Study on Oxygenation Performance of Solid Jet Aerator having Circular Opening corresponding to Variable Jet Length and Flow Area

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Abstract. Mechanical aerators are most commonly used for aeration process in treatment of waste water. Oxygen exchange mechanism by plunging jet of water is a superior method to transfer oxygen into pool of water than regular systems. Surface jet aerators, which are closed and simple systems, are uncomplicated in design, working and maintenance. In this study, experiments were conducted on models of solid jet aerators having circular shaped opening with variable jet lengths and area for different discharges. Penetration depth, oxygen transfer factor and Oxygenation efficiency were measured for different jet lengths, corresponding to each area and discharge. It was observed that penetration depth and oxygen transfer efficiency increments with increase in discharge and jet length in air whereas oxygen transfer factor increases with jet length in air only. With the results achieved, an efficient aerator model was suggested for a given set of inflow and environmental conditions.

Keywords: Plunging water jet, Oxygen transfer efficiency, oxygen transfer rate, Solid jet aerator

1. Introduction

Dissolved oxygen is most important component when survival of aquatic life is concerned [1,2]. Some organism use for their respiration while bacteria and other microbes use it for decomposition of complex organic compounds [3]. Aeration is one of the methods to induce oxygen in water or wastewater by increasing contact area between air and water either using mechanical or natural means [4] and is first major step in secondary treatment of wastewater and water [5-7]. Its efficiency depends on various factors which most importantly includes air-water interfacial area. There are many methods of aeration to achieve oxygenation of water [8] which are bubble type diffusers, surface aeration by mechanical agitators, turbine agitators, gas jet aerators, eddy jet mixtures, static tube mixtures and plunging jet aeration by surface jet aerators. Out of these methods, surface jet aerators have been used widely due to their easy operation, installation and maintenance. Surface jet aerators provide high oxygen transfer efficiency [9] as compared to other methods of aeration. Many studies are available in literature that study hollow plunging jet aerator, solid plunging jet aerator and expansion type aerator are experimented and several results obtained [10, 11]. Plunging jet aeration technique induces oxygen into pool of water by passing a jet with high speed first through air, thereby sweeping large amount of air into pool and then forming a two phase region to obtain large water-air interfacial area [12]. Using such aerators, efficiency of transfer of oxygen increases greatly, as these works on phenomenon of sudden expansion of jets, thereby sucking very large amount of air into the pool and thereby creating partial vacuum and thereby resulting in high oxygen transfer rate. Occurrence of oxygen (in mg/L) in water chiefly depends on pressure, temperature, salinity and altitude [13-16]. Solubility of oxygen in water is more in colder water and decreases with rise in temperature of water [17-22, 23-26].
2. Equations for Performance Evaluation of Aerator

A closed system is facilitated by surface jet aerator and hence a perfect mixture of air and water can safely be assumed. Therefore, for a closed system, volumetric oxygen transfer coefficient is given in eq. 1 [16]

\[ K_La_t = \frac{1}{t} \ln \left( \frac{C_s - C_o}{C_s - C_t} \right) \]  

(1)

Here \( C_o \) and \( C_t \) are, respectively, the concentration of dissolved oxygen at the commencement and after passage of duration of time ‘t’ of aeration. \( K_La_t \) represents the volumetric oxygen-transfer coefficient. The above equation shows that by measuring the values of \( C_o, C_t \) and \( C_o \), the value of \( K_La_t \) can be determined. To get a homogeneous basis for comparability of different aerator models, \( K_La_t \) is normalized at 20°C temperature which is taken as standard. The temperature dependency of \( K_La_t \) can be expressed [6] using the relations shown in eq. 2:

\[ K_La_t(20) = K_La_t \times \theta^{(20-T)} \]  

(2)

Where \( \theta \approx 1.024 \) for temperature 5-24°C
\( \theta \approx 1.028 \) for temperature 25-34°C
\( \theta \approx 1.031 \) for temperature 35-45°C

and \( K_La_t(20) \) denotes oxygen-transfer co-efficient at standard condition(l/sec) and \( K_La_t \) is that at \( T \) C (l/sec), \( T \) being temperature of water in degree Celsius.

The jet power (kW/m³) is expressed as given in eq. 3 [19]:

\[ P = \frac{0.5\rho Qv_j^2}{V} \]  

(3)

Here \( \rho \) is denseness of liquid (kg/m³), \( Q \) being rate of flow of water (m³/s) and \( v_j \) is jet velocity at the exit end of nozzle (m/s).

Transfer rate of oxygen is calculated as in eq. 4 [17]

\[ O_R = K_La_t(20) \times 3600 \times C_s^* \]  

(4)

Where \( C_s^* \) represents saturation oxygen concentration in water at 20°C Celsius. Further, oxygen-transfer efficiency (kgO₂/kWh) of an aerator can be expressed as (eq. 5) [18]:

\[ OTE = \frac{O_RV}{P} \]  

(5)

3. Materials and Methods

Methodology of the experiment has been presented in following subsections.

3.1 Experimental set-up

The experimental setup comprises of water tank made transparent acrylic sheet with dimensions of 0.5m×0.5m×0.6m. A C.I. pipe of 28mm internal diameter is provided at the bottom of the tank for input of water to a 1 Hp centrifugal pump fixed on a platform. A valve is fitted just after outlet of pump to the pipe to regulate flow of water (Discharge). The discharge of the flow into the measuring tank is measured using an electromagnetic flow meter attached to the pipe. The C.I. pipe is bent to end above the centre of the tank. A level of 0.45 m high from bottom of tank is maintained for each experiment. Tap water is used for experimentation. Another valve to empty the water from tank is connected to tank at the bottom. Pump and flow meter switches are connected to power supply to start and stop pump.
The aerating device consisted of a cylindrical C.I. holder in which discs having different number of openings are placed with the help of a rubber seal to make it air-tight. It is fitted to the outlet of C.I. pipe.

Non-steady state method was selected for the estimation of oxygenation efficiency as this method is more accurate than steady-state method. Initial D.O. present in water is depleted to zero by addition of sodium sulphite in addition with cobalt chloride as catalyst. The pump is run for sufficient time (one minute to two minutes depending on discharge) so that measurable amount of oxygen could be obtained. If the amount of oxygen induced is less, we can perform the experiment using other model with different opening. After D.O reaching certain limit, it has to be made zero for next procedure. As D.O depends on various factors, temperature also should be recorded. Fifteen numbers of aeration discs having shapes as mentioned in Table 2 were manufactured which had area of opening equivalent to 8%, 12% and 16% of pipe area with dimensions rounded off to single place of decimal in order to account for casting limitations. The details of shapes and configurations of solid jet plunging devices are presented in Table 1.

Table 1. Configuration of Solid Plunging Jet

| Serial No | Dimension of Jet | Flow Area of Jet, \( (A_f) \) (mm\(^2\)) | Surface Area of Jet per Unit Length, \( (A_s) \) (mm\(^2\)) | Nomenclature |
|-----------|------------------|---------------------------------|---------------------------------|---------------|
| Diameter (d) | \( A_f = n \times \frac{\pi}{4} d^2 \) | \( A_s = n \times \pi d \times l \) | | |

Figure 1. Schematic representation of experimental setup

Figure 2. Schematic representation of aeration device
3.2 Digital multi meter
HQ40D [27] portable multi meter is a device which has been designed for applications of water quality measurements like measuring Conductivity, pH, Salinity, TDS, Dissolved Oxygen (DO), etc. It has capabilities of storing the method settings, calibration history and minimizes errors and setup time. All connections between the meter and the probe are secure and waterproof. Connectors are colour-coded for quick identification. Information is displayed on the screen with back light enabling good vision in low light conditions. In the present experiment, we implemented only L.D.O sensor probe to measure dissolved oxygen.

![Figure 3. HACH multimeter with LDO probe](image)

3.3 Experimental Procedure
Each model was fitted in the aeration device and pump was run for a specified time (one minute to two minutes depending on discharge). The experimental procedure consisted of measurement of discharge using electromagnetic flowmeter, measurement of the temperature of water, measurement of dissolved oxygen content and determination of oxygen-transfer efficiency. When the power switch was turned on, the centrifugal pump sucked water from inlet. The discharge was regulated with the rotating valve attached just after the pump. The water recirculated and fell down at the centre of the tank through the aerator model attached at outlet of the pump. While water falling from the model, the water jets absorbed air in the way of falling and this air was brought to water in the tank. The air got mixed to water through turbulence produced due to momentum of falling water. By this method, the oxygen content in the water in the tank increased. This increased oxygen was measured in form of D.O. and efficiency of transfer of oxygen was measured using Eq. 10 as discussed in the previous section.

4. Results and Discussion
It was detected from Fig. 4(a, c and e) that efficiency of transfer of oxygen decreases with increase in discharge and hence increase in velocity due to increased loss of head at the end of exit. However, with the increment in length of jet, the value of OTE increases for all sets of aerators. Furthermore, it was observed that value of oxygen transfer efficiency first upsurges with decrease in area of opening of aerator and then decreases abruptly. This can be ascribed to the fact that with the decrease in area of opening of aerator for a given discharge, velocity of jet increases that forces oxygen deep into the pool.
but turbulence at the surface decreases. More reduction in area produces thinner jets which produce small turbulence which is also a very important factor responsible for oxygenation along with penetration of jet into the pool. On the other hand, $K_{La}(20)$ was observed to increase with discharge (fig. 4(b,d and e)) and hence velocity, jet length and also with decrease in flow area of aerator. Highest value of OTE equal to 30.95 kgO$_2$/kW-hr was obtained from aerator model C/16 at discharge of 1.05 l/s corresponding to jet length of 370 mm. Furthermore, maximum $K_{La}(20)$ was demonstrated by aerator model C/16 at discharge of 3.04 l/s for jet length of 470 mm and its value was found to be $7.30 \times 10^{-2}$ s$^{-1}$.

Figure 4 (a) : OTE vs velocity for C/16, (b) : $K_{La}(20)$ vs velocity for C/16, (c) : OTE vs velocity for C/12, (d) : $K_{La}(20)$ vs velocity for C/12, (e) : OTE vs velocity for C/08, (f) : $K_{La}(20)$ vs velocity for C/08 aerator models corresponding to varying jet lengths
5. Conclusion
As a result of current study, following conclusions were drawn.

- Standard Oxygen transfer factor ($K_t\alpha_{20}$) increments with increase in discharge and furthermore increases with increment in jet length in air.
- $K_t\alpha_{20}$ increases with decrease in flow area due to increased velocity and hence increased momentum at a given discharge.
- Highest oxygen transfer factor equal to 7.30×10² s⁻¹ was obtained for aerator having flow area of 98.52 mm² at a discharge of 3.04 l/s corresponding to jet length of 470 mm.
- Oxygen transfer efficiency (OTE) decreases with increment in velocity for a given flow area and jet length.
- Oxygen transfer efficiency increases with increment in jet length for a given flow area and velocity.
- Oxygen transfer efficiency first increases with increase in flow area and jet length due to increased jet surface area per unit length and turbulence and then decreases due to increased head loss.
- Overall highest OTE equal to 30.95 kgO₂/kW-hr was obtained from aerator having flow area of 98.52 mm² at a value of discharge equal to 1.05 l/s at jet length of 370 mm.

References
[1] T. Bagatur, A. Baylar, N and Sekardag. The effect of nozzle type on air entrainment by plunging water jets. Water Qual. Res. J. Canada, 37:599-612, 2002.
[2] Shukla, B.K., Bhowmik, A.R., Raj, R.B. and Sharma, P.K. Physico-Chemical Parameters and Status of Ground Water Pollution in Jalandhar – Phagwara Region. Journal of Green Engineering, 9(2):212-223, 2019.
[3] A.K. Bin. Gas entrainment by plunging liquid jets. Chem. Eng. Sci. J Great Britain, 48:3585-3630, 1993.
[4] A.K. Bin and J.M. Smith. Mass transfer in a plunging liquid jet absorber. Chem Engng. Commun, 15:367-383, 1982.
[5] H. Chanson, S. Aoki and A. Hoque. Physical modelling and similitude of air bubble entrainment at vertical circular plunging jets. Chem. Eng. Sc., 59:747-758, 2004.
[6] H. Chanson and T. Brattberg. Air entrainment by two-dimensional plunging jets: the impingement region and the very-near flow field. Proc. ASME FEDSM’98. Washington DC, 1-8, 1998.
[7] E.I. Daniil and J.S. Gulliver. Temperature dependence of liquid film co-efficient for gas transfer. J. Environ. Eng., 14:1224-1229, 1988.
[8] S. Deswal. Oxygenation by hollow plunging water jet. Journal of the Institution of Engineering, 7(1):1-8, 2008.
[9] S. Deswal, D.V.S. Verma. Air-Water Oxygen Transfer with Multiple Plunging Jets. Water Qual. Res. J. Canada, 42(4):194-201, 2007.
[10] K. Funatsu, Y. Ch. Hsu, M. Noda and S. Sugawa. Oxygen transfer in the water jet vessel. Chem. Eng. Commun., 73:121-139, 1988.
[11] M.L. Jackson and W. Collins. Scale-up of a Venturi aerator. Industrial & Engineering Chemistry Process Design and Development, 3(4):386-393, 1964.
[12] A. Kalinske. Economic evaluation of aerator systems. Environmental Science & Technology, 3(3):229-234, 1969.
[13] R. Novak. Techniques and Factors Involved in Aerator Selection and Evaluation. Journal (Water Pollution Control Federation), 40(3):452-463, 1968.
[14] A. Pasveer. Research on Activated Sludge: VII. Efficiency of the Diffused Air System. Sewage and Industrial Wastes, 28(1):28-35, 1956.
[15] N. Pillai, W. Wheeler and R. Prince. Design and Operation of an Extended Aeration Plant. Journal (Water Pollution Control Federation), 43(7):1484-1498, 1971.
[16] B.K. Shukla. Study on Surface Jet Aerators for Waste Water Treatment. M.Tech Dissertation, NIT Kurukshetra, Haryana, 2016.
[17] B.K. Shukla and A. Goel. Study on oxygen transfer by solid jet aerator with multiple openings. Engineering Science and Technology, an International Journal, 21(2):255-260, 2018.
[18] B.K. Shukla, V. Rajesh Kumar and A. Goel. Experimental Studies on the Effect of Variation in Jet Length on Oxygenation Performance of Elliptical Shaped Solid Jet Aerator. *Jour of Adv Research in Dynamical & Control Systems*, 10(08-special issue):1037–1044, 2018.

[19] B.K. Shukla, V. Rajesh Kumar and A. Goel. A Comprehensive Review of Surface Jet Aerators. *Pollution Research*, 37(may suppl.):20-25, 2018.

[20] K. Tojo, N. Naruko and K. Miyanami. Oxygen transfer and liquid mixing characteristics of plunging jet reactors. *Chem Eng. J. Netherlands*, 25:107-109, 1982.

[21] K. Tojo K and K. Miyanami. Oxygen transfer in jet mixers. *Chem Eng. J. Netherlands*, 24:89-97, 1982.

[22] E. Van de Sande and J.M. Smith. Mass transfer from plunging water jets. *Chem Eng. J. Netherlands*, 10:225-233, 1975.

[23] Srivastava S, Kumar A and Srivastava P. A kinetic study of RuIII catalyzed oxidation of Maltose by potassium bromate in alkaline medium. *Journal of Indian Chemical Societ*, 83:347-350, 2006

[24] Sharma V, Yañez O, Alegría-Arcos M, Kumar A, Thakur R C and Cantero-López P. A physicochemical and conformational study of co-solvent effect on the molecular interactions between similarly charged protein surfactant (BSA-SDBS) system. *Journal of Chemical Thermodynamics*, 14(2020):106022, 2020

[25] Kumar A and Bashir S. Review on Corrosion inhibition of Steel in Acidic media International. *Journal of ChemTech Research*, 8(7):391-396, 2015

[26] Sharma P K. A review on antimicrobial activities of important thiazines based heterocycles, *Drug Invent. Today*, 9(3):23-25, 2017

[27] R.M.R.Van den Broeck J, M.Van Impe Ilse and Y.M.Smets. Assessment of activated sludge stability in lab-scale experiments. *Journal of Biotechnology*, 141(3-4):147-154, 2009