Air-Water Oxygen Transfer with Multiple Plunging Jets

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Despite numerous works reporting on oxygen transfer by plunging jets, few studies have been carried out on multiple plunging jets. In this paper, the volumetric oxygen-transfer coefficient and oxygen-transfer efficiency of multiple plunging jets in a pool of water for different configurations in terms of varying numbers of jets and jet diameters were studied experimentally. This research suggests that the volumetric oxygen-transfer coefficient and oxygen-transfer efficiency of the multiple plunging jets for air/water systems were significantly higher than those of a single plunging jet for same flow area and other similar conditions. A relationship between the volumetric oxygen-transfer coefficient and jet parameters is also proposed. The suggested relationship predicted the volumetric oxygen-transfer coefficient for single and multiple plunging jet(s) within a scatter of ±15%.

Key words: multiple plunging jets, oxygen transfer, volumetric oxygen-transfer coefficient, oxygen-transfer efficiency.

Introduction

The impingement of a rapid flow into a pool of liquid at rest is termed as plunging jet flow. When a water jet impinges on the surface of a pool of still water, a large amount of air from the surrounding atmosphere may be entrained and carried below the free surface and form a large submerged contacting area between water and air, resulting in oxygen transfer to the pool water. This process is called plunging jet entrainment. This phenomenon is basically a combination of hydrodynamic and aerodynamic forces interacting between water jet and ambient air (Ervine et al. 1980). Plunging jet applications include aeration and flotation in water and wastewater treatment, oxygenation of mammalian-cell bio-reactors, biological aerated filter, bubble floatation of minerals, plunging columns, cooling systems in power plants, stirring of chemicals, as well as increasing gas-liquid transfer, plunging breakers, and waterfalls (Bin 1993; Cummings and Chanson 1997; Chanson et al. 2002; Chanson et al. 2004; Leung et al. 2006). A plunging jet aeration system has distinct advantages over other types of aeration systems to effect oxygen-transfer for various reasons (Kusabiraki et al. 1990; Bin 1993; Emiroglu and Baylar 2003): it does not require an air compressor; it facilitates make-up of the “closed” system, which enhances complete utilization of oxygen and volatile reactants; it keeps the solids in suspension near the bottom by the circulation and disperses them into the liquid by the jet; it is simple in design, construction, and operation; it does not require a separate stirring device because the water jet itself achieves aeration and mixing even in the lower region of the tank; it is energetically attractive as a straightforward means of contacting mechanisms in fouling or hazardous environments; and it is free of operational difficulties such as clogging in air diffusers, limitations on the installation of mechanical aerators by the tank width, etc. Supported by these potential advantages, there has been a growing interest in oxygenation by plunging water jets in last few years.

A substantial number of researchers have studied air-water oxygen transfer by plunging jets. Experimental studies on oxygen transfer by plunging water jets were carried out by Ahmed (1974), van de Sande and Smith (1975), van de Donk (1981), Tojo and Miyanami (1982), Bin and Smith (1982), Tojo et al. (1982), Bonsignore et al. (1985), Ohkawa et al. (1986), and Funatsu et al. (1988). These and the other related studies were reviewed by Bin (1993). Further, some of these researchers have presented their data in the form of empirical relationships. The simplest relationships recommended for single circular plunging water jets are by Ahmed and Glover (1972) (equation 1), Bin and Smith (1982) (equation 2) and by Tojo and Miyanami (1982) (equation 3):

\[
K_{La}(20) = 3.1 \times 10^{-4} + 4.85 \times 10^{-2} \frac{Q}{d^2} \tag{1}
\]
\[
K_{La}(20) = 9 \times 10^{-5} P \tag{2}
\]
\[
K_{La}(20) = 0.029 \left( \frac{P}{V} \right)^{0.65} \tag{3}
\]

where:
- \(K_{La}(20)\) is the volumetric oxygen-transfer factor at standard conditions (m³/h);
- \(Q\) is jet velocity at exit (m/s);
- \(d\) is jet diameter (m);
- \(P\) is jet power (W);
- \(K_{La}(20)\) is the volumetric oxygen-transfer coefficient at standard conditions (s⁻¹);
- \(P/V\) is jet power per unit volume (kW/m³).

(Note: all symbols and acronyms used in this paper are listed at the end of the document.)
Recently, Bagatur et al. (2002) and Emiroglu and Baylar (2003) reported the role of jet geometry (i.e., nozzle shapes/types) and jet plunge angle in air entrainment and oxygen transfer. Yamagiwa et al. (2001) studied the effects of liquid property on air entrainment and oxygen transfer rates of plunging jet reactors. Leung et al. (2006) investigated air/water oxygen transfer in a biological aerated filter. Thus, much useful information is available on oxygen transfer by single plunging water jets.

Earlier researchers have reported that jet velocity, jet diameter, and jet angle, and jet geometry are four variables affecting oxygen transfer by a plunging water jet aerator/oxy- genation system. So far, the number of jets, which is an important factor that may affect the performance of a plunging jet oxygenation system, has not been discussed in the literature. A review of existing studies on multiple plunging jets indicates that most of the work is carried out by using two plunging jets only. Tojo et al. (1982) and Van de Donk (1981) studied oxygen transfer in a system using two plunging liquid jets; Tojo et al. (1982), within their experimental range of jet power per unit volume from 0.005 to 0.15 kW/m³ for a jet diameter of 4.5 mm, observed that a single vertical plunging jet performs better than two vertical plunging jets. But their results showed a converging trend of the single and double vertical jets, which indicates that the double jets might have outperformed the single jet at a higher jet power. Van de Donk (1981) observed about 10% less oxygen transfer by two inclined jets than by a single jet. A wall effect in these experiments somewhat hindered a plausible explanation of the results obtained. On the other side, van de Sande and Smith (1975) indicated that the use of several/multiple jets instead of one is probably better for increasing the aeration capacity of the plunging jet aerator system under practical situations. Further, it has been pointed out in various studies that perfect mixing cannot be expected in a very large pool with only one plunging jet. However, it seems that there is no definite conclusive and extensive study where oxygen transfer by multiple plunging jets was investigated.

The objective of this paper was to study oxygen transfer, in terms of the volumetric oxygen-transfer coefficient at standard conditions \( K_{La,20} \) and oxygen-transfer efficiency (OTE), by multiple plunging jets, and especially the effect of varying the numbers of jets. A relationship for single and multiple plunging jets is also presented to predict the volumetric oxygen-transfer coefficient \( K_{La,20} \) as a function of jet parameters.

**Oxygen Transfer by Water Jets**

In the “closed” system of plunging liquid jet aerators, perfect mixing for the liquid phase in the pool and for plug flow in the circulation pipe can be assumed (Bin 1993). In such a case, an oxygen balance equation relating the instantaneous rate of change in dissolved oxygen concentration \( dC/dt \) to the rate of oxygen mass transfer between air and water can be written as:

\[
\frac{dC}{dt} = K_{L} \frac{A}{V} [C_{s} - C] \tag{4}
\]

where:
- \( K_{L} \) is the bulk liquid film coefficient;
- \( C_{s} \) is the saturation dissolved oxygen (DO) concentration in water at prevailing ambient conditions;
- \( A \) is the air-water contact area;
- \( V \) is the volume of water associated with this;
- \( A/V \) is the specific surface area (a) or surface area per unit volume;
- \( K_{L}A \) is the volumetric oxygen-transfer factor.

Integrating equation 4 between the limits of \( C = C_{0} \) and \( C = C_{t} \) and \( t = 0 \), and \( t = t_{e} \),

\[
\frac{C_{t} - C_{0}}{C_{0} - C_{s}} = \frac{1}{K_{L}A} \int_{t_{0}}^{t_{e}} dt
\]

which, after simplification, equation 5 can be written as:

\[
K_{L}A = \frac{1}{t_{e}} \ln \left( \frac{C_{0} - C_{s}}{C_{t} - C_{s}} \right) \tag{6}
\]

where:
- \( C_{0} \) and \( C_{t} \) are DO concentrations in the water at start and at time \( t \) of aeration, respectively;
- \( K_{L}A \) is the volumetric oxygen-transfer coefficient.

Equation 6 shows that values of \( K_{L}A \) can be obtained by substituting the measured values of \( C_{s} \), \( C_{0} \), \( C_{t} \), and \( t \). In order to have a uniform basis for comparison of different systems, \( K_{L}A \) is generally normalized at a 20°C standard. The temperature dependence of \( K_{L}A \) can be expressed (Daniil and Gulliver 1988) using the following empirical equation:

\[
K_{L}A_{20} = K_{L}A(T) \times (1.024)^{(20-T)} \tag{7}
\]

where:
- \( K_{L}A_{20} \) is the oxygen-transfer coefficient at standard conditions (s⁻¹);
- \( K_{L}A(T) \) is the oxygen-transfer coefficient at \( T \)°C (s⁻¹);
- \( T \) is water temperature (°C).

The oxy-genation performance of plunging water jets is generally expressed in terms of the OTE (kg O₂/kWh), and is given by equation 8:

\[
OTE = \frac{O_{a}V}{P} \tag{8}
\]

where:
- \( O_{a} \) is the oxygen-transfer rate (mg/L/h) at 20°C and 1 atmosphere (standard conditions);
- \( P \) is jet power (kW).

\( O_{a} \) and \( P \) can be expressed as:

\[
O_{a} = K_{L}A_{20} \times 3600 \times C_{s} \tag{9}
\]

\[
P (in kW) = \left( \frac{1}{2} \rho Q v_{j} \right) \frac{1}{10^{3}} = \left( \frac{3}{10} \rho \pi d_{j}^{2} v_{j} \right) \frac{1}{10^{3}} \tag{10}
\]
where:
\( C_s \) is saturation dissolved oxygen (DO) concentration in water at standard conditions (mg/L);
\( \rho \) is density (kg/m\(^3\));
\( Q \) is discharge or jet flow rate (m\(^3\)/s);
\( v_j \) is jet velocity at exit (m/s);
\( d_j \) is jet diameter (m).

**Experimentation**

**Experimental Setup**

To conduct experiments, a “closed” system with a complete recirculation of the water and a constant water holdup was used. A schematic representation of the experimental setup is shown in Fig. 1. The experimental setup consists of a water tank, a water pump, a flow regulating valve, an orifice meter, a thermometer, a multiple-plunging-jets device, a piezometer, and a scale. All experiments on oxygen transfer by multiple plunging jets were carried out in a water tank with dimensions of 1.02 m long by 1.02 m wide by 1.0 m deep. The water depth in the tank was kept at 0.6 m for all experiments and was measured with the help of a piezometer fitted to the water tank alongside a scale. The water in the experimental setup was circulated by a centrifugal pump. A flow regulating valve was provided at the location identified in Fig. 1 (item 2). A precalibrated orifice meter was installed in the pipeline for flow measurements. A digital thermometer with an accuracy of ±0.1°C was used for temperature measurements. The multiple-plunging-jets device was fitted to the vertical inflow pipe and adjusted such that the jets impinged vertically and centrally in the pool. The jet length, i.e., distance between exit of the jet and water surface in the pool, was kept at 0.1 m throughout the experimentation.

**Multiple-Plunging-Jets Device**

Figure 2 shows the details of the multiple-plunging-jets device used to produce four \((n = 4)\) multiple plunging jets, each with a diameter \((d_j)\) of 14 mm. The device has two main components: 1) a multiple-plunging-jets socket (MPJS) and 2) a multiple-plunging-jets disc (MPJD). The MPJS was fabricated with cast iron. It has internal threads so that it can be fitted to the inflow pipe after placing a MPJD in it. A MPJD is a 6 mm thick Perspex disc of 56 mm diameter in which circular hole(s) of the desired diameter \((d_j)\) were drilled to produce multiple plunging jets. Twelve such MPJDs were fabricated to produce multiple plunging jets of different configurations in terms of diameter \((d_j)\) and number of jets \((n)\) (Table 1).

In this study, the MPJDs were fabricated for three cross-sectional areas of jet(s) or flow areas \((A_j)\) equal...
Experimental Procedure

In this study, a series of laboratory experiments were carried out on single and multiple plunging jets to study and compare their volumetric oxygen-transfer coefficient \( (aKL) \) and \( OTE \). Each multiple jet configuration was tested at four jet flow rates or discharges \((1.33 \times 10^{-3}, 1.8 \times 10^{-3}, 2.5 \times 10^{-3}, 3.1 \times 10^{-3} \text{ m}^3/\text{s})\). To start, the multiple-plunging-jets device with a MPJD in the desired configuration was fitted to the inflow pipe. The water tank was then filled with tap water. The opening of the regulating valve was set at the desired flow rate using the precalibrated orifice meter in the supply line. Water in the tank was deoxygenated by adding an estimated quantity of sodium sulfite \((\text{Na}_2\text{SO}_3)\), and by adding cobalt chloride \((\text{CoCl}_2)\) to act as a catalyst. A representative sample of the deoxygenated water was taken, and the initial DO concentration \((C_0)\) was determined by the azide modification method (APHA et al. 2005). A microburette was used in all titrations for the determination of DO concentration. Aeration was then carried out for a fixed duration of time \((t = 60 \text{ seconds})\) which was measured with the help of a digital stopwatch having a least count of 0.01 seconds. Representative samples of aerated/oxygenated water were taken for the determination of DO concentration after time \(t\) \((C_t)\). The water temperature \((T)\) was recorded during the course of the experiment. The value of \(K_{i,a(C_0)}\) was then calculated by using equation 6, and the volumetric oxygen-transfer coefficient at standard conditions \(K_{i,a(20)}\) was obtained by using equation 7. The \(OTE\) and \(P\) values were calculated by using equations 8 and 10, respectively.

Results and Discussions

The following sections discuss the variation of the \(K_{i,a(20)}\) values for multiple plunging jets with jet velocity \((V_j)\) (Fig. 4) and jet power per unit volume \((P/V)\) (Fig. 5); the derivation of empirical relationship between the \(K_{i,a(20)}\) and the jet parameters; and the variation of the \(OTE\) of the multiple-plunging-jets, and its comparison with single jets (Fig. 7).

Replicate experiments were carried out to verify the reproducibility of air-water oxygen transfer by multiple plunging jets. Based on the repeated \(K_{i,a(20)}\) measurements, the mean values of \(K_{i,a(20)}\) for given configurations of multiple jets at given discharges were calculated. The errors from the mean values of \(K_{i,a(20)}\) were determined and shown using error bars in a plot between the volumetric oxygen-transfer coefficient and jet velocity (Fig. 4). In the replicate experiments, the variation in \(K_{i,a(20)}\) values was about \(\pm 2\%\) from the mean.
The effect of jet velocity on the volumetric oxygen-transfer coefficient of multiple plunging jets is shown in Fig. 4. It was observed from Fig. 4 that variation in $K_La_{(20)}$ is closely related to number of jets ($n$) in the multiple-plunging-jets device. The $K_La_{(20)}$ increased remarkably as $v_j$ increased in all the experiments. The increase in $K_La_{(20)}$ with an increase in jet velocity may be ascribed to the increased momentum of the jet flow. The values of $K_La_{(20)}$ for multiple jets were greater than those for single jets ($n = 1$). The $K_La_{(20)}$ increased with the increase in number of jets, at a given jet velocity. This increase in $K_La_{(20)}$ for multiple plunging jets with increasing number of jets may be ascribed to a greater quantity of air/oxygen becoming entrained due to the increased surface area of multiple jets in contact with the atmosphere per unit jet length ($A_j$). The relationship between the volumetric oxygen-transfer coefficient ($K_La_{(20)}$) and the jet velocity ($v_j$) (Fig. 4), depending upon the number of multiple jets, can be expressed by:

$$K_La_{(20)} \propto v_j^{1.66-2.06}$$  (11)

To study the effect of number of jets ($n$) on the volumetric oxygen-transfer coefficient, the $K_La_{(20)}$ data for single and multiple jets were compared in Fig. 5 in terms of the jet power per unit volume ($P/V$). It was observed that the values of $K_La_{(20)}$ increased with the increase in jet power per unit volume over the whole range of experiments. Moreover, the number of jets ($n$) was closely related to the $K_La_{(20)}$ at a given jet power per unit volume (Fig. 5). The volumetric oxygen-transfer coefficient gradually increased as the values of $n$ were increased for the multiple-plunging-jets device. This increase in $K_La_{(20)}$ was further strengthened with the increase in the jet power per unit volume. The multiple-plunging-jets device with $n = 4$ jets was found to have higher values of $K_La_{(20)}$ than those with $n = 1$ jet over the entire range of jet power per unit volume. The multiple-plunging-jets device with $n = 8$ jets was found to have higher values of $K_La_{(20)}$ than those for $n = 1$ jet as well as $n = 4$ jets, except at very low values of jet power per unit volume (0.005 and 0.009 kW respectively). In the case of $n = 16$ multiple plunging jets, the $K_La_{(20)}$ values were less than when $n = 1, 4, 8$ at lower ranges of jet power per unit volume; however, their performance started to improve as $P/V$ was increased. This demonstrated that as the jet power per unit volume increased, the multiple plunging jets with a greater number of jets started performing better in terms of the volumetric oxygen-transfer coefficient. This is possibly due to the fact that when the jet power per unit volume increases, the momentum and hence the penetration depth of the multiple plunging jets increases. This results in more oxygen transfer due to increased contact and mixing time between the air-water interfacial areas of the rising bubble column inside the pool water. It is therefore more logical to increase the number of jets at higher jet powers to achieve substantial improvement in oxygen transfer as compared with a single jet under similar conditions. On the other hand, the increase in the performance of multiple jets is not substantial as compared with a single jet at lower value of jet power per unit volume (Fig. 5).

**Fig. 4.** Oxygen transfer as a function of jet velocity.

**Fig. 5.** Oxygen transfer as a function of jet power.
For predicting the volumetric oxygen-transfer coefficient \( (K_L a_{20}) \) by single jets and multiple plunging jets, the following relationships between \( K_L a_{20} \) and \( P/V \) were obtained from the plot between \( K_L a_{20} \) versus \( P/V \) (Fig.5):

\[
K_L a_{20} = 0.082 (P/V)^{0.64} \quad \text{for} \quad n = 1
\]

(12)

\[
K_L a_{20} = 0.097 (P/V)^{0.66} \quad \text{for} \quad n = 4
\]

(13)

\[
K_L a_{20} = 0.14 (P/V)^{0.73} \quad \text{for} \quad n = 8
\]

(14)

\[
K_L a_{20} = 0.17 (P/V)^{0.8} \quad \text{for} \quad n = 16
\]

(15)

These relationships (equations 12, 13, 14, 15) are similar to expressions proposed by Bin and Smith (1982) (equation 2) and by Tojo and Miyanami (1982) (equation 3). But these equations can predict \( K_L a_{20} \) for a particular value of \( n \) only. To have a single relationship for predicting \( K_L a_{20} \) for different values of \( n \), multivariate linear regression was applied to formulate an equation/relationship between \( K_L a_{20} \) and jet parameters represented by \( P \) (i.e., \( n, v_j \) and \( d_j \)). The following relationship was developed:

\[
K_L a_{20} = 0.113 n^{0.84} v_j^{1.14} d_j^{1.53}
\]

(16)

The correlation coefficient and root mean square error between the experimental values of \( K_L a_{20} \) and the predicted values of \( K_L a_{20} \) using equation 16 were 0.98 and 0.067 respectively. A plot between the experimental \( K_L a_{20} \) and the predicted \( K_L a_{20} \) obtained by using equation 16, shows a scatter within ±15% of the line of perfect agreement (Fig.6). Thus, equation 16 can be helpful in providing information about the oxygen transfer of multiple plunging jets with fair precision. A simple selection of jet velocity (m/s), diameter (m), and number of plunging jets is therefore sufficient to predict the volumetric oxygen-transfer coefficient (in s\(^{-1}\)) for single and multiple plunging jets.

Figure 7 shows the ratio of \( OTE \) for multiple jets to that of single jets \([OTE(n) / OTE(n=1)]\) as a function of the number of jets \( (n) \). It was observed that the value of \( OTE \) generally increased as the number of jets were increased for a given jet power per unit volume. The \( OTE \) of multiple plunging jets increased up to 1.6 times (60%) that of a single jet under similar conditions. Further, Fig. 7 also indicates that the performance of multiple jets depends upon the jet power per unit volume. Multiple jets with higher values of \( n \) performed much better at higher \( P/V \) (Fig. 7). The performance of multiple jets (particularly \( n = 16 \)) was lower than that of the single jet at very low values of \( P/V \). This may be ascribed to lower values of \( K_L a_{20} \) for \( n = 16 \) as compared with \( K_L a_{20} \) for \( n = 1 \) at lower values of jet power per unit volume. It means that simply increasing the number of jets may not necessarily result in higher \( K_L a_{20} \) and/or \( OTE \). In fact, there exists an optimum configuration of multiple jets, in terms of \( n \) and \( d_j \), for a given jet power per unit volume. This optimum configuration can be obtained using equation 16.

Table 2 provides a comparison of the \( OTE \) of the
multiple plunging jets with other types of aeration/oxygenation equipment. It can be observed from this table that the multiple-plunging-jets device studied here has not only performed better than the single plunging jet under similar conditions, but it is also a useful and competitive device compared with the other conventional aeration/oxygenation equipment.

**Conclusions**

In this study, a series of laboratory experiments were carried out to obtain the values of the volumetric oxygen-transfer coefficient and the OTE of single and multiple plunging jets. Based on the findings of this study, the following conclusions were drawn:
- The effect of number of jets (n) is significant on the volumetric oxygen-transfer coefficient and on OTE of the multiple-plunging-jets device.
- The volumetric oxygen-transfer coefficient for the single and multiple plunging jets increased with the increase in jet velocity. For a given jet velocity, the $K_La_{20}$ values increased with an increase in the number of multiple jets for a constant flow area due to an increase in surface area of the multiple jets in contact with the atmosphere per unit jet length.
- The volumetric oxygen-transfer coefficient for multiple plunging jets was higher than that for a single jet at a given jet power. For the multiple-plunging-jets device, the volumetric oxygen-transfer coefficient gradually increased as the n values were increased from 1 to 16; this increase in $K_La_{20}$ was further strengthened with an increase in jet power per unit volume. The multiple-plunging-jets device should therefore be recommended for aeration/oxygenation instead of a single plunging jet at higher jet powers as in practical situations where large volumes of wastewater at higher discharges are to be oxygenated.
- The volumetric oxygen-transfer coefficient for multiple plunging jets was well correlated with the jet parameters (representing jet power). The relationship, represented by equation 16, predicted the $K_La_{20}$ from jet parameters within a scattering range of $\pm 15\%$.

This relationship would be quite useful for comparing the performance of single and multiple plunging jets of different configurations, and also for deciding the optimum configuration of multiple plunging jets for given flow conditions.
- The OTE of multiple plunging jets was increased with the increase in the number of jets, and was higher (up to 1.6 times) than that of a single jet under similar conditions. Further, the OTE of multiple-plunging-jets was very much competitive with the other conventional aeration/oxygenation equipment and thus suggest their practical application.
- In a practical situation, involving variations/fluctuations in the inflow to the aeration unit, the multiple-plunging-jets device suggested in the present study can be quite useful due to its flexibility compared with other aeration devices. A replacement of the multiple-plunging-jets disc with a disc of different configuration can meet the changed requirement. Further, in real situations, where perfect mixing cannot be expected such as in large sized aeration tanks with one plunging jet, multiple plunging jets have a distinct advantage over a single plunging jet. From the point of view of energy utilization, plunging jet aeration systems are energy efficient since they have efficient mixing ability without any requirement for a separate mechanical stirring device. However, it is important to choose a proper low-head pump that works at an optimum efficiency range that corresponds with good aeration performance of the plunging jets.

**References**


List of Symbols and Abbreviations

\begin{itemize}
  \item \(A\) air-water surface area contained in the volume \(V\) (m\(^2\))
  \item \(A_j\) cross-sectional area of jet/jets or flow area (mm\(^2\))
  \item \(A_s\) surface area of jet(s) in contact with atmosphere per unit jet length (mm)
  \item \(a\) specific surface area (A/V) or surface area per unit volume (m\(^2\)/m\(^3\))
  \item \(B\) breadth of the squared tank (m)
  \item \(C\) DO concentration in water (mg/L)
  \item \(C_0\) initial DO concentration in water at the start of aeration, i.e. at \(t = 0\) (mg/L)
  \item \(C_S\) saturation DO concentration in water at ambient conditions (mg/L)
  \item \(C_f\) DO concentration in the water at time \(t\) of aeration (mg/L)
  \item \(d_j\) jet diameter (mm, m)
  \item \(DO\) dissolved oxygen
  \item \(K_s\) bulk liquid film coefficient (m/s)
  \item \(K_{V}\) volumetric oxygen-transfer factor (m\(^3\)/s, m\(^3\)/h)
  \item \(K_{V,20}\) volumetric oxygen-transfer factor at standard conditions (m\(^3\)/h)
  \item \(K_a\) volumetric oxygen-transfer coefficient (s\(^{-1}\))
  \item \(K_{a,20}\) volumetric oxygen-transfer coefficient at standard conditions (s\(^{-1}\))
  \item \(K_{a(T)}\) volumetric oxygen-transfer coefficient at \(T^\circ\)C (s\(^{-1}\))
  \item \(L\) jet length i.e. distance between exit of the jet and water surface in the pool (m)
  \item \(MPJD\) multiple-plunging-jets disk
  \item \(MPJS\) multiple-plunging-jets socket
  \item \(n\) number of jets
  \item \(OTE\) oxygen-transfer efficiency (kg O\(_2\)/kWh)
  \item \(O_R\) oxygen-transfer rate (mg/L/h)
  \item \(P\) jet power (W, kW)
  \item \(P/V\) jet power per unit volume (kW/m\(^3\))
  \item \(Q\) jet flow rate or discharge (m\(^3\)/s)
  \item \(t\) aeration time (s)
  \item \(T\) water temperature (\(^\circ\)C)
  \item \(V\) volume over which \(C\) and \(A\) are measured or water in the aeration system, \(B^*Z\) (m\(^3\))
  \item \(v_j\) jet velocity at exit (m/s)
  \item \(Z\) water depth in the tank (m)
\end{itemize}