



---

## CFD Modeling of Biofouling in Membrane Bioreactor (MBR) with COMSOL Multiphysics software

Nima Nazari<sup>\*1</sup>, Mahdi Naseryar<sup>1</sup>, Alireza Bayat<sup>2</sup>, Maliheh Torki<sup>2</sup>, Moein Shahriyari<sup>3</sup>, Maryam Ghiassvand<sup>4</sup>, Khashayar Majedinasab<sup>5</sup>

<sup>1</sup>Department of Chemical Engineering, Islamic Azad University- South Tehran Branch, Tehran, Iran

<sup>2</sup>Department of Chemical Engineering, Islamic Azad University- Farahan Branch, Markazi, Iran

<sup>3</sup>Department of Mechanical Engineering, Universidad Politecnica de Valencia, Valencia, Spain

<sup>4</sup>Department of Biochemistry, Universität Bremen, Bremen, Germany

<sup>5</sup>Department of Environmental Engineering, Sapienza University, Rome, Italy

**Abstract** Today, membrane bioreactors have been used extensively in the water and wastewater treatment industry due to their proper function. Thus, the study on them seems to be necessary. In this research, a brief description of the membrane bioreactor and its application is first given, and then the various types of fouling in the membrane bioreactor (MBR) are investigated. Membrane bioreactors have been used to make tubular membranes. Tubular membranes are susceptible to fouling due to their shape. The most important membrane fouling agents in the membrane bioreactor are biological materials. Biological materials consist of Extracellular Polymeric Substances (EPS) and Soluble Microbial Products (SMP). The fouling of Biological materials is called Biofouling. The fouling process mechanism for EPS is different from SMP. These various mechanisms cause different results in laboratory research and modeling. In the following these results are compared with each other and the main cause of biological fouling in the membrane bioreactor is introduced. The most important parameter to compare fouling from EPS and SMP is the amount of flux reduction across the membrane. In this research, COMSOL Multiphysics software is used to simulate processes.

**Keywords** Membrane Bioreactor, Biofouling, Extracellular Polymeric Substances, Soluble Microbial Products, COMSOL Multiphysics, Modeling.

---

### 1. Introduction

Membrane technology for the first time used in environmental engineering, in water treatment field. Membranes were used to removal of specific compounds, including salinity and biological contamination. The use of MBR as a high-quality refinement method quickly expanded. Gradually, the trade samples of MBR units were built about 20 years ago. Membrane bioreactor, or MBR, is defined as a system that uses a membrane instead of a secondary diluter in the process of separating the solid phase from the liquid. If the secondary diluter and membrane are used together, the system is not called a membrane bioreactor. The reason for removing the secondary diluter is that in addition to the sedimentation role, MBR also plays the role of disinfection. The use of membrane bioreactors in the water treatment process has solved many of the problems associated with active sludge process, which is mainly related to the separation of sludge from treated wastewater. In the membrane bioreactor for the separation of sludge



from treated wastewater, instead of using the sedimentation process, the membrane separation process is used. The idea of using a filtration method instead of a sedimentation method was first proposed by Smith and his colleagues in 1969 [1]. Application of membrane bioreactors include: 1- In the process of urban wastewater treatment. 2- In the process of industrial wastewater treatment. 3- In the process of refining the municipal solid waste.

### 1.1. Study of Concentration Polarization and Fouling Phenomenon

The fluid velocity at the membrane surface is reduced, when the flow of fluid in the membrane is turbulent. Exposed components are accumulated near the membrane surface. This accumulation is called concentration polarization, which has serious consequences for membrane processes. However, if the flow rate is high, these compounds are immediately transferred to the fluid mass and their accumulation near the membrane surface is limited. If the phenomenon of concentration polarization continues, it leads to the fouling of the membrane surface. The results of the occurrence of fouling are: [2] 1- Reduction of flux passing through the membrane over time. 2- Change the power of the material to be repaired by the membrane and thereby reduce the efficiency. 3- Decrease membrane life. 4- Need to increase the pressure required for the process. 5- Need more membrane cleaning.

Generally, fouling can be divided into the following types: 1- Sediments 2- Biological materials 3- Suspended solids 4- Colloidal materials 5- Metal oxides 6- Oils and greases. Due to the fact that biological fouling is caused by biological materials, this study only deals with this kind of fouling.

### 1.2. Study of fouling by biological materials

The growth of biological materials on the surface of the membrane causes this kind of fouling, Which includes: iron reducing bacteria, sulfur reducing bacteria, microbacteria and metabolic products of these bacteria. The biological contamination of membranes is dependent on the composition of membrane materials. EPS and SMP are the most important causes of biological fouling.

## 2. Modeling and Methods

### 2.1. Main Equations

Following equations are used for modeling the biofouling in the Tubular Membranes. The production rate of SMP is calculated from the Leudeking-piret equation [3]:

$$r_{SMP} = \frac{dS_{SMP}}{dt} = \alpha \frac{dx}{dt} + \beta x = \frac{dS_{UAP}}{dt} + \frac{dS_{BAP}}{dt} \quad (1)$$

Where  $r_{SMP}$  is the SMP production rate,  $S_{SMP}$  is the SMP concentration in the fluid mass,  $S_{UAP}$  is the UAP concentration in the fluid mass,  $S_{BAP}$  is the BAP concentration in the fluid mass,  $\alpha$  is the UAP Impact form and  $\beta$  is the BAP Impact form.

Also the rate of EPS production is calculated by the Laspidou-Rittmann equation [3]

$$r_{EPS} = \frac{dx_{EPS}}{dt} = \alpha' \frac{dx}{dt} k_{hyd} x_{EPS} \quad (2)$$

Where  $r_{EPS}$  is the EPS production rate,  $x_{EPS}$  is the EPS mass concentration and  $\alpha'$  is the EPS Impact form,  $k_{hyd}$  is the EPS hydrolysis rate.

In this figure, schematic view of the membrane module can be seen:

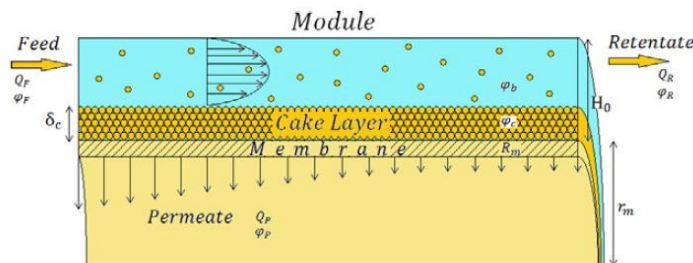


Figure 1: Schematic view of the membrane module [4]



The cake layer with constant resistivity can be calculated based on Darcy's law, given that our model has the series resistance [5]:

$$R_t = R_m + R_f + R_c \quad (3)$$

Where  $R_t$  is the total resistance,  $R_c$  is the cake resistance,  $R_m$  is the clean membrane resistance,  $R_f$  is the resistance due to membrane internal fouling.

$$J = \frac{\Delta P}{\mu (R_m + R_f + R_c)} \quad (4)$$

This equation is indicative of Darcy law where:  $J$  is the permeation flux,  $\Delta P$  is the transmembrane pressure and  $\mu$  is the dynamic viscosity of permeate. The following equation is obtained by the relationship between cake resistance  $R_c$  and cake specific resistance  $k_c$  in terms of the mass balance [1].

$$R_c = k_c H_0 \ln \left( \frac{H_0 + \delta_c}{H_0} \right) \quad (5)$$

Where  $k_c$  is the specific cake resistance,  $H_0$  is the channel height and  $\delta_c$  is the cake thickness. The overall mass balance for the liquid phase assuming an incompressible fluid is as follows [3].

$$Q_F = Q_p + Q_R \quad (6)$$

Where  $Q_F$  is the total feed flow rate,  $Q_p$  is the permeation flow rate,  $Q_R$  is the retentate flow rate. Also the mass balance for the solid particles can be written as follows [3,4]:

$$\rho_p \varphi_F Q_F - \rho_p \varphi_R Q_R - \rho_p \varphi_P Q_P = \frac{d}{dt} [\rho_p \pi (r_m + \delta_c)^2 L \varphi_c - \rho_p \pi r_m^2 L \varphi_c] \quad (7)$$

$$\rho_p \varphi_F Q_F - \rho_p \varphi_R Q_R - \rho_p \varphi_P Q_P = 2\pi (r_m + \delta_c) L \rho_p \varphi_c \frac{d\delta_c}{dt} \quad (8)$$

$$\rho_p \varphi_F Q_F - \rho_p \varphi_R Q_R - \rho_p \varphi_P Q_P = 2\pi r_m L \rho_p \varphi_c \frac{d\delta_c}{dt} \quad (9)$$

Where  $\rho_p$  is the particle density,  $\varphi_F$  is the Solid concentration of feed suspension in volume percentage,  $\varphi_R$  is the solid concentration of the suspension at module outlet in volume percentage,  $\varphi_P$  is the solid concentration of permeate product in volume percentage,  $\varphi_c$  is the solid concentration of the cake in volume percentage,  $r_m$  is the external radius of the membrane and  $L$  is the membrane length. Also the parameter of concentration of solids can be calculated as follows [3,4]:

$$\varphi_i = \frac{C_i}{\rho_s} \quad i = F, P, R \quad (10)$$

Where  $C_i$  is the particle concentration and  $\rho_s$  is the particle density.

## 2.2. Simulation

The simulation of fouling of EPS and SMP in the membrane bioreactor is utilized by the Comsol software version 5.2.

## 2.3. Geometry

The two-dimensional (2D) symmetric system is considered, because the geometry of the system is cylindrical, which has three parts: Feed, Porous media (membrane) and Permeate. The type of membrane used is tubular and the flow type is cross-flow. The geometry specifications are presented in the following table:

**Table 1:** The geometry specifications

| Media    | Width (m) | Height (m) |
|----------|-----------|------------|
| Feed     | 0.0008    | 0.1        |
| Membrane | 0.00003   | 0.1        |
| Permeate | 0.0004    | 0.1        |

In the following figure, the geometry view is shown in the software media:

For the feed and permeate parts, the Laminar flow and Transport of Diluted Species models and also for the membrane part, Free and Porous Media Flow and Transport of Diluted Species in Porous Media models are used.



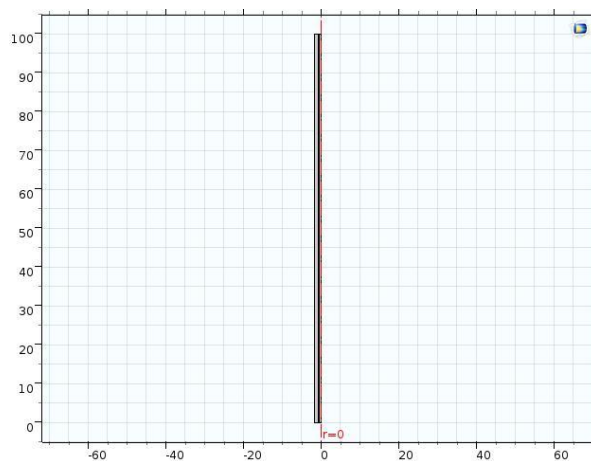


Figure 2: Geometry of system in the COMSOL area

## 2.4. Meshing

Meshing is one of the most important parts of the simulation. The type of mesh, that chosen for this system is Physics-Controlled and its size is normal.

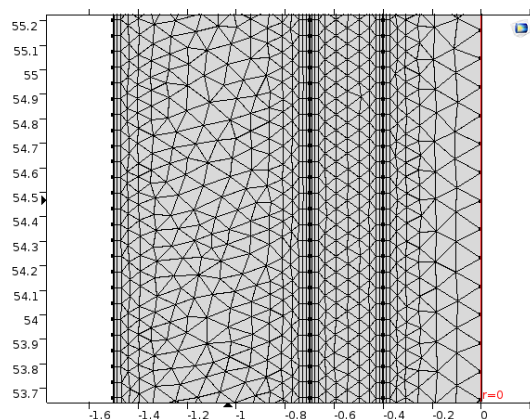


Figure 3: Schematic Meshing of Geometry

## 3. Results and Discussion

After performing all of the above steps, in two different studies, one of them is stable in which the speed equations are solved, for another study, the mass transfer equations are solved time-dependent.

### 3.1. Results in Feed Media

As shown in Fig.4 The speed value in the middle of the stream is about  $0.35 \frac{m}{s}$ . In the left sides of the flow, the surface flow rate value is about  $0 \frac{m}{s}$  on the outer surface of the membrane and the inner surface of the pipe.

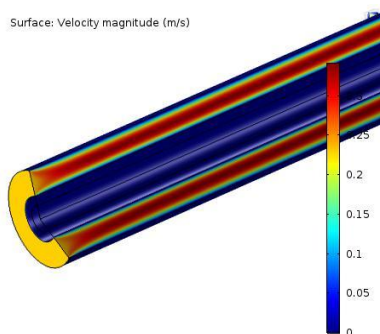


Figure 4: 3D Contour of speed in the Feed area

In Fig 5, it is assumed that the flow of current from the outer surface of the membrane only contains Extracellular Polymeric Substances (EPS). On the outer surface of the membrane, increasing concentration is observed. According to the Fig 5, the highest amount of concentration is observed on membrane surface (about  $13 \frac{\text{mol}}{\text{m}^3}$ ). By increasing the distance from the membrane surface, the concentration decreases logarithmically, and at the end of the boundary layer of Concentration Polarization, the concentration is equal to the concentration of Fluid Mass (about  $12.5 \frac{\text{mol}}{\text{m}^3}$ ).

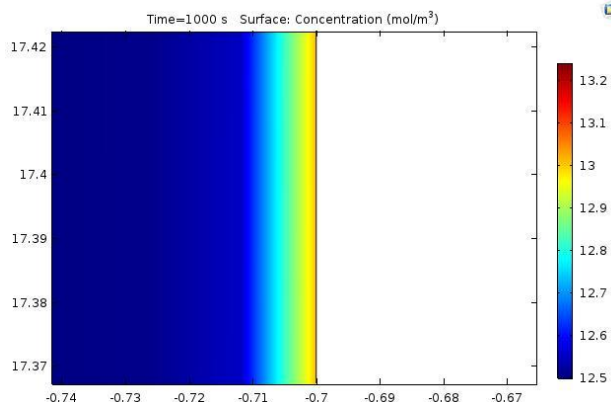


Figure 5: Increasing the concentration of EPS on the outer surface of the membrane

In Figure 6, it is assumed that the flow through the outer surface of the membrane only contains Soluble Microbial Products (SMP). On the outer surface of the membrane, increasing concentration is observed. Concentration is observed on the membrane surface is approximately  $3.09 \frac{\text{mol}}{\text{m}^3}$ . By increasing the distance from the membrane surface, the concentration decreases. and at the end of the boundary layer of Concentration Polarization, the concentration is equal to the concentration of Fluid Mass (about  $3 \frac{\text{mol}}{\text{m}^3}$ ).

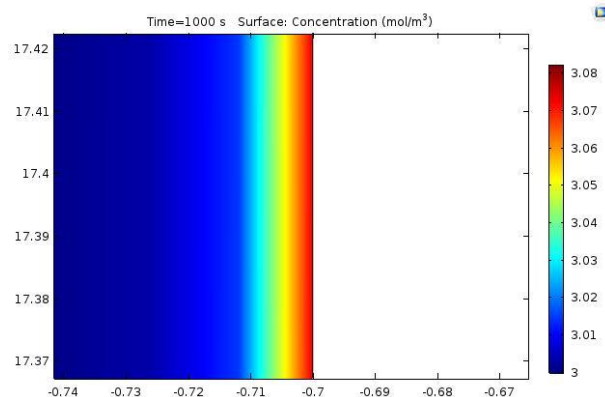


Figure 6: Increasing the concentration of SMP on the outer surface of the membrane

### 3.2. Results in Porous Media (Membrane)

In Fig 7, it is assumed that the flow of current from inside of the membrane only contains Extracellular Polymeric Substances (EPS). On the inner surface of the membrane, increasing concentration is observed. According to the Fig 7, the highest amount of concentration is observed on membrane surface (about  $500 \frac{\text{mol}}{\text{m}^3}$ ). By increasing the distance from the membrane surface, the concentration decreases logarithmically, and at the end of the boundary layer of Concentration Polarization, the concentration is equal to the concentration of Fluid Mass (about  $0 \frac{\text{mol}}{\text{m}^3}$ ).



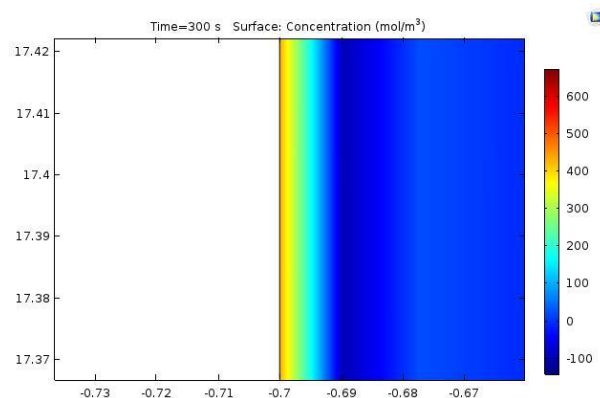


Figure 7: Decreasing the concentration of EPS on the inner surface of the membrane

In Fig. 8, it is assumed that the flow through the inner surface of the membrane only contains Soluble Microbial Products (SMP). On the inner surface of the membrane, increasing concentration is observed. Concentration is observed on the membrane surface is approximately  $125 \frac{\text{mol}}{\text{m}^3}$ . By increasing the distance from the membrane surface, the concentration decreases, and at the end of the boundary layer of Concentration Polarization, the concentration is equal to the concentration of Fluid Mass (about  $0 \frac{\text{mol}}{\text{m}^3}$ ).

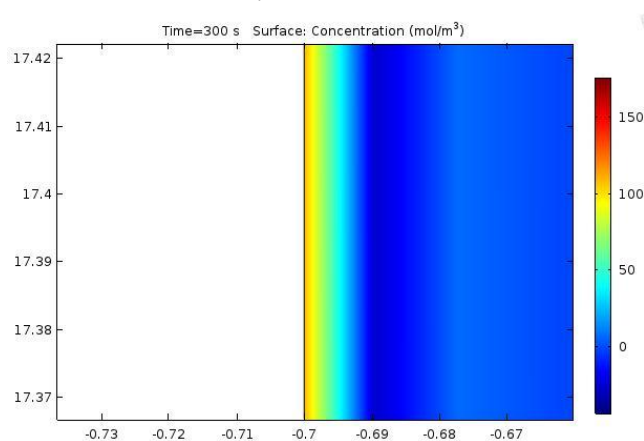


Figure 8: Decreasing the concentration of SMP on the inner surface of the membrane

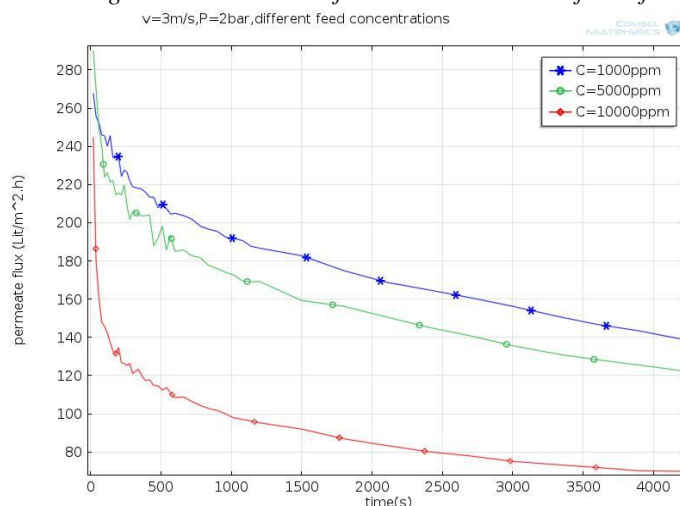


Figure 9: Effect of Feed Concentration on Output Flux



#### 4. Conclusion

In this study, the simulation of fouling of extracellular polymeric substances (EPS) and soluble microbial products (SMP) was performed using Comsolmultiphysics software, and the results were compared. It was found that EPSs and SMPs, although seemingly similar, but they are different. It was also found that among the biological materials, EPSs play the main role in membrane fouling. In the case of feed speed equal to  $3 \frac{m}{s}$  and feed pressure of 2 bar, and feed concentration of 5000 ppm, As shown in Fig.9 the green graph is obtained. Which indicates a drop in output flux over a period of 4500 seconds, that indicating fouling in the membrane. In the absence of fouling, the fluid passes through the membrane hardly, and the output flux is reduced. The blue graph is related to the feed concentration of 1000 ppm, and the red graph is related to the feed concentration of 10000 ppm. These graphs represent the reduction of the flux, or the membrane biofouling phenomenon. If the concentration increases, the output flux will decrease. Because more concentration will result in more fouling.

#### References

1. Stephenson T., Brindle K., Judd S., Jefferson P. Membrane Bioreactors for Wastewater Treatment, International water Association, London, 2000.
2. Baker, R.W., Membrane Technology and applications. John Wilwy and Sons, Ltd, United Kingdom, 2004.
3. Nazari, N., Shams, P., Moazeni, M., CFD Modeling of Fouling by Biological Materials in Tubular Membrane in Submerged Membrane Bioreactor with ANSYS FLUENT Software, Applied Research Journal, pp:459-466, 2016.
4. Kazemi, M.A., Soltanieh, M., Yazdanshenas, M., Mathematical modeling of crossflow microfiltration of diluted malt extract suspension by tubular ceramic membranes, Journal of Food Engineering, 116, pp: 926–933, 2013.
5. Mulder, M., Basic Principles of Membrane Technology, 2<sup>nd</sup> Edt., Kluwer Academic Publishers, 1996.

