International Journal of Science & Technology
Volume 1, No 1, 51-63, 2006

The Development of Aeration Performance with Different Typed Nozzles in a Vertical Plunging Water Jet System

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(Received: 03.10.2005; Accepted: 21.12.2005)

Abstract: It is well known that a water jet, which after passing through an air layer plunges into a water pool, entrains into this an important amount of air and forms a submerged two-phase region of considerable interfacial area. Therefore, oxygen transfer occurs between bubble dispersion and the pool water. Reviewing existing studies on water jets, most of these works were carried out in circular nozzles. Earlier researchers indicated that the factors affecting the air entrainment characteristics of a water jet were nozzle diameter, water jet velocity, jet length, and jet angle. However, it is insufficient to investigate or discuss the characteristics of a water jet only by these four factors. An important factor that cannot be overlooked is the difference in nozzle shape. This paper investigates oxygen transfer efficiencies of vertical plunging water jets from different typed nozzles such as venturi and circular nozzles with and without air holes. A negative pressure occurred at the air holes of the venturi and the circular nozzles and this phenomenon affected the water jet expansion, the water jet shape, the bubble penetration depth and hence the oxygen transfer efficiency. It was demonstrated that the venturi nozzle with air holes had the higher oxygen transfer efficiencies than the other nozzles tested. Thus, using a simple venturi nozzle with air holes could lead to significantly increased oxygen transfer efficiency.

Keywords: Water jet, Venturi nozzle, Aeration, Oxygen transfer

Dik Dalan Bir Su Jeti Sisteminde Farklı Tipli Ağızlıklar İle Havalandırma Performansının Arttırılması

Özet: Hava ortamından geçtikten sonra bir su havuzuna çarpan su jeti önemli miktarda havayı su kütlesi içerisine taşır ve iki fazlı (gaz-sıvı) bir bölge oluşturur. Böylece, havuz içerisine giren hava kabarcıkları ve havuz suyu arasında oksijen transferi meydana gelir. Bu konuda yapılan mevcut çalışmalar incelendiğinde, araştırmaların çoğunda dairesel ağızlıkların kullanıldığı görülmektedir. Bu çalışmalarda hava iletimini etkileyen faktörlerin ağızlık çapı, su jetinin hızı, su jetinin uzunluğu ve su jetinin çarpma açısı olduğu belirtilmiştir. Bununla beraber bir su jetinin hava iletimini etkileyen faktörlerin yalnızca bu dört faktör olduğunu söylemek doğru değildir. Bir su jetinin hava iletimini etkileyen diğer bir faktör de ağızlık biçimidir. Bu çalışmada, hava delikli ve hava deliksiz venturi ve dairesel ağızlıklardan çıkan düşey su jetlerinin oksijen transfer verimleri deneysel olarak incelenmiştir. Yapılan gözlemlere göre, kullanılan ağızlıkların hava deliklerinde negatif bir basınç meydana gelmiştir. Bu negatif basınç sebebiyle hava deliklerinden ağızlık içerisine çekilen hava; ağızlıktan çıkan su jetinin genişlemesini, biçimini, hava kabarcığı nüfuz derinliğini ve böylece oksijen transfer verimini etkilemiştir. Hava delikli venturi ağızlığının hava deliksiz venturi ağızlığı ve hava delikli ve deliksiz dairesel ağızlıklara oranla daha yüksek oksijen transfer verimine sahip olduğu görülmüştür. Böylece, basit bir hava delikli venturi ağızlığının su jeti sistemlerinde kullanılması önemli derecede artırılmış oksijen transferine yol açacaktır.

Anahtar Kelimeler: Su jeti, Venturi ağızlığı, Havalandırma, Oksijen transferi

1. Introduction

Dissolved oxygen (DO) refers to the volume of oxygen that is contained in water. The concentration of dissolved oxygen is an important indicator of the environments water quality. The presence of oxygen in water is a positive sign, the absence of oxygen is a sign of severe pollution. The ecological quality of water depends largely on the amount of oxygen the water can hold. The higher the level of dissolved oxygen the better the quality of the water system. By testing for dissolved oxygen, scientist may determine the quality of the water and the healthiness of the ecosystem. Dissolved oxygen concentrations can range from 0 to 15 mg/L. An adequate supply of dissolved oxygen is important in natural rivers and in some water treatment processes. Many naturally occurring biological and chemical processes use oxygen, thereby diminishing the dissolved oxygen concentration in the water. The physical process of oxygen transfer or oxygen absorption from the atmosphere acts to replenish the used oxygen. This process has been termed re-aeration or aeration.

Many industrial and environmental processes involve the aeration of a liquid by the entrainment of air bubbles produced when another liquid of the same or different properties impacts on its surface; e.g., a jet plunging into a pool, a breaking wave plunging in the ocean, a droplet impinging on a liquid surface, etc. A water jet impacting a pool of water will cause oxygen transfer when the jet velocity exceeds a critical value. This aeration system based on the air entrainment by a water jet is attractive compared to conventional aeration systems for several reasons: it doesn't need an air compressor; it is simple in construction and operation; and it is free of operational difficulties such as clogging in air diffusers, limitation of the installation of mechanical aerators by the tank width, etc. Supported by these potential advantages, therefore, many studies have been carried out experimentally on the oxygen transfer efficiencies of the plunging water jets [for example, Ahmed [1], van de Sande and Smith [2], Toerber and Mandt [3], van de Donk [4], Tojo and Miyanami [5], Tojo *et al.* [6], Bin and Smith [7], Bonsignore *et al.* [8], Ohkawa *et al.* [9], Funatsu *et al.* [10], and Yamagiwa *et al.* [11]].

As the factors affecting the air entrainment characteristics of a water jet, there are four operating variables that earlier researchers have adopted: nozzle diameter, water jet velocity, jet length, and jet angle. However, it is insufficient to investigate or discuss the characteristics of a water jet only by these four factors. An important factor that cannot be overlooked is the difference in nozzle shape. Reviewing existing studies on water jets, most of these works were carried out in circular nozzles. Thus, much useful information is available on the air entrainment characteristics in such systems using circular nozzle. However, it seems that there are not too many studies where the various characteristics of water jets were investigated by using different shaped nozzles. Recently, it has been conducted some experimental studies on inclined plunging water jets from different typed nozzles. Bagatur *et al.* [12] conducted a series of laboratory experiments on inclined plunging water jets and investigated the effect of nozzle shapes on air entrainment rate and oxygen transfer efficiency. Baylar and Emiroglu [13] studied the effect of varying numbers, positions, and the open/closed status of the air holes at the throat portion of a venturi nozzle on air entrainment rate and oxygen transfer efficiency. Emiroglu and Baylar [14] investigated air entrainment rate and oxygen transfer efficiency of a venturi nozzle with air holes along the length of the convergent-divergent passage, and in particular, the effect of varying numbers, positions, and open/close status of the air holes. Baylar and Emiroglu [15] conducted an experimental study on circular nozzles with and without air holes and studied the effect of varying the number, positions, and open/close status of the air holes of circular nozzles on air entrainment rate and oxygen transfer efficiency. Emiroglu and Baylar [16] investigated air entrainment rate of the circular nozzles with and without air holes, and in particular, the effect of varying numbers and positions of the air holes and distance between the location of the air holes and the nozzle exit. Bagatur and Sekerdag [17] studied air entrainment characteristics in a plunging water jet system using rectangular nozzles with rounded ends. Baylar *et al.* [18] conducted an experimental study on the use of venturi nozzle in a plunging water jet aeration system and investigated the effect of varying angle of diverging cone and outlet length of venturi tube on air entrainment rate. This paper investigates aeration efficiencies of vertical plunging water jets issued from different typed nozzles such as venturi and circular nozzles with and without air holes, as shown in Figures 1 and 2.

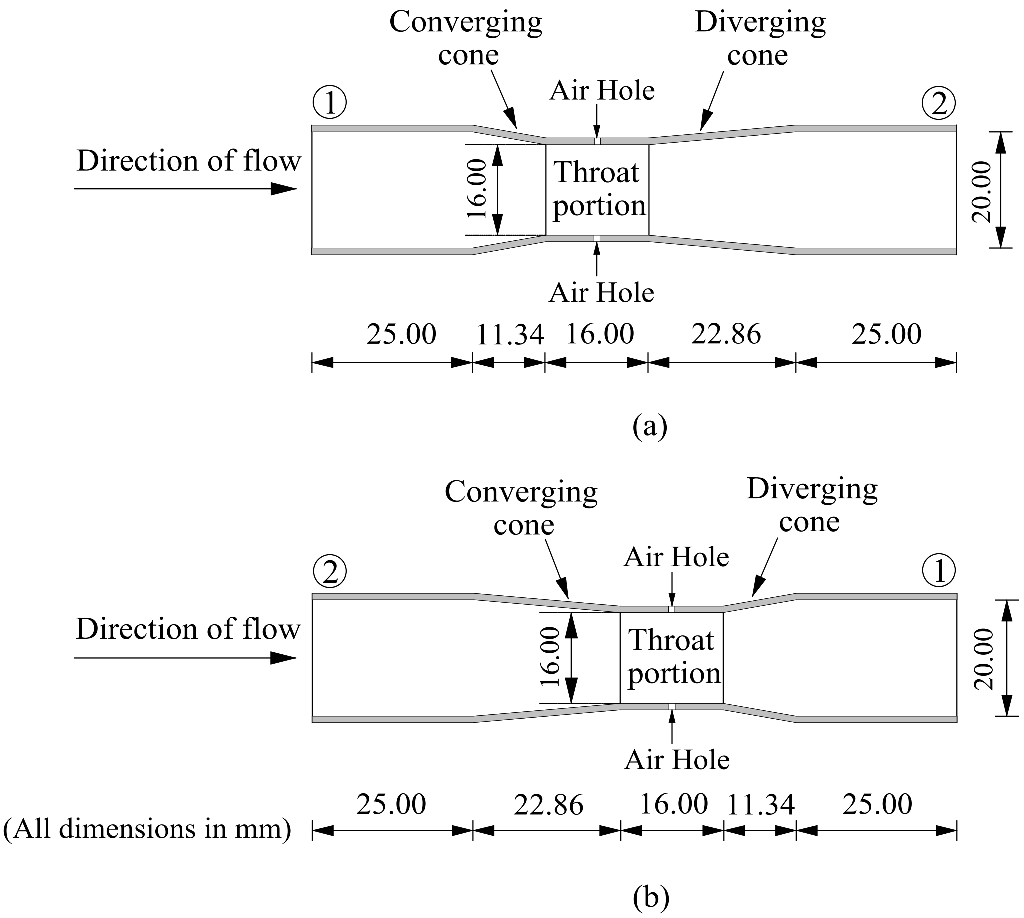

Fig. 1. Details of Venturi Nozzle (a) Direction of Flow from 1 to 2; (b) Direction of Flow from 2 to 1

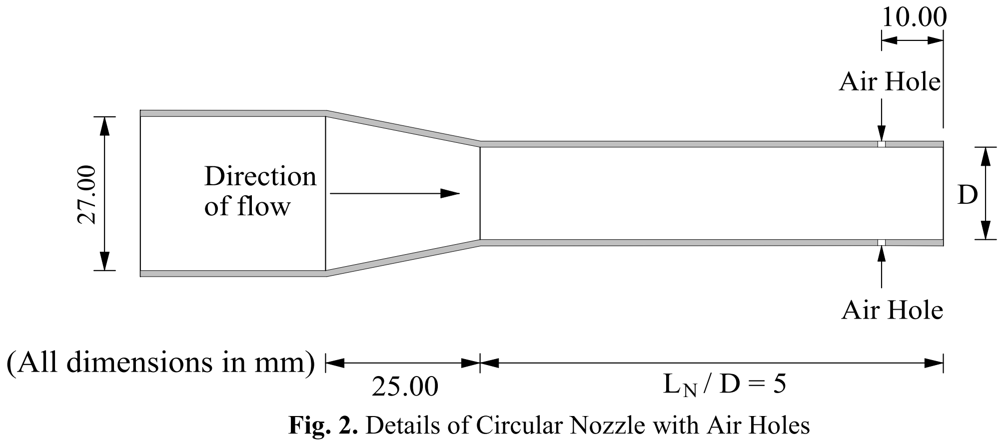

Fig. 2. Details of Circular Nozzle with Air Holes

2. Background

2.1. Aeration

When water is below saturation with DO, there is a net movement of oxygen molecules from atmosphere to water. At DO saturation, the number of oxygen molecules leaving the water surface equals the number entering (no net movement). There is net movement of oxygen molecules from water to atmosphere when water is supersaturated with DO. The greater the difference between the pressure of oxygen in water and atmosphere, the larger the movement of oxygen molecules from atmosphere to water or vice versa. The saturation of DO concentration for a particular water temperature and barometric pressure may be calculated as follows:

$$C_s = C_{tab}\left(\frac{BP - P_{H_2O}}{760 - P_{H_2O}}\right) \quad (1)$$

where C_s is DO concentration at saturation (mg/L), as given in Table 1; C_{tab} is DO concentration at the existing temperature and standard barometric pressure (mg/L); BP is barometric pressure (mm Hg) and P_{H_2O} is vapor pressure (mm Hg).

However, for practical purposes, the contribution of vapor pressure can be ignored and Eq. (1) can be written as:

$$C_s = C_{tab}\frac{BP}{760} \quad (2)$$

Table 1. The Solubility of Oxygen (mg/L) in Water at Different Temperatures and Salinities from Moist Air with Pressure of 760 mm Hg

Temperature (°C)	**Salinity (mg/L)**								
	0	5	10	15	20	25	30	35	40
0	14.621	14.120	13.636	13.167	12.714	12.277	11.854	11.445	11.051
5	12.770	12.352	11.947	11.554	11.175	10.807	10.451	10.107	9.774
10	11.288	10.933	10.590	10.257	9.934	9.621	9.318	9.024	8.739
15	10.084	9.780	9.485	9.198	8.921	8.651	8.389	8.135	7.888
20	9.092	8.828	8.572	8.323	8.081	7.846	7.617	7.395	7.180
25	8.263	8.032	7.807	7.588	7.375	7.168	6.967	6.771	6.581
30	7.558	7.354	7.155	6.961	6.772	6.589	6.410	6.236	6.066
35	6.949	6.767	6.590	6.417	6.248	6.084	5.924	5.768	5.617
40	6.412	6.249	6.090	5.935	5.783	5.636	5.492	5.352	5.215

2.2. Oxygen transfer

Lewis and Whitman [19] suggested that two laminar films or layers lie on either side of the air-water interface. Both films offer resistance to the passage of the oxygen molecules into the water. However, for a slightly soluble gas, such as oxygen in water, the resistance of the waterside is very much the greater of the two, and so this effectively controls the transfer process. The rate of mass transfer, $\partial m/\partial t$ of oxygen from the atmosphere to the body of the turbulent water generally is proportional to the difference between the existing concentration C and the equilibrium or saturation concentration C_s of oxygen in the water. It can be expressed as

$$\frac{\partial m}{\partial t} = K_L A (C_s - C) \quad (3)$$

where K_L= coefficient of diffusion of oxygen in the water; and A=area through which oxygen is diffusing. By noting

$$\frac{\partial m}{\partial t} = V\left(\frac{\partial C}{\partial t}\right) \quad (4)$$

where V=volume of the water. Then it can be expressed as

$$\frac{\partial C}{\partial t} = (K_L A/V)(C_s - C) \quad (5)$$

The parameter K_LA/V is generally designated by $(K_La)_T$, the overall oxygen transfer coefficient at test temperature T (°C).

Integrating the equation between the limits $C=C_0$ at time t=0 and $C=C_t$ at t=t, one obtains

$$(K_L a)_T = ln\left[\frac{(C_s - C_o)}{(C_s - C_t)}\right]/t \quad (6)$$

where *ln* represents natural logarithm of the given variables and the concentrations C_s, C_0, and C_t are usually expressed in parts per million (mg/L).

2.3. Oxygen transfer efficiency

In an aeration test, water is deoxygenated with cobalt chloride and sodium sulphite. Cobalt catalyzes the following reaction between molecular oxygen and sodium sulphite:

$$Na_2SO_3 + \frac{1}{2}O_2 \rightarrow Na_2SO_4 \quad (7)$$

Then, DO concentrations are measured with a DO meter at timed intervals while DO increases from 0% saturation to at least 80% saturation. At least 8 or 10 DO measurements equally spaced in time should be taken. The DO deficit is computed for each time that DO was measured during re-aeration:

$$DO_{deficit} = C_s - C_m \quad (8)$$

where C_s is the DO concentration at saturation (mg/L) and C_m is the measured DO concentration (mg/L). The natural logarithms of DO deficits (Y) are plotted versus the time of aeration (X); the line of best fit is drawn by visual inspection or by aid of regression analysis. The overall oxygen transfer coefficient is adjusted to 20°C with the following equation:

$$(K_L a)_{20} = \frac{(K_L a)_T}{1.024^{(T-20)}} \quad (9)$$

where $(K_La)_{20}$ is overall oxygen transfer coefficient at 20°C (1/hr) and T is water temperature (°C).

Results of oxygen transfer tests normally are reported on a clean water (tap water) basis. If the test cannot be run in clean water, the α-value must be determined for the water in which the aeration test was conducted and the test results adjusted [20]. The α-value is defined as:

$$\alpha = \frac{(K_L a)_{20} \text{ test water}}{(K_L a)_{20} \text{ tap water}} \quad (10)$$

The overall oxygen transfer coefficient is used to estimate the standard oxygen transfer rate. By definition, the standard oxygen transfer rate is the amount of oxygen that an aerator will transfer to water per hour under standard conditions. Standard conditions are 0 mg/L DO, 20°C, and clean water.

$$SOTR = (K_L a)_{20} \times C_s^* \times V \times 10^{-3} \quad (11)$$

where SOTR is standard oxygen transfer rate (kg O_2/h), Cs^* is saturated DO at 20°C and standard atmospheric pressure (mg/L), V is aeration tank volume (m^3), and 10^{-3} is factor for converting gram to kilogram.

The SOTR value may be divided by power applied to obtain the oxygen transfer efficiency (OE) [21].

$$OE = \frac{SOTR}{N_j} \quad (12)$$

where OE is oxygen transfer efficiency (kg O_2 / kW h) and N_j is water jet power (kW). N_j can be calculated from the following simple expression [22].

$$N_j = \frac{1}{2}\rho Q_w V_j^2 \quad (13)$$

where ρ = density (kg/m^3); Q_w = water discharge (m^3/s); and V_j = water jet velocity (m/s).

3. Air Entrainment Mechanisms at Vertical Plunging Water Jets

In a typical vertical plunging water jet three different regions of oxygen transfer can be distinguished:

(i) oxygen transfer to the turbulent free water jet passing through an air layer;

(ii) oxygen transfer to the free water surface of the pool;

(iii) oxygen transfer between bubble dispersion and the pool water.

According to estimates [23], the contribution of the first region of oxygen transfer is less than 1 % under typical hydrodynamic conditions. The contribution of the second region depends upon the jet turbulence and geometry of the pool. For the pools hitherto studied, this contribution is at most several percent of the total. Thus, the contribution of the third region is significantly more than the first two regions.

The mechanisms by which air is entrained and transferred into water because of a vertical plunging water jet are several and complex. Nevertheless, if we are understand fully the aeration performance of vertical plunging water jets, it is necessary to identify these mechanisms and relate them to characteristics of that performance. Ervine et al. [24] suggested four mechanisms for air entrainment depending on jet turbulence. A description of these stages is given in the following.

3.1. Smooth jet

The major source of air supply from smooth, solid jets occurs at a thin layer surrounding the jet and carried into the water upon impact, and therefore air entrainment capacity is limited. The water surface in the receiving pool is relatively undisturbed.

3.2. Rough jet

The air supply from rough, solid jets can be considered to originate largely from small air pockets entrapped between the jet surface roughness and the receiving water. At impact, the jet produces ripples on the pool surface. Compared to the smooth jet mechanism under similar conditions, this result in shallower bubble penetration depth and increased entrainment rate, because the bubbles are more densely packed in the biphasic zone.

3.3. Oscillating jet

The primary air source originates from large air pockets entrapped between the undulating jet and the pool surface. The pool surface is considerably agitated, and air may also be entrained by surface rollers and splashing. Large air pockets are transported from the surface into the water and broken down due to turbulence.

3.4. Disintegrated jet

The pool surface is intensely agitated, and air is entrained by the action of surface rollers and by engulfing air pockets as jet fragments hit the pool surface. The bubbles are generally only transported to relatively shallow depths. Disintegrated jets have the advantage over solid jets of greater surface area; however, Q_A and bubble penetration are significantly reduced because of energy loss to the surrounding atmosphere during fall.

4. Experimental Investigation

A series of laboratory experiments were carried out to investigate the oxygen transfer efficiencies OE of the venturi and the circular nozzles over a range of velocities between 2.5 and 15 m/s with length of water jet L_j of 0.30 m and plunge angle of water jet θ of 90°. The experiments were performed in 1.8 m^3 water tank, made of glass-wall (0.75 m wide x 2.0 m long x 1.2 m high). The water in the experimental set-up was circulated by a water pump through a flow meter. A schematic representation of the experimental set-up is shown in Figure 3.

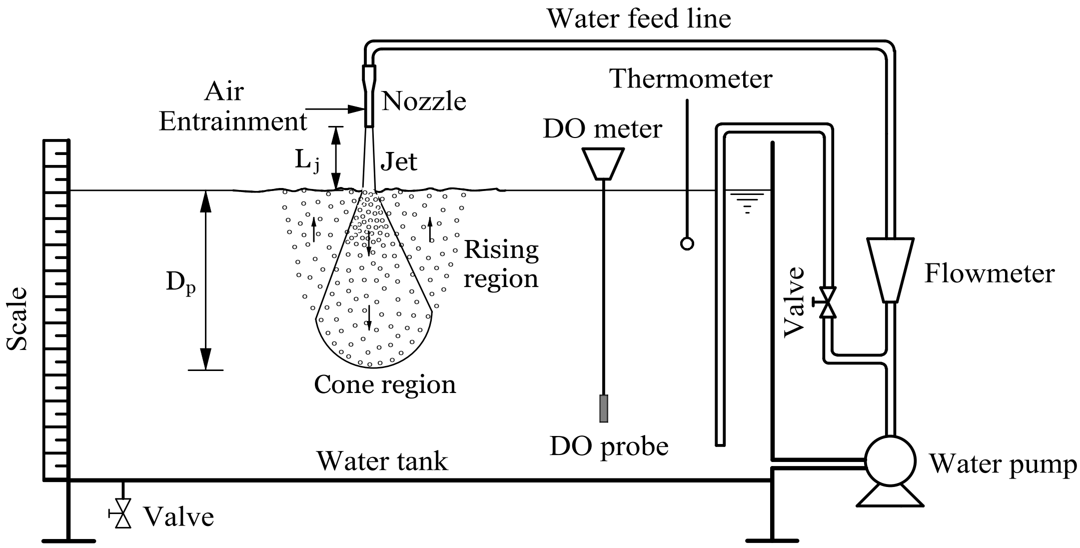

Fig. 3. Schematic Diagram of Experimental Setup

A vacuum (air suction) occurs at air holes of venturi nozzle (Figure 1). This is accomplished when a minimal amount of differential pressure (ΔP) exists between the inlet and outlet sides of the venturi nozzle. When a pressurized operating (motive) fluid, such as water, enters the venturi nozzle inlet, it constricts toward the throat portion of venturi nozzle and changes into a high velocity jet stream. The increase in velocity through the throat portion of venturi nozzle, as a result of the differential pressure, results in a decrease in pressure in the throat portion. This pressure drop enables air to be injected through the air holes and is dynamically entrained into the motive stream. As the jet stream is diffused toward the venturi nozzle outlet, its velocity is reduced and it is reconverted into pressure energy (but at a pressure level lower than venturi nozzle inlet pressure). The venturi nozzles are high efficient, requiring less than 20 % differential to initiate suction. The venturi nozzle used in experiments was manufactured according to recommended proportions of the ASME venturi tubes, as shown in Figure 1.

The venturi nozzle had diameter of 20 mm at inlet and outlet portion and diameter of 16 mm at throat portion. Two air holes were drilled in 2 mm diameter into the wall at the throat portion of the venturi nozzle, as illustrated in Figure 1. The circular nozzles had a length to diameter ratio of five and the diameters of the circular nozzles were 15 and 20 mm. The diameter of the feed line was 27 mm. Two air holes were drilled in 2 mm diameter on the circular nozzles, as shown in Figure 2. A vacuum (air suction) occurred at the air holes on the venturi and the circular nozzles. The resulting aeration of the water jet from the venturi and the circular nozzles affected its expansion, its shape, the bubble penetration depth and hence the oxygen transfer efficiency.

Expansions of water jets J_e issued from the venturi and the circular nozzles were measured with stainless steel digital caliper. Expansions were measured in the long axis of plunging water jet. Moreover, penetration depth, D_P, of the bubbles produced by the water jet, which was defined as the vertical distance from the water surface to the lower end of the submerged biphasic region in the water, was measured by a scale fitted to the water tank wall. In this study, the water depth was maintained greater than the bubble penetration depth to not affect the bubble flow path and the residence time of entrained air bubbles. In all of the experiments, it was observed that air bubbles did not reach the floor of the water tank.

The oxygen transfer efficiencies OE of the venturi and the circular nozzles were studied by varying open/close status of the air holes. Tap water was used for all of the experiments reported in this paper. Each experiment was started by filling the water tank with the tap water. Sodium sulphite (Na_2SO_3) and cobalt chloride ($CoCl_2$) were added to the tap water to reduce the DO concentration to 0 mg/L. 7.9 mg/L of Na_2SO_3 was added to remove 1 mg/L of

DO. Based on the DO of the test tap water, the approximate Na_2SO_3 requirements were estimated (a 10-20 % excess was used). 3.3 mg/L of $CoCl_2$ was added as catalyst for the deoxygenation reaction. DO concentrations were measured using calibrated portable HANNA Model HI 9142 oxygen meter at the location identified in Figure 3. DO meter was calibrated daily, prior to use, by the air calibration method. Calibration procedures followed those recommended by the manufacturer. The calibration was performed in humid air under ambient conditions.

5. Results

In this paper, the oxygen transfer efficiencies OE of the venturi and the circular nozzles were investigated depending on water jet velocity V_j and open/close status of the air holes on the venturi and the circular nozzles. Sodium sulphite and cobalt chloride were added to the water to reduce the DO concentration to 0 mg/L. Then, the water in the water tank to approach 100 % oxygen saturation was circulated using a pump. Thus, overall oxygen transfer coefficients $(K_La)_{20}$ of the venturi and the circular nozzles were determined. Then, the oxygen transfer efficiencies OE of the venturi and the circular nozzles values were calculated using Eq. 12. The following paragraphs discuss free water jet expansion at impact point J_e, bubble penetration depth produced by water jet D_p, and the oxygen transfer efficiency results OE, which are shown to vary with the water jet velocity V_j in Figures 4, 5, and 6.

Air entrainment that occurred by water jets issued from the venturi and the circular nozzles was sensitive to water jet velocity. Initially, a water jet with a relatively smooth surface issued from the circular nozzles without air holes and air entrainment taken place mainly at the surface of water tank. As the water jet velocity increased, the surface of the water jet became roughened, entraining air as described by rough jet mechanism. This resulted in greater air flow into the water tank. However, smooth jet mechanism did not occur in the venturi nozzles with and without air holes and the circular nozzles with air holes. Air entrainment was therefore by rough jet mechanism at the venturi nozzles and the circular nozzles with air holes.

Expansions of water jets J_e issued from the venturi and the circular nozzles were measured as a function of V_j and the variation in J_e is shown in Figure 4. J_e increased as V_j increased in all experiments tested. It was observed from Figure 4 that the variations in J_e were closely related to open/close status of the air holes on the venturi and the circular nozzles. Negative pressure occurring at the air holes on the venturi and the circular nozzles affected the shape of the water jet. The shape of the water jet was an oval in the circular nozzles with air holes, a circle in the circular nozzles without air holes, an oval in the venturi nozzle with air holes, and a circle in the venturi nozzle without the air holes. As shown in Figure 4, expansions of water jets issued from the venturi nozzles were significantly greater than those of the circular nozzles. It was observed from Figure 4 that the circular nozzles without air holes had the lowest values of J_e among all circumstances tested. Expansions of water jets issued from the venturi nozzles without air holes for flow from 1 to 2 and from 2 to 1 increased suddenly at the water jet velocity of 10 m/s, as illustrated in Figure 4.

Figure 5 demonstrates the variation in bubble penetration depths D_P produced by water jets issued from the venturi and the circular nozzles depending on open/close status of the air holes on the venturi and the circular nozzles as a function of V_j. It was observed from Figure 5 that D_P increased with increasing V_j. Bubble penetration depths were higher for the circular nozzle of 20 mm diameter without air holes than for the other nozzles tested. However, the circular nozzle of 15 mm diameter with air holes was observed to have the lowest values of D_p among all nozzles tested. The reason for these differences in D_p is that the water jets have different jet expansions and the jet shapes that are unique to each nozzles.

The experimental results indicated that open/close status of the air holes on the venturi and the circular nozzles were the most important factor influencing oxygen transfer efficiency OE. It was observed from Figure 6 that OE decreased as V_j increased in all nozzle types. The venturi nozzles without air holes had the lower values of OE than the venturi nozzles with air holes. The oxygen transfer efficiencies of the venturi nozzles with air holes for flow from 1 to 2 and from 2 to 1 were higher than for the other nozzles tested. The circular nozzles and the venturi nozzle without air holes for flow from point 1 to point 2 had the lowest values of OE among all nozzles tested, as shown in Figure 6. The most important cause for this variation in OE is differences in J_e and D_p. Moreover, the shapes of the water jets issued from the venturi and the circular nozzles depending on open/close status of the air holes on the venturi and the circular nozzles are also an important parameter influencing OE.

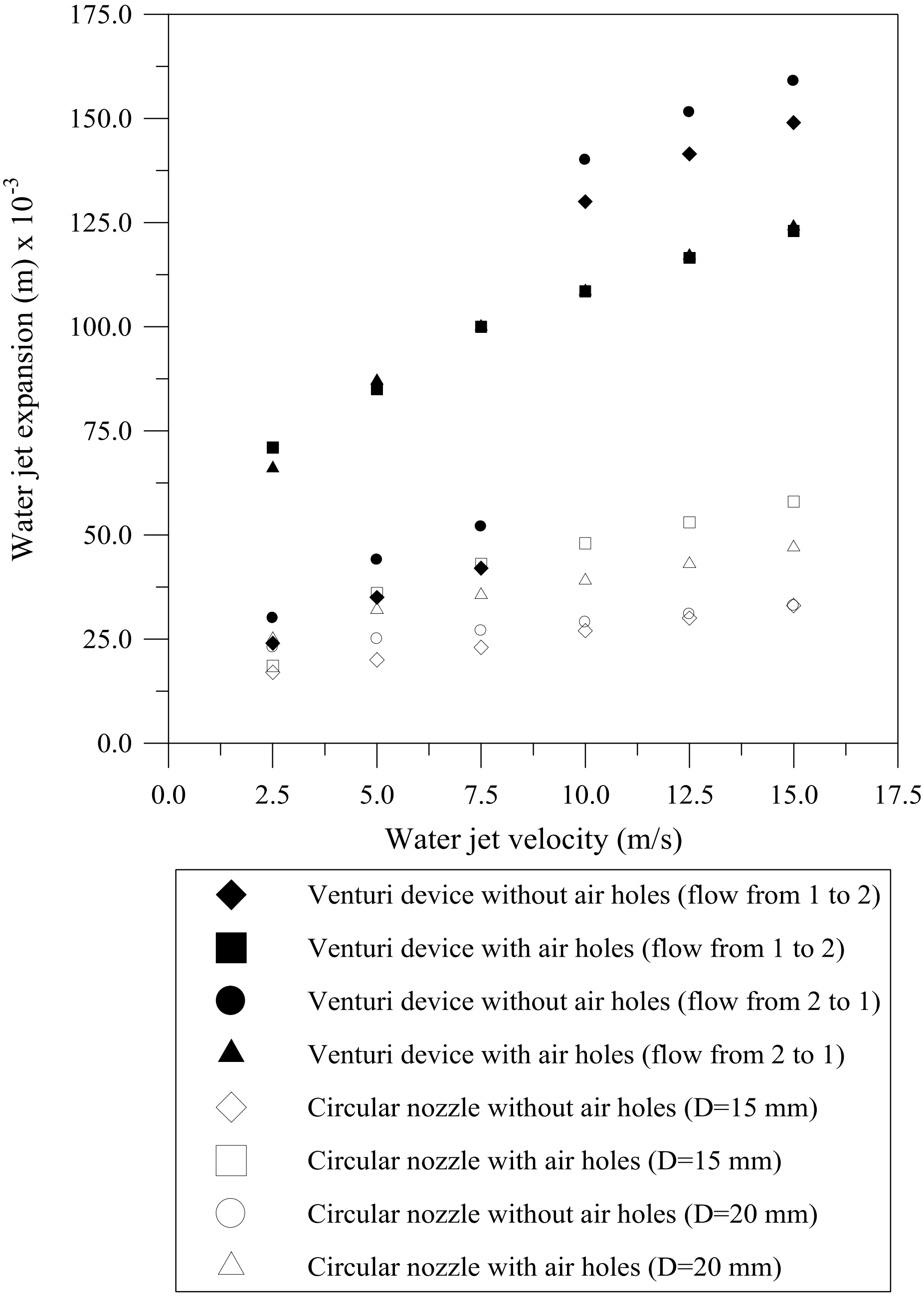

Fig. 4. Variation in Water Jet Expansion with Water Jet Velocity for Venturi and Circular Nozzles

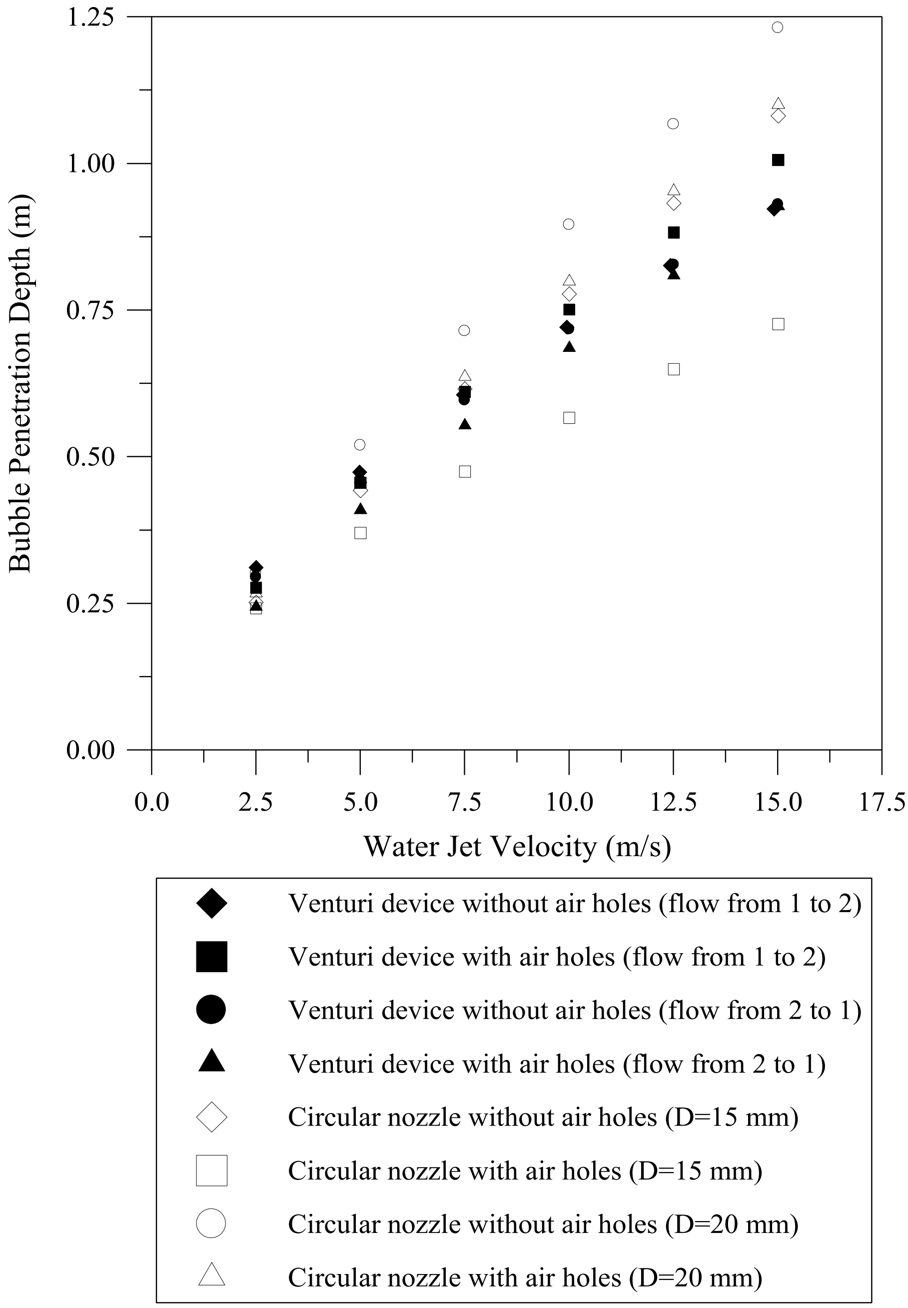

Fig. 5. Variation in Bubble Penetration Depth with Water Jet Velocity for Venturi and Circular Nozzles

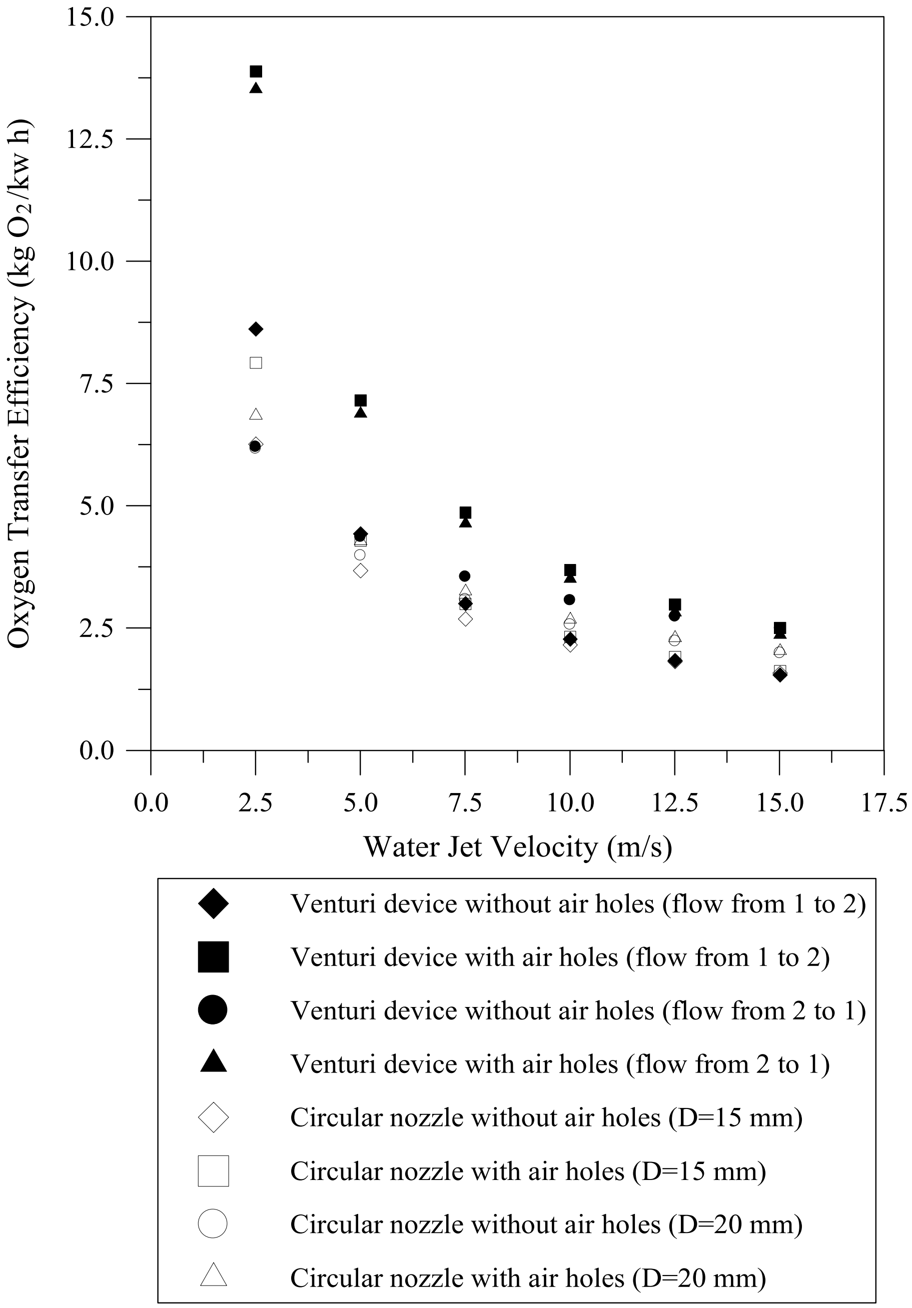

Fig. 6. Variation in Oxygen Transfer Efficiency with Water Jet Velocity for Venturi and Circular Nozzles

6. Conclusions

Oxygen is a necessary element to all forms of life. The level of dissolved oxygen is one of the best indicators of overall water quality. A water jet, which after passing through an air layer plunges into a receiving pool, entrains into this an important amount of air and forms a submerged two-phase region of considerable interfacial area. Therefore, oxygen transfer occurs between bubble dispersion and the pool water. The precise mechanism by which the air is entrained into the receiving pool is extremely complex and varies with water jet velocity and geometry. A series of laboratory experiments was carried out to study oxygen transfer efficiencies of vertical plunging water jets from different typed nozzles such as venturi and circular nozzles with and without air holes. The results indicated that open/close status of the air holes on the venturi and the circular nozzles were the most important factor influencing the oxygen transfer efficiency.

It was observed from the results that the venturi nozzle with air holes had the higher oxygen transfer efficiencies than the other nozzles tested. A negative pressure drew air in through air holes at the throat portion of the venturi nozzle. The resulting aeration of the jet affected its expansion and surface roughness and hence affected the oxygen transfer efficiency. Therefore, using a simple venturi nozzle with air holes could lead to significantly increased oxygen transfer efficiency.

The oxygen transfer efficiency decreased as the water jet velocity increased in all experiments tested. Although the oxygen transfer efficiency at low water jet velocities is very high, in practice these water jets have limited value because of the small bubble penetration depth. This is especially disadvantageous when large volumes of pool liquid have to be aerated. In a practical situation, economic considerations will establish the appropriate compromise involving tank size, jet diameter and flow rate, venturi and air hole geometry, which will lead to optimum oxygen transfer efficiency.

7. References

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8. Notation

a	specific surface area (A/V), or surface area per unit volume
A	area through which oxygen is diffusing
BP	barometric pressure
C	dissolved oxygen concentration in water
C_o	dissolved oxygen concentration in water at start of aeration
C_m	dissolved oxygen concentration measured
C_t	dissolved oxygen concentration in water at time t of aeration
C_{tab}	dissolved oxygen concentration at existing temperature and standard barometric pressure
C_s	saturation concentration of oxygen in water
C_s^*	saturation concentration of oxygen in water at standard conditions
D	diameter of nozzle
DO	dissolved oxygen
D_p	bubble penetration depth
J_e	free water jet expansion width at impact point
K_L	coefficient of diffusion of oxygen in water
(K_La)	overall oxygen transfer coefficient
$(K_La)_{20}$	overall oxygen transfer coefficient at standard conditions
$(K_La)_T$	overall oxygen transfer coefficient at T °C
L_j	length of water jet
L_N	length of circular nozzle
N_j	water jet power
OE	oxygen transfer efficiency
PH_2O	vapor pressure
Q_w	water discharge
SOTR	standard oxygen transfer rate
t	time
T	water temperature
V	volume of water
V_j	water jet velocity
ρ	density
θ	plunge angle of water jet
ΔP	differential pressure between inlet and outlet sides of venturi nozzle