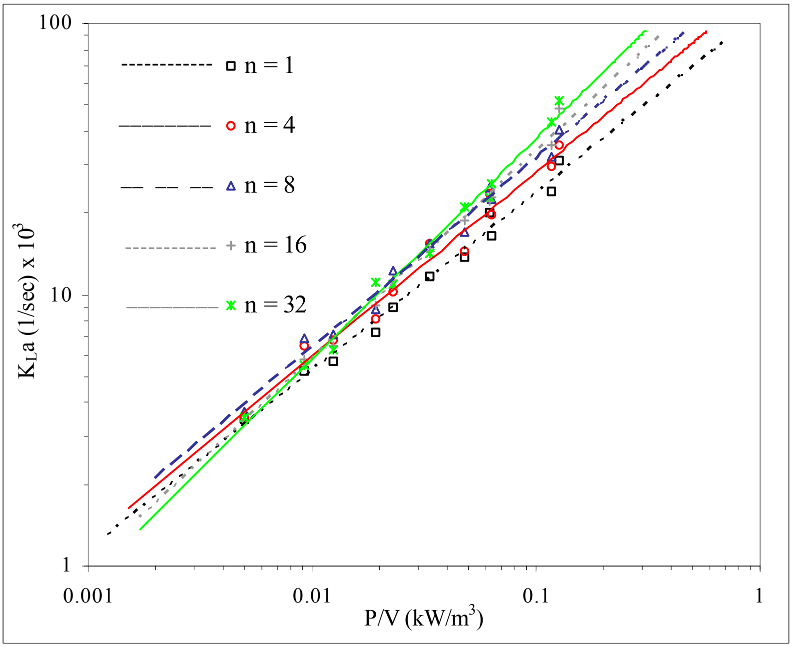

Figure 4: K_La vs. P/V for multiple inclined jets (IJs).

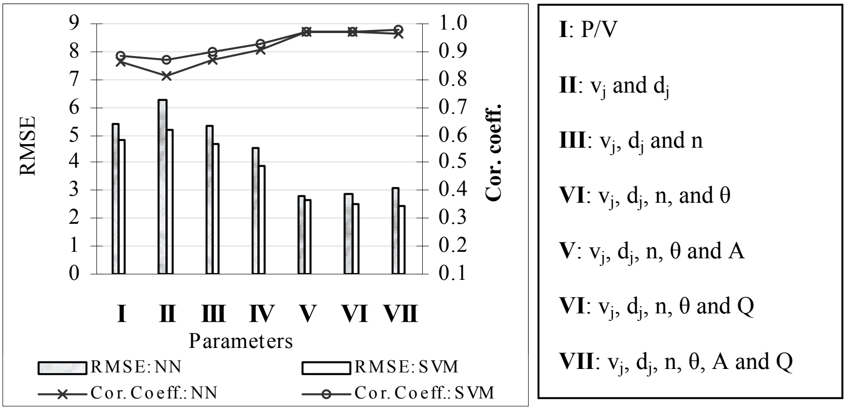

Figure 5: Effect of jet parameters on K_La.

$$K_La = 34.43 \times 10^{-3} \; V_j^{1.9\,a} \; d_j^{1.12\,m} \tag{7}$$

where *a* and *m* are numerical constants termed as "inclination factor" and "multiple jet factor" respectively, which can be estimated from experimental values. The inclination factor *a* for vertical plunging jets (i.e. when $\theta = 90^0$) is 1.0; whereas for inclined jets with an impact angle of 60^0, it is 1.063. Higher value of inclination factor for $\theta = 60^0$ indicates that inclined jets at this impact angle have higher oxygen transfer rate in comparison to vertically plunging jet under similar conditions. The multiple jet factor *m* can be estimated from the relationship, $m = 1/n^{0.148}$, where n is the number of multiple jets.

By using the above empirical relationship, the K_La values are predicted, and the correlation coefficient and root mean square come out to be 0.96 and 3.27 respectively. When the experimentally observed values of K_La are plotted against the predicted K_La values from eqn (7), the scattering is found to be within $\pm 20\%$ as shown in Figure 6 (except for n=32 in case of vertical multiple jets, which may be due to agglomeration of multiple jets with lesser spacing between them). The plot indicates that the empirical relationship provides direct information about K_La with reasonable accuracy for different configurations of vertical and inclined multiple plunging jets aeration systems, with appropriate values of *a* and *m*.

Both the modelling techniques (Neural network and Support vector machines) are also used for the prediction of overall volumetric oxygen transfer coefficient K_La. For predicting the values of K_La by a particular technique at a flow rate of 1.33 l/s, the training data set comprises of experimental data at all other remaining flow rates of 1.8 l/s, 2.5 l/s and 3.1 l/s for all types and configurations of jets. Similarly, the predicted values of K_La at flow rates of 1.8 l/s, 2.5 l/s and 3.1 l/s are obtained for all types and configurations of jets. The predicted values of K_La by both the modelling techniques are plotted against the observed K_La and the results are given in Figure 7 and Figure 8. The correlation coefficient and root mean square errors in case of Neural Network technique are 0.94 and 3.99 respectively and in case of Support Vector Machine 0.89 and 5.32 respectively. Out of these two modelling techniques, Neural network is found to be predicting relatively better in comparison to Support Vector Machines, suggesting its utility/application in such type problems.

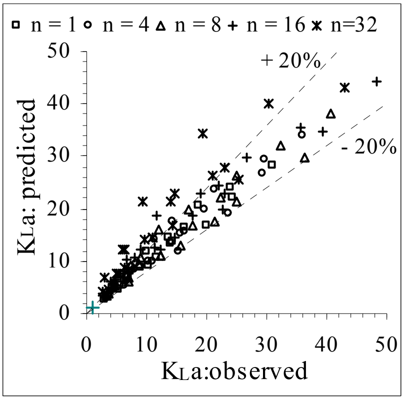

Figure 6: K_La (observed) vs. K_La (predicted) by eqn (7).

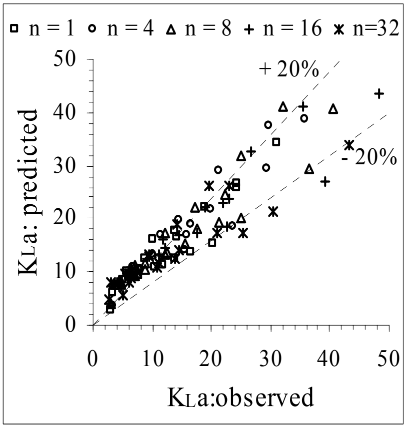

Figure 7: K_La (observed) vs. K_La (predicted) by NN.

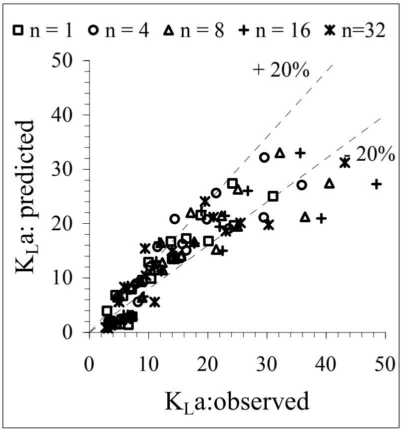

Figure 8: K_La (observed) vs. K_La (predicted) by SVM.

5 Conclusions

The gas-liquid mass transfer characteristics of vertical and inclined multiple plunging jets aeration system have been investigated by using air-water system. The findings of the present study clearly indicate that:

- Under similar conditions of experimentation multiple jets have higher oxygen mass transfer rates as compared to single jets.
- The performance of inclined jets with impact angle of 60^O is better than vertical jets.
- The significantly higher overall volumetric mass transfer coefficient of multiple jets in comparison to a single jet at higher jet velocities and flow rates is the most advantageous feature when larger volumes of water need to be aerated.
- The proposed empirical relationship suggested predicts the K_La for multiple plunging jets fairly well and can be quite helpful not only in the determination of optimum configuration of multiple jets but also in the scale up. Further, the relationship can also be used to compare the performance of other types and configuration of plunging jet aeration systems.
- Neural network and Support Vector Machines modelling techniques have been usefully employed in predicting K_La in such type of problems. But these techniques require further studies to explore their full potential for this type of work.

It is suggested that a suitable configuration of multiple plunging jets, instead of a single jet, can be used in a plunging jet aeration system to provide better efficiency.

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