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Modeling of Mass Transfer Coefficient in Rotating Biological Contactor with Perforated Discs (RPBC)

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Abstract

In order to make an improvement associated with rotating biological contactor (RBC), a new design of biofilm reactor called as Rotating perforated disc biological contactor (RPBC) was developed in which the rotating discs are perforated. The transfer of oxygen from air to wastewater was investigated. Mass-transfer coefficient (K_La) in the liquid phase was determined by measuring the rate transfer of oxygen. A laboratory scale of (RPBC) consisted of a semicircular trough was used with a working capacity of 40 liters capacity of liquid. Synthetic wastewater was used as a liquid phase, while air was used as a gas phase.

The effects of many parameters on the liquid phase mass transfer coefficient (K_La) were investigated. These parameters are; the disc rotational speed (N), the pore diameter (d) and clearance between the discs(C). It was found that the value of K_La was increased as the rotation speed (N) increased, and as the diameter of the pores in the disc (d) increased. While the values of (K_La) was decreased continuously with increasing the clearance(C). Suitable correlation was developed for estimating mass transfer coefficient (K_La) in this type of bioreactor.

$$\frac{K_L a}{N} = 4.87 \times 10^{-3} \, Re^{0.6} \, Fr^{0.46} \left(\frac{d}{D}\right)^{0.23} \left(\frac{S}{D}\right)^{-0.012}$$

Keywords: *Rotating biological contactor, Mass transfer coefficient, Wastewater treatment.*

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1. Introduction

Rotating biological contactors are successful wastewater biological treatment system which has been developed. They were widely used for the secondary treatment of domestic and industrial wastewater for COD/BOD removal and nitrification/denitrification purposes [1,2,3]. Diffusion limitations and COD/BOD removal kinetics coupled with diffusion of nutrients in biofilm reactors such as rotating discs were investigated by many researchers [4 -7].

Rotating perforated discs biological contactor (RPBC) which developed in this study contains a number of perforated discs which mounted on a horizontal shaft axis of the bioreactor. The wastewater inlets the trough at a certain flow rate.The perforated discs are submerged to 40% into the wastewater. When the perforated discs were rotated by a shaft, the lower portion of the perforated discs that submerged in the wastewater would be turned to the upper atmosphere phase thus microbial film on the disc is in contact with the nutrients of the wastewater phase while the oxygen in the atmosphere would then perform its metabolism [8]. Hence, the organic compounds in the wastewater serve as the nutrients for the microbes to digest and grow. By such periodical operation, the microbes would grow, and a certain thickness of the sludge film would be obtained [9]. The RPBC was proposed due to its advantages such as high degree of turbulence would occur due to the movement of liquid between the discs through the holes within the discs, high specific surface area, low maintenance and power consumption. The design of biological treatment processes for wastewater was described by Metcalf and Eddy [10].

Two approaches have been used to model the mass transfer coefficient in the rotating biological contactor (RBC). The first approach uses the relationship between mass transfer coefficient and both the Reynolds number (turbulence) and Froude number. The second approach is based on the effect of design parameters of contactors on K_La such as the diameter of the discs, the rotational discs speed and the submerging level of the discs in the liquid. [11]. Several models were suggested for estimation the liquid phase mass transfer coefficient(K_La) for (RBC) such as thin biofilm model, Friedman model and Sant Anna model [12]. The aim of this work is to study the effect of many design parameters such as rotational speed, disc pore diameter and clearance between discs on the mass transfer coefficient (K_La) in the rotating biological contactor with perforated discs (BPRC) as well as suggesting suitable empirical correlation to estimate the value of K_La in (BPRC).

2. Materials and Method

2.1. Experimental Set Up

Specification of the bioreactor : The laboratory scale of rotating perforated discs biological contactor (RPBC) was consisted of a forty liters trough of semicircular shape. The bioreactor consisted of two stages equal in volume. Polyethylene (PE) perforated discs are constructed on a horizontal shaft one - meter in length, which fit the trough length, through a central hole. Twenty four perforated discs (25 cm in diameter) were carried in the trough,each stage of the trough contained twelve discs, which nearly result in a total disc area of 2.3 m^2. The discs were 40% submerged in the trough and rotated at (5-15) rpm. Fifteen liters of wastewater was put in the trough in order to achieve the disc submerging depth of 40% . DC motor was used as a prime mover to rotate the discs. Five sets of discs were used, the first was non perforated discs while the others were perforated each with a certain pore diameter. Four pore diameter were used; 0.25, 0.5, 0.75 and 1 cm in order to study the effect of pore diameter on the performance of the bioreactor. The dimensions of the bioreactor are shown in Table 1. Figure (1) shows schematic diagramme of the RPBC that used in this study.

Table 1,
Design details of rotating perforated disc biological contactor (RPBC).

Item	Dimensions
No. of stages	2
No. of discs in each stage	12
Diameter of the disc	25 cm
Thickness of the disc	0.5 cm
Shaft diameter	5 cm
Shaft length	100 cm
Ttrough width	45 cm
Ttrough volume	40 lit.
Total discs surface area	2.3 m^2

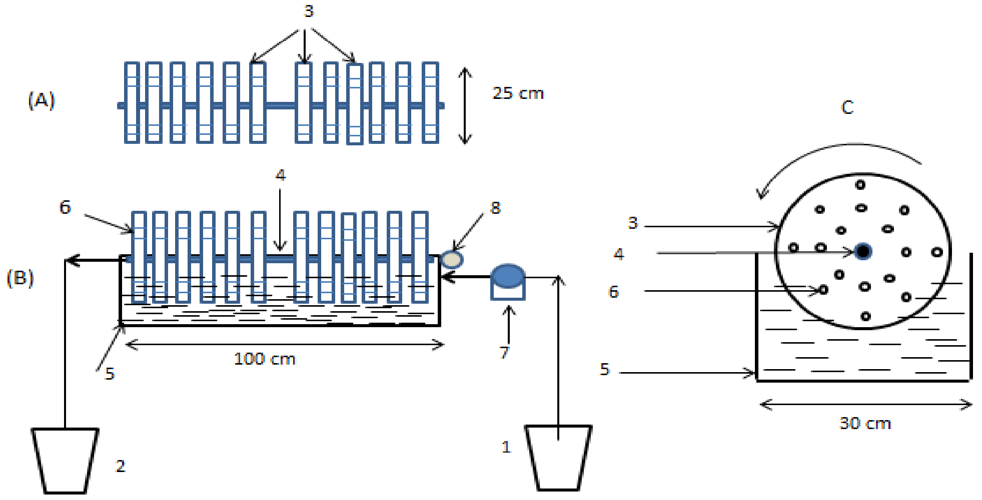

Fig. 1. Schematic diagramme showing the design of the small-scale RPBC. (A) Side view; (B) Stainless steel shaft with discs; (C) cross sectional view. 1- Feed wastewater reservoir. 2- Effluent wastewater collector. 3- Polyethylene perforated discs. 4- Stainless steel shaft. 5- Trough. 6- Holes. 7- Peristaltic pump. 8- Motor.

2.2. Synthetic Wastewater

In this study synthetic wastewater was used which contained of KH_2PO_4, $MgSO_4$, urea and glugose. These materials were mixed in a such proportions to obtain composition of p/ N /COD = 2/ 15 /150 which is necessary for microorganisms to grow [12]. The value of COD concentration in the feed was adjusted about 2000 ± 200 mg/l. The ratio of p/ N /COD was kept constant during the experiment. $MgSO_4$ concentration in the feed was kept constant at 40 mg/l as well. The feed acidity pH was about 7 and increased to 7.8 in the bioreactor trough because of ammonia liberation that results from urea hydrolyses.

2.3. Organisms

Culture of activated sludge was obtained from Al-Rustomiya industry wastewater treatment plant which located in the south of Baghdad. This culture was cultivated in the laboratory on a shaker and used for the inoculation of the system [13].

2.4. Experimental Work

Initially batch wise experiments were carried out. Fifteen litters of synthetic wastewater were put in the trough.‘‘ The wastewater was inoculated with activated sludge culture. The bioreactor (for both set up; perforated and non-perforated discs) were operated batch wise by changing the media in every four days until significant biofilm was noticed to be developed on the surfaces of the discs’’ [11]. The batch operation last for three weeks to obtain a biofilm thickness of about 1.5 – 2 mm. During the continuous operation, feed of wastewater was supplied from the reservoir tank on the inlet side of the bioreactor by means of the peristaltic pump at a constant flow rate of 40 ml/min resulting in a hydraulic retention time of about 6 hour. The outlet of wastewater was collected into a separate collection tank placed at the outlet of the trough. Experiments were carried out at temperature 23 ± 2°C and pH = 7.8± 0.4. pH was adjusted at 7.8 by adding dilute sulfuric acid manually. The thickness of biofilm,formed on the discs surfaces, was manually controlled at 2 mm by skimming the excess thickness of biofilm. For each experiment, the system was operated for one week. To evaluate the mass transfer coefficient K_La, the dissolved oxygen (DO) concentration in the wastewater was instantaneously measured using (DO) probe which was calibrated with distilled water . Nitrogen gas was supplied to the liquid phase until the dissolved oxygen (DO) concentration reached to about 0.2 mg/L. After that nitrogen addition was stopped , then the discs were begin to rotate .

2.5. Calculation of Liquid - Phase Mass Transfer Coefficient (KLa)

Oxygen transfer rate was used to determine the mass transfer rate coefficient K_La. A meter of dissolved oxygen was used to measure the oxygen transfer rate . The oxygen transfer rate is given by the following equation:

$$\frac{dC_{O2}}{dt}=K_La(C^*_{O2}-C_{O2}) \qquad \ldots(1)$$

Where C_{O2} is the concentration of dissolved oxygen in the synthetic wastewater at time t and C^*_{O2} is the saturation concentration. Oxygen probe was tested to show its order response. It was shown that the probes gave a first-order response, with a time constant of about 7 seconds. The expression for the probe can be written as

$$\frac{dC_p}{dt}=K_p\,(C_{O2}-C_p) \qquad \ldots(2)$$

Where C_p is the concentration of oxygen measured by the probe and k_P is the probe constant. The values of the k_p depend on the transport characteristics of the probe membrane [13]. The following dimensionless quantities were introduced:

$$Y_{O2}=\frac{C^*_{O2}-C_{O2}}{C^*_{O2}-C^o_{O2}} \qquad \ldots(3)$$

$$Y_p=\frac{C^*_p-C_p}{C^*_p-C^o_p} \qquad \ldots(4)$$

Rewrite Eqs 1 and 2 in dimensionless form as

$$\frac{dY_{O2}}{dt}=-K_La\,Y_{O2} \qquad \ldots(5)$$

$$\frac{dY_p}{dt}=K_p\,(Y_{O2}-Y_p) \qquad \ldots(6)$$

where C^o_P and C^o_{O2} are the concentrations of dissolved oxygen at time t = 0, Cp^* is the probe saturation concentration. But C^o_P = C^o_{O2} and C_p^*= C_{o2}^*. Equations (5) and (6) were solved simultaneously . The following equation was obtained:

$$Y_p = \frac{K_p e^{-K_L a\, t} - K_{La} e^{-K_p t}}{K_p - K_L a} \qquad \ldots(7)$$

"The value of K_p can be evaluated from the probe response to a step change input by transferring the probe from a container of water saturated with dissolved oxygen ($C_{O2}= C^*_{O2}$) to a container of oxygen-free sulfite solution (C_{O2}=0) and noting the probe reading"[13].

By assuming a value of K_La, the value of Y_p for a given time was calculated by eq. 7. Then, the value of the error for a given K_La in a given time was calculated according to the following equation

$$\text{Error} = \left(\frac{Y_{pA} - Y_{pE}}{Y_{pA}}\right)^2 \qquad \ldots(8)$$

The value of K_La was calculated from eq. (8). The best value of K_La will give the minimum value of Error. So value of K_La can be calculated by minimizing the total error in eq.(8) using the golden section optimization algorithm [11].

3. Results and Discussion

3.1. Effect of Rotation Speed

The effect of rotational speed (N) on the value of mass transfer coefficient (K_La) was studied for both perforated and non-perforated discs. Four values of (N) were used such as 3, 6,9 and 12 rpm. Figure(2) shows that the value of mass transfer coefficient (K_La) was increased till about N= 9 rpm after which the increasing rate become low and get nearly constant value at 0.058 s^{-1} for perforated disc and about 0.045 s^{-1} for non-perforated discs. Increasing rotational speed will lead to much turbulence in the broth solution in the trough. This turbulence will lead to decrease the biofilm thickness and hence results in increasing the value of liquid phase mass transfer coefficient (K_La). This finding is in agreement with Friedman who studied the effect of disc rotational speed (N) on biological contactor performance [11]. He noticed that with the doubling the value of (N), about 25 -30% improvement occur in the efficiency of the bioreactor. Figure (2) shows that the values of mass transfer coefficient (K_La) for perforated discs are nearly 19 - 25% greater than those for non-perforated discs, this may be due to the high degree of turbulence that made by moving the broth solution through the holes of the discs during agitation of the broth.

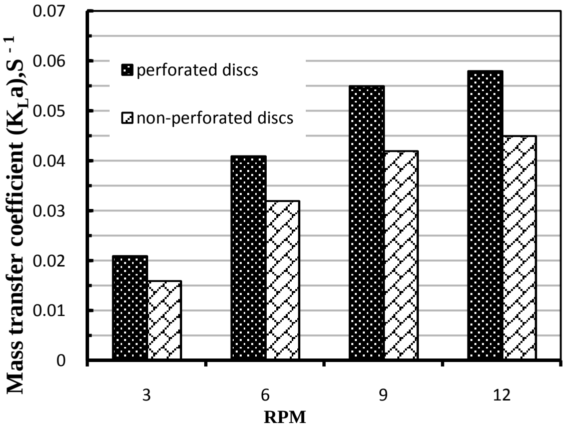

Fig. 2. Variation of mass transfer coefficient (K_La) with rotation speed (N) (pore diameter d = 1 cm and clearance C= 2 cm).

3.2. Effect of Total Perforated Disc Area (A^*)

In order to investigate the effect of total perforated area in the discs on the contactor performance in removing COD of the wastewater, four values of percent of perforated discs areas were studied; (A*/A)=10, 20, 30 and 40%. Where (A) is the total disc area and (A^*) is the total area of the pores in the disc. These tests were carried out for three values of pore diameter (d= 0.5, 0.75 and 1 cm). Figure 3 shows that the % COD removal increases as the percent of perforated disc area increased until it reaches 20% after which it begins to decrease and reaches low value at percent of area of 40%. This can be interpreted as; in the beginning increasing pores in the discs will help making turbulence by moving the liquid between the discs through these pores which lead to decrease the biofilm thickness and hence increasing the value of mass transfer coefficient (K_La) which leads to increase %COD removal [12,13]. But more increase in perforated disc area will lead to decrease the solid contact area of the disc with the biofilm and hence decrease the mass transfer rate which will decrease the % COD removal.

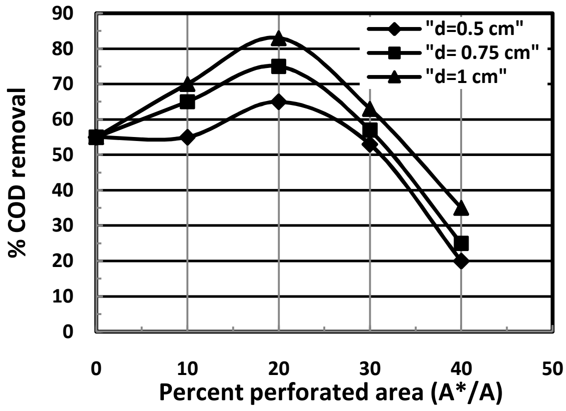

Fig. 3. Effect of perforated disc area on percent COD removal. (Clearence C = 2cm and RPM = 12).

3.3. Effect of the Pore Diameter (d)

The effect of the diameter (d) of pores within the disc on the value of mass transfer coefficient (K_La) was investigated . Four values of pore diameter were investigated; 0.25, 0.5, 0.75 and 1 cm. Figure (4) depicts the variation of K_La with pore diameter at different values of RPM. It was noticed that the effect pore size appear significantly at values of rotation above 8 rpm. Figure (4) shows that the values of K_La increased as the diameter of the pore increased till the values of 0.75 cm after which the difference in increasing the values of K_La is not significant. Also it was noticed that as the pore diameter is decreased the values of K_La approach that of blind disc (disc without holes). The holes in the rotating discs can take part in making surface turbulent during the rotation by the movement of liquid between the compartments through these holes. This turbulence will not permit building a heavy biofilm on the discs and hence improving the values of mass transfer coefficient in the liquid side (K_La). This finding is in agreement with that found by Cupta who showed that the value of mass transfer coefficient was increased when they introduced aeration turbulence in the trough of BRC [14].

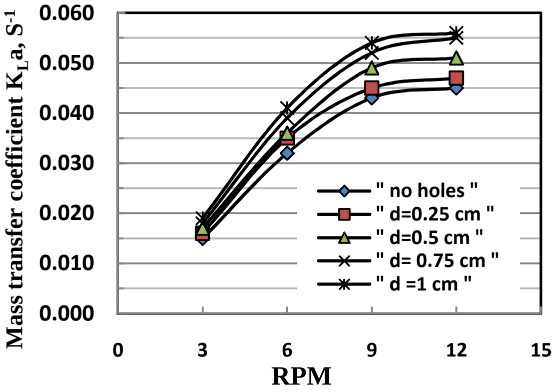

Fig. 4. Effect of hole diameter on mass transfer coefficient K_La. (clearance C = 2 cm).

3.4. Effect of Clearance (C)

Effect of clearance (the distance between two consecutive discs) was investigated to show its effect on the value of mass transfer coefficient (K_La). Three values of clearance (C) were selected; 2, 3 and 4 cm. Figure (5) shows that the values of liquid phase mass transfer coefficient (K_La) are decreased with increasing the value of clearance (c) that is due to the decreasing in the degree of turbulence occurring in the liquid phase between compartments which occur by rotation of the discs as well as the movement of circulating liquid through the holes of the discs. Similar finding was observed by Alaa who showed that increasing the clearance cause the region near the middle distance between compartments to become a weak agitation or a dead zone region and hence the turbulence within the fluid decreases the point which decreases the value of K_La. [15]

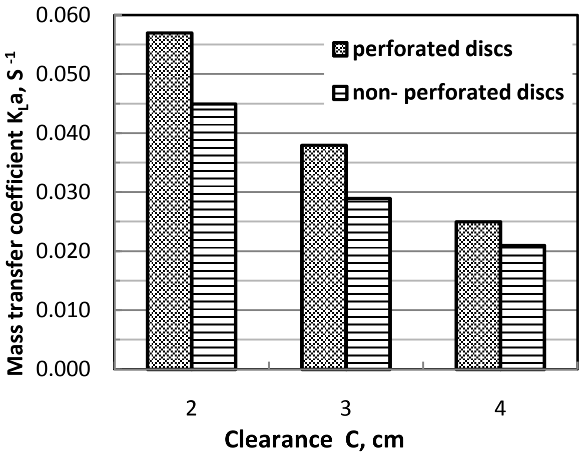

Fig. 5. Effect of clearance on the value of mass transfer coefficient K_La. (rpm = 12 and pore diameter d = 1 cm).

3.4. Dimensional Analysis

In order to establish a mathematical correlation between mass transfer coefficient (K_La), and the variables which investigated in this work: rotation speed (N), diameter of pores in the discs(d) and the clearance(C), the experimental data for this system were analyzed using dimensional analysis. K_La was assumed to be a function of several factors [16]; thus,

$$K_La = f(N, d, D, s, g, \mu, \rho) \qquad \ldots(11)$$

From dimensional analysis, it was noticed that the overall mass transfer coefficient can be related to dimensionless groups Reynolds number (Re) and Froude number (Fr), pore to disc diameter ratio(d/D) and clearance to disc diameter ratio(S/D),through the following equation:

$$\frac{K_La}{N} = 4.87x10^{-3} Re^{0.6} Fr^{0.46} \left(\frac{d}{D}\right)^{0.23} \left(\frac{S}{D}\right)^{-0.18} \qquad \ldots(12)$$

Where $Re = \frac{N\ D^2 \rho}{\mu}$ and $Fr = \frac{N^2\ D}{g}$

From eq.(12) it was noticed that the rotation speed (N) has the most effect on the value of (K_La).

4. Conclusion

It was found that in rotating perforated disc biological contactor(RPBC) the value of the mass-transfer coefficient (K_La) was increased as the rotation speed (N) increased, and as the diameter of the pores in the disc (d) increased. While the values of (K_La) was decreased continuously with increasing the clearance(C).

The percent COD removal was found to be increased as the percent of perforated disc area increased until it reaches 20% after which it begins to decrease and reaches low value at percent of area of 40%. The values of K_La in the biological perforated disc contactor (BPRC) were found to be 19 -27 % greater than that in non-perforated disc(BRC). Suitable correlation was developed for estimating mass transfer coefficient (K_La) in this type of bioreactor. From dimensional analysis, it was noticed that the overall mass transfer coefficient can be related to dimensionless groups; Reynolds number (Re), Froude number (Fr), pore to disc diameter ratio(d/D) and clearance to disc diameter ratio(S/D).

5. Nomenclature

A	Cross sectional area of the disc (m^2)
A*	Total area pores within the disc (m^2)
a	Interfacial area per unit volume (m^2/m^3)
BOD	Biological oxygen demand
C_{O2}	Concentration of O_2 in the bioreactor (g/l)
C^*_{O2}	Concentration of saturated oxygen in the bioreactor (g/l)
C_P	Concentration of O_2 measured by probe (g/l)
C^*_P	Concentration of saturated oxygen measured by probe (g/l)
C^0_{O2}	Oxygen concentration of O_2 at t = 0, C_{m0}, (g/l)
C^0_P	Probe oxygen concentration at t = 0 (g/L)
C	Clearance between two consecutive discs (m)
COD	Chemical oxygen demand
d	Pore diameter, (m).
D	Disc diameter (m)
D_{AB}	Difussivity of O2 through liquid(B)
Fr	Froude number N^2D/g
g	Gravitational acceleration (m/s^2)
k_La	Mass-transfer coefficient (s^{-1})
k_P	probe constant (s^{-1})
N	Rotational speed (s^{-1})
Re	Reynolds number $Nd^2\rho/\mu$
t	Time (s)
Y_m	Dimensionless oxygen concentration in the bioreactor
P	Phosphor
ρ	Density of liquid (Kg/m^3)
μ	Viscosity of liquid (Pa.s)

6. References

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نمذجة معامل انتقال المادة (K_La) في المفاعل الحيوي ذي الاقراص المثقوبة الدوارة (RPBC)

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الخلاصة

لغرض اجراء بعض التطويرات المتعلقة بجهاز الاقراص الدوارة ذي المعالجة الحيوية (Rotating Biological Contctor, RBC) تم استحداث تصميم جديد لهذا الجهاز بحيث تكون الاقراص مثقبة. وتم تسمية الجهاز (Rotating Perforated Biological Contctor ,RPBC). ان الاختلاف بين الجهازين يكمن في طبيعة الاقراص الدوارة، ففي الجهاز الاول (RBC) تكون الاقراص غير مثقبة بينما تكون مثقبة (RPBC) في الجهاز الثاني. تم دراسة معدل انتقال الاوكسجين من الهواء الى مياه الصرف المصنعة (synthetic) وكذلك حساب معامل انتقال المادة في جانب السائل (K_La) من خلال قياس معدل انتقال الاوكسجين. تم تصنيع جهاز ذي الاقراص المثقوبة للمعاملة الحيوية (RPBC) والذي يتكون من اسطوانة نصف دائرية بسعة ٤٠ لترا تحوي قضيبا محوريا قابلا للدوران يضم ٢٤ قرصا مثقوبا. تم دراسة تاثير عدة عوامل على قيمة معامل انتقال المادة (K_La) هذه العوامل هي: سرعة دوران الاقراص(N)، قطر الثقوب في الاقراص (d) والمسافة البينية بين كل قرصين متتاليين(**S**). بينت النتائج ان معامل انتقال المادة يزداد بزيادة سرعة دوران الاقراص وكذلك بزيادة قطر الثقوب بينما تقل قيمته بازدياد المسافة البينية بين الاقراص. تم ايجاد علاقة تجريبية تربط العلاقة بين معامل انتقال المادة (K_La) والمتغيرات التي تم دراستها وعلى وفق النحو الاتي:

$$\frac{K_La}{N} = 4.87 \times 10^{-3} Re^{0.6} Fr^{0.46} \left(\frac{d}{D}\right)^{0.23} \left(\frac{S}{D}\right)^{-0.012}$$
