MEMBRANE BIOREACTOR MODEL FOR BIOLOGICAL COD & NITROGEN REMOVAL

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ABSTRACT

A mathematical model for biological nitrogen and carbon content removal in activated sludge process along with soluble microbial products was established and was applied to the side stream membrane bioreactor (MBR) process, under simultaneous aerobic-anoxic condition. An experimental data and operation condition need to validate the model were taken from Fan et al. (1996). The results of present MBR model were compared with the model developed by other researchers. The unsteady state differential equations are solved using Runga-Kutta Method (MATLAB 7). The results were comparably in good agreement with these experimental data which indicate that the model could successfully describe the treatment performance in terms of carbon and nitrogen content than the previous models in literature.

Keywords: Membrane bioreactors; soluble microbial products; municipal wastewater

[I]. INTRODUCTION

In recent time, membrane bioreactor is gaining attentions 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. Many researchers have reported studies on membrane bioreactor systems with different kinds of wastewater. However, a few developments of mathematical models for membrane bioreactor are yet to be included [1, 2]. Lu et al. (2001) established a mathematical model of SMP formation – degradation based on the ASM1 (MBR1) and was applied to the membrane
bioreactors process with high concentration of Activated sludge under intermittent aerobic operating condition [3]. Esquerre et al. (2005) established a structured model for the biological treatment systems of industrial wastewater and demonstrated that the outlined modeling on the ASM3 and soluble microbial products (MBR2) formation can be easily and successfully applied to describe the biological status of the membrane bioreactors [4]. Innocenti et al. [13] performed the membrane bioreactor experiment with 0.4 m$^3$ volume with ultra filtration hollow fiber membrane module directly immersed in the bioreactor. The percentage removal efficiency of COD, ammonia nitrogen and phosphorus were 93.56, 97.80 and 75 respectively. Rosenberger et al. [10] conducted the study 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. The percentage removal efficiency of COD, ammonia nitrogen and phosphorus were 95, 95 and 85 respectively. Ahn et al. [11] studied the enhanced biological phosphorus and nitrogen removal from municipal wastewater using a sequencing anoxic/anaerobic membrane bioreactor with aerobic process. The system consists of bioreactors having 0.01 m$^3$ of volume with flat sheet micro filtration membrane module directly immersed in the bioreactor. The percentage removal efficiency of COD, ammonia nitrogen and phosphorus were 96, 60 and 93 respectively. Yoon et al. [14] conducted the study with bioreactor having 16.06 m$^3$ of volume with hydrophilic polyethylene hollow fiber membrane module directly immersed in the bioreactor. The percentage removal efficiency of COD, ammonia nitrogen and phosphorus were 96.3, 91.9 and 72.9 respectively. Lesjean et al. [12] performed the study of bioreactors having 2 m$^3$ of volume with hollow fiber membrane module directly immersed in the bioreactor. The percentage removal efficiency of COD, ammonia nitrogen and phosphorus were 95.3, 98.8 and 98.6 respectively.

The objective of the paper is to propose a mathematical model to remove nitrogen and carbon content of the municipal wastewater along with the concept of soluble microbial products.

**[II]. MODEL DEVELOPMENT**

The stoichiometric and composition matrices and process rate equation were same as considered in simplified Activated sludge model with modified SMP [7-9]. The model parameters include soluble and particulate inert soluble substrate, soluble and particulate biodegradable organic substrate, heterotrophic and autotrophic microorganisms concentration, nitrogen and oxygen concentration and soluble microbial products concentration. The process rate equation involve aerobic and anoxic hydrolysis, and growth and lysis of microorganisms.

### 2.1 Mass balance equations

Mass balance equations (Figure 1) across the membrane bioreactor are as follow.

For the dissolved oxygen concentration in the wastewater,

$$\frac{dS_{O_2}}{dt} = \left(1 - \frac{Y_{H,O_2}}{Y_{H,O_2}}\right) \rho_3 - \left(1 - \frac{Y_{SMP}}{Y_{SMP}}\right) \rho_4 - \left(\frac{4.57 - Y_{A}}{Y_{A}}\right) \rho_1$$  \hspace{1cm} (1)

For the soluble inert organic matter,

$$V \frac{dS_i}{dt} = Q_{O}S_{i0} - \left(Q_{P}S_{i}^{P} + Q_{H}S_{i}^{W}\right) + f_{S_1} \left(\rho_4 + \rho_2\right) V$$  \hspace{1cm} (2)
\[ V \frac{dS_{i}}{dt} = Q_{O}S_{i}^{0} - (Q_{p}S_{i}^{p} + Q_{w}S_{i}^{w}) + (1 - f_{SL})(\rho_{1} + \rho_{2})V \]
\[-\left(\frac{1}{Y_{H,02}}\right)(\rho_{3} + \rho_{4})V \]

For the soluble microbial product concentration,
\[ V \frac{dS_{SMP}}{dt} = Q_{O}S_{SMP}^{0} - (Q_{p}S_{SMP}^{p} + Q_{w}S_{SMP}^{w}) + \gamma_{UAP,H}(\rho_{3} + \rho_{4} + \rho_{5} + \rho_{6})V \]
\[ \gamma_{UAP,A} \rho_{7}V - \left(\frac{1}{Y_{SMP}}\right)(\rho_{4} + \rho_{6})V + f_{b}(\rho_{5} + \rho_{6})V \]

For the concentration of particulate inert organic matter,
\[ V \frac{dX_{i}}{dt} = Q_{O}X_{i}^{0} - (Q_{p}X_{i}^{p} + Q_{w}X_{i}^{w}) + f_{XI}(\rho_{1} + \rho_{2})V \]

For the concentration of slowly biodegradable substrate,
\[ \frac{dX_{S}}{dt} = Q_{O}X_{S}^{0} - (Q_{p}X_{S}^{p} + Q_{w}X_{S}^{w}) - (\rho_{1} + \rho_{2})V \]

For the dynamic behavior of the heterotrophic biomass concentration,
\[ V \frac{dX_{H}}{dt} = Q_{O}X_{H}^{0} - (Q_{p}X_{H}^{p} + Q_{w}X_{H}^{w}) + (\rho_{3} + \rho_{4} + \rho_{5} + \rho_{6} - \rho_{8})V \]

For the dynamic behavior of the autotrophic biomass concentration,
\[ V \frac{dX_{A}}{dt} = Q_{O}X_{A}^{0} - (Q_{p}X_{A}^{p} + Q_{w}X_{A}^{w}) + (\rho_{7} - \rho_{5})V \]

For the concentration of nitrate,
\[ V \frac{dS_{NO3}}{dt} = Q_{O}S_{NO3}^{0} - (Q_{p}S_{NO3}^{p} + Q_{w}S_{NO3}^{w}) + \left(\frac{1}{Y_{A}}\right)\rho_{7}V - \left(\frac{1 - Y_{H,NO3}}{2.86Y_{H,NO3}}\right)\rho_{5}V \]
\[-\left(\frac{1 - Y_{SMP}}{2.86Y_{SMP}}\right)\rho_{6}V \]

For the Nitrogen concentration in the wastewater,
\[ \frac{dS_{N2}}{dt} = \left(\frac{1 - Y_{H,NO3}}{2.86Y_{H,NO3}}\right)\rho_{5} + \left(\frac{1 - Y_{SMP}}{2.86Y_{SMP}}\right)\rho_{6} \]

For the ammonia concentration,
\[ V \frac{dS_{NH4}}{dt} = Q_{O}S_{NH4}^{0} - (Q_{p}S_{NH4}^{p} + Q_{w}S_{NH4}^{w}) + (i_{NBS} - i_{NSS})(\rho_{1} + \rho_{2})V \]
\[-i_{NBM}(\rho_{4} + \rho_{6})V + \left(\frac{1}{Y_{H,02}}\right)i_{NSS} - i_{NBM} \right)\rho_{7}V \]
\[ + \left(\frac{1}{Y_{A}}\right)i_{NBS} - i_{NBM} \right)\rho_{7}V \]
\[-\left(\frac{1}{Y_{H,02}}\right)i_{NSS} - i_{NBM} \right)\rho_{7}V \]
\[ + \left(\frac{1}{Y_{A}}\right)i_{NBS} - i_{NBM} \right)\rho_{7}V \]
\[ + (i_{NBM} - f_{XI}i_{NBS})(\rho_{5} + \rho_{6})V \]

2.2 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

\[ \text{flux} = \frac{\text{driving force}}{\text{viscosity} \times \text{resistance}} \]

Which in the case of pressure driven processes such as microfiltration, ultrafiltration, nanofiltration and reverse osmosis, becomes
\[ Q_p = A_m \cdot J = A_m \frac{\Delta P}{\eta R_t} \]

The various resistances contribute with different extent to the total resistance \( R_t \). In the ideal case, only the membrane resistance \( R_m \) is involved [5, 15, 16].

2.3 Solution Techniques

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 validate the model are taken from a simplified activated sludge model system [5, 15, 16].

2.4 Case Study

A side stream membrane bioreactor was installed in the municipal wastewater treatment plant [6] consisted of a bioreactors (volume 1.5 m\(^3\)) and ceramic ultrafiltration membrane module (surface area 1.4 m\(^2\), pore size 0.02 µm). The operating conditions applied in the experiment and experimental results for the present study are summarized in table 1 and table 2 respectively. In addition, the fraction of COD in municipal wastewater are shown in table 3.

III. RESULTS AND DISCUSSION

In the present, it is assumed that there is no fouling occurs only membrane resistance is considered for study. Therefore, Performance of MBR in term of removal efficiency is discussed. Table 4 shows the characteristics of membrane used.

3.1 COD Removal

Table 5 shows the validation of the present model and Table 6 gives the comparison the model results. Figure 2 to 4 shows the results of the present model for \( S_i \), \( S_S \) and \( S_{SMP} \) removal that responsible for COD removal. The influent and effluent concentration of \( S_i \) is constant and equal to 15 g/m\(^3\) all the models. The soluble inert organic matter (\( S_i \)) affected by hydrolysis process, but \( f_S \) equal to zero. Again, it is not affected by biochemical reactions occur in the process. Therefore, it is constant during the process.

There is almost complete decomposition of readily biodegradable substrate (\( S_S \)) for all three the models considered in present study. Reduction in \( S_S \) is mainly due to the aerobic and anoxic growth of heterotrophic bacteria in MBR1 and in present MBR model. In case of MBR2, it is affected by storage product. It is found that influent concentration of \( S_S \) is 169.38 g/m\(^3\), whereas effluent concentration is 0.58 g/m\(^3\), 0.13 g/m\(^3\) and 0.37 g/m\(^3\) for MBR1, MBR2 and present MBR model respectively.

Total COD concentration in the effluent is mainly affected by soluble microbial products. Its effluent concentration is 67.76 g/m\(^3\) and 0.13 g/m\(^3\) in MBR1 and in present MBR model respectively. In both MBR1 and present MBR model, there is increase in the concentration UAP due the aerobic and anoxic growth of heterotrophic organisms and aerobic growth of autotrophic organisms. The soluble microbial product concentration decreased in the concentration BAP due the aerobic and anoxic growth of heterotrophic organisms and lysis of autotrophic organisms. In case of MBR3, it is free of growth and death process. It only the function of a cell internal storage products. The effluent concentration is found to be 0.13 g/m\(^3\).

The major difference of current model from conventional activated sludge models is those models offer rational explanation for the observation that the bulk of the soluble biodegradable organic matter is of microbial origin and not just the substrate which remains in an undergraded state. SMP dominated most to the soluble COD in the reactor. In MBR1, \( S_i \)
contributed about 18% to total soluble COD and SMPs about 81.30% and Ss about 0.70% in the effluent concentration. In MBR3, Ss contributed about 98.30% to total soluble COD and SMPs about 0.85% and Ss about 0.85% in the effluent concentration. In present MBR model, Ss contributed about 88.44% to total soluble COD and SMPs about 9.38% and Ss about 2.18% in the effluent concentration. From results it is found that, present error in the MBR1 is very high than MBR3 (1.73% error) and present MBR model (13.07%) as experimental results.

3.2 Nitrogen Removal

Figure 5 and 6 gives the ammonia nitrogen and nitrate nitrogen removal for present MBR model. The model simulations for nitrogen provided a good agreement with the experimental data. In case of present MBR model, it is found that percent error between experimental effluent concentration and model effluent concentration for NH\(_4\), NO\(_3\) and TKN are 30%, 2.21%, 10% respectively.

In case of present model, the ammonia concentration is affected by growth and lysis of all microorganisms as ammonia is used as the nitrogen source for incorporation into the cell mass. The concentration is also the function of hydrolysis process. The experimental effluent concentration of NH\(_4\) was <0.3 g/m\(^3\) and that of model effluent concentration was 0.39 g/m\(^3\). The concentration of nitrate is only involved in two processes. It is increased by the nitrification and decreased by denitrification. The experimental effluent concentration of NO\(_3\) was 38 g/m\(^3\) and that of model effluent concentration was 38.84 g/m\(^3\).

Similarly, the experimental effluent concentration of TKN was <0.5 g/m\(^3\) and that of model effluent concentration was 0.55 g/m\(^3\).

In MBR3 and present MBR model, all Xs is contained in the influent and none is generated in decay process; consequently, Ss comes from the influent or hydrolysis of Xs embraced in the influent. On the other hand, in MBR1 and Present Model a large fraction of Xs is produced through decay; Xs is then hydrolyzed to Ss that is used as an extra source of electron donor for denitrification.

In present model, again Snd and Xnd parameter was not considered. Therefore, the modified ASM1 performed slightly better than the modified MBR3 in what regards the estimation of nitrate and present model gives results closer to experimental results and MBR1 model.

[IV]. CONCLUSIONS

The present MBR model for municipal wastewater provided to be most suitable model for side stream membrane bioreactor process with soluble microbial products. From Table 6 it is conclude that present Model gives less error than MBR1 for COD removal and gives less error than MBR2 for nitrogen removal with respect to experimental results.

NOMENCLATURE

\(A_m\) Membrane surface area, m\(^2\)
\(b_{AUT}\) Autotrophic rate constant for lysis, 1/day
\(b_{H}\) Heterotrophic rate constant for lysis, 1/day
\(f_{B}\) Inert fraction of biomass leading to soluble products, dimensionless
\(f_{p}\) Fraction of biomass yielding particulate products, dimensionless
\(f_{S1}\) Production of S1 in hydrolysis, g COD/g COD
\(f_{XI}\) Fraction of inert COD generated in biomass lysis, g COD/g COD
\(i_{BBM}\) N content of biomass, g N/g COD
\(i_{BS}\) N content of inert soluble COD, g N/g COD
\(i_{SS}\) N content of soluble substrates COD, g N/g COD
\(i_{XS}\) N content of particulate COD, g N/g COD
\(i_{SSS}\) N content of particulate substrates COD, g N/g COD
\(J\) Membrane flux, m\(^3\)/m\(^2\).day
\(k_{h}\) Hydrolysis rate constant, 1/day
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K_{O2} Saturation coefficient for oxygen for hydrolysis process, g O₂/m³
K_{O2, AUT} Saturation coefficient for oxygen for Autotrophs g O₂/m³
K_{O2, H} Saturation coefficient for oxygen for heterotrophs g O₂/m³
K_{NH4, AUT} Saturation coefficient for ammonia (substrate) for autotrophs, g NH₄-N/m³
K_{NH4, H} Saturation coefficient for ammonia as a nutrient for heterotrophs, g NH₄/m³
K_{NO3} Saturation coefficient for nitrate for hydrolysis process, g N/m³
K_{NO3, H} Saturation coefficient for nitrate for heterotrophs, g NO₃-N/m³
K_s Saturation constant for substrate for heterotrophs, g COD/m³
K_x Saturation coefficient for particulate COD, g COD/g COD
∆P Transmembrane pressure, KPa
Q_0 Influent flow rate, m³/day
Q_P Permeate flow rate, m³/day
Q_W Waste flow rate, m³/day
S_I Inert soluble organic material, g COD/m³
S_{NH4} Ammonia plus ammonia nitrogen, g N/m³
S_{NO3} Nitrate plus nitrite nitrogen, g N/m³
S_O2 Dissolved oxygen, g O₂/m³
S_R Readily biodegradable organic substrates, g COD/m³
S_SMP Soluble microbial products equals to BAP +UAP, g COD/m³
R_m Membrane resistance, 1/m
R_t Total resistance, 1/m
V Volume of membrane bioreactors, m³
X_AUT Nitrifying organisms, g COD/m³
X_I Inert particulate organic material, g COD/m³
X_H Heterotrophic organisms, g COD/m³
X_S Slowly biodegradable substrates, g COD/m³
Y_AUT Autotrophic yield coefficient (Biomass/Nitrate), g COD/g N
Y_{R, NO3} Anoxic yield of Heterotrophic biomass, g COD/g COD
Y_{R, O2} Aerobic yield of Heterotrophic biomass, g COD/g COD
Y_SMP Heterotrophic yield coefficient from soluble microbial products, g COD/g COD

Greek Symbols
α Correction factor, dimensionless
γ_{UAP, A} UAP formation constant of autotrophs, dimensionless
γ_{UAP, H} UAP formation constant of heterotrophs, dimensionless
µ_AUT Autotrophic max. Anoxic growth rate, 1/day
µ_H Heterotrophic max. Aerobic growth rate, 1/day
µ_{SMP} maximum specific growth rate of SMP for heterotrophs, 1/day
ρ_1 Process rate of aerobic hydrolysis, g COD/m³/day
ρ_2 Process rate of anoxic hydrolysis, g N/m³/day
ρ_3 Process rate of aerobic growth of heterotrophs wrt. to S_s, g COD/m³/day
ρ_4 Process rate of aerobic growth of heterotrophs wrt. to S_SMP, g COD/m³/day
ρ_5 Process rate of anoxic growth of heterotrophs wrt. to S_s, g N/m³/day
ρ_6 Process rate of anoxic growth of heterotrophs wrt. to S_SMP, g N/m³/day
ρ_7 Process rate of aerobic growth of autotrophs, g COD/m³/day
ρ_8 Process rate of lysis of heterotrophs, g COD/m³/day
ρ_9 Process rate of lysis of autotrophs, g COD/m³/day
η Viscosity, Kg/m-s
η_{NO3} Anoxic hydrolysis reduction factor, dimensionless

Superscript
O Input
P Permeate
W Waste

REFERENCES
wastewater treatment, Journal of Membrane Science, 216, 55-65


Table 1. Operating Condition of system

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of bioreactor</td>
<td>1.5 m³</td>
</tr>
<tr>
<td>Influent flow rate</td>
<td>2.4 m³/day</td>
</tr>
<tr>
<td>Waste flow rate</td>
<td>0.075 m³/day</td>
</tr>
<tr>
<td>HRT</td>
<td>15 hours</td>
</tr>
<tr>
<td>SRT</td>
<td>20 days</td>
</tr>
<tr>
<td>DO Saturation</td>
<td>&gt; 4 g/m³</td>
</tr>
</tbody>
</table>

Table 2. Experimental results of Activated sludge process

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Raw Wastewater</th>
<th>Treated Wastewater</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD</td>
<td>388</td>
<td>15</td>
</tr>
<tr>
<td>TKN</td>
<td>56</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>NH₄</td>
<td>40</td>
<td>&lt;0.3</td>
</tr>
<tr>
<td>NO₃</td>
<td>&lt;0.3</td>
<td>38</td>
</tr>
</tbody>
</table>

All value in g/m³

Table 3. The various fractions of COD in municipal wastewater

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value (g/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_I</td>
<td>15</td>
</tr>
<tr>
<td>S_S</td>
<td>169.38</td>
</tr>
<tr>
<td>S_SMP</td>
<td>7.76</td>
</tr>
<tr>
<td>X_I</td>
<td>37.29</td>
</tr>
<tr>
<td>X_S</td>
<td>111.88</td>
</tr>
<tr>
<td>X_H</td>
<td>44.75</td>
</tr>
<tr>
<td>X_A</td>
<td>1.94</td>
</tr>
</tbody>
</table>

All value in g/m³
Table 4. Characteristics of membrane

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane materials</td>
<td>Ceramic</td>
</tr>
<tr>
<td>Surface Area</td>
<td>1.4 m²</td>
</tr>
<tr>
<td>Transmembrane Pressure</td>
<td>20 KPa</td>
</tr>
<tr>
<td>Membrane resistance</td>
<td>$5 \times 10^{11}$ 1/m</td>
</tr>
</tbody>
</table>

Table 5. Validation of present ASM model

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Experimental Results</th>
<th>Model Results</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD</td>
<td>15</td>
<td>16.96</td>
<td>13.07%</td>
</tr>
<tr>
<td>TKN</td>
<td>&lt;0.5</td>
<td>0.55</td>
<td>10%</td>
</tr>
<tr>
<td>NH₄</td>
<td>&lt;0.3</td>
<td>0.39</td>
<td>30%</td>
</tr>
<tr>
<td>NO₃</td>
<td>38</td>
<td>38.84</td>
<td>2.21%</td>
</tr>
</tbody>
</table>

Table 6. Effluent concentration experimental work and model results

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Experimental Results</th>
<th>Model Results (ASM 1, ASM 3, Present ASM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD</td>
<td>15</td>
<td>83.34, 15.26, 16.96</td>
</tr>
<tr>
<td>TKN</td>
<td>&lt;0.5</td>
<td>0.68, 0.53, 0.55</td>
</tr>
<tr>
<td>NH₄</td>
<td>&lt;0.3</td>
<td>0.51, 0.38, 0.39</td>
</tr>
<tr>
<td>NO₃</td>
<td>38</td>
<td>38.71, 41.56, 38.84</td>
</tr>
</tbody>
</table>

All value in g/m³

Table 7. Percent error between experimental and model results

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Experimental Results</th>
<th>Model Results (%)</th>
<th>(ASM 1, ASM 3, Present ASM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD</td>
<td>15 g/m³</td>
<td>Very High</td>
<td>1.73, 1.07, 13.07</td>
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<tr>
<td>TKN</td>
<td>&lt;0.5 g/m³</td>
<td>36, 10</td>
<td></td>
</tr>
<tr>
<td>NH₄</td>
<td>&lt;0.3 g/m³</td>
<td>70, 30</td>
<td></td>
</tr>
<tr>
<td>NO₃</td>
<td>38 g/m³</td>
<td>1.87, 9.37, 2.21</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. Mass balance across membrane bioreactors

Figure 2. Soluble Inert Organic Matter Concentration Vs Time

Figure 3. Readily Biodegradable Substrate Concentration Vs Time
Figure 4. Soluble Microbial Products Concentration Vs Time

Figure 5. Ammonia Nitrogen Concentration Vs Time

Figure 6. Nitrate Nitrogen Concentration Vs Time