Oxygen Transfer – RBCs

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Abstract:

Rotating biological contactors (RBCs) are the most energy efficient aerobic biological treatment process. This energy efficiency is largely the result of high oxygen transfer efficiencies. For other mechanical aeration devices and diffused air aeration systems, there are algorithms for predicting oxygen transfer rates in clean water, with conversion factors for process water. For RBCs, no similar algorithms are in common usage, although some have been suggested. This paper explores one theoretical model (Chavan and Mukherji), developed using flat plates, and compares the oxygen mass transfer coefficient (K_{La}) predicted to field data from an RBC with deformed discs. The finding is that the Chavan and Mukherji dimensional analysis algorithm may be used for deformed discs, and its use is extremely important to efficient RBC design. The standard aeration efficiency (N_o) of a unique RBC design was tested, and it was found to be capable of over 5 kg/kWh.

Keywords: RBC, oxygen transfer, nitrification, standard aeration efficiency, mass transfer coefficient

1. Introduction

Of all aerobic, mechanical, biological, wastewater treatment processes, rotating biological contactors (RBCs) are the most energy efficient and simplest to operate (1/3 to 1/10 the power and less than 1/2 of the labor of suspended growth processes for a 1 to 2 mgd (3,786 m^3 to 7,572 m^3) plant).[1] A recent survey by a leading RBC manufacturer found that over 95% of operators of RBCs were either satisfied or very satisfied with them.[2] And, it is well documented that fixed film systems, such as RBCs, produce a lower volume of biosolids than suspended growth systems because of the greater concentration of the waste biosolids and the generally lower yield.[3]

With these attributes – low energy usage, low labor requirements, high operator satisfaction, and reduced biosolids volumes - , it would seem that RBCs would be much more prevalent than they are.

However, there are several reasons that RBCs do not dominate the biological treatment market.

The first reason is that when they were initially introduced to the US, primarily by one manufacturer, the steel shafts supporting the discs were improperly designed and constructed, resulting in numerous, catastrophic shaft failures. Other manufacturers had problems with media collapse or disintegration. Decades have passed since those failures and properly designed RBCs have been in successful service without shaft or media failures. While these issues are no longer relevant, their history creates reluctance on the part of engineers and regulators to consider this option.

The second reason is that many early installations were poorly designed from a process perspective and the initial stages were too heavily loaded with organic material, creating an anoxic condition. This low, to zero, dissolved oxygen condition often resulted in nuisance growths of fungi, filamentous bacteria, and/or anaerobic bacteria that plugged the interstitial spaces on the discs, encouraged the growth of sulfur reducing bacteria creating objectionable odors, and reduced performance. These problems often cascaded down stream to subsequent stages, and effluent limits were sometimes not met.

The last major problem is that commonly used design algorithms for nitrification often result in an uneconomical number of RBCs for plants requiring nitrification.

Addressing these last two issues requires an understanding of oxygen transfer and the ability to predict it. Oxygen transfer is a central issue for suspended growth system design and operation and has been thoroughly studied, with the science and algorithms largely settled. This should also be the case for RBCs, but it is not. This paper is intended to advance a suggested solution to this shortcoming.

Not directly including oxygen transfer calculations in RBC design results in a tendency to overdesign the first stages, or perhaps more accurately to underload them, to prevent low dissolved oxygen conditions. This results in designs that are not as economical as they could be. This lack of information has also resulted in some existing RBCs with operational issues being needlessly abandoned, or problems being inadequately addressed.

For designs requiring nitrification, it has been commonly accepted that nitrification cannot occur until the soluble BOD has been reduced to less than 10 to 15 mg/l. This "rule of thumb" stems from the empirical observation that nitrification does not seem to occur, to any significant degree, in conventional RBCs, when the soluble BOD is above these levels. It has been hypothesized that this is because the heterotrophs outcompete the nitrifiers (autotrophs), and until the heterotroph's food source, BOD, is diminished the slower growing nitrifiers cannot successfully establish themselves in sufficient numbers. This has long been known to be untrue, but like a lot of mythology has persisted over the years.[4]

The actual fact is that nitrifiers require a fairly high level of dissolved oxygen to thrive and if those conditions exist, the heterotrophs and nitrifiers coexist. The importance of understanding this is that designing RBCs for nitrification without being able to begin nitrification until the soluble BOD has been reduced to less than 10 or 15 mg/l results in oversized systems.

Based on the above, understanding oxygen transfer is the key to proper design and should be an important factor in selecting an RBC supplier. However, very few designers are aware of this and fewer still have any idea how to assess oxygen transfer in RBCs. And lastly, while researchers have looked at various methods of predicting oxygen transfer, most of that research has not been verified with real world experience.

2. Oxygen Transfer Model

This paper aims to incorporate what is known about RBC oxygen transfer theory and compare it to an actual RBC system to determine its viability for use in design.

Since 1975, there have been at least six major research papers[5,6,7,8,9,10] attempting to provide theoretical models of oxygen transfer by RBCs, initially based on thin film theory and subsequently supplemented by consideration of turbulence, to predict oxygen transfer. Almost all of these models were corroborated by laboratory testing of small diameter flat plates with fairly good correlation with their own testing, but not between each other and with full scale RBCs.

In 2008, Drs. Chavan and Mukherji at the India Institute of Technology took a different approach.[11] They performed a dimensional analysis of the oxygen transfer problem, considering all factors found by others to affect oxygen transfer, and achieved excellent correlation (R^2 = 0.99) with flat plate transfer efficiency in the lab and with the results of other researchers.

This study also compared the portion of oxygen transfer that occurs because of liquid film transport to that which occurs because of turbulence. Proportionally, turbulence was found to be the more important mechanism and that it could be separately predicted using dimensional analysis.

The dimensional analysis for overall oxygen transfer by Drs. Chavan and Mukherji was correlated, using non-linear regression, to lab results for clean water oxygen transfer at 20°C on small diameter flat plates. The resulting equation follows:

$$\left(\frac{K_{La}\rho A_d}{\mu}\right) = \left(\frac{D}{A_d^{1/2}}\right)^{-.327}\left(\frac{\delta}{V^{.33}}\right)^{.743}\left(\frac{\rho A_d \omega}{\mu}\right)^{1.018}\left(\frac{A_d}{A_t}\right)^{.624}$$

Where:

K_{La} is volumetric oxygen transfer, sec^{-1} (also known as mass transfer coefficient)
ρ is density of water, gm/m^3
A_d is surface area of discs exposed to air, m^2
μ is dynamic viscosity of water, gm/m-s
D is diameter of the discs, m
ω is rotational speed, rps
A_t is surface area of tank, m^2
δ is thickness of water film, m
V is volume of liquid in tank, m^3

δ may be estimated using the following equation.

$$\delta = 1.2\cdot \cdot 10^{-4}\cdot\ v_{pz}\cdot^{0.5}.$$

Where:

v_{pz} is the vertical component of velocity as the disc exits the water in the tank, m/s

The temperature correction factor for oxygen transfer is commonly assumed to be:

$$1.024^{T-20}.$$

The independent variables are surface area of the discs and the speed of rotation. The most efficient RBC design for oxygen transfer will maximize available surface area and provide for variable speed drives.

Finally, the exponents used in the Chavan and Mukherji formula are specific to the media used in their testing and correlated well with the results of other flat discs tested by others. Since no commercial supplier of RBCs uses flat discs, but use deformed discs of varying designs, it is recommended that each RBC manufacturer complete testing on their media to determine the exponents that best fit their particular design.

3. Disc Surface Area - BOD Removal and Nitrification

Both BOD removal and nitrification require oxygen and therefore it is important to compare the amount of oxygen that is transferred to the wastewater to the amount of oxygen demanded, for purposes of optimizing design or addressing operational problems.

Commonly, 0.9 to 1.3 pounds (0.4 kg to 0.9 kg) of oxygen are assumed to be required for each pound of BOD removed corresponding to SRTs of 5 and 20 days respectively in suspended growth systems.[12] For nitrification, 4.33 pounds (2.06 kg) of oxygen are required per pound of ammonia converted to nitrate.[13]

3.a. BOD Removal

For soluble BOD removal, the second order, modified Grady equation is commonly used, as follows, for 20°C domestic wastewater:

$$S_n = (-1 + ((1 + 4 \times 0.00974 \times (A_d/Q) \times S_{n-1})^{.5}) / (2 \times 0.00974 \times (A_d/Q))$$

Where:

S_n = effluent soluble BOD_5, mg/l
A_d = surface area of media, m^2
Q = flow rate, m^3/d
S_{n-1} = influent soluble BOD_5, mg/l

It has been found, empirically, to accurately predict soluble BOD removal.

The temperature correction factor for BOD removal is commonly given as:

1.014^{T-20},

and is applied to the square feet of surface area calculated to be required at 20°C.

As for oxygen transfer, the independent variable is surface area.

3.b. Nitrification

For nitrification, either a zero order reaction that proceeds at a rate of X gm/m^2-d (literature often cites a maximum value of 1.5 gm N/m^2-d at 20°C for design, higher values have often been reported from field testing), where m^2 is the actual surface area of the RBC, or a first order reaction related to ammonia levels is used. In either case, dissolved oxygen levels must be 2 mg/l or greater for nitrification to proceed. Note, the literature often suggests a first order relationship of the rate of nitrification to soluble BOD. Field testing has found this to not be the case when sufficient DO is present.[14]

No matter what nitrification rate equation is used, zero order or first order, disc surface area is the independent variable.

The first order equation used by Pano, et al[15] is as follows:

$$C_i = (Q * K_N * C_{i-1} - A_d * k_n) / Q * K_N$$

Where:

C_i = effluent ammonia, mg/l
A_d = surface area of media, m^2
Q = flow rate, m^3/d
C_{i-1} = influent ammonia, mg/l
K_N = half saturation constant, mg/l, assumed to be 0.45
k_n = maximum reaction rate, g/m2-d, assumed to be 2.334

The temperature correction factor for nitrification is commonly given as:

1.08^{T-20},

and is applied to the maximum reaction rate assumed at 20°C.

4. Field Testing

BioMass Technologies, LLC, of Farmington Hills, Michigan (BMT) has developed a unique RBC plate that consists of a multitude of approximately 4 mm diameter pins, approximately 18 mm tall, spaced at about 5 mm on either side of a flat plate. It has an enormous amount of surface area per unit of volume. Its surface area per unit of volume is approximately 2.5 times the surface area of a conventional RBC.

A 3 foot (0.92 m) diameter disc of this construction is shown in the following photo:

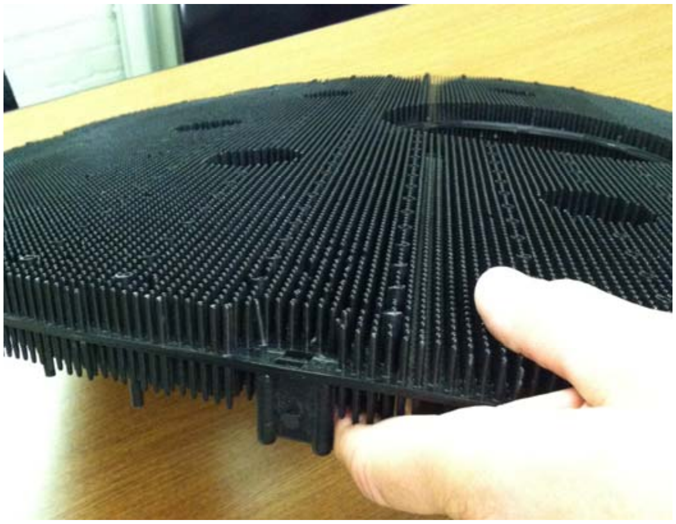

Photo of Test RBC Disc

Using this unusual disc design, BMT was able to treat very high BOD loadings (up to 5 times the normally accepted upper limit of 20 gm/m^2 – d), while maintaining dissolved oxygen concentrations above 2 mg/l, and to nitrify from the first to the last stage. It was apparent that the oxygen transfer efficiency was quite high. The question was how high and did this unusual surface design perform in accordance with the dimensional analysis that predicted the performance of flat plates.

BMT created two pilot units to test its concept. One was a 9 inch (0.23 m) diameter disc and the other a 3 foot (0.92 m) diameter disc. In the case of the 9 inch discs they were mounted on a 60 inch (1.54 m) long shaft. The 3 foot diameter discs were mounted on an 8 foot (2.46 m) long shaft with three stages. Both were mounted in fabricated steel tanks. The drives were fractional horsepower, electric motors (220V), controlled by variable frequency drives.

The field test procedure was to fill the RBCs with tap water and then to deoxygenate that water using sodium bisulfite. A calibrated field oxygen probe and thermometer were then inserted into the tank and the RBC run at a constant speed. The initial temperature was recorded and the dissolved oxygen in the tank was recorded versus time. The tap water TDS was taken from the water utilities records. The field mass transfer coefficient (K_{LaT}) was calculated from this data and the standard conditions K_{La20} calculated, correcting for temperature and TDS. Simultaneously, the power consumption of the drives was measured using the electronics package supplied with the variable frequency drives over the period of each test.

This procedure, while it did not have all of the controls of a laboratory test, has been used for many years to estimate clean water oxygen transfer.

5. Results and Conclusions

The results of these field tests, compared to the calculated results, using the Chavan and Mukherji with the flat plate exponents, are shown in the following table:

Standard Oxygen Transfer Rate - Field v. Calc.

Clean Water, Clean Disc

Handy Township, 4-2-2013 & 4-19-2013

Date	Disc Diam, ft.	Disc, rpm	Act. K_{La20}, min^{-1}	Calc. K_{La20}, min^{-1}	Act. kg/kWh	K_{La20}, Act./Calc.
2-Apr	3	2	0.025	0.028	3.84	0.90
2-Apr	3	3	0.039	0.049	5.34	0.79
2-Apr	3	4.2	0.051	0.078	5.70	0.66
19-Apr	0.75	10	0.063	0.174	5.88	0.36
19-Apr	0.75	4.2	0.038	0.052	6.44	0.72

Given that these were field tests, the mass transfer coefficient (K_{La20}) correlation is very good between that predicted by the model and that measured in the field. The 10 rpm test using the 0.75 foot diameter disc was not well correlated and is assumed to be an anomaly resulting from test procedures. For design purposes, the Chavan and Mukherji dimensional analysis may be applied, even to unusually constructed discs. However, carefully controlled laboratory testing will likely reveal that different exponents in the formula will result in a better fit with each particular media design.

From an oxygen transfer rate standpoint, it is also worth noting that the test RBCs transferred on the order of 5.5 kilograms of oxygen per kilowatt hour in clean water (standard aeration efficiency, N_o). Using an α factor of 0.8 (commonly assumed for low speed, surface aerators), an actual oxygen transfer rate of approximately 5 kg/kW-hr may be expected. This is more than twice the efficiency of mechanical aeration systems both in clean and process water.[16] It is also approximately 50% greater than fine bubble aeration in process water.[17]

While rotational speed has a dramatic impact on oxygen transfer, there is a practical limit to the range of speeds that may be employed to prevent scouring of the biomass. Each manufacturer should test their media for these limits and the designer/operator should make provisions to be able to vary the speed of rotation within this range.

Using this information, along with the wastewater characteristics of the particular wastewater to be treated, a relatively simple design calculation can be made that will predict dissolved oxygen transfer and bulk liquid dissolved oxygen. From these computations, appropriate and efficient stage sizing can be accomplished and nuisance growth conditions avoided.

Incorporating oxygen transfer considerations into RBC design allows the designer to efficiently design RBCs and to address the issue of nuisance growth and odors that may result from low dissolved oxygen conditions. It also allows designing an RBC system for nitrification that utilizes the entire disc surface area.

The maximum rate of nitrification for design has commonly been accepted to be approximately 1.5 gm NH_4-N/m^2 – d and this correlates to the oxygen transfer rate of conventional RBCs. Researchers have found that higher rates may be achieved if the oxygen transfer rate is increased, but the effect of a dissolved oxygen concentration above 2 mg/l is modest.[18] This suggests that there is a second order equation that may better describe nitrification; but that for design, it is probably not worth considering. It also suggests that a higher maximum rate of nitrification may be used where the dissolved oxygen level may be sustained above 2 mg/l.

For the operator, having the ability to predict oxygen transfer provides a tool for understanding his or her plant's condition and to make an informed decision on how to address issues that may occur.

RBCs have the potential to be an excellent choice for aerobic biological treatment. The primary reasons that many exclude them from consideration no longer exist.

Finally, incorporation of RBC technology into a municipal wastewater treatment plant has the potential to bring a municipal wastewater treatment facility closer to net zero energy than any other facility improvement, including anaerobic digestion. The net reduction in energy usage could be from 600 to over 2,000 kWh per million gallons treated. Energy audits are generally unlikely to achieve more than 100 kWh per million gallon reductions and anaerobic digestion with power generation is unlikely to achieve much more than 400 kWh per million gallons treated.

Recommendations

1. Each RBC manufacturer should develop oxygen transfer data, mass transfer coefficient and oxygen transfer rate, for its disc design.
2. RBC manufacturers should reevaluate their designs to improve oxygen transfer.
3. RBC design equations should incorporate oxygen transfer.
4. Each RBC manufacturer should evaluate maximum rotational speed that can be achieved without adversely affecting biological treatment
5. Incorporation of bio P removal into RBC design should be studied.

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