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## Relationship between biofouling and recovery ratio: the theoretical approach and one experimental case

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### Abstract

Biofouling is the undesirable accumulation of microorganisms on the membrane surface and it is one of the major problems affecting the performance and the economy of many membrane installations for the treatment of seawater and wastewater. Unlike inorganic fouling, biological fouling due to microorganisms can be dependent on their growth rate. The paper examines from a theoretical point of view the influence of the membrane recovery ratio on the concentration of biomass in the membrane module. An attempt of validation of the model has been tried using a submerged microfiltration hollow-fibre membrane set-up.

**Keywords:** Biofouling, Hollow fibre, Submerged membrane reactor

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### 1. Introduction

Biological fouling (biofouling) is the undesirable accumulation of microorganisms on the membrane surface. Biofouling of UF/MF and RO membranes is an important factor affecting both membrane life and replacement rates as well as

the quality of the membrane permeate [1]. The current market is leading towards the increase of membrane recovery in order to decrease both capital and operating costs.

While the impact of inorganic fouling and, in particular, of scaling can be easily predicted and mitigated through the adoption of anti-scaling compounds, biofouling still remains somewhat

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unpredictable. Unlike inorganic fouling, biological fouling due to microorganisms can be dependent on their growth rate.

The paper examines, from a theoretical point of view, the influence of the membrane recovery ratio on the concentration of biomass in the membrane module. An attempt of validation of the model has been tried using a submerged micro-filtration hollow-fibre membrane set-up used as a bioreactor.

**2. Theoretical approach and model equations**

The material balances have been formulated on the basis of the model scheme depicted in Fig. 1. The membrane is kept in contact with the feed in a volume  $V$ , and a stream with a concentration of biomass  $\omega_1$  is fed into the membrane module. The membrane depending on the operating conditions (e.g. transmembrane pressure) produces a permeate which does not contain biomass. The biomass can grow at the expense of the substrates present in the feed stream. The basic theories for biological growth are usually based on the Monod equation [2].

$$\mu = \frac{\mu_{\max} \cdot S}{K_s + S} \tag{1}$$

where  $\mu$  is the microorganism specific growth rate,

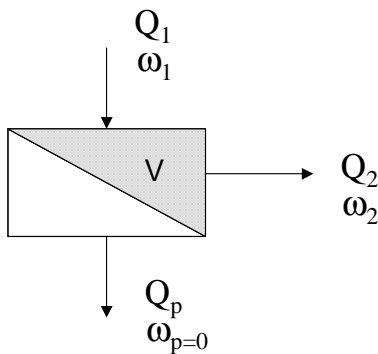


Fig. 1. Scheme of the model: inlet and outlet streams in the membrane module.

$\mu_{\max}$  represents the maximum specific biological growth rate,  $K$  is the half-velocity constant and  $S$  is the limiting substrate concentration. The  $\mu_{\max}$  value depends on the type of microorganisms as well as on the environmental conditions (e.g. operating temperature).

Then the rate of microorganism growth is

$$r_g = \mu \cdot \omega \tag{2}$$

Assuming that the liquid in the volume  $V$ , which is in contact with the membrane, is sufficiently well mixed and the biomass distribution is uniform (this condition can be obtained for example in bioreactors [3,4]), the continuous stirred tank approach can be used to formulate the material balance for the biomass.

$$Q_1\omega_1 = Q_2\omega_2 - r_g V \tag{3}$$

where  $Q_1$  and  $Q_2$  represent the flow-rate at the inlet and outlet of the membrane respectively.

Rearranging the terms of Eq. (3) combined with Eq. (2) we obtain:

$$\omega_2 = \omega_1 \frac{Q_1}{Q_2 - \mu V} \tag{3a}$$

The recovery ratio is defined by the following equation:

$$\varepsilon = \frac{Q_p}{Q_1} = \frac{Q_1 - Q_2}{Q_1} \tag{4}$$

Then we can express the outlet flow-rate in terms of  $\varepsilon$ :

$$Q_2 = Q_1(1 - \varepsilon) \tag{5}$$

Combining the two equations above we can obtain the following relationship between the biomass concentration at the outlet of the membrane and the recovery ratio used during the process:

$$\omega_2 = \omega_1 \frac{1}{(1-\varepsilon) - \mu \frac{V}{Q_1}} \quad (6)$$

As seen in Eq. (6), an increase in the membrane recovery ratio  $\varepsilon$  corresponds to an increase in the biomass concentration at the membrane outlet and consequently on the biofilm on the membrane surface. Moreover the equation demonstrates that the biomass concentration tends to decrease with the increase of the influent flow-rate.

An in-depth discussion of the features of Eq. (6) will be presented in the results analysis subsection.

### 3. Experimental approach

A membrane bioreactor was chosen to test experimentally the validity of the model. A full description of the experimental set-up has been provided in a different paper [5]. Here we will only give the experimental details useful for the understanding, and regarding the test carried out to validate the model. Fig. 2 shows the membrane bioreactor configuration considered. Microfiltration

hollow-fibre membranes were submerged in the bioreactor. The nominal pore diameter of the hollow-fibre membranes was  $0.4 \mu\text{m}$  and the total membrane area was  $0.2 \text{ m}^2$ . As a consequence the configuration used into the bioreactor volume ( $V$  was about 3 L) corresponded to the volume of the membrane module described in the model equations reported above. Wastewater, containing a high concentration of mineral hydrocarbons used by the biomass as substrate, was fed into the bioreactor volume.  $\text{NH}_4\text{NO}_3$  and  $\text{KH}_2\text{PO}_4$  were added to the feed water in order to have a non-limiting concentration of nutrients. A peristaltic pump was used to create the transmembrane pressure necessary to carry out the filtration process through the hollow-fibre membrane and particular care was taken in order to keep membrane fluxes inside the sub-critical flux region (the critical flux, where the biofouling strongly affected the permeate flux, was found to be between  $3 \text{ L/m}^2\text{h}$  and  $5 \text{ L/m}^2\text{h}$ ). The biomass concentration in the feed and in the bioreactor was determined by mixed liquor suspended solids using the weight procedure for the total suspended solids described in the APHA standard methods [6].

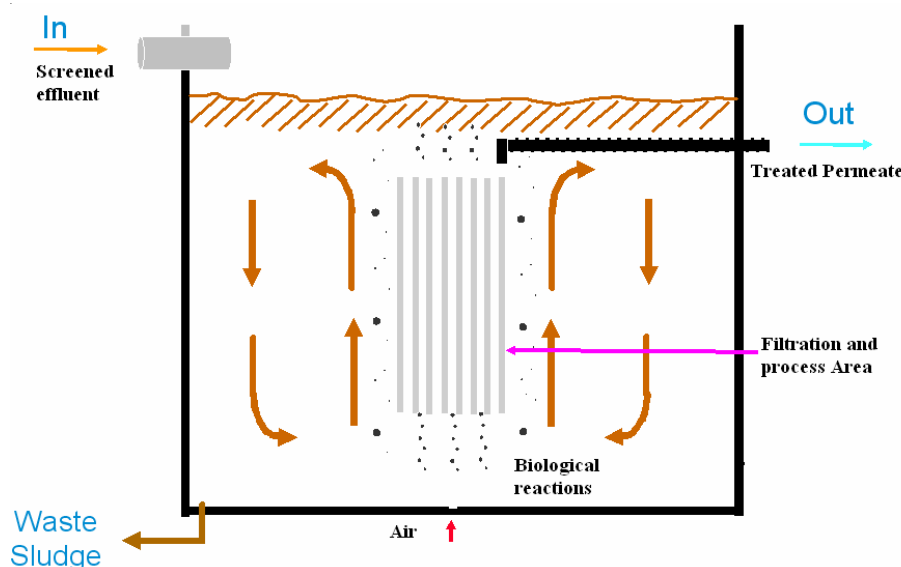


Fig. 2. Scheme of the hollow-fibre membrane reactor.

To resume, the process streams in the bioreactor were the following:

- 1) The inlet stream was composed by a volumetric flow  $Q_1$  having a biomass concentration  $\omega_1$ .
- 2) A permeate stream with flow-rate  $Q_p = J_p \cdot A$  was obtained from the membrane and its biomass concentration was zero ( $\omega_p = 0$ ).
- 3) A stream of flow-rate  $Q_2$  at a biomass concentration  $\omega_2$  went out from the reactor volume.

#### 4. Results and discussion

Table 1 resumes the results of three experimental tests carried out in the hollow-fibre membrane bioreactor. In all three tests the use of a large membrane area combined with low transmembrane pressure allowed the system to achieve very high recovery ratios. Some experiments were carried out to determine  $\mu$ . Fig. 3 shows the results of a logarithmic plot of the biomass concentration against time for one batch experiment of the biomass growth. Under the condition used the biomass growth followed an exponential law, i.e.  $\mu^{\max} = 2.4 \times 10^{-3} \text{ h}^{-1}$

As seen in Table 1, for all tests the  $V/Q_1$  ratio, representing the hydraulic retention time on the membrane surface, was always lower than 200 h indicating the validity of the assumption of non-limited growth of the biomass. Therefore:

$$\mu = \mu^{\max} \quad (7)$$

Table 1  
Experimental results of the hollow-fibre membrane bioreactor

	Test A	Test B	Test C
$Q_1$ , L/h	0.308	0.094	0.261
$Q_p$ , L/h	0.3	0.084	0.25
$\omega_1$ , g/L	0.0708	0.256	0.136
$\varepsilon$	0.971	0.892	0.957
$V/Q_1$ , h	9.7	31.8	11.5
$\omega_2$ , g/L	14	8.4	9.2

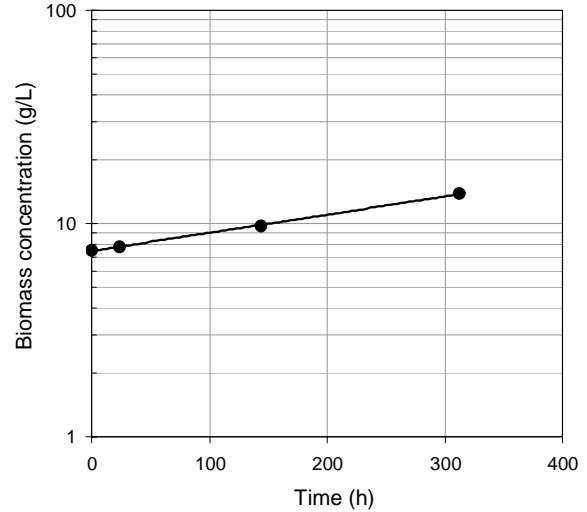


Fig. 3. Biomass growth curve as a function of time in a semi-logarithmic diagram. The continuous line passing through the experimental points is the regression curve from which  $\mu^{\max} = 2.4 \times 10^{-3} \text{ h}^{-1}$ .

On the basis of the inlet conditions reported in the test of Table 1 the outlet biomass concentration could be plotted using Eq. (6) against the recovery ratio (Fig. 4). The increase of the calculated biomass at the bioreactor outlet showed a pseudo-exponential trend for all three test conditions. The high biomass levels reached at the system outlet (and in the membrane bioreactor volume) could be explained by the fact that the biomass was growing in the system. For example when the inlet flow-rate was very high and/or the reactor volume was very low and it was:

$$\mu \frac{V}{Q_1} \ll (1 - \varepsilon) \quad (8)$$

Therefore the outlet biomass concentration that could be achieved depended only on the recovery ratio and was lower in the previous cases. The experimental outlet biomass concentration,  $\omega_2^{\text{exp}}$  was reported in Fig. 4 and with respect to the theoretical curve the experimental results showed a

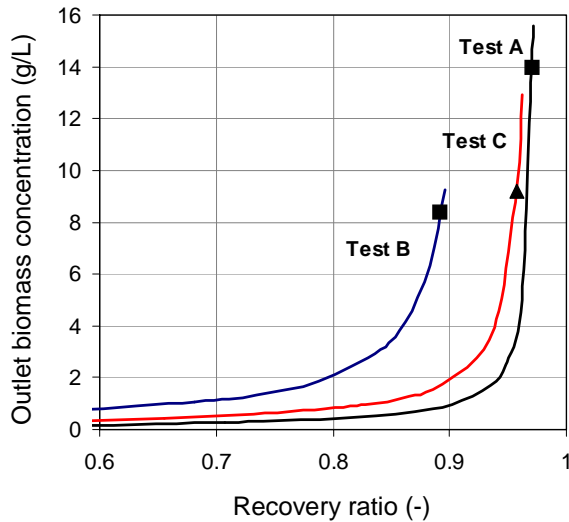


Fig. 4. Calculated outlet biomass concentration (continuous curves) from the experimental inlet conditions and experimental outlet biomass concentration (points) for the three experimental tests.

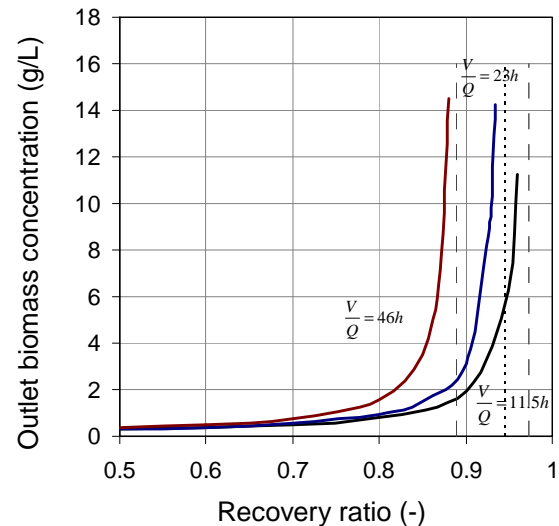


Fig. 5. Calculated outlet biomass concentration as a function of the recovery ratio for different hydraulic residence times ( $V/Q_1$ ) in similar conditions to those used in the experimental tests.

very good match, confirming the validity of the model.

Fig. 5 shows the outlet biomass concentration as a function of the recovery ratio by changing the hydraulic residence time  $V/Q_1$  in the bioreactor. It should be noted that an asymptote was reached for a given  $V/Q_1$  ratio. The asymptote corresponded to the condition:

$$\varepsilon = 1 - \mu \frac{V}{Q} \quad (9)$$

An increase of the  $V/Q$  ratio lowered the value of the maximum recovery ratio that could be applied with the maximum biomass concentration tolerable by the system.

## 5. Conclusions

A simple model for the accumulation of biomass in membrane system was developed on the

basis of a mass balance, which took into consideration the biomass growth kinetics. The model showed the importance of the recovery ratio for the determination of the biomass concentration in the outlet. The importance of the biomass concentration level that could be achieved was relevant because in turn it could affect the characteristics of the biofilm on the membrane surface. An attempt to validate the model was carried out on the basis of some experiments in a hollow-fibre membrane reactor. The match between the model and the experimental results was excellent. Further experiments still need to be carried out to prove the reliability of the model in other membrane systems and to study the influence of limiting substrate kinetics. The model could constitute a useful tool for industrial large scale plants in order to project the biomass concentration achievable in the submerged membrane systems as well as for the troubleshooting and analysis of departures from optimal operating conditions in real cases.

**Symbols**

$K_s$	—	Half-velocity constant, g/L
$Q$	—	Volumetric flow rate, L/h
$r_g$	—	Rate of biomass growth, g/(L h)
$S$	—	Substrate concentration, g/L
$V$	—	Active volume of the bioreactor, L

*Greek*

$\varepsilon$	—	Recovery ratio
$\mu$	—	Specific growth rate, 1/h
$\mu_{\max}$	—	Specific growth rate, 1/h
$\omega$	—	Biomass concentration, g/L
$\omega^{\text{exp}}$	—	Experimental biomass concentration, g/L

*Subscripts*

1	—	Refers to inlet
2	—	Refers to outlet
$p$	—	Refers to permeate

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