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# MODELING OF BIOOLOGICAL PHOSPHORUS REMOVAL USING MEMBRANE BIOREACTOR: PART I

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## ABSTRACT

A mathematical model for biological phosphorus removal with simultaneous nitrification – denitrification in activated sludge process was established and was applied to the membrane bioreactor (MBR) process, under simultaneous aerobic-anoxic-anaerobic condition. An experimental data need to validate the model are taken from the various studies on MBR. Activated sludge Model no.2 (ASM2) is used to consider various processes occurring in the MBR. The unsteady state differential equations are solved using Runga-Kutta Method (MATLAB 7). The results were in good agreement with these experimental data which indicate that the model could successfully describe the treatment performance in terms of Chemical Oxygen Demand (COD), ammonia Nitrogen and phosphorus removal.

Key Word: Biological phosphorus removal; Modeling; Membrane bioreactor; Municipal wastewater

## I. INTRODUCTION

In recent time, membrane bioreactor is gaining attention for wastewater treatment for better effluent quality compared to conventional activated sludge process. Mathematical models are tools by which the biological wastewater treatment designers can predict the performances of a number of potential systems under a variety of conditions [1]. Many researchers have reported studies on membrane bioreactor systems with different kinds of wastewater [1-3]. However, a few developments of mathematical models for membrane bioreactor are yet to be included.

Modeling of Membrane bioreactors for COD and Nitrogen removal has become a standard practice and valuable instrument for process design and operation. Earlier studies have used Activated Sludge Model no.1 (ASM1) [1,2] and Activated Sludge Model no.3 (ASM3) [3] as a base model to develop the MBR model by incorporating resistance in series model (Membrane fouling phenomena). In respect of biological phosphorus removal, very limited studies have reported found in literature. The objective of the paper is to propose a mathematical model to remove phosphorus biologically along with COD and ammonia nitrogen by membrane bioreactor from municipal wastewater treatment by using Activated sludge model 2 (ASM2).

## LITERATURE REVIEW

The MBR model has been validated by using five pilot plant studies and input data to validate the model given in table 1. Lesjean et al. [5] performed the study at Berlin wastewater treatment plant for biological phosphorus and nitrogen removal from municipal wastewater. The system consists of bioreactors having 2 $m^3$ of volume with hollow fiber membrane module directly immersed in the bioreactor. It was operated at the flow rate of 2.6 $m^3$/day at temperature between 16 -19 $^{O}$C. The percentage removal efficiency of COD, ammonia nitrogen and phosphorus were 95.3, 98.8 and 98.6 respectively. Innocenti et al. [6] performed the MBR experiment at Fusina, Italy to study the effect of sludge age on nutrient removal from the municipal wastewater. The system consists of bioreactors having 0.4 $m^3$ volume with ultra filtration hollow fiber membrane module directly immersed in the bioreactor. It was operated at hydraulic retention time of 4 h (for Anoxic/anaerobic phase 1.5 h and for aerobic phase 2.5 h). The percentage removal efficiency of COD, ammonia nitrogen and phosphorus were 93.56, 97.80 and 75 respectively. Rosenberger et al. [7] conducted the study at Germany federal environmental agency in Berlin to study the performance of MBR. The system consists of bioreactors having 3.9 $m^3$ of volume with hollow fiber micro filtration membrane module directly immersed in the bioreactor. It was operated at flow rate of 6 $m^3$/day temperature 10-20 $^{O}$C. The percentage removal efficiency of COD, ammonia nitrogen and phosphorus were 95, 95 and 85 respectively. Ahn et al. [4] studied the enhanced biological phosphorus and nitrogen removal from municipal wastewater using a sequencing anoxic/anaerobic membrane bioreactor with aerobic process at Korea Institute of Science and Technology. The system consists of bioreactors having 0.01 $m^3$ of volume with flat sheet micro filtration membrane module directly immersed in the bioreactor. It was operated at the flow rate of 0.03 $m^3$/day. The percentage removal efficiency of COD, ammonia nitrogen and phosphorus were 96, 60 and 93 respectively. Yoon et al. [8] conducted the study at South Korea municipal wastewater treatment. The system consists of bioreactor having 16.06 $m^3$ of volume with hydrophilic polyethylene hollow fiber membrane module directly immersed in the bioreactor. It was operated at flow rate of 57.6 $m^3$/day and hydraulic retention time 6 h at temperature 10-28$^{O}$C. The percentage removal efficiency of COD, ammonia nitrogen and phosphorus were 96.3, 91.9 and 72.9 respectively.

## II. MODEL DEVELOPMENT

The stoichiometric and composition matrixes and process rate equations ($\rho_1$ to $\rho_{17}$ ) were same as considered in simplified Activated sludge model no. 2 (ASM2)[9]. The process rates include aerobic, anoxic and anaerobic hydrolysis, growth and lysis of the entire three microorganism. The model parameters include a fermentable readily organic substrate, fermentable product (acetate), ammonia concentration and phosphorus concentration.

### 3.1 Assumptions

Following assumption are made for formulating the model equations to study the COD, ammonia nitrogen and phosphorus removal from municipal wastewater and to develop the model. :

2.1.1 System is under unsteady state process and flow is continuous with completely mixed membrane bioreactor.

2.1.2 Simultaneously aerobic, anoxic and anaerobic process occurring in the bioreactor.
2.1.3 System is under constant pH and alkalinity term has been removed
2.1.4 The system operates at constant temperature
2.1.5 Influent substrate concentration remains constant
2.1.6 The volume of reactor is constant
2.1.7 Complete rejection of particulate matter
2.1.8 Soluble substrate is not rejected completely

### 3.2Membrane Bioreactor Model Equation

A set of ordinary differential equations is formulated to make MBR model are presented as follows

The concentration of fermentable, readily organic substrate

$$V\frac{dS_F}{dt} = Q_O S_F^o - \left(Q_P S_F^P + Q_W S_F^W\right) + \left(\rho_1 + \rho_2 + \rho_3 - \rho_8\right)V - \left(\frac{1}{Y_H}\right)\left(\rho_4 + \rho_6\right)V \qquad 1)$$

The concentration of fermentable product (acetate)

$$V\frac{dS_A}{dt} = Q_O S_A^0 - \left(Q_P S_F^P + Q_W S_A^W\right) - \left(\frac{1}{Y_H}\right)\left(\rho_5 + \rho_7\right)V + \left(\rho_8 - \rho_{10} + \rho_{15}\right)V \qquad 2)$$

The ammonia concentration

$$\frac{dS_{NH4}}{dt} = Q_O S_{NH4}^0 - \left(Q_P S_{NH4}^P - Q_W S_{NH4}^W\right) + i_{NSI}\left(\rho_1 + \rho_2 + \rho_3 + \rho_8\right)V - i_{NBM}\left(\rho_5 + \rho_7 + \rho_{12}\right)V - \left(i_{NBM} - \frac{i_{NSF}}{Y_H}\right)\left(\rho_4 + \rho_6\right)V + \left(\frac{i_{NBM} - f_{XI} i_{NXI}}{2}\right)\left(\rho_9 + \rho_{13} + \rho_{17}\right)V - \left(\frac{1}{Y_H} - i_{NBM}\right)\rho_{16}V \qquad 3)$$

The phosphorus concentration

$$\frac{dS_{PO4}}{dt} = Q_O S_{PO4}^0 - \left(Q_P S_{PO4}^P + Q_W S_{PO4}^W\right) + f_{SI}\left(\rho_1 + \rho_2 + \rho_3\right)V - \left(i_{PBM} - \frac{i_{PSF}}{Y_H}\right)\left(\rho_4 + \rho_6\right)V + i_{PSF}\left(\rho_8 + \rho_9 + \rho_{13} + \rho_{17}\right)V - i_{PBM}\left(\rho_5 + \rho_7 + \rho_{12} + \rho_{16}\right)V - \left(\rho_{11} -_{14}\right)V + \left(Y_{PO_4}\right)\rho_{10}V \qquad 4)$$

The set of differential and algebraic equations constitute an Initial value Problem (IVP).Initial condition for the model. The model equations are highly stiff in nature. Therefore, the numerical differentiation formulas with backward difference formula have been used to solve the IVP. In the present model, ode15s has been used to solve the stiff differential equations in MATLAB 7.Kinetic parameters, conversion factor for nitrogen and stoichiometric parameters need to valid the model are taken from a simplified activated sludge model no.2 [9]

### 3.3 Resistance In Series Model

The performance of any membrane to achieve a particular separation is depends mostly on the flux-time relationship. The convective flux through the membrane can be written as follows

$$flux = \frac{drivingforce}{vis\cos ity.resis\tan ces} \qquad 5)$$

Which in the case of pressure driven processes such as microfiltration, ultrafiltration, nanofiltration and reverse osmosis, becomes

$$Q_P = A_m J = A_m \frac{\Delta P}{\eta R_t} \qquad 6)$$

The various resistances contribute with different extent to the total resistance $R_t$. In the ideal case, only the membrane resistance $R_m$ ( in present model ,$R_m$= 5 x $10^{11}$ 1/m)is involved.

## IV . RESULTS AND DISCUSSION

The concentration of $S_I$, $S_A$ and $S_F$ in municipal wastewater, are generally found to be in the range of 5-10 %, 2-10 % and 10-20 % of total COD concentration respectively. In present study, it is assumed to be 5 % for $S_I$, 2 % for $S_A$ and 10 % $S_F$ of total COD concentration. Rest of the concentration of other components of the COD is simulated to get close results to validate the MBR model with experimental results.

### 4.1 COD Removal

In the present study, the COD percentage removal efficiency using MBR model was found to be approximately 94 for all condition by following decreasing trends with time (figure 4). The percentage errors found in model are 0.91 (Lesjean et al. [10]), 1.00 (Innocenti et al. [11]), 0.24 (Rosenberger et al. [12]), 2.08 (Ahn et al.[9]) and 2.17 (Yoon et al.[13]). The permeate COD includes the $S_I$, $S_F$ and $S_A$. The variation of $S_F$ and $S_A$ with time shows the decrease in trends (figure. 1-2) , but there is no variation of $S_I$ with time (figure. 3). This indicates that efficiency of COD removal based on the percentage of soluble inert in wastewater. In our case it is 5.00 % of total COD.Other parameter that is responsible for COD removal is DO concentration. In this study, DO concentration is maintained at constant value so to get better efficiency in simultaneous aerobic anoxic anaerobic process

### 4.2 Biological Ammonia Nitrogen And Phosphorus Removal

In the present study, the ammonia nitrogen percentage removal efficiency using MBR model was found to be 95.25 (Lesjean et al. [10]), 91.95 (Innocenti et al. [11]), 95.30 (Rosenberger et al.[12]), 63.00 (Ahn et al.[9]) and 90.00 (Yoon et al.[13] ) with the percentage error found in model are 3.60, 5.98, 0.31, 5 and 2.07 respectively. Figure. 5 shows decrease in ammonia nitrogen concentration with time. It is basically a nitrification process occurs due to anoxic process in the absence of oxygen. Nitrate is the main electron acceptor in this case. Concentration of COD in terms autotrophic microorganisms is the main factor that affect the removal efficiency.

In the case of phosphorus percentage removal efficiency using MBR model was found to be 95.33 (Lesjean et al. [10] ) , 72.88 (Innocenti et al. [11] ), 85.33 (Rosenberger et al. [12] ), 85.52 (Ahn et al. [9] ) and 68.81 (Yoon et al. [13]) with the percentage error found in model are 3.32, 2.87, 0.39, 3.53 and 5.60 respectively. Figure. 6 shows decrease in phosphorus concentration with time. The main parameters that are found to be the responsible factor for phosphorus removal are presence of PAO. More the presence of PAO in wastewater more will be the phosphorus removal efficiency .In most of the case concentration of PAO found to be 0 – 1 % of total COD in municipal wastewater. In the present study it is assumed to be 1.00 %.

## III. CONCLUSION

In the present paper mathematical model is applied to describe MBR performance. The MBR model is able to predict with an excellent accuracy for the biological phosphorus removal through simultaneous aerobic/anoxic/anaerobic processes. The model matched the observed trends for effluent COD, ammonia nitrogen and phosphorus, which gives significance that the model can be used to identify the cause for performance trends. The results were in good agreement with the experimental data which indicate that the model can successfully describe the treatment performance terms of Chemical Oxygen Demand, Nitrogen and phosphorus removal. The average error found in model is around 1.28 % for COD, 3.52 % for ammonia nitrogen and 3.13 % for phosphorus removal efficiency.

## NOMENCLATURE

**$A_m$** Membrane surface area, $m^2$
**$f_{SI}$** Production of $S_I$ in hydrolysis ,g COD/g COD

**$f_{XI}$** Fraction of inert COD generated in biomass lysis, g COD/g COD

**$i_{NBM}$** N content of biomass ,g N / g COD

**$i_{NSI}$** N content of inert soluble COD ,g N / g COD

**$i_{NSA}$** N content of soluble substrates COD , g N / g COD

**$i_{NSF}$** N content of soluble substrates COD , g N / g COD

**J** Membrane flux, $m^3/m^2$.day

**$\Delta P$** Transmembrane pressure, KPa

**$Q_0$** Influent flow rate, $m^3$/day

**$Q_P$** Permeate flow rate, $m^3$/day

**$Q_W$** Waste flow rate, $m^3$/day

**$S_I$** Inert soluble organic material, g COD/$m^3$

**$S_{NH4}$** Ammonia plus ammonia nitrogen, g N/$m^3$

**$S_{NO3}$** Nitrate plus nitrite nitrogen, g N/$m^3$

**$S_A$** Fermentable product (acetate), g COD/$m^3$

**$S_F$** a fermentable readily biodegradable organic substrates, g COD/$m^3$

**$R_m$** Membrane resistance, 1/m

**$R_t$** Total resistance, 1/m

**V** Volume of membrane bioreactors, $m^3$

**$Y_H$** Yield of Heterotrophic biomass, g COD/g COD

*Greek Symbols*

**$\rho$** Process rate Equations, g COD / $m^3$ day or g N / $m^3$ day or g P / $m^3$ day

**$\eta$** Viscosity,Kg/m-s

*Superscript*

**O** input

**P** Permeate

**W** Waste

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**Table 1 Experimental Data For Membrane Bioreactor**
**From Municipal Wastewater**

| Parameters | [4] | [5] | [6] | [7] | [8] |
|---|---|---|---|---|---|
| Influent Flow rate ($m^3$/d) | 0.03 | 2.6 | 2.4 | 6 | 57.6 |
| Reactor Volume ($m^3$) | 0.01 | 2 | 0.4 | 3.9 | 16.06 |
| DO(g/$m^3$) | 8 | 2 | 8 | 2 | 5 |
| COD(g/$m^3$) | 244.6 | 998 | 441 | 786 | 295.9 |
| $NH_4$(g/$m^3$) | 32.1 | 41.3 | 33.9 | 49.4 | 15.4 |
| $NO_3$(g/$m^3$) | 0.06 | 0.42 | 3.9 | 0.79 | 0.8 |
| $PO_4$(g/$m^3$) | 3.66 | 10.5 | 5.9 | 11.8 | 4.2 |
| $S_F$ (% COD) | 10 | 10 | 10 | 10 | 10 |
| $S_A$(% COD) | 2 | 2 | 2 | 2 | 2 |
| $S_I$ (% COD) | 5 | 5 | 5 | 5 | 5 |

**Table 2** Model Results From Various Studies

| Ref. | Para-meters | Experimental Study (Percentage removal) | Model results (Percentage removal) | % Error |
|---|---|---|---|---|
| [4] | COD | 96 | 94 | - 2.08 |
| | $NH_4$ | 60 | 63 | + 5.00 |
| | $PO_4$ | 88.65 | 85.52 | - 3.53 |
| [5] | COD | 95.7 | 94.83 | -0.91 |
| | $NH_4$ | 98.8 | 95.25 | -3.60 |
| | $PO_4$ | 98.6 | 95.33 | - 3.32 |
| [6] | COD | 93.56 | 94.5 | + 1.00 |
| | $NH_4$ | 97.80 | 91.95 | - 5.98 |
| | $PO_4$ | 75 | 72.88 | -2.83 |
| [7] | COD | 95 | 94.77 | - 0.24 |
| | $NH_4$ | 95 | 95.30 | + 0.31 |
| | $PO_4$ | 85 | 85.33 | + 0.39 |
| [8] | COD | 96.3 | 94.21 | - 2.17 |
| | $NH_4$ | 91.9 | 90 | - 2.07 |
| | $PO_4$ | 72.9 | 68.81 | -5.60 |

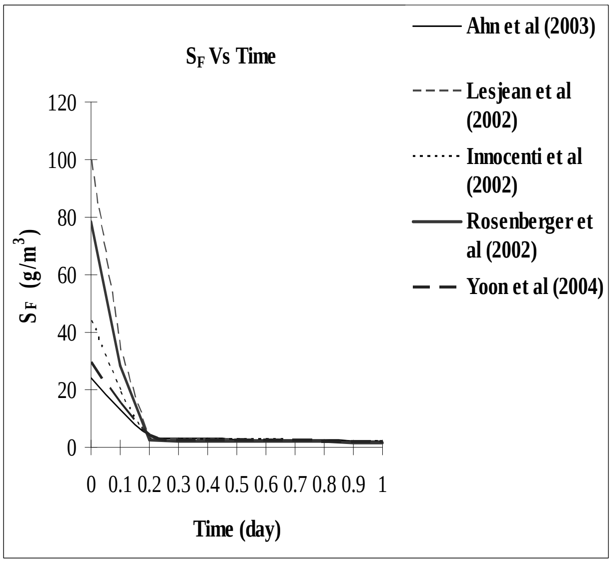

Figure 1. Variation Of Fermentable Readily substrates with Time

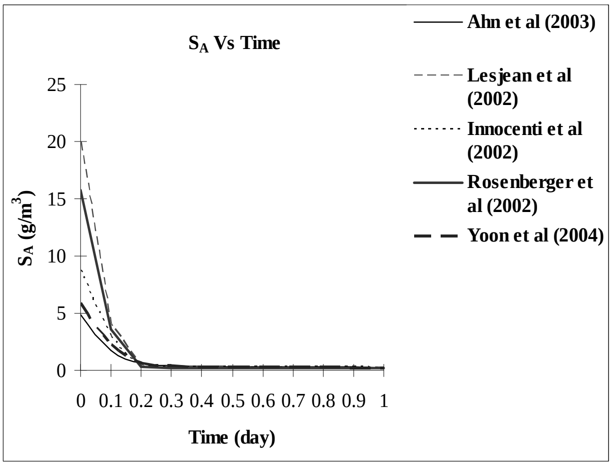

Figure 2. Variation Of Fermentation Products Biodegradable (Acetate) With Time

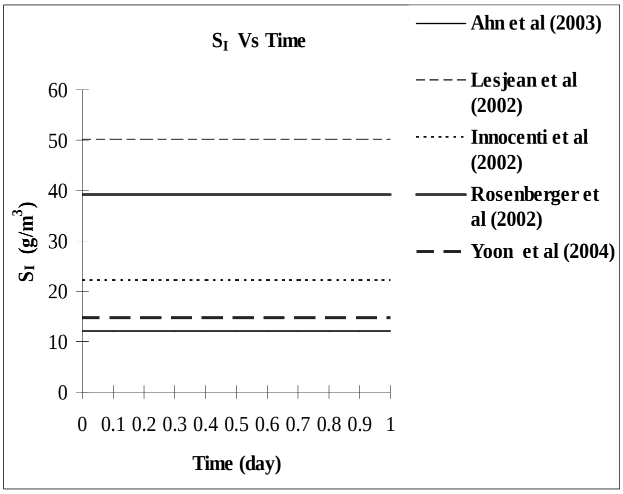

Figure 3. Variation Of Inert Soluble Substrate with Time

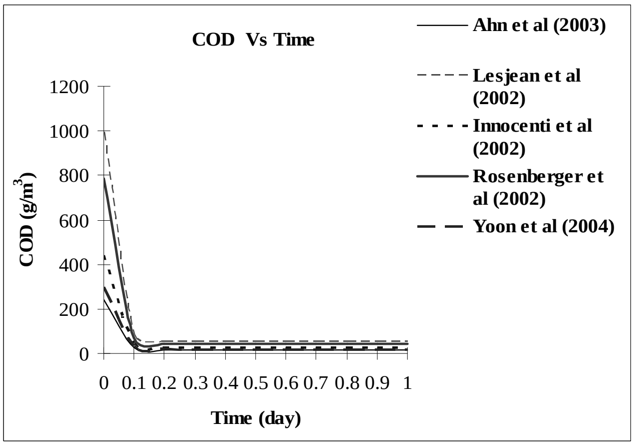

Figure 4. Variation of Chemical Oxygen Demand With Time

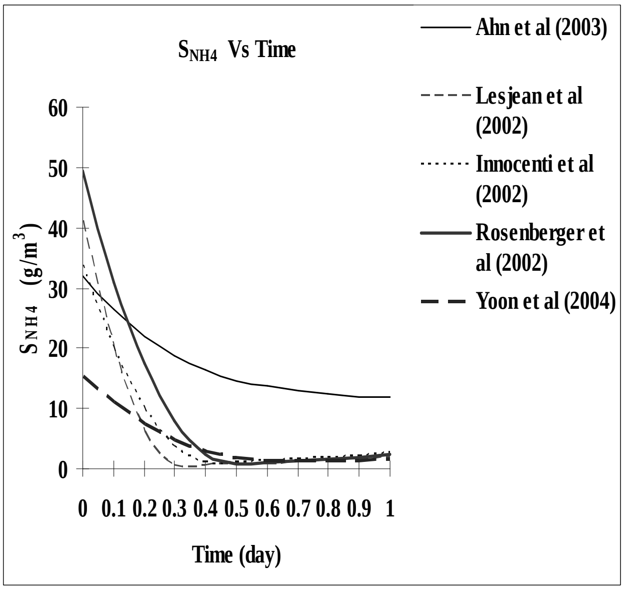

Figure 5. Variation Of Ammonia Nitrogen With Time

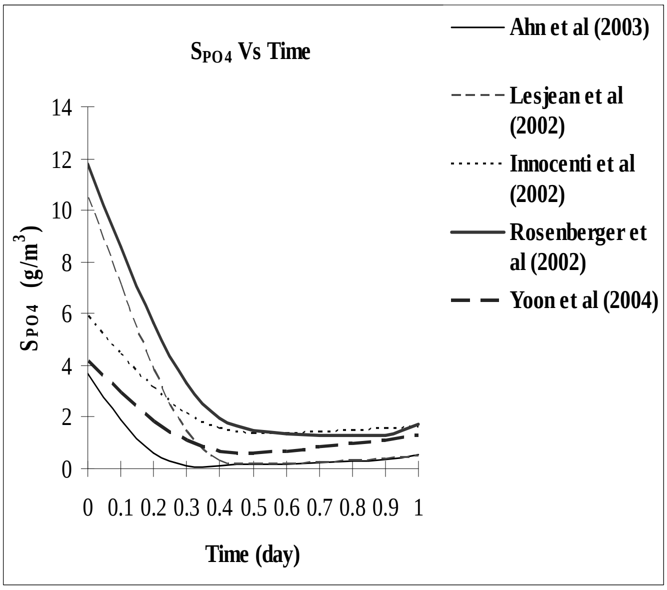

Figure 6. Variation Of Phosphorus With Time