*Desalination and Water Treatment*
www.deswater.com
doi: 10.5004/dwt.2022.28947

276 (2022) 301–308
November

# Performance evaluation of spray aeration in a pilot scale model

Ammar Thamir Hamad*, Layth Abdulaleem Mahmood, Mohammad Salim Mahmood

*University of Mosul, College of Engineering, Environmental Engineering Department, Mosul, Iraq, Tel. +964 7701825015; email: dr.ammarthamir@uomosul.edu.iq (A.T. Hamad), Tel. +964 7704140002; email: laythabdulaleem@uomosul.edu.iq (L.A. Mahmood), Tel. +964 7701899686; email: Mohammedsalim@uomosul.edu.iq (M.S. Mahmood)*

Received 11 April 2022; Accepted 25 September 2022

**ABSTRACT**

The spray of water over a basin using a perforated disk accelerates oxygen transfer. The laboratory model, employed in the current work, consists of a vertical riser that discharges water by free fall into a basin. Four fall heights of water of 2.4, 1.8, 1.2, and 0.6 m were investigated to evaluate the performance of this system. This system was also tested at flow rates of 46.8, 93.7, 140.6, and 187.5 mL/s. This study showed that the oxygen mass transfer coefficient was directly proportional to both the fall height and flow rate of water. The maximum standard aeration efficiency (SAE) value was recorded at the maximum fall height of 2.4 m and flow rate of 187.5 mL/s, at which a maximum $K_{La20}$ = 1.82 $h^{-1}$ was recorded. The multilinear regression-based model developed in this study successfully predicted mass transfer coefficient ($K_{La20}$) and standard aeration efficiency (SAE values that agree well with actual measurements under given conditions, with a scattering within ±5%. The optimum flow rate and fall height that achieve the minimum operating cost were obtained at certain $K_{La20}$ values. The cost of aeration of 1 $m^3$ of water was calculated, ranging from 0.0076 to 0.008 USD/$m^3$.

*Keywords:* Spray aeration; Mass transfer coefficient; Aeration efficiency; Standard oxygen transfer rate

## 1. Introduction

Aeration is an essential step in water and wastewater treatment. There are several methods for injecting dissolved oxygen (DO) into water and wastewater, including small, medium, and large bubble-type diffusers, static tube mixtures, spray and jet aeration, and mechanical surface aerators [1].

A spray aerator has one or more spray orifices or nozzles mounted on a pipe manifold. Water moves through the pipe by pressure and leaves the nozzles or orifices in the form of fine water droplets or jets, which fall through the surrounding air, creating a large air–water interface and increasing the amount of DO in water [2].

Spray aeration is simple, inexpensive, operates without difficulty, and is easily incorporated into existing facilities. In this system, air is induced into the water jet naturally via contact with the atmosphere [3]. It maintains a closed system with recirculation; thus, it does not require a mixing device because the water jet and the multiple recirculation manner achieve oxygenation and blending.

In association with its inherent and natural character, the spray aeration technique will be a promising approach aimed at reducing carbon emissions, which are expected to rise by 218 million tons/y by 2040 [4]

A spray aeration system may be classified into two types: "plunging jet system" and "spray nozzle system". Most of the early research has focused more on plunging jet systems. In this regard, Deswal and Verma [5] studied the air–water oxygen transfer using multiple plunging jets of varying numbers and diameters. They revealed that the oxygen transfer coefficient and oxygen-transfer

* Corresponding author.

efficiency of the multiple plunging jet systems are significantly higher than those of a single plunging jet under the same conditions. On the other hand, Shukla et al. [2] tested multiple solid jet aerators with a square-shaped nozzle of rounded ends for different jet lengths of 15, 30, 45, and 60 cm, openings of 1, 2, 4, and 8, and discharge rates of 1.20, 2.30, 3.10, 3.90, and 4.80 L/s. The maximum oxygen transfer efficiency of 26.15 kg·$O_2$/KWh was obtained for a jet discharge rate of 1.2 L/s and a jet length of 60 cm; however, the maximum oxygen transfer coefficient of 3.5 × $10^{-2}$ $s^{-1}$ was obtained at a jet discharge rate of 4.80 L/s and a jet length of 60 cm for an aerator with a single opening. Meanwhile, Deswal and Pal [6] used a statistical theoretical approach (multilinear regression) to model and predict the mass transfer by multiple plunging jets. Their results showed that the mass transfer is up to 1.6 times greater for multiple inclined plunging jets than vertical multiple plunging jets under the same conditions. Similar results have been reported by Bagatur et al. [7] and Singh et al. [8] using an experimental approach.

The second type "spray nozzle system" disintegrates water into small drops, resulting in a large air–water interface. The energy consumption of spray aerators is 10–50 Wh/$m^3$, depending on the type of aerator [9].

Spray nozzle aerators are divided into two groups: upward and downward spray aerators. The Amsterdam spray aerator represents the first group. In this type, two jets are directed upward perpendicular to each other, splashing water into fine droplets. During their fall, water droplets abstract air from the atmosphere. An example of the second type of sprayer is the Dresden Sprayer. Here, water flows downward, forming the shape of an umbrella. The energy used for spraying should ensure a fall height and pressure drop of 1.5–4 m. The system is capable of oxygen addition in the range of 80%–90% [9]. However, in the literature, limited researches have been dedicated to this type of spray aerators. Roshan et al. [3] investigated the effect of different geometric factors (radius of curvature of shower plate and number of openings) on the aeration characteristics of a showering aeration system. Their experimental model consisted of a cemented concrete rectangular tank of dimensions (2 m × 4 m × 1.5 m). The arrangement of pipes and showers was set up at an average height of 1.0 m from the water surface. The maximum standard aeration efficiency (SAE) obtained from their experimental trials was 1.4429 kg·$O_2$/KWh. To achieve maximum SAE, the optimum radius of curvature and number of openings should be 10 mm and 80, respectively.

Smith [10] studied the effects of spray aeration on the total trihalomethane (TTHM) removal using a specially fabricated grid nozzle in a lab-scale model. The amount of TTHM removed ranged between 37.7% and 45.2%.

Notably, most of the studies in this context have focused on predetermined operating conditions in which pressure (Head), flow rates, and temperature remain constant, that is, the potential variation in these operational conditions was not or is rarely considered.

A spray aeration system was investigated in this study. A perforated disk with 70 openings (orifices) of 1 mm diameter, mounted on a riser pipe, was used to spray water over a water tank.

## 2. Research objectives

- Investigate the effect of the fall height and flow rates of water on the oxygen uptake rate, oxygen mass transfer coefficient, total power consumption, standard oxygen transfer rate (SOTR), and standard aeration efficiency (SAE) for the spray aeration system developed in this study.
- Suggest multilinear regression relationships to predict both the oxygen transfer coefficient and SAE for the aeration system under consideration. This will help compare the experimental and predicted values of these parameters.
- Apply an optimization approach to predict the optimum values of the flow rate and fall height of water that yield the minimum operating cost of this aeration process.

## 3. Methodology

A continuous flow closed system pilot scale model was employed in this study. As shown in Fig. 1, it consists of a cylindrical tank with a conical base. The aluminum cylindrical tank contained 120 L of liquids. It was equipped with a centrifugal pump with a rating power of 0.5 kW and suction and discharge piping at the bottom of the

(a)

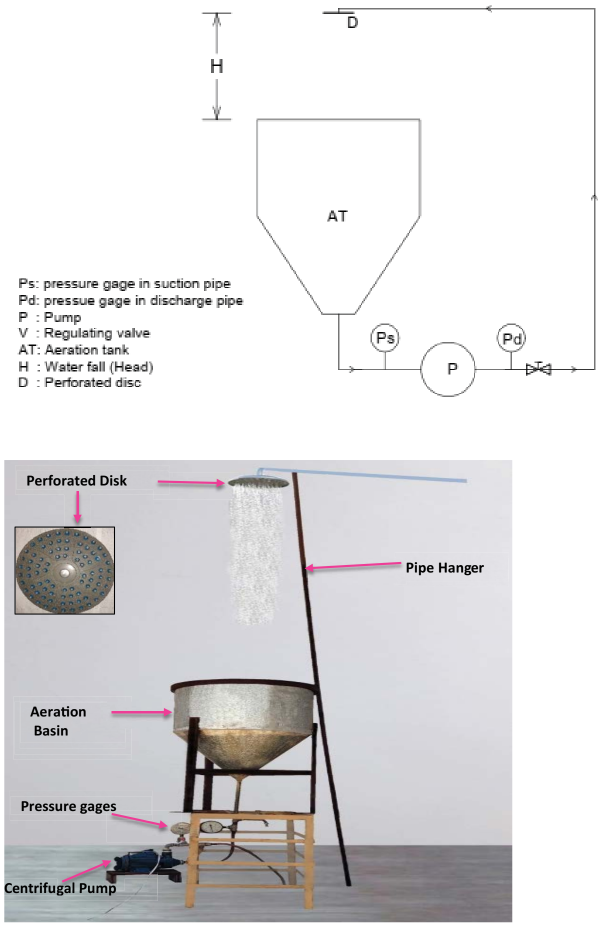


Fig. 1. Experimental set-up: (a) schematic and (b) photograph.

tank. The system was connected to a vertical riser that discharges water by free fall into a basin via a perforated disk.

The riser operated on the variable heads of water. Four levels of fall distances of 2.4, 1.8, 1.2, and 0.6 m were investigated to study the performance of the system. At each desired head, the system was tested at four flow rates of 46.8, 93.7, 140.6, and 187.5 mL/s.

The riser feeds water into a nozzle connected to a perforated disk with 70 openings of 1 mm diameter, which spray water over the basin. Notably, this study was not intended to serve as an assessment of the varying number of openings; rather, the focus is on the application of spray aeration in water treatment. Moreover, full-scale systems of this aeration system could produce different results based on operating conditions, including higher water flow rates, friction losses, and energy requirements.

This system supplies water via a regulating valve in the discharge piping, which is used to control the water flow rate. The corresponding pressure in both suction and discharge piping is measured using a Borden gage attached to this system.

The unsteady-state aeration procedure described by Eckenfelder [11] and ASCE [12] has been adopted in this study. The test involves the chemical removal of DO by the addition of sodium sulfite, with cobalt added as a catalyst.

The procedure can be illustrated as follows: The tap water filled in the basin is deoxygenated using the above-mentioned standard method. After fixing the desired head, the flow rate is varied by throttling the valve. DO concentrations are measured at time intervals using a DO meter type (EXTECH407510) as DO increases from zero to saturation level.

### 3.1. Oxygen mass transfer coefficient ($K_La$)

Aeration is a mass transfer process that occurs at the interface of water and air. The variation in oxygen concentration in water as a function of time is expressed by Eq. (1) [13]:

$$\frac{dc}{dt} = K_L a_{(T)} \left(C_s - C_t\right) \tag{1}$$

where $t$: time (s), $C_s$: saturation DO concentration (mg/L), $C_t$: concentration at time (t) (mg/L), $K_La_{(T)}$: mass transfer coefficient at $T$ °C ($s^{-1}$).

Rearranging and integrating Eq. (1) within the proper limits will yield:

$$\frac{\left(C_s - C_t\right)}{\left(C_s - C_o\right)} = K_L a_{(T)}.t \tag{2}$$

The mass transfer coefficient was determined graphically by plotting the ln($C_s$–$C_t$) vs. time (t) on a semi-log paper, which gives a straight line. The slope of the line is the mass transfer coefficient $K_La_{(T)}$ for the aeration device tested.

To compare results under the same conditions, $K_La_{(T)}$ is generally normalized at a standard temperature of 20°C by using the following empirical Eq. (3) [14,15]:

$$K_L a_{(20)} = K_L a_{(T)} .\left(\theta\right)^{(20-T)} \tag{3}$$

where θ = empirical temperature correction factor, a temperature-dependent term whose value was equal to 1.025 for a temperature of 5°C–25°C and 1.028 for a temperature range of 25°C–45°C [16].

### 3.2. Power consumption

The dynamic head of the pump is calculated from the pressure gage reading in both suction and discharge piping [Eq. (4)] [17]:

$$H_p = \frac{\left(p_d - p_s\right)}{\gamma} \tag{4}$$

where $H_p$: dynamic head of the pump; $p_d$: pressure reading in discharge piping (kPa), $p_s$: pressure reading in suction piping (kPa), γ: weight density of water (KN/$m^3$).

The consumed power by this system was calculated according to Eq. (5) [17]:

$$P = \left(p_d - p_s\right)Q \tag{5}$$

where $P$: power consumed (W), $Q$ = water flow rate through the system ($m^3$/s).

### 3.3. Standard oxygen transfer rate

The SOTR is calculated using Eq. (6) [3]:

$$\text{SOTR} = K_{\text{La}20}.C_{s20}.V \tag{6}$$

where SOTR: standard oxygen transfer rate (g/h), $C_{s20}$: saturation oxygen concentration at 20°C (g/$m^3$), $V$: volume of the aeration tank ($m^3$).

### 3.4. Aeration efficiency (SAE)

The SAE was obtained from Eq. (7) [18]:

$$\text{SAE} = \frac{\text{SOTR}}{P} \tag{7}$$

where SAE is the standard aeration efficiency (kg·$O_2$/KWh).

## 4. Results and discussion

DO concentrations and power consumption were recorded during all 16 runs of experiments at varying fall heights and flow rates of water.

### 4.1. Effects of flow rate and fall height of water

The variation of oxygen uptake with aeration time for all experiments is presented in Figs. 2–5. The figures show that the percentage uptake reduced over time. As expected, the behavior of mass transfer in this system follows the

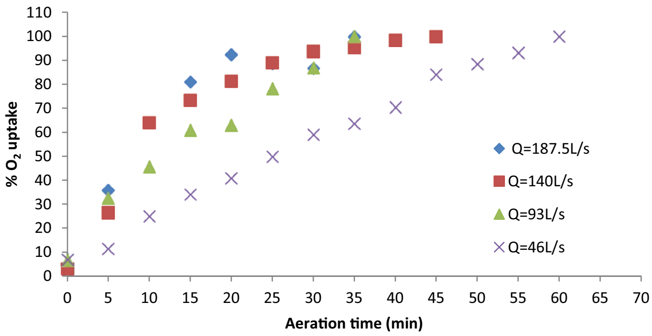


Fig. 2. Variation in % $O_2$ uptake with aeration time for different flow rates at ($H$ = 0.6 m).

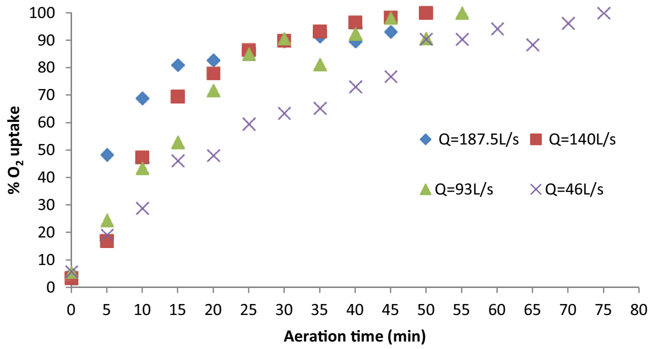


Fig. 3. Variation in % $O_2$ uptake with aeration time for different flow rates at ($H$ = 1.2 m).

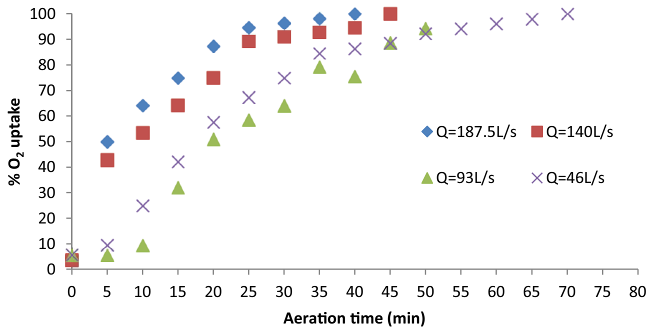


Fig. 4. Variation in % $O_2$ uptake with aeration time for different flow rates at ($H$ = 1.8 m).

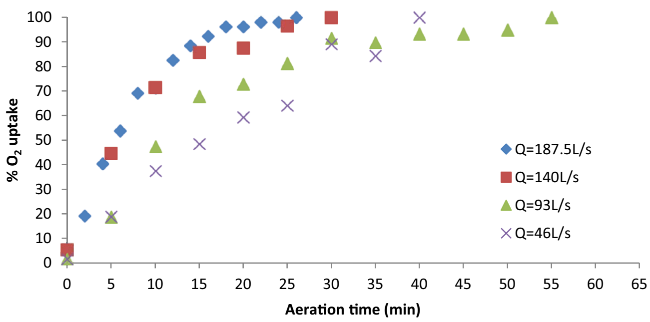


Fig. 5. Variation in % $O_2$ uptake with aeration time for different flow rates at ($H$ = 2.4 m).

mixed order kinetics, that is, a high oxygen uptake rate at the beginning, followed by a significant decrease in the rate as time passes and the saturation level is approached.

As shown in the figures, as the flow rate increases, the time required to reach the oxygen saturation level reduces. Similarly, the higher the fall height of water, the less time it takes to reach the oxygen saturation level.

The effects of the fall height of water at different flow rates on the oxygen mass transfer coefficient are illustrated in Fig. 6. The figure shows that the oxygen mass transfer coefficient is directly proportional to both the fall height and flow rate of water. At a certain height, as the flow rate increases, the number of water cycles increases, thereby reducing the time required to reach the saturation level. On the other hand, at a certain flow rate, as the fall height of water increases, the surface area of water exposed to aeration increases [18].

The experimental results of the oxygen transfer coefficient ($K_La_{(T)}$) under different operating conditions ($Q$, $H$, and $T$) and the corresponding ($K_{\text{La20}}$) are summarized in Appendix 1.

### 4.2. Effect on power consumption

The power consumption under different conditions is plotted in Fig. 7. The results reveal that power consumption is significantly more influenced by the water flow rate than by the fall height of water. This may be attributed to an increase in head losses through the pipe as the flow rate increases because head loss varies as the square of the flow rate [17,19].

The effects of the fall height and flow rate of water on the SOTR are shown in Fig. 8.

Fig. 9 describes the relationship between the SAE and the fall height at different flow rates. There was no significant effect of the fall height on the SAE. However, the SAE increased remarkably with a decrease in flow rate. This may be attributed to a decrease in the amount of power consumed at low flow rates, as mentioned earlier.

Notably, beyond the fall height of 1.8 m, the SAE becomes more sensitive to an increase in fall height at the flow rates of 140 and 187.5 mL/s. The highest SAE value was recorded at the maximum fall height of 2.4 m and flow rate of 187.5 mL/s, at which a maximum ($K_{\text{La20}}$ = 1.82 h$^{-1}$) is recorded. At this instant, the maximum SAE, as shown in Fig. 9, is approximately 0.075 kg·$O_2$/KWh.

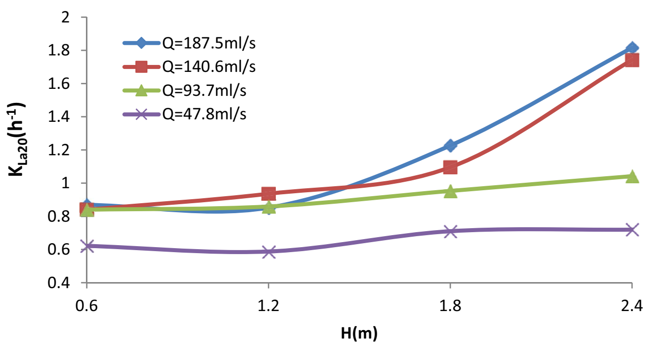


Fig. 6. Oxygen mass transfer coefficient vs. fall height of water for different flow rates.

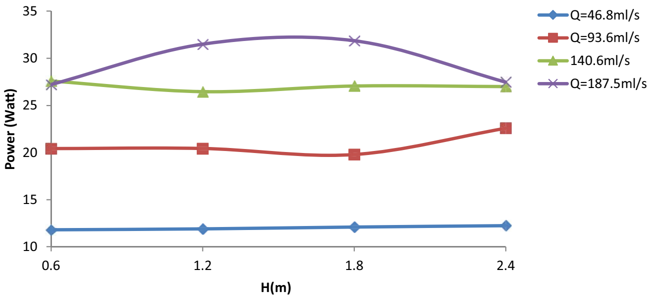


Fig. 7. Effect of fall height and flow rate on power consumption.

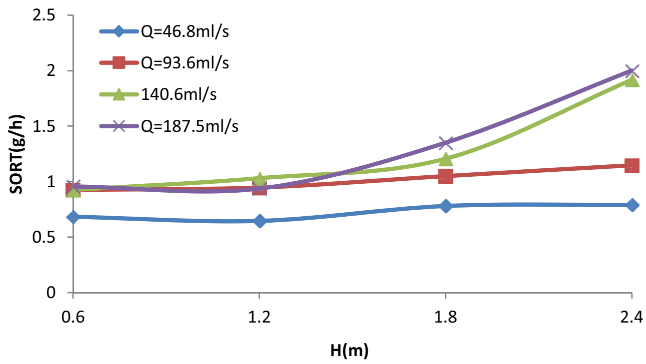


Fig. 8. Effects of fall height and flow rate of water on SOTR.

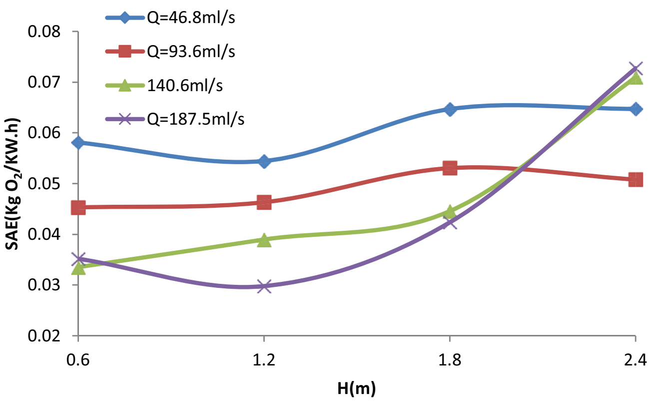


Fig. 9. Effects of fall height and flow rate of water on SAE.

## 4.3. Statistical modeling

The multilinear regression model is tested to represent the results of this study. This model is more representative than a linear model in fitting the relationship between the mass transfer coefficient as a dependent variable and independent variables: the flow rate and fall height of water. The analysis of variance (ANOVA) reveals a significant relationship between the dependent and independent variables. This multilinear regression relationship is expressed in Eq. (8):

$$K_{\mathrm{La}20}\left(\frac{1}{h}\right) = 0.12676 \times Q^{0.411} \times H^{0.309} \tag{8}$$

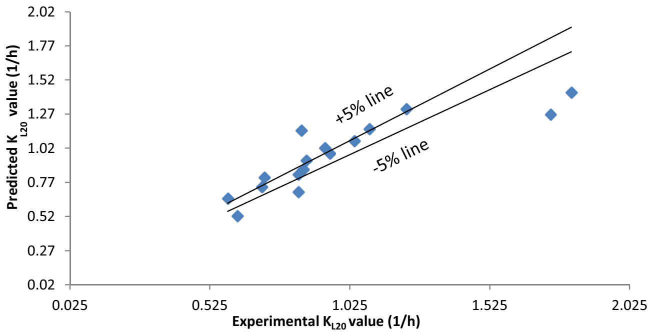


Fig. 10. Experimental $K_{\mathrm{La}20}$ values against predicted $K_{\mathrm{La}20}$ values.

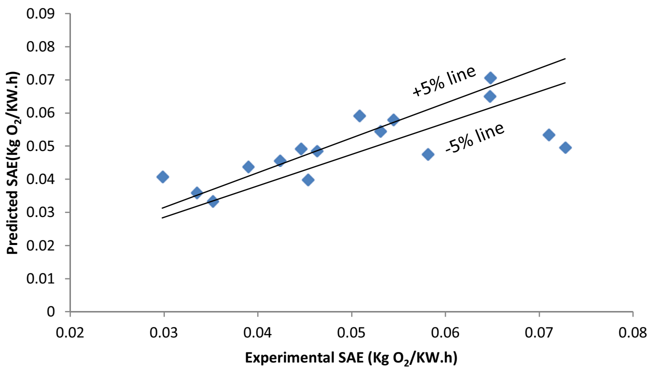


Fig. 11. Experimental SAE values against predicted SAE values.

Table 1
Statistical coefficients of the two developed models

| Developed model equation number | $R^2$ | Probability value ($P$) | Standardized coefficient (β) |
|---|---|---|---|
| 8 | 0.762 | <0.0001 | For $Q$ = 0.698<br>For $H$ = 0.524 |
| 9 | 0.581 | 0.004 | For $Q$ = −0.507<br>For $H$ = 0.596 |

The predicted $K_{\mathrm{La}20}$ values using Eq. (8) are compared with the actual experimental values, as shown in Fig. 10. The results reveal a scattering within ±5%.

Another statistical model was developed to represent the relationship between the SAE and the flow rate and fall height, as expressed in Eq. (9).

$$\mathrm{SAE} = 0.1462 \times Q^{-0.254} \times H^{0.285} \tag{9}$$

The predicted SAE values using Eq. (9) are compared with the actual experimental values, as shown in Fig. 11. The results reveal a scattering within ±5%.

The statistical coefficients and the results of ANOVA for the two mathematical models are summarized in Table 1.

As observed in Table 1, the ($P$) values indicate strong significance between the variables under study. Referring to the adjusted $R^2$, the independent variables under consideration contribute to the interpretation of approximately 76% and 58% of the results in Eqs. (8) and (9), respectively. Furthermore, the standardized coefficient (β) in Eq. (8) indicates that the flow rate has a greater effect on $K_{La20}$ than the fall height, whereas this behavior is reversed in Eq. (9), that is, on the value of SAE.

### 4.4. Optimization approach

The aeration process consumes electrical power (kWh), the magnitude of which is determined primarily by the flow rate and fall height of water. Consequently, the cost of this aeration system is related to these two variables. Hence, there are certain values of the flow rate ($Q$) and fall height ($H$) of water that maintain a minimum amount of power consumption. An optimization approach was used to minimize the operating cost of our spray aeration system. The power expression was obtained by dividing the power ($P$) (kW) consumed in each run by the corresponding $K_{La20}$ ($h^{-1}$). Then, multilinear regression is applied to the developed relationship between these variables, as described in Eq. (10):

$$\text{Power Consumed}\left(\text{KW.h}\right) = 0.00753 \times Q^{0.254} \times H^{-0.285} \quad (10)$$

Considering that the electrical energy cost in Iraq, according to the Ministry of Electricity, is equal to 0.041 USD/kWh [20], the objective function [Eq. (11)] (cost function) will be:

$$\text{Operating cost}\left(\text{USD}\right) = C \times \text{Eq.10} \quad (11)$$

where $C$ = 0.041 USD/kWh.

Thus, the objective function is subject to:

$$\text{Eq. (8) - Input } \left(K_{La20}\right) = 0 \quad (12)$$

where the ranges of constraints defined in this research are $187.5 \geq Q \geq 46.8$ and $2.4 \geq H \geq 0.6$.

To minimize the operating cost of this aeration system, the Lingo software (version 14) was used. The results obtained using the software indicate that the input values of $K_{La20}$ in Eq. (12) that lead to a solution of the equation are in the range 0.526–1.427 $h^{-1}$. The optimum $Q$ and $H$ values that achieve the minimum operating cost are shown in Fig. 12. Thus, the power consumption for operating this aeration system at optimum $Q$ and $H$ constraints with a maximum oxygen transfer coefficient $K_{La20}$ was predicted using Eq. (10). It was equal to 0.022 kWh. Since, the volume of water under aeration in this experiment is 120 L, the aeration of 1 $m^3$ of water will consume 0.185 kWh, and the operating cost of aeration of 1 $m^3$ of water [calculated using Eq. (11)] using this system is approximately 0.0076 USD/$m^3$. In contrast, at the minimum oxygen transfer coefficient $K_{La20}$, the predicted power consumption is equal to 0.192 kWh/$m^3$ and the operating cost of aeration of 1 $m^3$ of water is approximately 0.008 USD/$m^3$.

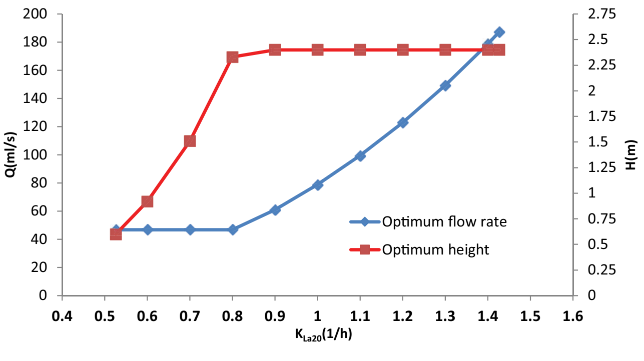


Fig. 12. Optimum flow rate and fall height of water corresponding to $K_{La20}$ to achieve minimum cost.

## 5. Conclusion

This study investigates the effects of the flow rates and fall height of water on the oxygen mass transfer in a spray aeration system. We observed that the oxygen mass transfer coefficient was directly proportional to both the fall height and flow rate.

Regarding the SAE and fall height at different flow rates, before the fall height of water of 1.8 m, the fall height had no significant effect on the SAE. However, after that level, the SAE becomes more sensitive to an increase in height for the flow rates of 140 and 187.5 mL/s. The highest SAE value was recorded at the maximum fall height of 2.4 m and flow rate of 187.5 mL/s, at which a maximum ($K_{La20}$ = 1.82 $h^{-1}$) was recorded.

Both the oxygen transfer coefficient and SAE predicted by the developed multilinear regression relationships agree well with actual measurements under the given conditions. This study also showed that the flow rate has a greater effect on $K_{La20}$ than the fall height, whereas this behavior is reversed in Eq. (9), that is, on the SAE.

The study recommends additional research to investigate other variables that may affect the oxygen mass transfer in this aeration system; for example, nozzle diameter and spray velocity.

The optimization approach was used to find a solution that minimizes the operating cost of this aeration system. The optimum $Q$ and $H$ values that achieve the minimum operating cost were found at certain values of $K_{La20}$. The cost of aeration of 1 $m^3$ of water was calculated, ranging between 0.0076 and 0.008 USD/$m^3$.

## Acknowledgment

The authors acknowledge Mosul University/Environmental Engineering Department for their support and for providing valuable resources.

## References

[1] J.C. Crittenden, R. Trussell, H. Rhodes, H.W. David, J. Kerry, G. Tchobanoglous, MWH's Water Treatment: Principles and Design, 3rd ed., John Wiley & Sons, Inc., New Jersey, 2022.

[2] B.K. Shukla, P. Pandey, M.K. Sen, V.R. Kumar, M. Bashir, Performance Characteristics of Multiple Plunging Surface Jet Aerator With Variable Jet Length, Proceeding of the 5th International Conference on Computing for Sustainable, 2018, pp. 4575–4579.

[3] R.U. Roshan, T. Mohammad, S.M. Roy, R. Rajendran, Design characteristics of showering aeration system, J. Water Supply Res. Technol. AQUA, 71 (2022) 139–153.
[4] M.W. Shahzad, M. Burhan, L. Ang, K.Ch. Ng, Energy-water-environment nexus underpinning future desalination sustainability, Desalination, 413 (2017) 52–64.
[5] S. Deswal, D.V.S. Verma, Air-water oxygen transfer with multiple plunging jets, Water Qual. Res. J. Can., 42 (2007) 295–302.
[6] S. Deswal, M. Pal, Multi-linear regression based prediction of mass transfer by multiple plunging jets, World Acad. Sci. Eng. Technol., Int. J. Environ. Ecol. Eng., 8 (2014) 488–491.
[7] T. Bagatur, A. Baylar, N. Sekerdag, The effect of nozzle type on air entrainment by plunging water jets, Water Qual. Res. J., 37 (2002) 599–612.
[8] S. Singh, S. Deswal, M. Pal, Performance analysis of plunging jets having different geometries, Int. J. Environ. Sci., 1 (2011) 1154–1167.
[9] P.J. Moel, J.Q. Verberk, J.C. Van Djik, Drinking Water Principle and Practices, World Scientific Publishing, Singapore, 2013.
[10] C.T. Smith, Trihalomethane Removal and Reformation in Spray Aeration Processes Treating Disinfected Groundwater, M.Sc. Thesis, University of Central Florida, USA, 2015.
[11] W.W. Eckenfelder, Industrial Water Pollution Control, 3rd ed., McGraw-Hill Book Company, Inc., New York, 2000.
[12] ASCE Standards, Measurement of Oxygen Transfer in Clean Water, 2nd ed., American Society of Civil Engineers, New York, 2007.
[13] Metcalf and Eddy, Wastewater Engineering, Treatment and Resource Recovery, 5th ed., McGraw-Hill Education, New York, 2014.
[14] ASCE Standards, Measurement of Oxygen Transfer in Clean Water, 2nd ed., American Society of Civil Engineers, New York, 1992.
[15] R.A. Corbitt, Handbook of Environmental Engineering, 2nd ed., McGraw-Hill Handbooks, New York, 2004.
[16] E.I. Daniil, J.S. Gulliver, Temperature dependence of liquid film coefficient for gas transfer, J. Environ. Eng., 114 (1988) 1224–1229.
[17] Metcalf and Eddy, Inc., Wastewater Collection and Pumping of Wastewater, McGraw-Hill Book Company, Inc., New York, 1981.
[18] Th.E. Jenkins, Aeration Control System Design: A Practical Guide to Energy and Process Optimization, John Wiley & Sons, Inc., New Jersey, 2014.
[19] Y.A. Cengel, J.M. Cibala, Fluid Mechanics Fundamentals and Applications, 4th ed., McGraw-Hill Education, New York, 2018.
[20] https://www.globalpetrolprices.com/Iraq/electricity_prices/

## Appendix 1

Mass transfer coefficient ($K_{La}$) values at different operating conditions ($Q$, $H$, and $T$) and the corresponding $K_{La20}$ values

| Operating conditions | $K_{La}$ ($h^{-1}$) at (temperature) °C | $R^2$ | $K_{La}$ ($h^{-1}$) at (20)°C |
|---|---|---|---|
| $Q$ = 46.8 mL/s<br>$H$ = 0.6 m | 0.918<br>(34.07) | 0.99 | 0.6224 |
| $Q$ = 93.7 mL/s<br>$H$ = 0.6 m | 1.0551<br>(28.25) | 0.98 | 0.84 |
| $Q$ = 140.6 mL/s<br>$H$ = 0.6 m | 1.1664<br>(31.87) | 0.94 | 0.84 |
| $Q$ = 187.5 mL/s<br>$H$ = 0.6 m | 1.2402<br>(32.84) | 0.84 | 0.87 |
| $Q$ = 46.8 mL/s<br>$H$ = 1.2 m | 1.032<br>(38.41) | 0.96 | 0.5882 |
| $Q$ = 93.7 mL/s<br>$H$ = 1.2 m | 1.1577<br>(30.8) | 0.86 | 0.8593 |
| $Q$ = 140.6 mL/s<br>$H$ = 1.2 m | 1.204<br>(29.12) | 0.89 | 0.936 |
| $Q$ = 187.5 mL/s<br>$H$ = 1.2 m | 1.152<br>(30.89) | 0.73 | 0.8527 |
| $Q$ = 46.8 mL/s<br>$H$ = 1.8 m | 1.074<br>(34.94) | 0.92 | 0.7108 |
| $Q$ = 93.7 mL/s<br>$H$ = 1.8 m | 1.23<br>(29.22) | 0.97 | 0.9534 |
| $Q$ = 140.6 mL/s<br>$H$ = 1.8 m | 1.536<br>(32.23) | 0.90 | 1.0957 |
| $Q$ = 187.5 mL/s<br>$H$ = 1.8 m | 1.65<br>(30.72) | 0.84 | 1.2271 |
| $Q$ = 46.8 mL/s<br>$H$ = 2.4m | 1.0613<br>(34.05) | 0.93 | 0.72 |
| $Q$ = 93.7 mL/s<br>$H$ = 2.4 m | 1.434<br>(31.55) | 0.85 | 1.0424 |
| $Q$ = 140.6 mL/s<br>$H$ = 2.4 m | 2.292<br>(29.93) | 0.90 | 1.7423 |
| $Q$ = 187.5 mL/s<br>$H$ = 2.4 m | 2.43<br>(30.54) | 0.88 | 1.8161 |