A Comparative Study on Effect of Variation in Opening Shape on Oxygenation Performance of Surface Jet Aerators used in Water and Wastewater Treatment

1Bishnu Kant Shukla, 2Amsal Khan, 3Gopalam Saikiran, 4Macherla Sriram

1Assistant Professor, School of Civil Engineering, Lovely Professional University, Phagwara, India. E-mail: bishnukantshukla@gmail.com
2Student, School of Civil Engineering, Lovely Professional University, Phagwara, India. E-mail: amsalkhan48@gmail.com
3Student, School of Civil Engineering, Lovely Professional University, Phagwara, India. E-mail: gopalamsaikiran@gmail.com
4Student, School of Civil Engineering, Lovely Professional University, Phagwara, India. E-mail: macherlasriram@gmail.com

Abstract

In the present study, experiments were performed on models of solid surface jet aerators with openings having circular, elliptical, rectangular, square and rectangular shape with rounded edges for a number of discharges and area of openings. Aeration parameters of each model were measured corresponding to numerous discharges and penetration depth, factor of oxygen transfer and oxygenation efficiency was calculated. It was observed that penetration depth and factor of oxygen transfer increases with increase in value of discharge. However, efficiency of oxygen transfer was found to decrease with increase in magnitude of discharge for each model. Further, it was also found that aerators with square shaped openings demonstrated least value of oxygen transfer factor and efficiency whereas aerators having rectangular shaped openings with round edges were found to have highest value of these parameters under similar discharge conditions. A comprehensive comparison of various models under study was performed based on different oxygenation parameters and suggestions were made for selection of a particular type of aerator under given operating and environmental conditions

Keywords: Plunging jet, Oxygenation, Oxygen-transfer rate, Oxygenation efficiency, Opening Shape.
1 Introduction

Oxygen in dissolved state in water is considered non-compound and free oxygen present in water and it is one of the most important components for survival of aquatic life [1]. Some organisms use oxygen for respiration while microbes such as fungi and bacteria use D.O for decomposition of organic matter [2]. Aeration is the process by which the area of contact between water and air is increased either by mechanical devices [3] or by natural methods and it is considered an important process in the treatment of water and wastewater [4-6] to induce dissolved oxygen (D.O.). The efficiency of aeration depends on the amount of surface contact between air and water. Different methods of aeration are available to induce dissolved oxygen [7] into water bodies such as bubble type diffusers, surface aeration by eddy jet mixtures, mechanical agitators, gas jet aerators, turbine agitators, plunging jet aeration by the means of surface jet aerators and static tube mixtures. The surface jet aeration mechanisms are widely used in the process of aeration because of their ease in installation and reliable operation and maintenance cost along with high oxygen transfer efficiency [8]. Earlier different methods of surface jet aerators namely expansion type aerators, hollow jet aerators and solid plunging jet aerators have been experimented and several results were obtained as a result of these studies obtained [9, 10]. Process of entrainment of air or aeration by using a plunging water jet is the process when a falling water jet, after it passes through the contiguous air, entrains a great sum of air bubbles into the water pool and as a result a large submerged double-phase (gas–liquid) contact area is formed [11]. Oxygen-transfer efficiency increases by using this type of aerator, as these works on the phenomenon of sudden expansion of jets that sucks large amount of air into water by creating partial vacuum resulting in high oxygen transfer. Presence of oxygen dissolved in water (in mg/L) depends on altitude, pressure, temperature and salinity [12-15]. Solubility of oxygen is highly dependent on temperature and decreases as temperature of water rises and dissolved oxygen also increases as pressure increases for both atmospheric and hydrostatic pressures [16-18]. This is also noteworthy to mention that water at lower altitudes, due to high pressure, holds larger quantity of oxygen dissolved in water as compared to higher altitudes. Saturation of oxygen is the relative measurement of concentration of oxygen dissolved in a medium to the maximum concentration of oxygen that can be dissolved in that medium at the temperature and pressure under stable equilibrium [19-21].

2 Related Works

A number of authors worked on different models of surface jet aerators. Most of the works were concentrated on circular and conical aerators and very few compared relative oxygenation efficiency of different models of aerators. As a result of extensive studies, Bagaturet. al. [1] concluded that conical aerators having 60° plunge angle produce highest oxygen transfer as compared to vertical aerators under similar set of conditions. A number of studies [2-5] were carried out to assess the nature of gas entrainment into the pool and nature of air-liquid interaction was studied which concluded that aerators produce a two phase region at the contact region of water and air and turbulence is major factor responsible for air entrainment into the pool. Deniil and Gulliver [6] studied the temperature dependence of liquid film co-efficient and found that with change in temperature, characteristics of liquid film changes which, in turn, changes rate of oxygen transfer. A number of researchers [8-9, 15-16] worked on effect of multiplicity of jets and concluded that with increase in number of opening, aeration of water also increases. Work was done to evaluate economical installation of
aerators [7, 11-12, 14] in different types of plants under different sets of flow and discharge conditions. It was also found that, for low discharge condition, ventury aerators [10] performed much better than conventional aerators. Use of aerators under diffused air flow was studied in details by researchers [13, 22] who concluded that diffused air-systems are most efficient in activated sludge process of wastewater treatment. A number of studies on mass transfer of air into pool of water revealed the characteristics of surface film and its role in air-entrainment into pool of water and thus overall efficiency of aerators [19-21]. The role of surface film has been separately described in subsequent sections. As a result of extensive literature survey, no proper study was found which compared efficiency of solid jet aerators having different shapes of nozzle with varying area which paved way for the current study.

3 Theory of Alteration
Theory of aeration has been described in the following subsections

3.1 Affecting Factors on Rate of Oxygen-Transfer
Rate of transfer of oxygen can be given by Eq. 1, which shows that rate of variation in concentration of dissolved oxygen during aeration is proportional to interfacial contact area, (A) and oxygen deficit (Cs-Ct) and is inversely proportional to thickness of liquid film, Yf. Hence any factor affecting these parameters will also affect the rate of oxygen transfer [15, 17].

3.1.1 Wastewater Characteristics
Not only the saturation concentration but oxygen, transfer rate also changes with the change in dissolved impurities and surface-active agents. So, the oxygen transfer characteristic of tap water is different from wastewater and the wastewater with dissolved impurities and surface-active agents tend to concentrate at the interface, create a sort of barrier to diffusion [15]. Surface tension gets reduced due to small concentration of surface-active agents and as a result rate of oxygen transfer also gets reduced. Aerators are rated for their performance in tap water; their oxygenation capacity has to be modified when used for wastewater treatment [15]. Modification factor α is introduced which should be multiplied with oxygenation factor of aerator when used for the water treatment as shown by eq. 1 below:

$$\alpha = \frac{\text{rate of oxygen transfer for wastewater}}{\text{rate of oxygen transfer for tap water}}$$

The value of “α” lies between 0.65 and 0.98 depending on the characteristics of water.

3.1.2 Turbulence
The value of “α” as obtained in Eq.1 will get influenced by turbulence in aeration [15] as following:

- Resistance to diffusion in bulk of liquid is greater than the film resistance. When fluid motion has no or negligible effect on “α” at lower degree of turbulence,
At moderate degree of turbulence, there is decrease in resistance to diffusion in bulk of liquid and as a result, diffusion rate is controlled by film resistance. At this point, “α” reaches its minimum value.

- With further increase in turbulence “α” approaches to unity and which breaks up film.

Since any reduction in film thickness increases the rate of oxygen transfer, coefficient of transfer of oxygen also rises with the intensification in turbulence.

### 3.1.3 Miscellaneous Factors

Due to effects of diffusivity and viscosity, the oxygen transfer co-efficient is influenced by temperature of liquid, T and to evaluate and compare performance of any aerator, a standard temperature of 20°C is selected. The geometry/ size of the aeration tank affect the change in pattern of mixing and also the relative velocities of water and bubbles [18]. The fine bubble aeration system gets affected by the configuration of aerator and the geometry of the aeration tank. Vapour pressure is another important factor on which saturation of oxygen and hence amount of oxygen to be dissolved depends. Apart from this, salinity and other dissolved solids also affect rate of oxygen transfer in a pool by aerator [16]. Considering all these factors, rate of oxygen transfer is determined as explained in article 2.2.

### 3.2 Equations for Performance Evaluation of Aerator

Due to close system, a impeccable mixing of water and air as soon as jet of water plunges into the pool, equation of balance of oxygen, which correlates the prompt rate of change of concentration of dissolved oxygen with rate of mass-transfer of oxygen between water and air can be presented by Eq. 2[15]:

\[
\frac{dC}{dt} = K_L \frac{A}{V} (C_s - C)
\]  

Where “K_L” denotes co-efficient of film of liquid bulk, “C_s” represents the concentration of oxygen in dissolved state in water at the certain temperature “T” the value of which can be evaluated by Table 1[15]. “A” shows contact area of water and air and “V” denotes volume of water into the pool. Replacing the term “A/V” by “a” i.e., surface area of jet per unit volume, Eq. 3 is obtained.

\[
K_L \frac{A}{V} = K_L a_t
\]  

The text mining techniques and its application shows an important role in preprocessing. Now in this it has the following four stages word (token) extraction, stop words and stemming.

The Eq. 2 can be rewritten as in Eq. 4

\[
\frac{dC}{dt} = K_L a_t (C_s - C)
\]  

If integration is performed on Eq. 3 using value of lower limit of C = C_0 corresponding to t = 0 and upper limit, C = C_t corresponding to t = t, Eq. 5 is obtained.
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Table 1. Value of dissolved oxygen in saturation state corresponding to different temperatures

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Solubility of oxygen (ppm)</th>
<th>Temperature (°C)</th>
<th>Solubility of oxygen (ppm)</th>
<th>Temperature (°C)</th>
<th>Solubility of oxygen (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>14.6</td>
<td>16</td>
<td>10</td>
<td>32</td>
<td>7.4</td>
</tr>
<tr>
<td>1</td>
<td>14.2</td>
<td>17</td>
<td>9.7</td>
<td>33</td>
<td>7.3</td>
</tr>
<tr>
<td>2</td>
<td>13.8</td>
<td>18</td>
<td>9.5</td>
<td>34</td>
<td>7.2</td>
</tr>
<tr>
<td>3</td>
<td>13.5</td>
<td>19</td>
<td>9.4</td>
<td>35</td>
<td>7.1</td>
</tr>
<tr>
<td>4</td>
<td>13.1</td>
<td>20</td>
<td>9.2</td>
<td>36</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>12.8</td>
<td>21</td>
<td>9</td>
<td>37</td>
<td>6.9</td>
</tr>
<tr>
<td>6</td>
<td>12.5</td>
<td>22</td>
<td>8.8</td>
<td>38</td>
<td>6.8</td>
</tr>
<tr>
<td>7</td>
<td>12.2</td>
<td>23</td>
<td>8.7</td>
<td>39</td>
<td>6.7</td>
</tr>
<tr>
<td>8</td>
<td>11.9</td>
<td>24</td>
<td>8.5</td>
<td>40</td>
<td>6.6</td>
</tr>
<tr>
<td>9</td>
<td>11.6</td>
<td>25</td>
<td>8.4</td>
<td>41</td>
<td>6.5</td>
</tr>
<tr>
<td>10</td>
<td>11.3</td>
<td>26</td>
<td>8.2</td>
<td>42</td>
<td>6.4</td>
</tr>
<tr>
<td>11</td>
<td>11.1</td>
<td>27</td>
<td>8.1</td>
<td>43</td>
<td>6.3</td>
</tr>
<tr>
<td>12</td>
<td>10.8</td>
<td>28</td>
<td>7.9</td>
<td>44</td>
<td>6.2</td>
</tr>
<tr>
<td>13</td>
<td>10.6</td>
<td>29</td>
<td>7.8</td>
<td>45</td>
<td>6.1</td>
</tr>
<tr>
<td>14</td>
<td>10.4</td>
<td>30</td>
<td>7.6</td>
<td>46</td>
<td>6</td>
</tr>
<tr>
<td>15</td>
<td>10.2</td>
<td>31</td>
<td>7.5</td>
<td>47</td>
<td>5.9</td>
</tr>
</tbody>
</table>

\[
\int_{C_o}^{C_t} \frac{dC}{C_s - C} = K_t a_t \int_0^t dt
\]  

(5)

After performing simplification, Eq. 4 takes the form as shown in Eq. 6.

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

(6)

The terms \(C_t\) and \(C_o\) are concentrations of dissolved oxygen after time “t” of process of aeration and at the start of the experiment, respectively. \(K_t a_t\) represents the volumetric coefficient of transfer of oxygen. To get a similar basis for performance comparison of numerous models of aerators, normalization of \(K_t a_t\) is done at standard temperature of 20°C. Dependency on temperature of \(K_t a_t\) has been expressed [6] in Eq. 7:

\[
K_{t(a_t)} \theta = K_t a_t \times \theta^{(2 \theta + T)}
\]  

(7)

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 coefficient of transfer of oxygen at standard condition in litre/seconds is denoted by \(K_{t(a_t)}\) whereas \(K_t a_t\) represents the same quantity at T°C (l/sec), where T is water temperature measured in Celsius scale.
Eq. 8 expresses the jet power per unit volume (expressed in kW/m$^3$) [18].

$$\frac{P}{V} = 0.5\rho Q \nu_j^2$$

(8)

Here density of liquid (water in present case) is denoted by $\rho$ (kg/m$^3$), discharge is represented by $Q$ (m$^3$/s) and $\nu_j$ denotes velocity of jet of water at exit end of nozzle (m/s).

Rate of transfer of Oxygen can be evaluated by Eq. 9 [16].

$$O_R = K_L a(t) \times 3600 \times C_s^*$$

(9)

Where $C_s^*$ represent saturation oxygen concentration in water at 20°C Celsius. Further, efficiency of transfer of oxygen (expressed in kgO$_2$/kWh) for an aerator is expressed as in Eq. 10 [17]:

$$OTE = \frac{O_R V}{P}$$

(10)

4 Methodology

Methodology of aeration is explained in subsequent subsections.

4.1 Experimental Setup and Aeration Device

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 tank bottom 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.
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Figure 1. Schematic diagram of experimental setup

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 was depleted to zero by adding predetermined quantity of sodium sulphite in addition with cobalt chloride acting as catalyst. The pump was 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 was less, we performed the experiment using other model with different opening. After D.O reaching certain limit, it was made zero for next procedure. As D.O depends on various factors, temperature was also recorded. Fifteen numbers of aeration discs having shapes as mentioned in Table 2 were casted with opening area equal to 8%, 12% and 16% of pipe area with dimensions, which was rounded off to one place of decimal to account for limitations of casting. The details of shapes and configurations of solid jet plunging devices are presented in Table 2.

Figure 2. Schematic diagram of a solid plunging jet device
Table 2. Configuration and nomenclature of aeration devices

<table>
<thead>
<tr>
<th>Jet Geometry</th>
<th>Jet Dimension (in mm)</th>
<th>Flow Area of Jet, (A_f) (mm(^2))</th>
<th>Surface Area of Jet per Unit Length, (A_s) (mm(^2))</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elliptical</td>
<td>5.6 2.8 -</td>
<td>8% of area of pipe</td>
<td>27.80</td>
<td>EP/01</td>
</tr>
<tr>
<td>Circular</td>
<td>- - 7.9</td>
<td></td>
<td>24.82</td>
<td>CR/01</td>
</tr>
<tr>
<td>Rectangular</td>
<td>10 5 -</td>
<td></td>
<td>30.00</td>
<td>RT/01</td>
</tr>
<tr>
<td>Square</td>
<td>7 7 -</td>
<td></td>
<td>28.00</td>
<td>SQ/01</td>
</tr>
<tr>
<td>Rectangular with rounded edge</td>
<td>8.4 - 4.2</td>
<td>12% of area of pipe</td>
<td>30.00</td>
<td>RR/02</td>
</tr>
<tr>
<td>Elliptical</td>
<td>7 3.5 -</td>
<td></td>
<td>34.75</td>
<td>EP/02</td>
</tr>
<tr>
<td>Circular</td>
<td>- - 9.7</td>
<td></td>
<td>30.47</td>
<td>CR/02</td>
</tr>
<tr>
<td>Rectangular</td>
<td>12 6 -</td>
<td></td>
<td>36.00</td>
<td>RT/02</td>
</tr>
<tr>
<td>Square</td>
<td>8.6 8.6 -</td>
<td></td>
<td>34.40</td>
<td>SQ/02</td>
</tr>
<tr>
<td>Rectangular with rounded edge</td>
<td>10.4 - 5.2</td>
<td>16% of area of pipe</td>
<td>37.14</td>
<td>RR/02</td>
</tr>
<tr>
<td>Elliptical</td>
<td>8 4 -</td>
<td></td>
<td>39.72</td>
<td>EP/03</td>
</tr>
<tr>
<td>Circular</td>
<td>- - 11.2</td>
<td></td>
<td>35.18</td>
<td>CR/03</td>
</tr>
<tr>
<td>Rectangular</td>
<td>14 7 -</td>
<td></td>
<td>42.00</td>
<td>RT/03</td>
</tr>
<tr>
<td>Square</td>
<td>10 10 -</td>
<td></td>
<td>40.00</td>
<td>SQ/03</td>
</tr>
<tr>
<td>Rectangular with rounded edge</td>
<td>12 - 6</td>
<td></td>
<td>42.85</td>
<td>RR/03</td>
</tr>
</tbody>
</table>

4.2 Digital multi meter
HQ40D [22] portable multi meter is a device which has been designed for measurement of water quality parameters like measuring Conductivity, pH, Salinity, Dissolved Oxygen (DO), TDS, etc. It has capabilities of storing the history of calibration, setting of method and reduces setup time and minimizes errors. Secure connection is obtained between probe and meter and all connections are waterproof. Colour coding of connectors are in-built in the equipment for quick identification. Screen displays measurement information 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 digital multimeter with LDO probe](image-url)
4.3 Experimental Procedure

Pump was run for a identified period of time (one minute to two minutes depending on discharge) after a particular model was placed at appropriate place in aeration device. The procedure of experimentation consisted of determination of discharge of water using electromagnetic flow meter, evaluation of the water temperature, determination of content of dissolved oxygen and measurement of efficiency of transfer of oxygen. Water was sucked by the centrifugal pump at in-let after switching one of the power switch. Regulation of discharge was done using gate valve which was attached just after the pump. In the process, recirculation of water was done through various models of aerator and it plunges into the pool after passing through nozzle opening of aerator. During falling into the pool from aerator, plunging jet swiped air and this air was inducted into the pool after the jet mixes with water through turbulence which was generated as a result of momentum of plunging water jet. Content of oxygen increased in the tank by this procedure. This rise in content of oxygen was calculated in form of dissolved oxygen and efficiency of transfer of oxygen was determined by Eq. 10 as already discussed in preceding section.

4.3.1 Measurement of Discharge

The electromagnetic flow meter attached to C.I pipe displayed the value of discharge during the process of operation of the aerator when centrifugal pump was run. Digital value of discharge was displayed in m$^3$/s.

4.3.2 Measurement of Temperature

Temperature of water is simultaneously measured using D.O. probe of HACH multimeter during the process of measurement of concentration of dissolved oxygen. The temperature and dissolved oxygen concentration at any instant was measured at five places across the tank and average of these reading were taken to provide accurate result.

4.3.3 Dissolved Oxygen Measurement

Measurement of concentration of dissolved oxygen (D.O) in the measurement tank was measured at least thrice for a single experiment. Firstly, the D.O. was measured using the D.O meter before the start of experiment and then according to the available dissolved oxygen in the water, necessary quantities of anhydrous sodium sulphite and cobalt chloride were added to deplete the D.O. to zero or to nearest range and the water was stirred using rod for twenty minutes. Later D.O. was measured to ensure that D.O. of the water in the tank is zero or to nearest range and should be stable throughout the tank. If it was found not stable all through the tank, the water was again stirred for some time to ensure all the chemicals added to water before gets dissolved and then D.O. was measured. After this the pump was started for predetermined time and then the water in the tank was slowly stirred by stirring rod. Probe was connected to the D.O meter and was placed into the water tank. Light at centre of probe indicated that the process was running. After the reading of D.O. meter became stable, dissolved oxygen concentration was noted down from display screen. The same procedure was followed before, during and after the experiment to conclude the value of oxygen induced into pool. Measurement of D.O. was carried out five times for each set of model and discharge and average of these five readings were taken to minimise errors.
4.3.4 Measurement of Oxygen-Transfer Efficiency

After the measurement of concentration of dissolved oxygen and water discharge through aerator, tabulation of the data collected during the experiment was done. Later the efficiency of transfer of oxygen was calculated using Eq. 9 and 10.

5 Results and Analysis

The results of standard oxygen transfer co-efficient (K_La(20)) were plotted for different aerator model with respect to velocity of jet (Fig. 4). It was found that value of K_La(20) rises with escalation in velocity for each set of aerator. However, the rate of increase of standard oxygen transfer coefficient was highest in aerators with rectangular shaped openings having rounded ends and minimum in aerators having square shaped openings. This may be ascribed to the fact that in square shaped openings, flow is obstructed at sharp corners which increases the energy losses. On the other hand, openings having rounded edges minimized losses which resulted in increased aeration. Highest value of K_La(20) was found corresponding to aerator having rectangular shaped opening with rounded edge having area equal to 50.65 mm^2 at a velocity of jet equal to 12.61 m/s and the its value was equal to 3.1×10^{-2} s^{-1}.

![Figure 4. K_La(20) as a function of jet velocity](image)

Fig. 5 shows disparity of oxygen transfer efficiency (OTE) of different models of aerators with respect to velocity of jet. This was observed that with increase in velocity, the oxygen transfer efficiency of all aerator models decrease. This can be ascribed to the fact that with increase in velocity, head loss at exit end increases which increases power required and in turn decreases efficiency. However, at the same value of velocity, the efficiency of transfer of oxygen was observed to be most in aerators having rectangular shaped openings with rounded ends. On the other hand, efficiency of aeration was found to be least at the same conditions for aerators having square shaped openings due to more obstruction to flow at its sharp corners.
On careful observations, it was concluded that at higher value of velocity, effect of opening shape diminishes and at velocities greater than 10 m/s, all aerators depicted similar efficiency of oxygen transfer. Highest value of OTE was obtained for aerator having rectangular shaped opening with rounded edge corresponding to velocity of 1.1 m/s for aerator having area of flow equal to 12% of area of pipe.

6 Conclusion

Based on the current study, following conclusions can be drawn:
- Oxygen transfer into a pool depends on velocity of jet, jet power, amount of oxygen already present in the pool of water, water quality and shape of opening of aerator.
- With increase in velocity of aerator, rate of transfer of oxygen increases but efficiency of aerator decreases.
- Aerators having square shaped openings produce least oxygen transfer whereas aerators having rectangular shaped openings with rounded ends produce highest oxygen transfer.
- Highest value of oxygen transfer in the current set of experiment was obtained corresponding to aerator having rectangular shaped opening with rounded edge having area of opening equal to 50.65 mm² at a jet velocity of 12.61 m/s and the its value was measured to be equal to $3.1 \times 10^{-2}$ s⁻¹.
- Highest oxygen transfer efficiency was obtained for aerator having rectangular shaped opening with rounded edge corresponding to velocity of 1.1 m/s for aerator having area of flow equal to 12% of area of pipe.
- Oxygenation efficiency for aerators corresponding to area of 12% of pipe area was found to be more than that corresponding to aerators having 8% and 16% area.
References


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Biographies

Bishnu Kant Shukla, born in February 1986, graduated from JSS Academy of Technical Education, Noida and post graduated from National Institute of Technology, Kurukshetra India in field of civil engineering and currently pursuing Ph.D. in environmental and water resources engineering. He is working as Assistant Professor in School of Civil Engineering, Lovely Professional University, Phagwara, Punjab, India. He is having a total experience of 6 years in administration, teaching and research. He is having his areas of interests like environmental and water resources, green buildings, transportation system modeling, pervious concrete, energy efficient buildings, water and wastewater treatment technologies, environmental designs, water resource management, river pollution control and industrial wastewater treatment etc. In addition to teaching, he has served and officiated administrative designations like Academic Counselor and Warden. He has been the author of more than 20 International/National Conference research papers and published 7 journal papers. He has also authored two book chapters. Two of his conference papers were awarded best paper award. He is reviewer of Applied Water Science of Springer Nature, Journal of Environmental Chemical Engineering of Elsevier and Mediterranean Journal of Chemistry and has reviewed many papers of these journals. He has guided 14B.Tech level projects on various topics of civil engineering. He has submitted one project proposed to be funded from DST, India. He has attended many workshops of international and national repute. He is life member of Indian Science Congress Association.

Amsal Khan has done B.Tech in civil engineering from Lovely Professional University, Phagwara, Punjab. His areas of interest are wastewater management, green engineering and energy efficient buildings.
Gopalam Saikiran has done B.Tech degree in civil engineering from Lovely Professional University, Phagwara, Punjab. His areas of interest are environmental engineering, green engineering, energy efficient buildings etc.

Macherla Sriram has done B.Tech degree in civil engineering from Lovely Professional University, Phagwara, Punjab. His areas of interest are environmental engineering, wastewater management and energy efficient buildings.