MODELING OF OXYGEN TRANSFER IN SELF-ROTATING BIOLOGICAL CONTACTORS (sRBC)

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ABSTRACT

A new form of self-rotating biological contactors (sRBC) was used in the present study which was free rotating discs (without any mechanical power). A comparison of various reported models in the literature for computing volumetric oxygen transfer coefficient (K_La) has been done. The models were evaluated namely, Friedman et al. (1979), Sant' Anna (1980), Kim and Molof (1982), Kubsad et al. (2004) and Chavan and Mukherji (2008). Self-RBC oxygen model was established in the present study based on dimensional analysis by performing non-linear regression for 45 runs of the experimental values. This model was expressed as a function of rotational speed (ω), disc diameter (ϕ) and area of discs (A_d). Increasing of rotational speed (ω) and disc diameter (ϕ), increase K_La. Regression coefficient (R^2) obtained is 0.99. Two empirical models were also derived based on Sant' Anna (1980) and Chavan and Mukherji (2008) models, where has regression coefficient (R^2) 0.987 and 0.965 respectively. Results indicated that the proposed models provides a good fitting and correlation for a wide range of reactor design parameters and operating conditions as reported in the present study from the variation in flow rate, % of disc submergence in water and reactors size. These proposed empirical models will facilitate scale-up of sRBC discs. Due to the flow of water, revolution per minute (rpm) of sRBC disc occurs. Then, non-dimensional rpm formula was estimated as a function of flow rate, diameter and area of disc, working volume, area of tank and immersion factor. Regression coefficient (R^2) is 0.994. Predicted values of rpm came closest to the experimental values.

Keywords: Modeling, Rotating biological contactors (RBC), Volumetric oxygen transfer coefficient (K_La), Revolution per minute (rpm), Submergence, Flow rate.

1. INTRODUCTION

One of the critical points in the use of a RBC is the estimation of aeration/oxygenation capacity during treatment. Various authors have done experiments and provided physical oxygen transfer data (**Kim and Molof, 1982; Bintanja et al., 1975; Zeevalkink et al., 1979).** Also, few researchers have attempted to develop empirical/mathematical relationship for estimation of oxygen transfer in a rotating biological contactor. **Kim and Molof (1982)** suggested how oxygen transfer occurs in RBC systems based on the following mechanisms:

* oxygen absorption at the liquid film flowing over the disc's surface during the air exposure cycle,
* direct oxygen transfer at the air-reactor liquid interface, with this diffusion being the result of the turbulence created by the rotating discs, .
* direct oxygen absorption by the microorganisms during the air exposure of the discs.

In fixed film processes like RBC, the mass transfer phenomenon plays an important role in system performance in addition to biological reaction kinetics. These transfer aspects associated with both the liquid phase as well as biofilm result in concentration gradients from bulk liquid to reaction sites and normally control the system performance. Aeration is one of the important aspects in design of a RBC system **(Rittmann et al., 1983)**. A new form of rotating biological contactor (self-RBC discs) was developed by **Elmonayrie et al., 2009** where used UPVC as structural material discs and rotation of these discs achieved due to the hydraulic flow of the drain's water (without any mechanical power). This new form of self-RBC discs achieved high values for COD removal ratio.

2. MATERIALS AND METHOD

The experimental work was carried out in steel channel constructed in the laboratory of the environmental engineering department, faculty of engineering, Zagazig university. In addition to a steel feeding tank with dimensions of 2.0*2.0*0.6 m. Photo 1 shows the channel and installation of used self-rotating RBC discs, while figure 1 shows schematic representation of the channel. This channel has a about of 3.0 m in length including 0.5 m for each upstream and downstream chambers with dimensions of 0.5*0.5*0.6 m. The cross-section of the channel was trapezoidal shape with o.4m in width and a depth of 0.12 m for the downstream weir. Initially, one pump (maximum power 6.5 HP) was used to raise tap water from feeding tank to the channel through UPVC (2.0 inch) pipe. Tap water was pumped into the channel and recycled again to tank. Another pump (1.0 HP) was used in overflow condition. When influent and effluent discharge was the same, steady state conditions occur, hence tap water recycled in longitudinal closed path to the channel. Mechanism of rotation was stopped to start oxygen transfer studies. At emergency cases there were drained UPVC pipes to main sewers. Five laboratory scale RBC reactors were used in the present study in order to evaluate oxygen transfer coefficient (K_La). These reactors were installed in series along the length of the channel. All reactors were constructed from acrylic discs 5.0 mm in thickness and differed in diameter, number of disc and spacing between discs. Each reactor contains four acrylic curvature rips interconnected between discs. Each rip has 1.0 mm in thickness and 270mm in length but differed in width. Table 1 indicates design specification of self-RBC reactors based on the range of parameters and dimensionless numbers considered for RBC model of **Chavan and Mukherji (2008)**. Acrylic discs were mounted in horizontal steel shaft 12mm in diameter which ended with two stainless steel bearings 32 mm in diameter which suspended with two screw bars to be adjustment % of disc submergence in water. All reactors were supported on the top sides of the channel as shown in photo 1.

Photo 1: Installation of self-RBC discs on the channel

Oxygen transfer studies were carried out for each reactor using sodium sulfite method **Eckenfelder (2000)**. The DO prob was placed before and after each reactor, in addition to the inlet and outlet chambers of channel. After reaching steady state conditions, DO in tap water contained in the channels was depleted by addition of sodium sulphite (8 mg/l of DO) (Anhydrous, 95% pure) and cobalt (0.05 mg/l) (Cobaltous chloride, Laboratory reagent grade), was added as a catalyst. The DO depleted water was mixed uniformly. The initial DO was measured using a calibrated DO meter. After depleting DO, flow of water was initiated. The DO values were noted over a period of time until saturation was reached. Linear regression was utilized to determine (K_La) based a plot of Ln $[(C_s - C_o)/(C_s - C_t)]$ versus time (t).

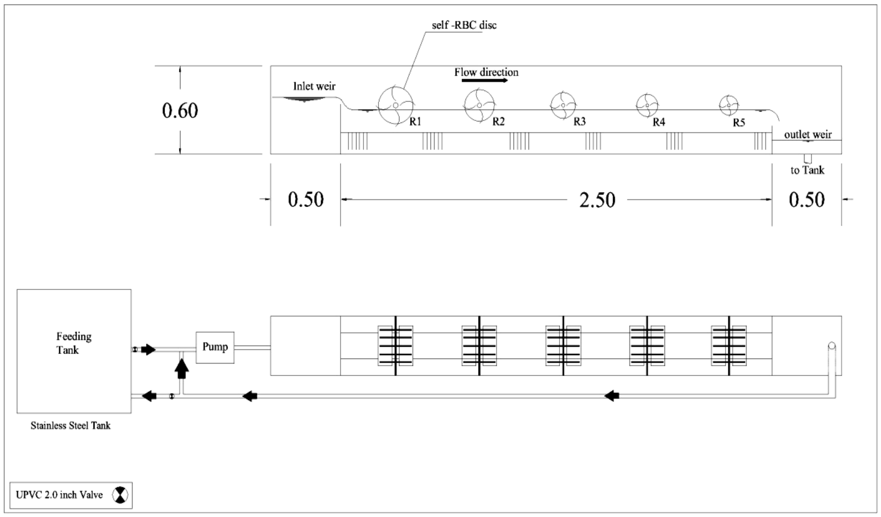

Figure 1: Shows schematic representation of the pilot channels

Table 1: Design specification of self-RBC discs

RBC reactors specification	R1	R2	R3	R4	R5
Diameter of disc (mm)	230	170	140	120	100
No of discs	2.0	4.0	7.0	7.0	6.0
Number of disc (including rips)	4.56	8.6	11.53	13.17	12.25
Width of rips (mm)	100	100	70	70	50
Spacing between discs (mm)	43.8	23.2	17.34	15.18	16.318
Total surface area of discs (m^2)	0.3791	0.391	0.355	0.298	0.1925
Working volume (m^3)	0.0171	0.0119	0.0102	0.0085	0.0068
Specific surface area of discs (m^{-1})	22.169	32.857	34.8	35.058	28.308

3. EXPERIMENTAL PROGRAM

For the five reactors R1, R2, R3, R4 and R5, the experimental program was divided into two sets according to the variation of flow rates and % of disc submergence. First set was at 30% submergence while the variable was flow rate which ranged (2.0, 2.75, 3.6, 4.5 and 5.5 l/s). Second set was performed with optimum flow rate obtained from the first set and the variable was % of disc submergence which ranged (20%, 25%, 30%, 35% and 40%). First and second sets included 45 runs.

4. RESULTS AND DISCUSSION

Oxygen mass transfer data for 45 runs of experimental values applied at the present study in different operation conditions due to the variation in flow rates and % of disc submergence. Based on regression analysis, results indicated that average oxygen transfer coefficient (K_La) achieved 0.177, 0.135, 0.11, 0.077 and 0.06 min $^{-1}$ for R1, R2. R3, R4 and R5 respectively at optimum flow rate, 5.5 l/s and 35% for % of disc submergence. Figure 2 represents oxygen mass transfer in the five RBC reactors at optimum flow rate (5.5 l/s) and disc submergence (35%).

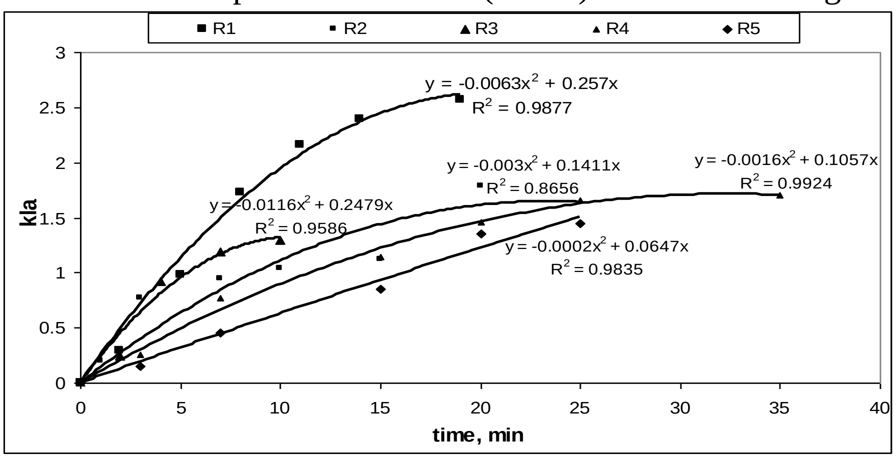

Figure 2: Oxygen mass transfer in the five sRBC reactors at optimum flow rate (5.5 l/s) and disc submergence (35%).

5. MODEL COMPRISN

5.1 Friedman et al, 1979 model

A simple empirical model was proposed by **Friedman et al. (1979)** by only considering the rotational velocity of the disc and presented the following relationship $\ln K_L = a \ln \omega + b$ where the unit of K_L was10 $^{-6}$ m/s and that of (ω) was rpm. Linear regression analysis is performed and fitting parameters is estimated as a=1.94 and b=1.1064. Regression coefficient (R^2) obtained is 0.912.

Kim and Molof, (1982) and Kubsad et al. (2004) models

Kim and Molof (1982) used three differently sized laboratory scale RBC units to find oxygen transfer into mixed liquor. The physical parameters studied included spacing between the discs, size of the discs and rotational speed. They suggested the volume renewal number $kN_v = \omega^{1.5}\phi^{0.5} S^{-1}$, where, S is the half distance between the discs, the relationship between (K_La) and kN_v was $K_La = a\,(kN_v)^b$. **Kubsad et al. (2004)** developed **Kim and Molof (1982) model** where the concept of volume renewal number is similar. Volume renewal number (Nv) was $N_v = 1.697A\ n\ \omega^{1.5}\phi^{0.5}/V$ which takes into consideration the tank liquid volume (*V*), actual disc surface area exposed to air (A). The expression obtained is, $K_La = a(N_v)^b$. Figure 3 represents the models given by Kim and Molof (1982) and Kubsad et al. (2004) applied to the experimental data at the present study. Regression analysis was performed and the regression coefficient (R^2) obtained is 0.695 and 0.918 for Kim and Molof (1982) and Kubsad et al. (2004) respectively. This difference in regression coefficient of two models may be attributed to the large space between discs in self-RBC reactors.

5.2 Dimensional analysis and modeling the transfer

Some empirical models have been developed for determination of oxygen transfer coefficient through dimensional analysis methods and experimental data regression analysis. **Ouano (1978)** used dimensional analysis to estimate oxygen transfer in RBC and correlated the overall liquid phase oxygen mass transfer coefficient (K_L) and Reynolds number.

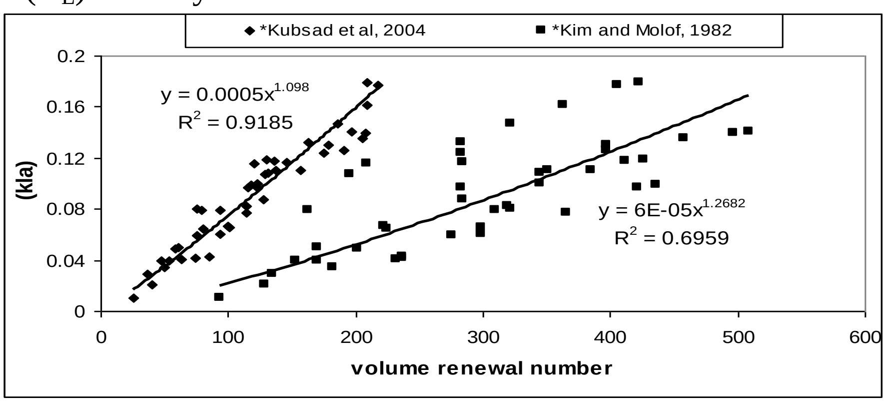

Figure 3: Kim and Molof (1982) and Kubsad et al. (2004) models for oxygen transfer coefficient in RBC based on experimental values for the present study.

5.3 Sant' Anna (1980) model

Sant' Anna (1980) proposed the following relationship;
$(K_L\phi/D) = Sh = K(\omega^{-}\phi^{2}/v)^{l}\,(\omega^{-2}\phi/g)^{m}\,(\phi - \phi_o/\phi)^{n}$, ($Sh = K\,Re^{l}\,Fr^{m}\,YI^{n}$), where Sh, Re and Fr are, respectively, Sherwood's number, Reynold's number, and Froude's number and YI is an immersion factor, where (D) defines diffusivity coefficient. Fitting parameters are estimated, K =1.7, l =0.8, m = 0.13 and n = 0.74. **Boumansour and Vasel (1998)** derived an empirical model based on **Sant' Anna (1980)** model as $Sh = 2.673\,Re^{0.769}\,Fr^{0.135}\,YI^{0.865}$, which came closest to the experimental values of most outhers. An empirical model based on **Sant' Anna**

(1980) model was derived in this study. Non-linear regression based on 45 runs of experimental values was performed using SPSS 16.0. Fitting parameters estimated are, K = 346.99,
l = 0.968, m = 0.06 and n = -0.021. Figure 4 illustrates the modified model based on Sant, Anna (1980) model. It is observed that the modified proposed model gives a good fitting and correlation for a wide range of reactor design. Regression coefficient (R^2) obtained is 0.987. Regression coefficient achieved high value than that of the previous discussed models. This may be attributed to the complete mixing due to turbulence.

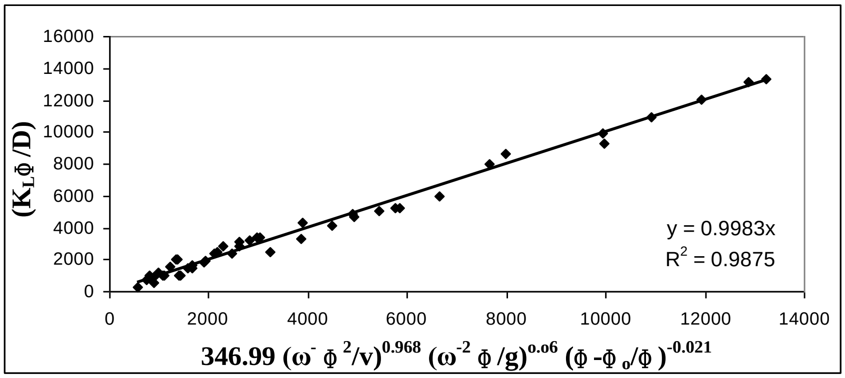

Figure 4: Test of Modified Sant' Anna (1980) model for oxygen transfer coefficient in RBC based on the experimental data for the present study.

5.4 Chavan and Mukerji, (2008)

Chavan and Mukerji, (2008) established two models. One of them due to turbulence only and the other for the overall oxygen transfer (K_La). They stated that, the design and operating parameters that appeared to affect oxygen transfer in RBC were identified as diameter of disc (ɸ), area of discs (A_d), rotational speed (ω), cross-sectional area of tank (A_t), density (ρ) and viscosity (μ) of water. In addition to the thickness of liquid film (δ) and volume of the reactor (V). The model was based on the assumption that mixing in the reactor due to rotation of discs is complete. They established a relationship between four dimensionless groups as,

$(K_L a \rho A_d /\mu) = (D/A_d^{1/2})^{\psi}(\rho A_d \omega/ \mu)^{\varepsilon} (\delta/V\wedge 0.33)^{\lambda} (A_d/ A_t)^{\theta}$

$K_La = K_L (A / V)$, where;

K_La = Volumetric oxygen transfer coefficient $[T^{-1}]$

a = Specific surface area of exchange, A / V $[L^{-1}]$

A = Interfacial surface area of exchange $[L^2]$

V = Control volume of the physical medium $[L^3]$, **(Sanjay Dutta, 2007)**

Fitting parameters estimated were, ψ = -0.327, ε = 1.018, θ = 0.743 and λ = 0.624. In the present study non-linear regression based on 45 runs of the present study estimates fitting parameters ψ = -0.145, ε = 0.797, θ = 0.765 and λ = 0.603. Figure 5 illustrates modified model based on Chavan and Mukerji, (2008) model.

Regression coefficient (R^2) is 0.965. It is evident that the predicted values came closest to the experimental values.

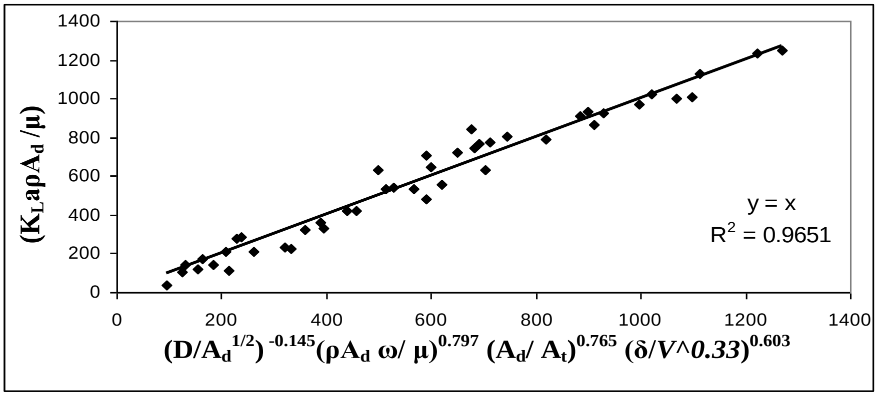

Figure 5: Test of Modified Chavan and Mukerji, 2008 model based on the experimental data in present study.

5.5 Self-rotating RBC model

Revolution per minute (rpm) in this new form of self-RBC with free rotation results due to the hydraulic discharge of water. Parameters that appeared to affect on rpm can be identified as, flow rate (Q), diameter of disc (ϕ), area of disc (A_d), working volume (V), area of tank (A_t) and immersion factor, rpm predicted formula can be written as a function of these parameters. Dimensional and regression analysis applied and rpm formula established as,

$(\omega\rho\phi^2/\mu) = 41.967(Q\rho A_d/V\mu)^{0.442}(\phi/A_d^{1/2})^{3.135}(A_d/A_t)^{1.318}(\phi - \phi_o/\phi)^{0.644}$ -----(1)

Non-linear regression based on the experimental values in the present study was performed. Figures 6 illustrates non-dimensional model of rpm predicted based on the experimental results in the present study. Regression coefficient (R^2) obtained

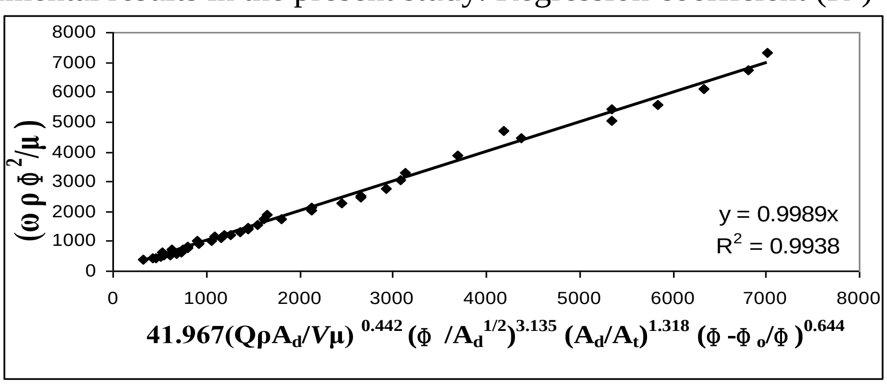

Figure 6: Test of non-dimensional rpm model based on the present study.

is 0.9938. Results indicated a good estimation of rpm predicted values for self-RBC disc. According to the modified models of **Chavan and Mukerji, (2008)** and **Sant' Anna (1980),** the design and operating parameters that appeared to affect oxygen transfer coefficient ($K_L a$) in RBC can be identified as, rotational speed (ω), density (ρ), diameter of disc (ϕ), viscosity of water (μ), area of disc(A_d), cross-sectional area of tank(A_t). Oxygen transfer (K_La) can be written as a function of (ω, ϕ , ρ, μ, A_d, A_t). According to the Buckingham theorem, from the seven variables and three basic dimensions (mass, length and time), it is possible to establish a relationship between four dimensionless groups as,

$(K_L\phi /D) = (\omega\rho\phi^2/\mu)^{\alpha} (\phi /A_d^{1/2})^{\beta} (A_d/A_t)^{\gamma} (\phi - \phi_o/\phi)^{\theta}$-----------------------------(2)

Figures 7 and 8 illustrate self-RBC model applied to the experimental values of the present study. Non-linear regression based on 45 runs of the experimental data were performed using SPSS 16 and it yielded the following fitting parameters α = 1.207, β = -0.414, γ = -0.676 and θ = -0.104. The regression coefficient (R^2) for the plot of predicted and experimental (K_La) obtained is 0.9899. In this non-linear regression the estimates for fitting parameters were characterized by wide 95% confidence intervals. It was observed that the proposed model provides good fit for a wide range of reactor design parameters and operating conditions as reported in the present study from the variation in flow rate, % of disc submergence and reactors size. Regression coefficient (R^2) obtained is 0.986 for the term ($\omega\rho\Phi^2/\mu$) only. For the two non-dimensional terms ($\omega\rho\phi^2/\mu$) and ($\phi /A_d^{1/2}$) regression coefficient (R^2) obtained is 0.987. For the three terms ($\omega\rho\Phi^2/\mu$), ($\Phi/A_d^{1/2}$) and (A_d/A_t) regression coefficient (R^2) obtained is 0.989. Regression analysis indicated that the term ($\omega\rho\Phi^2/\mu$) affects mainly in oxygen transfer and the other terms has low effect.

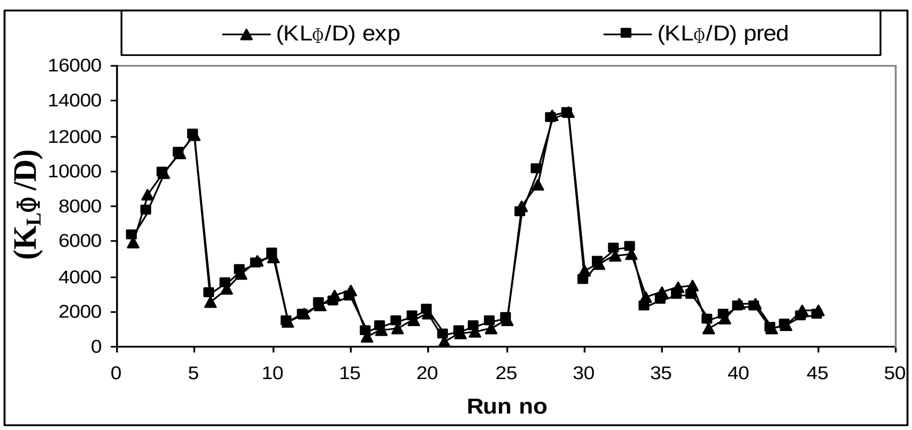

Figure 7: Plot of predicted and experimental ($K_L\phi$ /D) for sRBC model based on the present study.

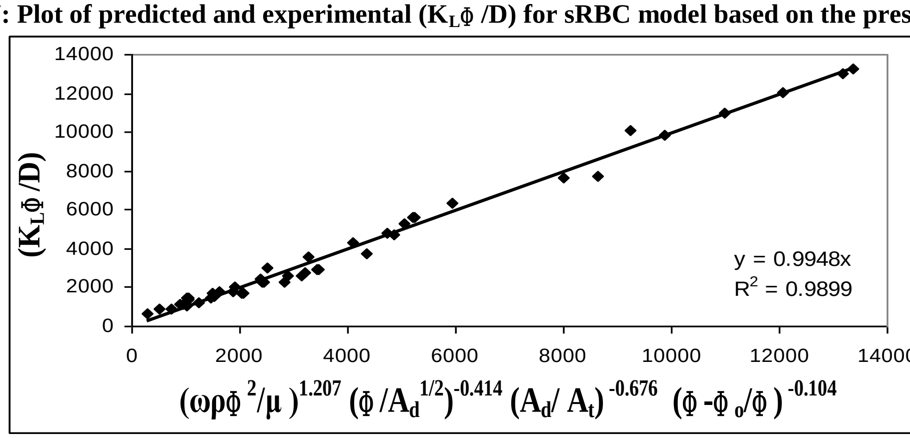

Figure 8: Goodness of the proposed non-dimensional model for self-RBC disc based on the present study.

By substituting from equation 1 in equation 2, the final form of oxygen model derived as,

$$(K_L\phi /D) = 90.95\ (Q\rho A_d/V\mu)^{0.533}\ (\phi /A_d^{1/2})^{3.366}\ (A_d/A_t)^{0.914}\ (\phi - \phi_o/\phi)^{0.673}$$

This model referred to the relation of oxygen transfer coefficient with the flow rate, working volume, area of tank, immersion factor in addition to the diameter and area of discs.

6. CONCLUSION

The oxygen mass transfer coefficient (K_La) is often inadequately predicted by the available models. Two empirical models were derived based on Sant' Anna (1980) and Chavan and Mukherjie, (2008) models. Non- linear regression applied on 45 runs for the experimental values in the present study. Regression coefficient (R^2) for the plot of predicted and experimental (K_La) obtained is 0.987 and 0.97 respectively, which also higher than in the other reported models. It is revealed that the modified empirical models gives good correlation with the significant physical parameters. Based on dimensional analysis by performing non-linear regression using 45 runs of experimental values in the present study, self-RBC oxygen model was established. It is a function of parameters affecting oxygen transfer and can be used as practical tool in computing oxygen transfer coefficient for self-RBC discs. In addition to the non-dimensional formula for estimating rpm predicted values, which is applicable in the form of rotating biological contactors in free rotation.

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