USE OF THE ROTATING BIOLOGICAL CONTACTOR FOR APPROPRIATE TECHNOLOGY WASTEWATER TREATMENT

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ABSTRACT

The performance of a Rotating Biological Contactor (RBC) was studied using a rate of 0.1 gallon/ft^2/day. The biochemical oxygen demand (BOD_5) of domestic wastewater was reduced 98% from 150 mg/liter to 3 mg/liter. The total suspended solids were reduced from 73 mg/liter to 32 mg/liter and ammonia was completely oxidized to nitrate. The economics of wastewater treatment at this low loading rate will be favorable for applications which require maintenance-free operation, or where operational expertise is unavailable.

A mathematical model for the RBC was also developed. The model includes material balances on both oxygen and substrate in the biofilm and bulk solutions. The resultant set of non-linear, parabolic partial differential equations was solved using an implicit numerical technique similar to Crank-Nicolson. Since model predictions were within 10% of the experimental results, the model should provide a basis for future development.

The following is a condensation of the original paper.

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INTRODUCTION

The Rotating Biological Contactor consists of a series of discs attached to a common shaft. The discs are partially submerged in a trough of continuously flowing wastewater. As the discs rotate, a film of microorganisms growing on the discs consume oxygen from the air and substrate from the wastewater. In this way, organic materials (substrate) are removed from the wastewater.

The advantages claimed for RBC are: simplicity of maintenance and operation, low power consumption, freedom from flies and objectionable odors, ability to withstand shock or toxic loads and desirable sludge settling properties.

The RBC is an appropriate technology because there exists a universal need for economical, simple wastewater treatment. Existing wastewater treatment has often taken the form of sophisticated and energy-intensive treatment plants which require few, but highly trained operators. When applied to less developed countries this sophisticated technology has resulted in poor performance, due to a lack of technical knowledge and support.

EXPERIMENTAL EQUIPMENT AND ANALYTICAL TECHNIQUES

Experimental Equipment:

To verify the mathematical model, data were collected from a pilot plant using domestic sewage as the substrate. Domestic sewage rather than synthetic substrate was used for more meaningful results.

The Rotating Biological Disc pilot plant was purchased from Autotrol Corporation in Milwaukee, Wisconsin, in June, 1978. It consisted of a hemicylindrical tank made of fiberglass. The tank was divided into five stages. The last four stages were each 13 inches long and 11-1/2 inches in radius with a volume of 9.25 gallons. The first stage was nine inches long and was inteded for temporary wastewater storage. A central steel shaft ran through the whole length of the tank (62 inches) and was used to support the polyurethane discs. For each stage there were 9 discs. Each disc had a diameter of 18-5/8 inches, and they were attached together in each stage to maximize surface area for a given volume. The total surface area for 36 discs was 250 ft^2, providing a volume-to-surface area ratio of 0.148 gallons/ft^2. The discs were 40% submerged and rotated at a constant speed of seven RPM, providing a peripheral velocity of 34.1 ft/min.

Flow from stage to stage was through U-shaped PVC fittings. A hydraulic gradient was established so that the substrate flowed in only one direction. The substrate was pumped by a variable speed Master Flex pump from a drum where primary settling took place. Fresh domestic sewage was fed into the drum daily. The experimental setup is shown in Figure 1.

The wastewater used was found to contain an exceptionally high organic nitrogen content. Since organic nitrogen lowers pH when it is converted from ammonia to nitrate, sodium carbonate was used to make sure the effluent pH would not fall below the effluent standard. The RBC was maintained at ambient temperature (13-30°C).

Analytical Techniques:

Throughout the experiment ammonia, pH, and nitrate data were collected five days a week while BOD_5, chemical oxygen demand (COD), and total dissolved solids (TSS) data were collected two days a week. Influent nitrate and phosphate data were only collected twice and were found to be sufficient.

A dissolved oxygen (D.O.) meter, made by Yellow Spring Instrument, was used to measure the initial and final D.O. The meter was calibrated by oxygen-saturated water whose D.O. was found by the Winkler method in the "Standard Methods in Wastewater Management."

A model Corning 12 meter was used to measure pH. Ammonia and nitrate were measured

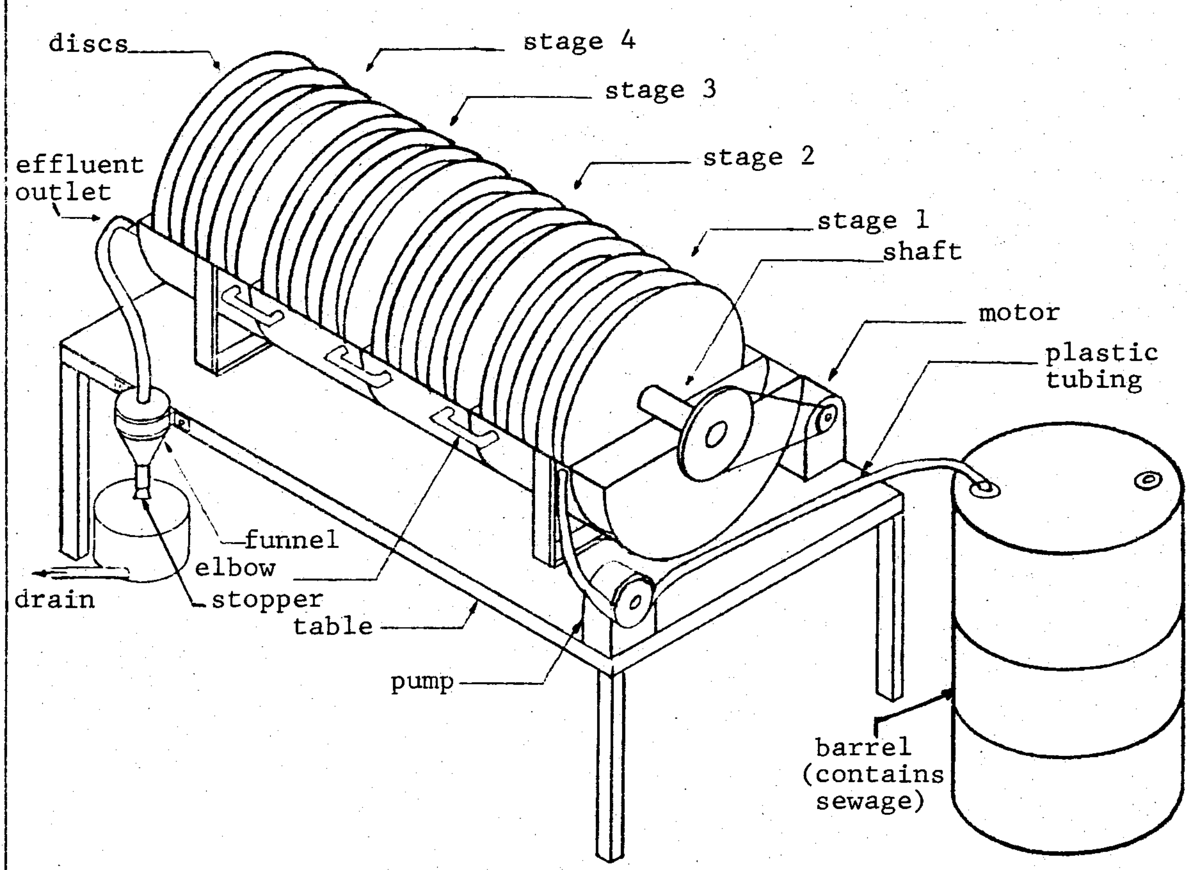

FIGURE 1. EXPERIMENTAL SETUP OF THE RBC PILOT PLANT

by an Orion Research 407A meter with a specific ion electrode. The meter was calibrated by standard solutions made by the same company. The following measurements were performed according to "Standard Methods in Wastewater Management." COD was measured by the potassium dichromate Method 508. TSS was measured by Method 208A. The stannous chloride method was used with initial persulfate digestion (Method 425C III and 425E) to measure phosphate.

REVIEW OF RELEVANT LITERATURE

Operational Data:

The review of relevant literature revealed research and experimentation dating from the 1920's. Only selected samples are reported in this condensed paper.

Antonie (1) found that the RBC performed better with varying flow rates than constant rates. Power consumption was 20-80 hp-hr/1000 pounds BOD_5 removal. Settled sludge contained 4% solids with dairy wastes.

Torpey (2) used a 10-stage RBC and removed 93% BOD_5.

Pretorius (3) found that RBC bacteria in the first stage were sphaerotilus and beggiatoa while other stages contained mostly nitrate forming bacteria and fungi. He found that COD was removed at a rate of 0.49 g COD/g biomass/day and nitrification occurred at a rate of 0.138 nitrate-nitrogen/g biomass/day.

Autotrol Corporation (4) has specified two process design criteria for a maximum removal rate: a peripheral velocity of 58 ft/min. and a spacing of 0.5 inch between disc surfaces.

Labella (5) compared the capital and maintenance cost of RBC, activated sludge, and activated lagoon. The costs were based on a 0.4 million gallons per day plant in 1972.

Type of System	Capital Cost	Maintenance Cost (annual)
Activated Lagoon	$240,000	$17,000
Activated Sludge	$175,000	$17,000
RBC	$245,000	$ 9,200

Bintanja (6) found that using pure oxygen removes more COD and produces less sludge with better settling properties.

Mathematical Models for Microbial Growth:

To develop the mathematical model for the RBC, several mathematical models developed by previous researchers were investigated. These models are presented fully in the original paper. Only selected material will be presented here.

In 1950, Monod (7) defined specific growth rate, μ, as the rate of increase of organism concentration per unit concentration of organisms, and derived an expression for batch reactor kinetics. However, many deviations from this expression have been noted.

Busch and Hughmark (8) found that most fixed-film models were only good for laminar flow. From their experimental data they discovered that eddy diffusion takes place in the liquid film.

Antonie and Welch (9) developed a RBC model using dimensional analysis to find a relationship between different systems parameters and a systems efficiency.

Sheikh (10) studied the relationship between organic retention time and trickling filter efficiency.

Monadjemi and Behn (11) in modeling a trickling filter, applied mass diffusion theory. They also derived an equation linking efficiency of the filter with oxygen uptake rate.

Quirk, Lauler and Matusky (12) developed a model for fixed-film reactors. The model prediction approximated operating data from municipal sewage treatment.

Grieves (13) derived the first RBC dynamic model in 1972. The prediction seemed to match his experimental data (using synthetic substrate). However, the model is only good if substrate is the limiting factor. For high substrate concentration or high flow rate in which the system is deprived of oxygen, the model is not applicable.

Kornegay (14) derived two models; one for trickling filters and another for RBC. The equation for the RBC was found to be useful only for high and low loading rates. Maximum efficiency occurred when discs were 50% submerged.

For the trickling filter, efficiency was higher when filters were placed in series than when in parallel. Recycling would increase efficiency if flow rate was higher than 600 gallon/day/ft^2. For most economical operation, the area-to-volume ratio should be 27 ft^2/ft^3.

In 1974, Bintanja and Boelhouwer (15) derived an equation for calculating the amount of oxygen transferring from air to liquid film on the RBC.

In 1976, McCarty and Williamson (16) derived a model on substrate utilization in bacterial film. The verification showed that prediction was accurate for deep biofilms and when the liquid was stagnant.

Howell and Atkinson (17) developed a model for trickling filters to show the influence of sloughing on trickling filter BOD_5 removal efficiency. The following parameters were found to affect the filter efficiency.

a) sloughing concentration
b) influent concentration

c) size of filter packing
d) number of filter units
e) time intervals of sloughing

Friedman, Robbin and Woods (18) examined the effect of RBC rotational speed on efficiency. From the experimental data they collected, disc rotational speed was quite insignificant at low loading rates. However, at high loading rates, BOD removal depended significantly on rotational speed. By studying other RBC's, they found that most of them had been overdesigned and effluent BOD was below effluent standard. This resulted in high wastewater treatment cost.

THEORETICAL CONSIDERATIONS

Owing to the many variables of the RBC system, the following assumptions were made when developing this mathematical model.

1. There is no change in substrate concentration in the radial or θ direction.
2. The microorganism concentration is assumed to be constant throughout the biofilm.
3. The mass of liquid film adheres to the same biofilm throughout the disc's rotation.
4. There is no substrate removal in the bulk liquid in the reactor.
5. Substrate removal in the liquid film occurs only through diffusion into the biofilm.
6. The coefficient of diffusion for the substrate and oxygen are based on a water medium.
7. The model is valid only for conditions when the biofilm thickness can be assumed constant.

Four principal elements were used in developing the mathematical model. These were: mass balance on substrate in biofilm, mass balance in liquid film, mass balance of oxygen in liquid film, and mass balance in the completed mixed reactor.

There were two non-linear parabolic partial differential equations which were required to be solved simultaneously. The Crank-Nicolson method was used to obtain the accuracy desired. In order to use the Crank-Nicolson method, the boundary conditions must be known. To find the relationship among boundary points, three more equations were derived for the model and the boundary conditions for each new time level were calculated from them.

Parameter Value Selection:

Before the mathematical model can be solved, values for the parameters to be used in the model must be known. Stated briefly, the parameters of importance are as follows:

L, δ - thickness of biofilm and liquid film, respectively. A value of 150 microns was chosen.

ρ - maximum specific growth rate. Kornegay obtained a value of 0.28/hr. for a fixed film system with glucose as a substrate; thus this value was used.

Y - yield coefficient. An average value, 0.40, was used.

X - density of active mass in the biofilm. In this case, 20 mg/ml was chosen.

K1, K2 - Monod Saturation Coefficient, for oxygen and substrate, respectively. K1 has been found to be approximately equal to 1 mg/l. A middle value of 80 mg/l was chosen for K2.

D_{13}; D_{23} - diffusion of oxygen and substrate respectively. For oxygen, a value of 5.0×10^{-5} cm^2/sec was chosen. For substrate, the value of glucose diffusing in pure water, 0.64×10^{-5} cm^2/sec at 20°C was chosen.

K_L - liquid film transfer coefficient across the liquid-solid interface. In this case, a middle value, 1.0×10^{-2} cm/sec was used.

He, P - Henry's constant and partial pressure for oxygen respectively. The value chosen was 45500 atm./mole fraction. The partial pressure for oxygen is 0.21 atm.

EXPERIMENTAL RESULTS

Data were collected from a pilot plant for three months. The following were measured.

1. Five Days Biological Oxygen Demand (BOD_5)
2. Chemical Oxygen Demand (COD)
3. Ammonia-nitrogen (NH_3-N)
4. Nitrate-nitrogen (NO_3-N)
5. Nitrite-nitrogen (NO_2-N)
6. Phosphate (PO_4)
7. Total Suspended Solids (TSS)
8. Dissolved Oxygen in RBC bulk liquid (D.O.)
9. pH

Influent samples were taken from the barrel containing the collected sewage. Samples were taken two hours after collection. Samples were also collected from the biodiscs. An eight-inch diameter funnel was used to clarify the RBC effluent. Collection of data began after the system had reached a steady state.

BOD_5 was measured twice a week. Influent BOD_5 had an average value of 150 mg/l. BOD_5 in the first stage was reduced 80% to 30 mg/l. The final BOD_5 reduction in the clarified effluent was to 3 mg/l. The loading rate was 1 gallon/hour/ft^3 with a retention time of 37 hours.

COD tests were run and data collected on the influent, effluent, clarified effluent and soluble effluent. COD data and BOD_5 data were compared for possible relationships. In this case, the COD/BOD_5 ratio was found to vary between 1.5 and 2.5.

TSS data were collected twice a week. The TSS of the influent was reduced 56% from 73 mg/l to 32 mg/l. Over 98% of the solids were settled in the clarified effluent.

Ammonia-nitrogen and nitrate-nitrogen data were collected five days a week. In the RBC, nitrification was essentially completed after the first stage. To maintain a pH value of 6 or higher, a pH buffer of sodium carbonate was used.

Two nitrite-nitrogen tests showed very small amounts of NO_2-N present. A single mea-urement of phosphate found enough P to sustain microorganism growth.

Two dissolved oxygen tests found an average of 6 mg/l in stage one with 8 to 9 mg/l in the rest of the stages.

Influent sewage temperature was 22-27°C. Due to water evaporation, the RBC effluent temperature was a few degrees less.

ENGINEERING SIGNIFICANCE

The RBC is an efficient method of treating wastewater because the system is simple to maintain and is energy efficient. High capital costs can be offset by savings in maintenance and operation. Consider the following example. A small town of 4,000 people has a sewage generation rate of 100,000 gallon/day and the BOD_5 of sewage of 250 mg/l. The town is required to reduce their BOD_5 by 92%. Comparing the operating costs of an activated sludge plant and a RBC shows that the activated sludge requires a 24-hp motor for the bubble diffuser and two 1/2-hp motors for the recycle pump and the pump from the aeration tank to the clarifier. The total power required therefore is 25 hp. The power required for the RBC is a 2-hp pump. Furthermore, the RBC requires less labor for maintenance. The annual savings realized from operation and maintenance cost savings would be $9910/year.

CONCLUSION AND DISCUSSION

1. The RBC is an efficient method of treating wastewater because it is simple to operate and maintain.
2. RBC energy consumption is equivalent to or less than extended aeration activated sludge plants.
3. The capital costs of RBC is lower than activated sludge plants when the plants are small.
4. The mathematical model developed in this report has proved to be quite successful. The difference between the prediction and the experimental data is only 10% in the loading rates with sufficient data for verification.
5. More work should be done to include:

a) diffusion in the radial direction since peripheral velocities for different radial distances are not the same.
b) diffusion in the bulk liquid of the RBC since the concentration of oxygen and substrate are not constant in the bulk liquid.
c) diffusion in the liquid film.
d) changes of the biofilm thickness.

6. The mathematical model should be scaled up for larger RBC wastewater treatment plants.

The original report also includes a computer program for the RBC mathematical model, an appendix of experimental data, and a bibliography. The tables of experimental data include BOD_5, COD, Total Suspended Solids, pH, Nitrite-Nitrogen, Dissolved Oxygen, Temperaature, Phosphate, and Biofilm Thickness. Data is provided from selected interval days.

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