Determination of Standard Oxygen Transfer Rate in Venturi Aeration System

Anamika Yadav¹, Avinash Kumar¹, Sudipto Sarkar¹

¹Department of Agricultural Engineering, Triguna Sen School of Technology, Assam University, Silchar, Assam, India

E-mail: anamika.iit26@gmail.com

Abstract. The oxygen transfer is the process of atmospheric oxygen diffusion from a gas stage to a liquid stage in the form of dissolved oxygen (DO). The previous research works have successfully proven that the DO concentration level effortlessly rises by adopting a venturi as an aeration method in aquatic bodies. Present experimental study was conducted on laboratory scale aeration tank with two different sizes of venturi (40 and 80 mm throat length). The objective of the current study was to determine the oxygen transfer coefficient at different discharge rates through venturi aeration system. The system was operated with three different discharges of 0.50, 0.58 and 0.67 liter/second (l/s) to circulate 200 liter volume of water, was aimed for circulation in a closed loop system. During the operations, water moves through the inlet section into the contract section of the venturi, which increases the rate of water flow and reduces the pressure as per the Bernoulli’s theorem. In order to study the oxygen transfer coefficient at varying discharge, the system worked by a single hole and accordingly applied to the larger number of holes for both the throat lengths of venturi. It was observed that the oxygen transfer coefficient proportionally linked to the DO diffusion with increasing rate of discharge. The oxygen transfer coefficient found to be increased by 31% and 55% at 40 and 80 mm throat length respectively, with increasing the discharge. The rate of DO diffusion found higher causes more surface area of contact between air and water through maximum air entrainment. Moreover aeration efficiency also increases with the rate of increasing discharge for the maximum size of throat length. The maximum SOTR values was obtained 0.0035, 0.0041, and 0.0050 kgO₂/h at varying discharge of 0.50, 0.58 and 0.67 l/s respectively for 40 mm throat length. For the 80 mm throat length, the SOTR values varies from 0.0042, 0.0062 and 0.0091 kgO₂/h at increasing discharge of 0.50, 0.58 and 0.67 l/s respectively with increasing number of holes.

1. Introduction
The dissolved oxygen concentration (DO) is very crucial for the production of aquatic species in aquacultural systems. By incorporating any aerator in water course, sufficient amount of oxygen can be infused which promotes growth and productivity [1]. Such methods are incredibly helpful in maintaining sufficient DO concentration which positively impact the survival of aquatic species from around 29.0 % to 81.8 % [2] and also for enhancing water quality [3]. The aeration method naturally or artificially blends air and water together and raises the interface area between them, to allow more oxygen distribution at that moment and also to prevent stratification to water bodies [4]. Venturi aeration is very apt technology that stimulates high yielding and healthy global environment by maximizing the DO concentration in intrinsic water bodies [5, 6]. It has perfect combination of productivity, low cost, reliable production, high volume of distribution, low power consuming, more efficient, required less than 20 % differential to initiate vacuum and also the venturi system have a long operating life [7]. Venturi has three different sections: converging, throat, and diverging section, as shown in figure 1. Each section of venturi has a significant aspect in the aeration process. The venturi has been developed to mix air and water before inserting into the mass liquid at its maximum restricted point [6]. The study of [8] has asserted that, in accordance with the Bernoulli principle, when the flowing liquid has been accelerated to the high velocity stage, the static pressure drastically false at the constricted point of venturi. The throat section (constricted portion) of venturi produces vacuum, which draws air into the liquid. A negative pressure drags atmospheric air through the holes presents in the throat or in the way of outlet section to the bulk liquid [9].
A bulk of experimental studies has been conducted on the numerous venturi designs under different circumstances. Air entrainment and oxygen transfer relies on numerous geometric parameters of the venturi designs adopted by various researchers, such as, length of the throat, diameter of air hole, flow velocity, inlet and outlet angles [5, 10, 11 and 12]. Many of the researchers have performed their work by selecting the appropriate parameters intended for performance evaluation of the aeration systems; in the study of [13] and [14] they worked by using the overall oxygen transfer coefficient as a typical parameter of the aeration system whereas the study by [15] have elected the individual standard oxygen transfer efficiency. The effect of geometrical parameters on the performance of a venturi type bubble generator has been conducted by [16]. Three different significant parameters were analyzed including the diameter of air injection hole, number of air holes and the varying angle. The effect of a converging angle on the air entry rate can be described by the sum of radial flow generated in the suction chamber and the pressure force flowing through the nozzle and throat portion [17]. The experimental research conducted by [5] on the air entry rate and oxygen transfer efficiency with air holes along the length of converging-diverging waterway in the venturi nozzle, mainly the impact of variable numbers, positions, and open/close status of the air holes. Additional study on the plunging water jet by [18] have been conducted on the air entrainment features of a plunging water jet system utilizing rectangular nozzles of rounded ends. Furthermore, a combine research by utilizing a venturi nozzle with plunging water jet aeration system was examined by [9] they have analyzed the impact on the intensity of air entry rate by changing the diverging cone angle and diverging length of venturi tube. In the study of [19] examined the influences of contract nozzle angle of a vertical plunging water jet on air entrainment. Emiroglu and Baylar asserted that air entrainment occurs when there is a change from laminar flow to turbulent flow in jet, characteristically described in terms of Reynolds numbers. However the entrainment rate not individually depends on the Reynolds number but similarly on the nozzle model [20]. The experimental study was conducted by [21] on the performance of venturi with varying numerous geometric parameters to determine the standard aeration efficiency value. It can be seen from the result that the highest value of standard aeration efficiency was obtained 1.166 kg O$_2$/kWh for venturi aeration with a nozzle diameter of 14 mm, aeration depth of 60 cm and the venturi tube angle of 45°. To acquire the advantages in order to improve the aeration efficiency, two separate aerator modules structures (parallel and series connected) were tested by [22]. The aeration efficiency calculated on the basis of oxygen transfer coefficient, and the values attained by [22] were 0.07, 0.06, and 0.06 kg O$_2$/kWh for the module where three venturies are connected in series, and 0.14 and 0.10 kg O$_2$/kWh for the module where two venturies were connected parallel. It was observed by [23] in his study that, the aeration efficiencies varies with the position of venturi nozzles in the water column at various depths.

In the present study, the adaptation of venturi of two different sizes has been made for aeration to observe the experimental investigation of oxygen transfer coefficient under laboratory conditions at varying discharge rates.
2. Oxygen Transfer Mechanism

Two-film theory [24, 25 and 26] has been a significant theory used for evaluating the oxygen transfer rate. The process of oxygen diffusion includes the transition of atmospheric oxygen mass transfer from gas stage to liquid stage, which is a three step process as shown in figure 2. The following assumptions were made for the development of two-film theory: laminar flow along both sides of the gas-liquid interface, steady state conditions and instantaneous establishment of equilibrium conditions between gas-liquid phases at the interface [25]. The mass transfer through diffusion is typically given by the equation (1) as:

$$\frac{dM}{dt} = -D_L \cdot A \cdot \frac{dC}{dy}$$  \hspace{1cm} (1)

where \(\frac{dM}{dt}\) is the rate of mass transfer by diffusion (kg/s); \(A\) is the cross-sectional area through which diffusion occurs (m²); \(D_L\) is the oxygen molecular diffusion coefficient in water (m²/s) and \(\frac{dC}{dy}\) represents the concentration gradient of oxygen in the direction perpendicular to the cross-sectional area (kg/m³/s). The differential form of oxygen mass transfer coefficient at \(T \degree C\) can be expressed as following according to the two-film theory:

$$\frac{dC}{dt} = K_{LaT}(C^* - C)$$  \hspace{1cm} (2)

where, \(K_{LaT}\) is the total volumetric oxygen transfer coefficient at some \(T \degree C\) temperature; \(t\) is the time; \(C\) is the liquid-phase oxygen concentration; and \(C^*\) is the equilibrium liquid-phase oxygen concentration.

The combined form of equation (2) can be stated in exponential form and expressed as follows [27]:

$$K_{LaT} = \ln(C_x - C_0) - \ln(C_x - C_t)$$  \hspace{1cm} (3)

where, \(ln\) signifies a natural logarithm and \(C_x, C_0\) and \(C_t\) are the dissolved oxygen concentrations in parts per million (ppm). \(C_s\) is the saturation oxygen concentration, \(C_0\) is the initial oxygen concentration and \(C_t\) is the oxygen concentration at time \(t\). \(K_{LaT}\) is also standardized to a standard temperature value of 20 \(\degree C\) to deliver a clear source for comparing different systems. Equation (4) defines the performance of venturi aeration in oxygen transfer efficiency with the effect of temperature [28].

$$K_{La20} = K_{LaT} \times \theta^{(20-T)}$$  \hspace{1cm} (4)
The aerator capability to transfer off oxygen from atmosphere to water is evaluated through standard oxygen transfer rate (SOTR) by [28]. SOTR is the amount of oxygen transfer into the water body per unit time at the standard conditions of 20 °C water temperature, 0 mg/l initial DO concentration, one atmospheric pressure, and clear tap water [29]. SOTR can be determined as follows:

\[
SOTR = K_L a_{20} \times (C_s - C_0) \times V \times 10^{-3}
\]

where, \(C_s\) is the saturation concentration of DO at 20 °C, \(V\) is the volume of water (m³), SOTR is the standard oxygen transfer rate (kgO₂/h).

3. Materials and Methods

The experimental set-up and the method employed to fulfill the requirement of the present study was organized in the Agricultural Engineering Department of Assam University Silchar, India for the assessment of the venturi performance on SOTR. The detailed information of the experimental setup, specification of venturi, the experimental procedure and the experimental design is given below.

3.1 Experimental Setup

A 200 liter capacity of water tank having dimensions of 90 cm × 55 cm × 49 cm (length × breadth × depth) was used for determining the venturi aeration performance on the SOTR. The experimental setup involves a water tank, axial flow pump, venturi unit, valves, and water meter linked with the pipe fittings for circulation of water through a closed loop as shown in figure 3. The venturi unit is supported by another supporting structure and is being operated by a 1.02 HP axial flow pump.

![Figure 3. Line diagram of experimental setup](image)

3.2 Specifications of Venturi

The work began with the fabrication of different venturi parts. The fabricated venturi was made of 5 mm thick aluminum, which could be dismantled from each other as shown in figure 4 with three substantial parts (converging, throat and diverging section). The length and diameter for both the sections of converging and diverging were kept equal as 113 mm and 60 mm respectively. The converging and diverging angles were kept at 10°. Two different sizes of throat length i.e. 40 mm and 80 mm were selected with 5 and 13 number of holes with 2 mm diameter respectively; the holes are kept at an equal interval of 5 mm, which signify the difference between two adjacent air holes as presented in figure 5. The diameter of throat section was kept 20 mm constant.
3.3 Experimental Procedure

The venturi operated by an axial flow pump, which is used to circulate the clean tap water throughout the experiments of venturi under laboratory conditions. Water flowing starts from converging to the throat section, which allows the water flow rate to increase and pressure decreases. Due to the pressure variation the transition of oxygen from air to water continues through the air holes further moves towards the outlet section [30]. For each experiment, the non-steady re-aeration study was carried out to deoxygenate the water [31]. In every experiment, for reducing each mg/l of DO, the clean tap water used to deoxygenate through a solution of 10 mg sodium sulphite (Na2SO3) and 0.1 mg cobalt chloride (CoCl2) as a catalytic agent per liter water tank volume [3, 25]. Subsequently for the DO concentration measurements during the experiments, the EXTECH dissolve oxygen meter 407510 is mounted at the base of the tank by the installation of luminescent dissolved oxygen (LDO) sensor. During the experiments, DO readings and temperature were taken regularly at equal intervals up to DO concentration reaches 80% saturation. For each noted value of the DO concentration, the DO deficit values were also determined. The oxygen transfer coefficient was determined from the most appropriate gradient line produced by graphical compression between natural logarithms for DO deficits on the Y axis, and the aeration period on the X-axis, which has been adjusted by temperature correction factor of 20 °C at the examining water temperature [32]. Moreover, the values of $K_{La}$, $K_{La20}$ and SOTR were calculated by using equation (3), (4) and (5) respectively. Since this study was carried out in the lower part of the Assam (Silchar) and a large number of impurities i.e. iron and fluoride are found in groundwater beyond its permissible limit. Even after the purification of groundwater, some impurities remained in the tap water. During the experiments, some difficulties were faced to get the clean tap water and the purification of tap water again conducted.

3.4 Experimental Schedule

In the present study, the determination of oxygen transfer coefficient has been done with two sets of venturi (40 mm and 80 mm throat length) at three different pump discharge rates i.e. 0.50, 0.58 and 0.67 l/s, respectively. The discharge rate of pump was varying with valve fixed in all the sets of experiments. Mainly the experiments were performed with a single hole and consequently expanded to a larger number of holes for both the throat length of venturi. A total 54 number of experiments were conducted with varying the discharge rate. The schedule of experiments for venturi aerator is given in Table 1.
Table 1. Schedule of experiments of venturi aerator.

| Set of experiments | Pump Discharge (l/s) | Throat Length (mm) | Variation of number of air holes |
|--------------------|----------------------|--------------------|----------------------------------|
| Set-I              | 0.50                 | 40                 | 1 to 5                           |
|                    |                      | 80                 | 1 to 13                          |
| Set-II             | 0.58                 | 40                 | 1 to 5                           |
|                    |                      | 80                 | 1 to 13                          |
| Set- III           | 0.67                 | 40                 | 1 to 5                           |
|                    |                      | 80                 | 1 to 13                          |

4. Result and Discussion

The experimental results representing the deviations of ln \((D_{O_2}-D_{O})\) over time to determine the oxygen transfer coefficient at different discharge rate is shown in figure 6. It can be seen in the figure 6 that, the \(D_{O}\) absorption rises with declining the \(D_{O}\) deficit \((D_{O_2}-D_{O})\) until it reaches to the saturation level at which the oxygen dissolution rate is equivalent to the intake rate of dissolved oxygen. It was also found that at maximum discharge, the distribution of \(D_{O}\) concentration is reached more rapidly than the lower discharge rate.

Moreover, the effect of discharge on the oxygen mass transfer coefficient for 40 mm and 80 mm throat length is presented in figure 7 (a & b). The magnitude of overall oxygen mass transfer coefficient rises with increasing the air holes for each throat length of venturi. Also, a similar trend of increment was found for the oxygen mass transfer coefficient at increasing discharge rate. In general, the overall oxygen transfer coefficient is the combined form of area interface between two phases (air and water phase) and the oxygen transfer coefficient. In this specific venturi aeration, the air entrainment rate fluctuates with number of holes, which leads to increase more surface area interaction between air and water. This could be due to the large amount of holes that maximize the performance of the aeration device and creates higher ambient oxygen dispersion. Hence, the collective result has contributed to a consistent increase in overall oxygen transfer coefficient for venturi aeration with increasing discharge rate, which delivers a proportionate relation with \(D_{O}\) diffusion. The overall oxygen transfer coefficient raises 31% and 55% from 0.50 to 0.67 l/s discharge range for 40 and 80 mm throat length respectively. Table 2 provides the comprehensive findings for \(K_{LaT}\), \(K_{La20}\) and \(SOTR\) values according to the experimental sets.
In order to see the impact of discharge on DO diffusion, the each set of experiments were carried out by varying the discharge with two different throat lengths as mentioned in Table 1. Figure 8 and 9 shows the experimental result on the DO diffusion over aeration time at three different operating conditions for 40 and 80 mm throat length. It can be found from the figure (8 and 9) that DO concentration proportionally rises with time. The maximum DO diffusion occurs with the maximum discharge (Q= 0.67 l/s) for both the throat lengths of venturi with in minimum time. The experiments were conducted until the DO reaches 80 % of saturation level at the specific temperature of experiment. The high concentration of DO was found at 6.30 mg/l in 19 min for discharge 0.67 l/s with maximum 13 numbers of air holes and 80 mm throat length. Similarly, at each operating discharge, it was observed that the DO diffusion follows almost similar trend for each hole of 40 and 80 mm throat length.

It can be observed from Table 2 that the SOTR values are equally growing for each experimental set with the increasing number of holes. The variation of SOTR with different water discharge (0.50, 0.58 and 0.67 l/s) for two different size of venturi is illustrated in figure 10 and 11. The result indicates that the minimum SOTR was obtained with the minimum discharge of 0.50 l/s for both the sizes of venturi. It can be seen that the SOTR keeps on increasing with increasing discharge throughout the experiments. Also a similar trend was found in relation to the number of holes of 40 and 80 mm throat length. For the particular 40 mm throat length, the SOTR range varies between 0.0033-0.0035 kgO₂/h, 0.0037-0.0041 kgO₂/h, 0.0041-0.0050 kgO₂/h at increasing discharge of 0.50, 0.58 and 0.67 l/s respectively with increasing number of holes.

The maximum SOTR values were calculated 0.0035, 0.0041, and 0.0050 kg O₂/h at different discharge of 0.50, 0.58 and 0.67 l/s respectively for 5 numbers of hole and 40 mm throat length. Also for the 80 mm throat length, the SOTR values varies from 0.0028-0.0042 kgO₂/h, 0.0029-0.0062
kgO₂/h, 0.0036-0.0091 kgO₂/h at increasing discharge 0.50, 0.58 and 0.67 l/s respectively with increasing number of holes. It can be said that the maximum number of holes are able to improve the SOTR for all discharge rate. And the maximum SOTR values found as 0.0042, 0.0062 and 0.0091 kgO₂/h at discharge 0.50, 0.58 and 0.67 l/s respectively with 13 number of hole. With increasing the discharge rate from 0.50 to 0.67 l/s leads to an increase in the SOTR by 30.14 % and 54.12 % for 40 and 80 mm throat length.

![Figure 10. Variation of SOTR with different discharge rate at particular throat length 40 mm](image)

![Figure 11. Variation of SOTR with different discharge rate at particular throat length 80 mm](image)

### Table 2. Experimental result of venturi aeration

| Throat Length | Number of Holes | K_{L,T} (h⁻¹) | K_{L,A2O} (h⁻¹) | SOTR (kgO₂/h) |
|---------------|-----------------|----------------|-----------------|---------------|
|               | 0.50 l/s | 0.58 l/s | 0.67 l/s | 0.50 l/s | 0.58 l/s | 0.67 l/s | 0.50 l/s | 0.58 l/s | 0.67 l/s |
| Hole 1         | 2.100   | 2.389   | 2.623   | 1.800   | 2.062   | 2.269   | 0.0033   | 0.0037   | 0.0041   |
| Hole 2         | 2.129   | 2.501   | 2.692   | 1.843   | 2.154   | 2.348   | 0.0033   | 0.0039   | 0.0043   |
| Hole 3         | 2.209   | 2.528   | 2.924   | 1.875   | 2.162   | 2.501   | 0.0034   | 0.0039   | 0.0045   |
| Hole 4         | 2.206   | 2.572   | 2.954   | 1.895   | 2.174   | 2.575   | 0.0034   | 0.0039   | 0.0047   |
| Hole 5         | 2.555   | 2.674   | 3.251   | 1.919   | 2.273   | 2.748   | 0.0035   | 0.0041   | 0.0050   |
| Hole 6         | 1.797   | 1.824   | 2.283   | 1.529   | 1.573   | 1.966   | 0.0028   | 0.0029   | 0.0036   |
| Hole 7         | 1.786   | 2.033   | 2.375   | 1.534   | 1.755   | 2.034   | 0.0028   | 0.0032   | 0.0037   |
| Hole 8         | 1.801   | 2.022   | 2.810   | 1.543   | 1.739   | 2.352   | 0.0028   | 0.0032   | 0.0043   |
| Hole 9         | 1.871   | 2.101   | 2.753   | 1.581   | 1.763   | 2.338   | 0.0029   | 0.0032   | 0.0042   |
| Hole 10        | 1.845   | 2.534   | 2.782   | 1.585   | 2.047   | 2.368   | 0.0029   | 0.0037   | 0.0043   |
| Hole 11        | 1.841   | 2.653   | 2.889   | 1.590   | 2.263   | 2.467   | 0.0029   | 0.0041   | 0.0045   |
| Hole 12        | 1.954   | 2.849   | 3.244   | 1.636   | 2.402   | 2.774   | 0.0030   | 0.0044   | 0.0050   |
| Hole 13        | 2.121   | 2.925   | 3.455   | 1.797   | 2.519   | 2.965   | 0.0033   | 0.0046   | 0.0054   |
| Hole 14        | 2.335   | 3.347   | 3.778   | 1.983   | 2.815   | 3.207   | 0.0036   | 0.0051   | 0.0058   |
| Hole 15        | 2.422   | 3.420   | 3.785   | 2.086   | 2.949   | 3.221   | 0.0038   | 0.0053   | 0.0058   |
| Hole 16        | 2.493   | 3.430   | 3.893   | 2.142   | 2.944   | 3.341   | 0.0039   | 0.0053   | 0.0061   |
| Hole 17        | 2.545   | 3.482   | 4.450   | 2.208   | 2.985   | 3.828   | 0.0040   | 0.0054   | 0.0069   |
| Hole 18        | 2.671   | 3.928   | 5.954   | 2.305   | 3.395   | 5.025   | 0.0042   | 0.0062   | 0.0091   |

5. Conclusion and Future Work

The aeration performance in laboratory was estimated at varying discharge rate with two different size of venturi. It can be concluded that the performance of the venturi varies with the increasing discharge rate. The overall oxygen transfer coefficient was found maximum at higher discharge rate with the large size of throat length. Also the respective values of SOTR follows a similar trend for both the sized of
venturi with increasing discharge rate. Accordingly the aeration can be improved with increasing the size of venturi for the maximum number of holes. Therefore it can be concluded that number of holes on the throat section of venturi plays a major role in the aeration. This work can be further extended by altering the size and angle of the converging and diverging section to determine the influences on the aeration efficiency of the venturi aeration system.

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