Dicle University
Journal of Engineering
https://dergipark.org.tr/tr/pub/dumf
duje.dicle.edu.tr

Research Article

Experimental study on the aeration performance of water jet which is performed by a venturi device

Şermin KOÇYİĞİT[1*], Muhammet Emin EMİROĞLU[2]

[1] Dicle University Construction Technology Department, serminkocyigit01@gmail.com, Orcid No: 0000-0002-7283-8967

[2] Firat University, Civil Engineering Department, memiroglu@firat.edu.tr, Orcid No: 0000-0002-3603-0274

ARTICLE INFO

Article history:

Received 2 November 2023
Received in revised form 22 November 2023
Accepted 24 November 2023
Available online 29 March 2024

Keywords:

Water jet, venturi, aeration, oxygen transfer, nozzle

Doi: 10.24012/dumf.1385014

* Sorumlu Yazar

ABSTRACT

The purpose of aeration in water is to transfer or remove gases from the water. Dissolved oxygen is critical for living life. In water engineering, aeration and oxygen transfer using water jets are common. In this study, various venturi nozzles with air holes in the throat portion were manufactured and meaningful experiments were conducted to determine their oxygen transfer efficiency and aeration performance., the venturi nozzles with throat diameters 14, 17 and 20 mm were used in the experimental study. The ratio of the diameter of the air holes to the diameter of the throat portion is taken as 0.1, 0.2 and 0.3. Different experiments were carried out for nine different hole diameters. In addition, the ratio of the throat portion length to the throat portion diameter was taken as 1.00 and 0.50. For all nozzles, the ratio of outlet length to outlet diameter was taken as 1 and 2. In addition, comprehensive experiments were carried out for a venturi, considering the ratio of outlet length to outlet diameter as 1, 2, 3, 4 and 5. The experiments were also conducted for the circular nozzle to make comparisons. In this study, venturi nozzles gave better results than circular nozzles, and higher aeration performance values were obtained for the ratios 0.2 and 0.3, 1, 0.50 and 0.50. It was found that the aeration performance of the venturi nozzle was approximately 6.5 times higher than the air entrainment rate performance of the circular nozzle and 2.5 times higher in terms of oxygen transfer.

Introduction

One of the important parameters in terms of water quality is dissolved oxygen concentration. Oxygen is used in many biological activities and chemical reactions occurring in water. Thus, the dissolved oxygen concentration in the water tends to decrease. The process of replacing this decreasing amount is made possible by oxygen transfer, in other words, by taking oxygen from the atmosphere and returning it to water. Aeration of water is needed in the removal of volatile organic compounds in water, in cases where oxygen is required to be supplied to the system in case of decreased dissolved oxygen concentration in ponds, reservoirs or rivers, in the removal of gases that cause bad taste and odour in water, in the removal of carbon dioxide dissolved in water, in cases such as supplying oxygen to the system in biological treatment [1, 2].

There are different aeration systems. Unlike conventional aerators known as mechanical aerators and compressed air diffusers in ventilation units, water jet aeration systems are also commonly used [1, 2]. There is no need for an air compressor in the aeration system with water jet. Water jets are easy to operate and require very little maintenance. They also ensure a good mixing in the receiving pool [1, 3, 4].

Free water jets are impinged in a perpendicular or angled manner to the water surface. Thus, it is ensured that the air in the atmosphere is transferred into the water by entraining the air bubbles with water. It is possible to see this phenomenon in free-falling structures in nature (such as streams flowing in mountainous regions, cascades, waterfalls). In addition, such phenomena are also encountered in dam spillways, weir flows and sluice outlet structures. In many hydraulic structures such as stepped spillways, energy dissipation is realised while aeration can also be performed at the same time. Water jets are used in aeration (removal of gases such as carbon dioxide, hydrogen sulphide, methane dissolved in water), flotation, oxygen transfer, waste water treatment, as well as metal cutting, metal cooling, marble cutting.

In natural phenomena, water jets play an important role in the entrainment of air, the transmission and distribution of entrained air in the form of air bubbles in the water body, and the provision of an effective air-water contact surface. In practical applications, jet aerators are used in chemical engineering to improve mixing processes and gas-liquid transfer, and in environmental engineering for drinking water treatment plants and where oxygen transfer is required [1-4].

Canepa and Hager [5] investigated the effect of air mixing when examining scour from water jets. They stated that the more air bubbles are mixed into the downstream pool with the water jet, the less the scour depth decreases. Emiroglu and Baylar [6] opened air holes close to the exit point of the classical circular nozzle and experimentally investigated the effect of this on aeration efficiency (i.e., air entrainment rate). The holes created negative pressure and changed in the impact point the shape of the jet. In this way, more air bubbles were entrained into the receiving pool. They found that the nozzle with holes on it has more aeration efficiency than the nozzle without air holes. Emiroglu and Baylar [7] investigated the aeration efficiency of the venturi nozzle. They drilled longitudinal holes at different points of the venturi nozzle and analysed their effects. These holes are drilled both in the throat portion and in the diverging cone and converging cone zones. As a result of the experiments, it was found that more aeration efficiency was obtained in case of a hole in the throat portion. Baylar and Emiroglu [8] conducted a series of experiments for a venturi nozzle with air holes in the throat portion. In this way, they determined that the shape of the jet changed. In this case, they determined that much more aeration efficiency was obtained. Out et. al. [9] conducted a number of physical experiments using a single-hole, elevated bucket to generate a stream that falls into the receiving pool. The main variables, hydraulic flow, hole diameter and height of drop were varied in an applied area. A video was shot to examine the bubble penetration depth. Regression equations were developed to predict bubble penetration depth and statistical variation. The standard deviation regression equation can be used to estimate the statistical variation of the bubble penetration depth. The bubble penetration depth decreased with increasing height of drop and remained constant at a height of drop of 50 cm. Penetration depth increased with increasing hole diameter for all height of drop and hydraulic flows. Yamagiwa et. al. [10] investigated the effect of nozzle contraction angle on the air entrainment rate of a vertical liquid jet. Jet surface roughness increases with increasing nozzle contraction angle up to 40º. The volumetric air entrainment rate increases according to $\sin\theta=0.21$, similar to the increase in jet surface roughness. For each power consumption, air entrainment rate and nozzle contraction angle were also analysed. They stated that the power efficiency of air entrainment was almost independent of the nozzle shrinkage angle. Bin [11] gave a comprehensive review of the possible results of existing experimental and theoretical studies on gas entrainment in liquid jets. The author gave detailed presentations on bubble propagation characteristics such as bubble volume, bubble penetration depth, bubble settling time, gas retention; mechanisms; initial conditions of gas entrainment; amount of entrained gas and mass transfer. In his article, he made a compilation of all articles on the subject. His work has been cited in over 50 references. Practical applications of jet aeration in the waste treatment, fermentation and flotation industries and their aeration performance in comparison with known conventional aeration systems are also included.

Kusabiraki et. al. [12] experimentally investigated the interactions in the air entrainment rate (Q_A) when the nozzle length to diameter ratio (L/D) takes different values for an inclined jet aeration system using low viscosity fluid. The changes in Q_A were related to the pre-impact jet shape and the propagation of the liquid velocity at the point of gas dispersion. An empirical equation was presented to predict the penetration depth of the air bubble entrained by the jet propagation. The behaviour of bubble entrainment was also reviewed in terms of the volume of the entrained bubble and the rate distribution of the impacting liquid. Sene [13] conducted a series of theoretical and experimental studies on the mechanism of water jets. Taking into account the work of other authors, he suggested that the air entrainment mechanism undergoes a qualitative change with increasing jet impact rate (U_i). Different models of air entrainment rates (Q_A) in low and high rate systems are presented and it is seen that both theoretical and experimental results give values of $Q_A \sim U_i^3$ at low rate and $Q_A \sim U_i^{3/2}$ at high rate. Quantitative predictions of Q_A in high-rate jets were consistent with experimental results. Van de Sande and Smith [14] presented a theory of aeration caused by the impact of a high rate water jet on the water surface. Experimental study provided a more satisfactory compliance than theory developed over a wide area. The boundary conditions of the theory have a physical meaning. The jet must submit to the air friction coefficient ($W_e>10$) and the accompanying air boundary layer must be laminar ($Re_L<5\times10^5$). In the case of a turbulent boundary layer, the same type of analyses can be used, but only if reliable solutions suitable for that layer cannot be found. Zhang and Zhu [15] experimentally investigated the trajectories of bubbling jets in cross flow by vertically injecting air-water mixtures through a circular nozzle. Based on dimensional analysis, they developed a semi-empirical relationship to predict the separation height of bubbly jets with strong initial momentum. The centreline trajectories of both water and air phases of the bubble jets were investigated. They observed that it decreased significantly after the separation of bubbles from water jets. Khound et. al. [16] investigated the aeration efficiency of the venturi device. The authors stated that the aeration performance of the venturi device was very high. Shukla et. al [17] made a review study about the aeration process of water using water jets. The authors found that water jets had a good performance in aeration and oxygen transfer of water and wastewater treatment plants. Yadav et al. [18] conducted an experimental study on the design of venturi aeration systems. Puri et al. [19] made a review article on the use of venturi ducts, venturi nozzles, weirs, cut-and-cover areas in aeration and oxygen transfer. In their study, the authors evaluated the aeration performance of such hydraulic structures by using artificial intelligence techniques. Dange and Warkhedkar [20] conducted an experimental study to determine the efficiency of venturi aeration systems. In this study, standard oxygen transfer efficiency (SOTR), standard aeration efficiency (SAE), volumetric oxygen transfer coefficient of the venturi system (K_La20) parameters was analysed in detail. In conclusion, the authors emphasised that the venturi device was a very suitable weight for aeration. Yadav and Roy [21]; Reda Hamed [22]; Ochoa [23] also investigated the aeration efficiency of the venturi device.

The aeration performance of the venturi device was analysed in detail according to d/D (the ratio of the diameter of the throat portion to the outlet diameter), ℓ / d (the ratio of the length of the throat portion to the diameter of the throat portion), h_d / d (the ratio of the diameter of the air hole opened in the throat portion to the diameter of the throat portion) and L/D (the ratio of the length of the outlet section to the outlet diameter) in order to obtain design criteria different from the literature. In the studies in the literature, circular cross-section nozzles are mostly used as water jet nozzles. The length of the throat area of the venturi device, the variation of the length of the outlet part, the variation of the diameter of the hole opened in the throat portion and thus their aeration efficiency was investigated.

Theoretical Information

Gas transfer in water is carried out for different purposes. Air entrainment rate and oxygen transfer are carried out in order to add chlorine to the water, to increase the dissolved oxygen concentration or to remove gases such as carbon dioxide and hydrogen sulphide from the water. The solubility of a gas in water depends on the type of gas, pressure, temperature of water and concentration of pollutants in water. Gas transfer occurs at the interface between the liquid and gas phases. This transfer process continues until equilibrium is achieved between the liquid and the gas. When equilibrium is achieved, the gas concentration in the liquid reaches saturation [1-4].

$$\frac{dC}{dt} = K_L \frac{A}{V_w}(C_s - C) \tag{1}$$

where; $C_s = P_a / H$ and is the saturation concentration of oxygen in water. The term A/V_w is often replaced by "a", which indicates the specific interface surface.

If C=C_o and C=C in Equation (1) are integrated for t=0 and t=t, it is

$$\int_{C_o}^{C} \frac{dC}{C_s - C} = (K_L a)\int_{o}^{t} dt \tag{2}$$

From the solution of this equation;

$$\ell n\left(\frac{C_s - C_t}{C_s - C_o}\right) = -(K_L a)t \tag{3}$$

is obtained. Where; C_o and C_t= oxygen concentrations of water at the beginning and at time t, K_La= mass transfer coefficient. According to Equation (3), the values of K_La are obtained by using t time against $-\ell n\left(\frac{C_s - C_t}{C_s - C_o}\right)$ on a semi-logarithmic paper. K_La is normalised at 20 ºC for comparison in different systems.

$$(K_L a)_{20} = (K_L a)_T (1.024)^{(20-T)} \tag{4}$$

Oxygen transfer efficiency is defined as the ability of the structure to provide oxygen to reach the saturation concentration of water, i.e., the performance of the aeration device. The greater the oxygen transfer efficiency, the higher the efficiency of the aeration. In other words, the higher the aeration efficiency of the system, the higher the oxygen transfer efficiency. Oxygen transfer efficiency is calculated by the following equation [1-4].

$$OE = \frac{OR.V_w}{N_j} \tag{5}$$

$$OR = (K_L a)_{20} C_s^* \tag{6}$$

$$N_j = \frac{1}{2}\rho Q_w V_j^2 \tag{7}$$

where; OE is the oxygen transfer efficiency (kgO_2/kw-hour), oxygen transfer rate at 20ºC and 1 atm pressure (mg/ℓ/hour), Nj is the net power of the jet (W), V_w is the water volume (m^3), C_s^* is the saturation concentration of dissolved oxygen (mg/ℓ), Q_w is the water flow rate (m^3/s), ρ is the mass density of water (kg/m^3), V_j is the jet velocity (m/s).

Materials and Method

Tap water was used in all experiments. Each experiment started by filling the tank with tap water. Sodium sulphite (Na_2SO_3) and cobalt chloride ($CoCl_2$) were added to tap water to reduce the DO concentration to 0 mg/L. 1.185 m^3 of water was used in the experiments. To reduce the DO concentration of this water to 0 mg/L, about 110 g Na_2SO_3 was added and 3 g $CoCl_2$ was added as a catalyst.

This study was conducted in the Hydraulic Laboratory of the Department of Civil Engineering, Faculty of Engineering, Firat University. The schematic view of the experimental set is given in Fig. 1. The experimental setup consisted of a water tank, water pump, flowmeter, thermometer, dissolved oxygen (DO) meter, DO probe, venturi device, anemometer, air trap, relief valve and ruler. All experiments were carried out in a water tank made of sheet metal and glass with a volume of 1.80 m^3 (0.75 m width, 2.0 m length, and 1.2 m height). The water was circulated by means of a water pump. The water velocity in the venturi device was calculated by considering the diameter at the inlet of the venturi. In circular nozzles, it was calculated by considering the outlet diameter. The discharge of the system was determined using a flowmeter. The venturi device used in the experiments was manufactured using a plastic, transparent material. The diameters of the air holes in the venturi device were taken as 1.4, 1.7, 2.0, 2.8, 3.4, 4.0, 4.2, 5.1, and 6.0 in mm.

The residence time of air bubbles transported to the water is an important parameter in terms of oxygen transfer efficiency. The residence time is related to the penetration depth (D_p), which is the vertical distance from the water surface to the bubble flow path and hence the bubble area submerged to the bottom of the water. Below the point where the jet contacts the water, two different bubble areas are formed. It can be expressed as an inner cone of high turbulence where the bubble spreads freely and an outer area where larger bubbles rise out of the cone and rise towards the water surface. The tank depth was therefore designed so that it was not to affect the penetration depth.

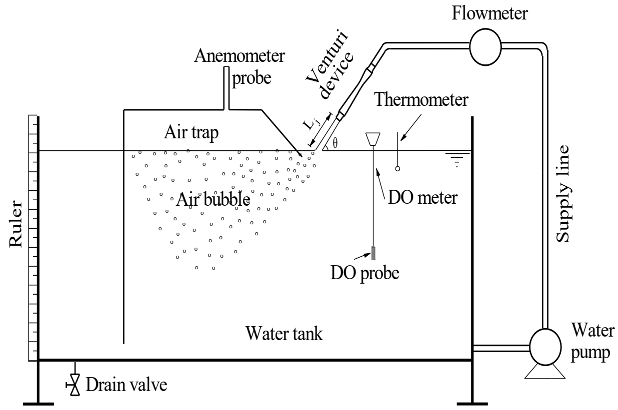
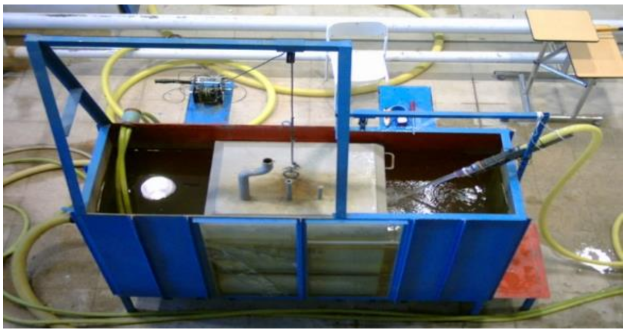


Fig. 1. Schematic view of the experimental setup

In this study, an air trap with dimensions (0.70 m × 0.85 m ×1.10 m) with an anomometer placed on its surface was used to measure the air flow rate (Fig. 2). This trap was an effective tool for measuring Q_A value. DO concentrations were measured using a HANNA Model HI9142 adjustable, portable oxygen meter shown in Fig. 3(a). The DO metre was calibrated daily before use. The adjustment methods were carried out as recommended by the manufacturer. The calibration was performed in humid air under the current weather conditions. Air entrainment rate (Q_A) was measured using a Testo 435 model anemometer shown in Fig. 3(b).

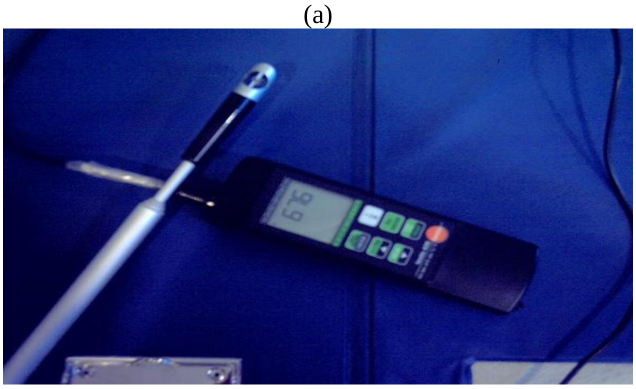
(a)



(b)

Fig. 2. (a) Top view of the experimental set, (b) Water tank and trap

(a)



(b)

Fig. 3. Appearance of a) oxygen meter b) anemometer used in the experiments

In this study, the nozzles given in Fig. 4 and Fig. 5 were manufactured and used. Each nozzle was tested at jet velocity (V_J) values ranging from 2.50 m/s to 15.00 m/s. These velocity values belong to the part where the feeding line ends and the nozzle starts. These values were used when calculating Re$\left(=\frac{V_j \times D}{\nu}\right)$values. Where, V_j is the jet velocity, D= diameter and ν is the kinematic viscosity of water. The water jet length (L_J) from the nozzle exit of the jet on the water surface to the impact point was taken as 0.30 m. The angle of impact was 45° for air entrainment and OE experiments. Air holes were drilled in the throat portion of the venturi device. Baylar and Emiroglu [9] found that the holes drilled in the throat portion had the best aeration efficiency in their study. Therefore, in this study, the holes on the venturi device were drilled in the throat portion. Since Baylar and Emiroglu [8] gave the best angle values for aeration as 21º and 7º in their study, it was taken as α_1=21º and α_2=7º.

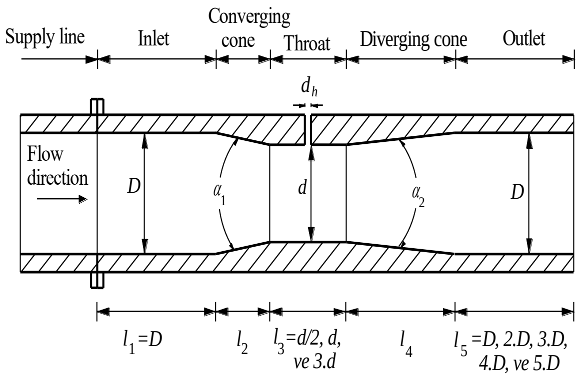


Fig. 4. Details of the venturi nozzle type used in the experiments

where $\ell_2 = \dfrac{D-d}{2\,tg\,(\alpha_1)}$; $\ell_4 = \dfrac{D-d}{2\,tg\,(\alpha_2)}$

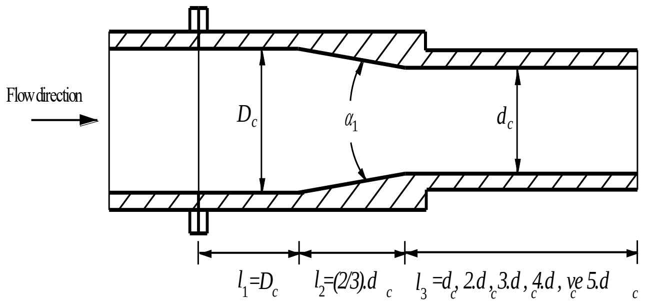


Fig. 5. Details of the circular nozzle type used in the experiments

where $\ell_2 = \dfrac{D-d}{2\,tg\,(\alpha_1)}$

The features of the venturi nozzles and circular nozzles used in this study are as follows: Venturi nozzles with *d*=14 mm, *d*=17 mm, *d*=20 mm throat portion diameter was used. In jet expansion, air entrainment rate and penetration depth experiments, the ratio of throat potion diameter to nozzle diameter was taken as *d*/*D*=0.50 and *d*/*D*=0.75. The ratio of the diameter of the air holes to the diameter of the throat portion was taken as h_d/d=0.1, h_d/d=0.2 and h_d/d=0.3. In addition, ℓ/d =1.00 and ℓ/d =0.50 were taken. In addition, *L*/*D*=1 and *L*/*D*=2 were evaluated for all nozzles. In order to compare the effect of different outlet lengths on jet expansion, air entrainment rate and penetration depth Only for the venturi nozzle with *d*=17 mm, step by step experiments were carried out between 5, 4, 3, 2 and 1 varying values of *L*/*D* for *d*/*D*=0.50, ℓ/d =3 and h_d/d =0.2 and the results were evaluated. For the venturi nozzle with *d*=17 mm, *L*/*D*=1, *d*/*D*=0.50 and ℓ/d =0.50 while h_d/d=0.4 and h_d/d=0.5 values were also taken and the data obtained as a result of this situation were evaluated; In addition, with these variables, the amount of air entrained by the holes was measured by immersing the jet in water. In oxygen transfer efficiency experiments, it was takes as *L*/*D*=2, *d*/*D*=0.50 and *d*/*D*=0.75, ℓ/d =1.00 and ℓ/d =0.50, h_d/d=0.2. Again, in order to make some comparisons while performing OE experiments *L/D*=1, 2, 3, 4 and 5 values were considered for *L*/*D*=1, 2, 3, 4 and 5 for *L*/*D*=1, *d*/*D*=0.50 and ℓ/d =1.00 for *d*=17 mm nozzle; *L*/*D*=1, *d*/*D*=0.50 andℓ/d =1.00 for *d*=20 mm nozzle and *d*/*D* =0.50 and □□/*d*=3.00 for *d*=17 mm nozzle.

In circular nozzles, nozzle diameters of *D*= 18.67 mm, 22.67 mm, 26.67 mm, 28 mm, 34 mm, and 40 mm were taken to be the same with the outlet diameters of venturi nozzles. In all experiments with circular nozzles, it was taken as *L*/*D*=1 and *L*/*D*=2. In order to make some comparisons with these mouthpieces, in the OE experiments, For *D*=34 mm, *L*/*D*=1, 2, 3, 4 and 5 values were taken and in the jet expansion, air entrainment rate and penetration depth experiments, *L*/*D*=5 value for *D*=34 mm was taken.

In this study, a series of laboratory experiments were conducted with a perforated venturi nozzle and a circular nozzle to determine the variation of the air entrainment rate and oxygen transfer efficiency in the third portion. The reason for experimenting with circular nozzle was to make a comparison. A vacuum (air suction-negative pressure) is created in the air holes of the venturi device. If a minimum differential pressure (ΔP) occurs between the inside and outside of the venturi device, this is a success. When a pressurised liquid, such as water, enters the venturi device, it is squeezed into the throat of the venturi device and transformed into a high-speed jet flow. As a result of the differential pressure, the increase in the rate in the throat portion of the venturi device leads to a decrease in the pressure in the throat portion. This pressure drop allows air to enter through the holes. As the jet stream propagates outside the venturi device, its rate decreases and is converted into pressure energy at a pressure level lower than the internal pressure of the venturi device. Venturi devices are highly efficient and require less than 20% differential to initiate suction.

A trap and an anemometer were used to determine the air entrainment rate. The flow rate of the air coming out of the pipe at a sufficient height above the trap was measured for about 60 s and averaged. With the measurement made in this way, relaible results were obtained than the measurements made with the air flowmeter. For this reason, an anemometer was used in this study instead of an air flowmeter. Jet expansions were measured at the point of impact in the receiving using callipers.

Penetration depths were determined with the help of a ruler placed on the tank and photographed. The water was then circulated to 100% saturation. Taking *t* on the *x*-axis and $-\ell n\left(\dfrac{C_s - C_t}{C_s - C_o}\right)$ on the *y*-axis, the line was fitted using the least squares method according to these two parameters and thus ($K_L a$) values were obtained.

Findings and Discussion

Oxygen Transfer Efficiency of Venturi Device

In Fig. 6, a series of experiments were carried out to investigate the oxygen transfer efficiency with the water jet formed by the venturi device by taking d/D=0.50, □/d=3.0, D=34 mm as constant. The variation of L/D was considered for a wide range and experiments were performed for L/D= 1, 2, 3, 4 and 5. As seen in Fig. 6, oxygen efficiency values also changed with the change of L/D ratio. It is clear that L/D is an important parameter. The oxygen efficiency values obtained for L/D=1 are higher. High values were also obtained for L/D=2 and L/D=3. This is because as the L/D ratio increases, the expansion and shape of the water jet changes. When L/D =1, it is observed that the shape of the water jet hitting the water surface is crescent-shaped and the perimeter length of the jet is higher than the others. The longer the perimeter of the jet, the more air bubbles are transported to the receiving pool and thus more OE values are obtained. A decrease in oxygen transfer efficiency was observed with increasing rate. This is due to the increase in jet net power N_j. Oxygen transfer efficiency increased with the growth of diameter This is due to the increase in jet momentum. In addition, OE values obtained with circular nozzle were lower for all L/D values. The OE values obtained with the Venturi device are about 2.5 times higher than those obtained with the circular nozzle.

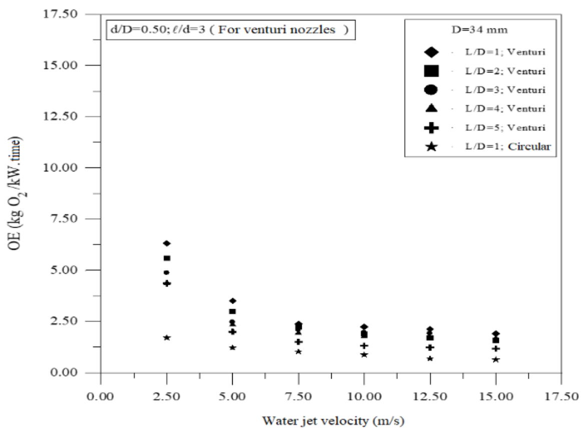


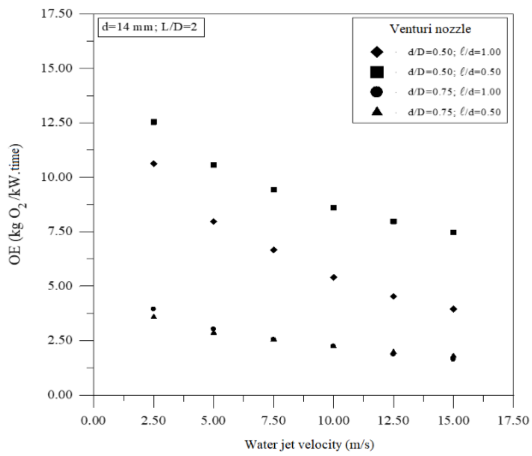
Fig. 6. Variation of L/D in venturi nozzles with oxygen transfer efficiency depending on the water jet velocity

In Fig. 7, L/D=2 was taken as constant and a series of experiments were carried out to examine the oxygen transfer efficiency with the water jet formed by the venturi device to see the effect of ℓ/d and d/D for d=14, 17 and 20 mm. It was taken as ℓ/d =0.50 and 1.00 and d/D=0.50 and 0.75. It is also seen from the figure that the values of d/D=0.50 are considerably higher than d/D=0.75. Also, the best OE values were obtained when it was ℓ/d =0.50. Figure 7(a) shows the OE values for ℓ/d =1.00 and Fig. 7(b) shows the OE values for ℓ/d =0.50 for different diameters. An increase in OE values was also observed with the increase in the diameter in the throat area. It can be seen from the figures that the OE values of d/D=0.50 are much higher than the OE values of d/D= 0.75 for all tested cases. While comparing the venturi nozzle with the circular nozzle, the values of D= 40 mm, which has the best OE value of the circular nozzle, are shown in this graph. It is seen that there is a big difference between the OE values of the venturi nozzle and the OE values of the circular nozzle.

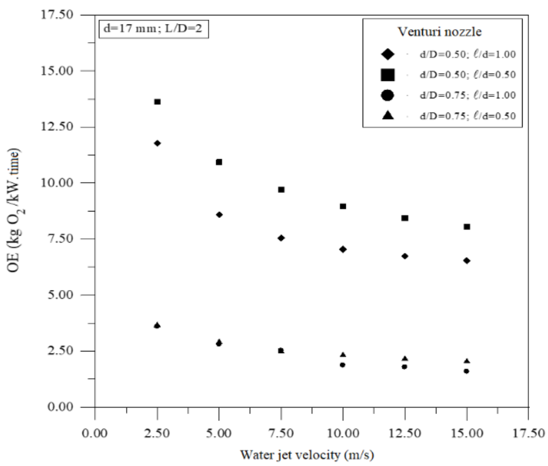
Van de Sande and Smith [12] presented the oxygen transfer efficiencies of 3.9, 5.8, 8, 10, 12 mm circular nozzles. The maximum velocity was taken as 15 m/s. K_La values increased with increasing rate. The slope of the obtained graph is consistent with the slopes of the values obtained in this master's study. In the study by Van de Sande and Smith [12], a graph was drawn between jet velocity and OE and OE values decreased with increasing velocity. Graphs in the same trend were obtained in this study. Bin [11], proposed the following equation:

$$\text{OE} = 2.07 \times N_j^{-0,23} \times D^{0,1} \times L_j^{0,5} \quad (8)$$

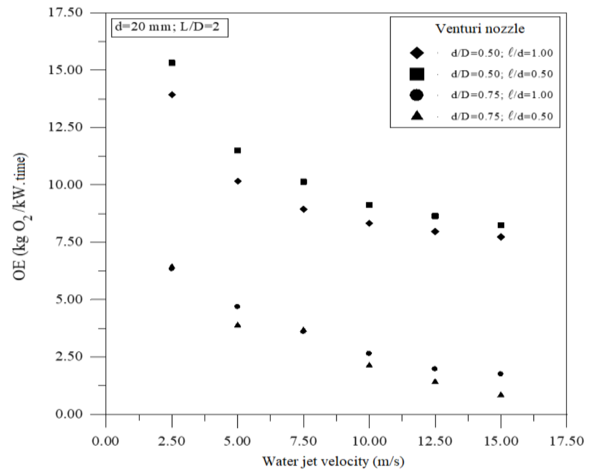
where; N_j= (kW), OE= (kgO_2kW^{-1}h^{-1}), D= (m), L_j= (m) The OE values given by Baylar and Emiroglu [8] are consistent with the values obtained in this study. For the circular nozzle with D=28 mm, V_j=5.0 m/s, L_j=30 cm and Re=137254.9 values; OE=0.342 value was obtained with Eq. (8) presented by Van de Sande and Smith and OE=1.789 value was obtained with Eq. (10) presented as a result of the study studies.



(a)



(b)



(c)

Fig. 7. Variation of d/D and ℓ/d in venturi nozzles with oxygen transfer efficiency depending on the rate

In Fig. 8, the oxygen transfer efficiencies of the water jet created by the venturi device and the circular device are compared. As seen in Fig. 8, OE values increase with the growth in the diameter of the throat are of the venturi device. This is due to the increase in momentum. OE values decreased with the increase in d/D. This is due to the increase in the diameter in the throat portion and the decrease in the exit velocity in the venturi device. As can be seen from Fig. 8, the OE values of the circular nozzle are considerably lower than the venturi nozzle. This shows that the performance of the venturi device is very high compared to the circular nozzle.

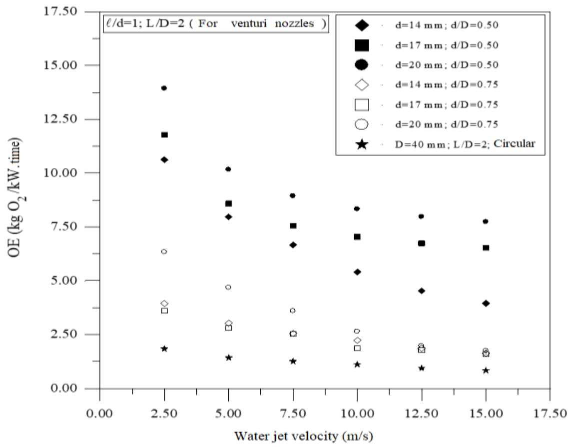


Fig. 8. Comparison of the change of D in circular nozzles, d in venturi nozzles and d/D in circular nozzles with the oxygen transfer efficiency depending on the rate

Air Entrainment Rate Performance of Venturi Device

Figure 9 shows the variation of ℓ/d and h_d/d in venturi nozzle with air entrainment rate (Q_A) depending on water jet velocity. For venturi nozzles, the tendency of Q_A to increase with increasing water jet velocity is very high. In general, the values of ℓ/d =0.50 were higher than the air entrainment rate values of ℓ/d =1.00. The values of h_d/d=0.2 and h_d/d=0.3 are higher than the values of h_d/d=0.1. At d=14 mm, no significant differences were observed in the Q_A values measured according to the variation of ℓ/d and h_d/d. In this case, the highest air efficiency was observed at d=14 mm when d/D=0.50, L/D=1, ℓ/d =0.50 and h_d/d=0.2

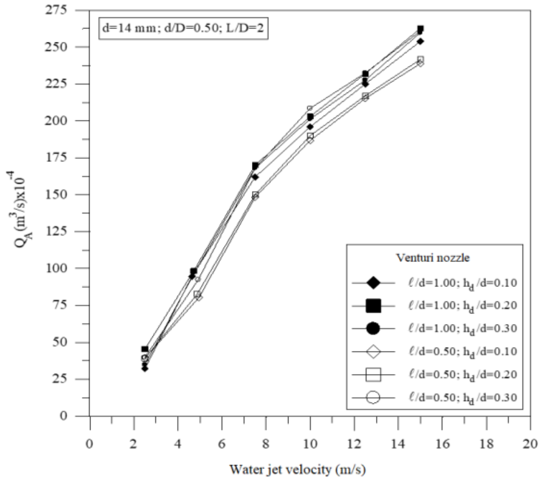
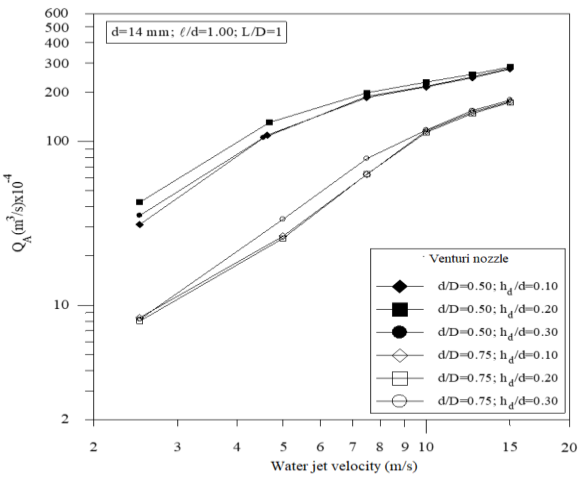


Fig. 9. Variation of ℓ/d and h_d/d in venturi nozzle with air entrainment rate depending on the water jet velocity

Figure 10 shows the variation of d/D and h_d/d in venturi nozzle with air entrainment rate (Q_A) depending on water jet velocity. To see the variation, d, ℓ/d and L/D were taken as constant. Q_A values decrease significantly with increasing d/D ratio. The reason for this is that the exit velocity increases with the narrowing of the throat area and the amount of air drawn from the hole in the throat area increases and the shape of the jet changes. Thus, an increase in the amount of air bubbles transferred to the receiving environment is observed.



F ig. 10. Variation of d/D and h_d/d in venturi nozzle with air entrainment rate depending on the rate

Figure 11 shows ℓ/d. As seen in Fig. 11, Q_A values decreased with increasing ℓ/d. As mentioned above, the hole or holes in the throat area change the shape of the jet. If the length of the throat portion increases, the change in the shape of the jet decreases. Thus, Q_A values decrease with the increase of ℓ/d.

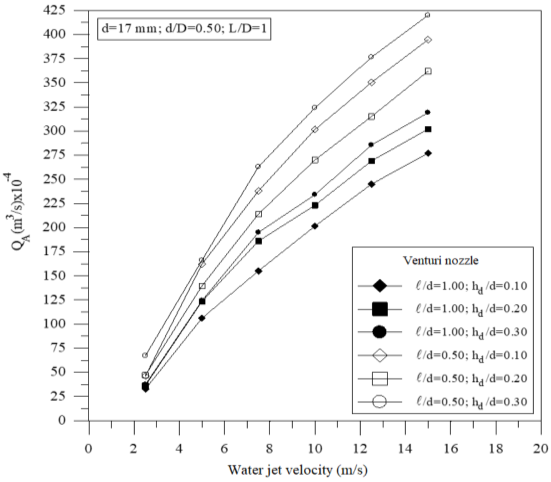


Fig. 11. Variation of ℓ/d and h_d/d in venturi nozzle with air entrainment rate depending on the water jet velocity

Figure 12 shows d/D ve h_d/d. Q_A values decrease with increasing d/D. In case of d/D=0.50, the change of h_d/d did not change the Q_A values much and close results were obtained. This is due to the fact that at small d/D ratios, the amount of air intake in the holes in the throat portion does not differ much due to the high velocity.

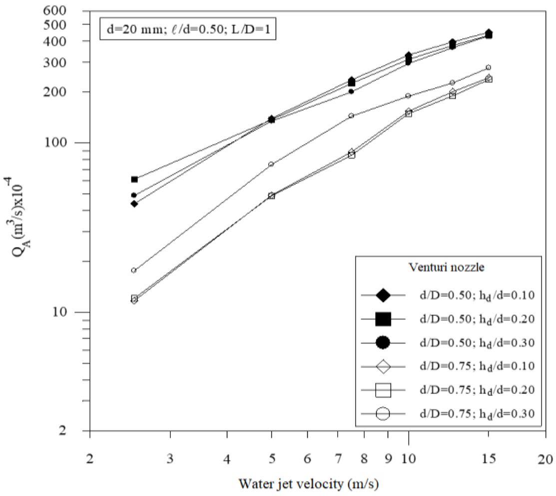


Fig. 12. Variation of d/D and h_d/d in venturi nozzle with air entrainment rate depending on the water jet velocity

In Fig. 13, the variation of Q_A for venturi nozzle is analysed for d=14, 17 and 20 mm, d/D=0.50, ℓ/d =0.5 and 1.0 and h_d/d=0.1 and 0.2 and compared with circular nozzle with the same nozzle outlet diameter. Compared to the circular nozzle, the Q_A values of the venturi nozzle were observed to be considerably higher. It can be seen from the figure that the Q_A values of the venturi nozzle are approximately 6.5 times higher than the circular nozzle. In Fig. 13; the venturi nozzle was immersed in water and the amount of air drawn from different holes was measured and given in the figure. It was observed from the experiments that the air drawn by the negative pressure created by h_d/d=0.1 gave the lowest value. In case of h_d/d=0.3, the most air was drawn. The values of h_d/d=0.5 were less than h_d/d=0.4. In other words, no direct proportionality was observed between the increase in hole diameter and the amount of air drawn. With the increase in diameter, an increase in Q_A values is also observed. This is because the momentum of the jet increases. In the study conducted by Bin [20], Q_A values increase with increasing velocity. In this paper, the results of experiments performed on very small diameters were presented. The Q_A values in the study by Baylar and Emiroglu [8] are consistent with the results of this study.

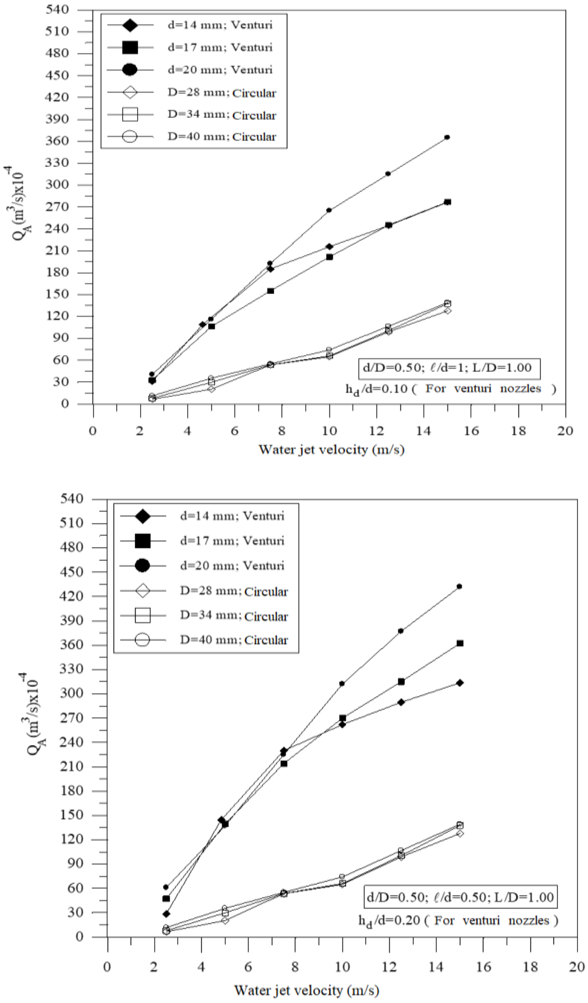


Fig. 13. Comparison of the variation of d and D in venturi and circular nozzles with air entrainment rate as a function of water jet velocity

In this study, analyses were made for air entrainment rate and oxygen transfer efficiency and their equations were developed. The analyses were performed using the least squares method. The developed equations are presented below:

$$Q_A = \left[A \times \mathrm{Re}^{B} \times \left(\frac{d}{D}\right)^{C} \times \left(\frac{l}{d}\right)^{D^{\wedge}} \times \left(\frac{h_d}{d}\right)^{E} \right]^{G} \quad (R) = 0.975 \qquad (9)$$

where, A = 0.010634, B = 0.267650, C = -0.174515, $D^{\wedge}$ = -0.049683, E = 0.014116 ve G = 3.594574.

$$OE = \left(\exp\left[\mathrm{Re}^{B} \times \left(\frac{d}{D} \right)^{C} \times \left(\frac{l}{d} \right)^{D^{\wedge}} \right] \right)^{E} \quad (R) = 0.942 \qquad (10)$$

where, B = -0.133437, C = -1.94335, $D^{\wedge}$ = -0.128016 ve E = 2.821326. A, B, C, $D^{\wedge}$, E and G: experimental constants, Re= Reynolds number (-), d= throat potion diameter (m), D= outlet diameter (m), ℓ= throat portion length (m), h_d= diameter of the hole in the throat portion (m)

The degree of accuracy of the equations found are provided in Fig. 14 and 15. It can be seen from the figures that all the equations obtained are consistent with the measured values.

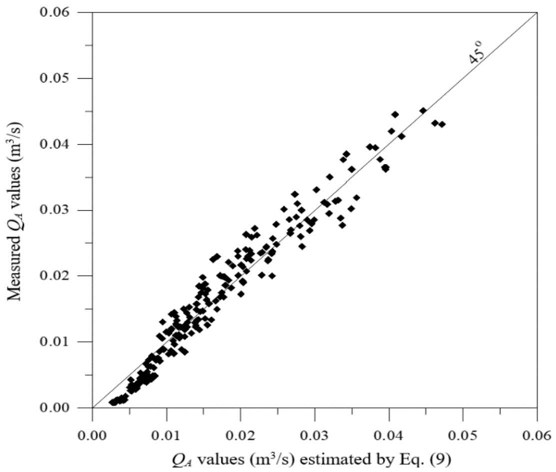


Fig. 14. Comparison of Q_A estimated by Eq. (9) with measured Q_A values

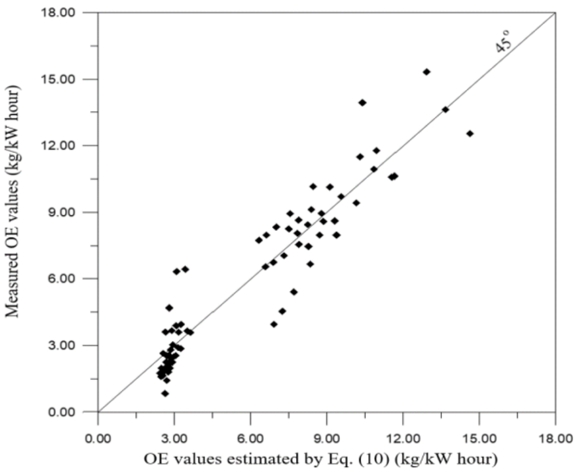


Fig. 15. Comparison of OE estimated by Eq. (10) and measured OE values

Conclusion

In this study, water jets were formed with venturi nozzles with different nozzle diameters and circular nozzles with the same outlet diameters as venturi nozzles. Significant experiments were carried out to determine the air entrainment rate and oxygen transfer efficiency of each nozzle by providing air entrainment into a water-filled tank with these nozzles. The results obtained from this study are summarised below.

- ✓ Venturi nozzles have a higher aeration efficiency than that of circular nozzles.
- ✓ As the velocity of the water jet increases, air entrainment rate and mass transfer coefficient also increase. But oxygen transfer efficiency decreases.
- ✓ The type of nozzle is an important factor affecting the aeration performance.
- ✓ Air entrainment rate and mass transfer coefficient values of venturi nozzle are considerably higher than that of circular nozzle.
- ✓ Varying diameters of the air holes in the throat portion significantly affected air entrainment rate, jet expansion, oxygen transfer efficiency and penetration depth. No increase in air entrainment rate was observed with increasing hd/d' Generally, higher data were obtained for hd/d=0.2 and hd/d=0.3.
- ✓ It was observed that the ratio of nozzle outlet length to outlet diameter has a significant effect on air entrainment rate, jet expansion, oxygen transfer efficiency and penetration depth. When the air entrainment rate values in venturi nozzle are compared for L/D=1, L/D=2 and larger values, it is observed that L/D=1 reaches the highest values.
- ✓ The ratio of throat portion length to throat portion diameter was effective on ℓ/d; air entrainment rate, jet expansion, oxygen transfer efficiency and penetration depth. ℓ/d =0.50 generally gave better results than ℓ/d =1.00.
- ✓ It was observed that the data provided by d/D=0.50 was significantly higher than d/D=0.75 for all venturi nozzles tested.
- ✓ In practice, the use of a venturi nozzle instead of a circular nozzle, which makes no difference in terms of cost, will result in approximately 6.5 times higher air entrainment rate and 2.5 times higher oxygen transfer efficiency.

Ethics committee approval and conflict of interest declaration

"There is no need to obtain ethics committee permission for the prepared article" "There is no conflict of interest with any person / organisation in the prepared article".

Author Contributions

Koçyiğit: This study was produced from the Master's Thesis Study of Şermin Koçyiğit. The experiments of this study were carried out by a graduate student and the supervisor.

Emiroğlu: Şermin Koçyiğit's Master's thesis supervisor.

Acknowledgement

This study was supported by Firat University Scientific Research Projects (FÜBAP) Unit with project number 898. We express our gratitude to FÜBAP.

References

[1] Koçyiğit, Ş. (2004). *Examination of the Ventilation Performance of the Water Jet Created with the Venturi Device.* Master's Thesis, Fırat University, Institute of Science and Technology, June 2004, Elazığ.

[2] Bağatur, T., 2000, *The effect of nozzle type on ventilation performance in water jet ventilation system,* Doctoral Thesis, Fırat University Institute of Science and Technology, 89 s.

[3] Jennekens, H., 1975, *Waterstrall beluchting voor biologische waterzuiverings installaties,* H_2O, 8, 479-482.

[4] Ohkawa, A., Kusabiraki, D., Shiokawa, Y., Sakai, N. and Fujii, M., 1986, *Flow and oxygen transfer in a plunging water system using inclined short nozzles and performance characteristics of its system in aerobic treatment of wastewater,* Biotechnol. Bioeng., 28, 1845-1856.

[5] Canepa, S. and Hager W.H., 2003, *Effect of jet air content on plunge pool scour,* Journal of Hydraulic Engineering – ASCE, 129(5), 358-365.

[6] Emiroglu, M.E. and Baylar, A., 2003, *Role of nozzles with air holes in air entrainment by a water jet,* Water Quality Research Journal of Canada, 38(4), 785-795.

[7] Emiroglu, M.E. and Baylar, A., 2003, *Study of the influence of air holes along length of convergent-divergent passage of a venturi device on aeration,* Journal of Hydraulic Research, 00, 0, 1-8.

[8] Baylar, A. and Emiroglu, M.E., 2003, *The influence of air holes at the throat portion of a venturi device on air entrainment and oxygen transfer,* Water & Maritime Engineering 156, 1-7.

[9] Out, L., Timmons, M.B. and Vinci, B.J., 2001, Characterizing bubble penetration from a falling stream, Aquacultural Engineering, 24(4), 279-287.

[10] Yamagiwa, K., Ito, A., Tajima, K., Yoshida, M. and Ohkawa, A., 2000, *Effect of nozzle contraction angle on air entrainment rate of a vertical plunging liquid jet,* Journal of Chemical Engineering of Japan, 33(5), 805-807.

[11] Bin, A.K., 1993, *Gas entrainment by plunging liquid jets,* Chem. Eng. Sci., 48, 21, 3585-3630.

[12] Kusabiraki, D., Murota, M., Ohno, S., Yamagiwa, K., Yasuda, M. and Ohkowa, A., 1990, *Gas entrainment rate and flow pattern in a plunging liquid jet aeration system using inclined nozzles*, Journal of Chemical Engineering of Japan, 23(6), 704-710.

[13] Sene, K.J., 1988, *Air entrainment by plunging jets,* Chemical Engineering Science, 43, 10, 2615-2623.

[14] Van de Sande, E. and Smith, J.M., 1973, *Surface entrainment of air by high velocity water jet*, Chemical Engineering Science, 28, 5, 1161-1168.

[15] Zhang, W., & Zhu, D. Z. (2014). Trajectories of air-water bubbly jets in crossflows. Journal of Hydraulic Engineering, 140(7), 06014011.

[16] Khound, A., Yadav, A., Sarkar, S., & Kumar, A. (2017*). Influence of throat length and flow parameters on a venturi as an aerator.* International Journal of Agriculture, Environment and Biotechnology, 10(6), 717-724.

[17] Shukla, B. K., Kumar, V. R., & Goel, A. (2018). *A comprehensive review of surface jet aerators.* Pollut. Res, 37, 20-25.

[18] Yadav, A., Kumar, A., & Sarkar, S. (2019). *Design characteristics of venturi aeration system.* International Journal of Innovative Technology and Exploring Engineering, 8(11), 63-70.

[19] Puri, D., Sihag, P., & Thakur, M. S. (2023). A review: *Aeration efficiency of hydraulic structures in diffusing DO in water.* MethodsX, 102092.

[20] Dange, A., & Warkhedkar, R. (2023). *An experimental study of venturi aeration system.* Materials Today: Proceedings, 72, 615-621.

[21] Yadav, A., & Roy, S. M. (2023). *An artificial neural network-particle swarm optimization (ANN-PSO) approach to predict the aeration efficiency of venturi aeration system.* Smart Agricultural Technology, 4, 100230.

[22] Reda Hamed, M. A. (2023). *Configuration influence in relation to fluid flow of venturi system.* Environmental Quality Management, 32(3), 203-208.

[23] Ochoa, E. D. O., García, M. C., Padilla, N. D., & Remolina, A. M. (2022). *Design and experimental evaluation of a Venturi and Venturi-Vortex microbubble aeration system.* Heliyon, 8(10).