A combined blocking model for cross flow membrane filtration

Sourav Mondal and Sirshendu De*
Department of Chemical Engineering, Indian Institute of Technology Kharagpur, Kharagpur 721302, India

*corresponding author email: sde@che.iitkgp.ernet.in

Abstract

Membrane fouling during filtration is one of the major concerns in the field of membrane technology. Fouling is caused by the development of the concentration polarization layer over the membrane surface, formation of a cake layer and/or by blocking of the membrane pores. The pore blocking can further be classified as complete, intermediate and partial (Field et al., 1995). Theoretical description of the blocking mechanisms has been first described by Hermia (1987). Several researchers (Bowen et al., 1995; Ruohomaki and Nystrom, 2000; Ho and Zydney, 2000; Yuan et al., 2002; Taniguchi et al., 2003; Orsello et al., 2006; Bagga et al., 2008) have analyzed the fouling mechanisms in batch filtration mode considering a single mechanism or simultaneous occurrence of the cake and pore blocking phenomenon. The blocking principle for continuous cross flow filtration has been developed by Field et al. (1995), which has been analyzed during ultrafiltration of depectinized pineapple juice (Barros et al., 2003), mosambi juice (Rai et al., 2006) and blood orange juice (Cassano et al., 2007). In all these studies it has been observed that only one mechanism is prevalent at a time. However, it is likely that more than one fouling mechanism can occur during the filtration. In another study by Mondal and De, (2009, 2010), sequential occurrence of complete pore blocking followed by cake and intermediate followed by cake has been presented.

Theoretical development of sequential or simultaneous presence of these mechanisms for a continuous steady state filtration is not available. In the present work, a generalized formulation for steady state continuous filtration is attempted, considering simultaneous occurrences of complete pore blocking and intermediate pore blocking followed by cake filtration. Various parameters are combined in non-dimensional numbers and flux decline analysis is carried out in terms of these non-dimensional numbers. A complete map in parameter space is presented to identify the relative dominance of fouling mechanism. The analysis presents the domain of dominant fouling mechanism that can take occur during continuous filtration. Apart from identification of the dominant fouling mechanism, in cases of enzyme immobilization over membrane surface (Hibino et al., 1989), where cake formation is particularly essential or impregnation of catalyst in hollow fiber membrane (Caro et al., 2007) for gas phase catalytic reaction, where pore blocking is essential, the present analysis provides useful information about selection of parameters to operate the filtration in their respective regimes.

Theoretical Development

In the combined model, it is reasonable to consider that complete pore blocking proceeds from the beginning of the experiment upto a time of operation (t_1) when cake formation starts. Once the cake formation starts, solutes start depositing over the membrane surface, there is hardly any scope of pore blocking to take place. Therefore, the governing equation of flux decline due to pore blocking can be written directly from Hérmia's model (Field et al., 1995).

$$-\frac{dJ}{dt} = k_0 J^n \tag{1}$$

where, n = 1 for complete pore blocking, n = 2 for intermediate pore blocking and n = 3 for cake formation.

Flux decline for $t < t_1$

Substituting n = 1 and 2 we obtain,

$$J = J_0 \exp(-k_1 t) \tag{2}$$

for complete pore blocking and,

$$\frac{1}{J} = \frac{1}{J_0} + k_2 t \tag{3}$$

for intermediate pore blocking, where J_0 is the pure water flux $\left(J_0 = \frac{\Delta P}{\mu R_m} \right)$. In terms of resistance, the pore blocking resistances were defined as,

$$R^*_{CPB} = \frac{R_{CPB}}{R_m} = \exp(k_1 t) - 1 \tag{4}$$

$$R^*_{IPB} = \frac{R_{IPB}}{R_m} = J_0 k_2 t \tag{5}$$

Flux decline for $t > t_1$

Growth of cake resistance is restricted due to external cross flow of the feed. In this case, the flux decline equation is obtained from the modified equation of Field et al., (1995)

$$\frac{dJ}{dt} = -k_c (J - J_{ss}) J^2 \tag{6}$$

where, J_{ss} is the steady state flux. In terms of resistance, the expression of the flux becomes at $t > t_1$,

$$J = \frac{\Delta P}{\mu[R_m + R_{CPB}(t_1) + R_{IPB}(t_1) + R_c(t - t_1)]} \tag{7}$$

The above equation can be expressed in terms of non-dimensional resistances as,

$$J = \frac{J_0}{[1 + R^*_{CPB} + R^*_{IPB} + R^*_c]} \tag{8}$$

Permeate flux at time $t = t_1$ is obtained as

$$J_{t_1} = \frac{J_0}{\left[1 + R^*_{CPB}(t_1) + R^*_{IPB}(t_1)\right]} \tag{9}$$

Combining the above two equations, the following expression is obtained,

$$J = \frac{J_{t_1}}{\left[1 + R^{**}_c\right]} \tag{10}$$

where, R^{**}_c is defined as, $R^{**}_c = \frac{R^*_c}{[1 + R^*_{CPB}(t_1) + R^*_{IPB}(t_1)]}$ (11)

Taking the derivative of equation Eq. (11) with respect to t, the rate of flux change is obtained as, $\frac{dJ}{dt} = -\frac{J_{t_1}}{(1 + R^{**}_c)^2}\frac{dR^{**}_c}{dt}$ (12)

Using Eqs. (8) and (14), the governing equation of cake resistance is obtained,

$$\frac{dR^{**}_c}{dt} = \frac{J_{t_1} k_c}{(1 + R^{**}_c)}[J_{t_1} - J_{ss}(1 + R^{**}_c)] \tag{13}$$

At the steady state, $\frac{dR^{**}_c}{dt} = 0$ and therefore, from Eq. (13), the following criterion at the steady state is obtained, $J_{t_1} = J_{ss}(1 + R^{**}_{cs})$ (14)

Considering Eq. (8-11), we can transform Eq. (14) as,

$$R^*_c = \frac{J_0}{J_{ss}} - (1 + R^*_{CPB} + R^*_{IPB}) \tag{15}$$

Formation of non-dimensional groups

From the continuity equations at $t = t_1$, the flux obtained through both the mechanisms would be equal, which implies,

$$\left.\frac{dJ}{dt}\right|_{t=t_1-\delta} = \left.\frac{dJ}{dt}\right|_{t=t_1+\delta} \tag{16}$$

Using Eqs. (2), (3) and (6) in Eq. (18), we obtain,

$$k_1 \exp(k_1 t_1) + J_0 k_2 = J_0 k_c (J_{t_1} - J_{ss}) \tag{17}$$

Selecting non-dimensional parameters as $k_1 t_1 = \tau$, $\frac{k_c J_0^2}{k_1} = G_1$ and $\frac{J_0 k_2}{k_1} = G_2$, we obtain Eq. (17) as $\exp(\tau) + G_2 = G_1\left(\frac{1}{\exp(\tau) + G_2\tau} - \frac{J_{ss}}{J_0}\right)$ (18)

Comparison of resistances

Since, from Eq. (4) and (5), complete and intermediate pore blocking resistances are quantified. Therefore,

$$\frac{R_c^*}{R_{IPB}^*} = \frac{1}{J_0 k_2 t_1}\left[\frac{J_0}{J_{ss}} - \exp(k_1 t_1)\right] - 1 \tag{19}$$

In terms of non-dimensional terms (using Eq. 18) Eq. (19) can be transformed to

$$\frac{R_c}{R_{IPB}} = \frac{(e^\tau + G_2)(e^\tau + G_2\tau)^2}{G_2\tau[G_1 - (e^\tau + G_2)(e^\tau + G_2\tau)]} \tag{20}$$

Similarly, $\frac{R_c}{R_{CPB}}$, $\frac{R_c}{R_{CPB} + R_{IPB}}$ and $\frac{R_{CPB}}{R_{IPB}}$ can be obtained as

$$\frac{R_c}{R_{CPB}} = \frac{1}{(e^\tau - 1)}\left[\frac{G_1 G_2\tau + (e^\tau + G_2)(e^\tau + G_2\tau)}{G_1 - (e^\tau + G_2)(e^\tau + G_2\tau)}\right] \tag{21}$$

$$\frac{R_c}{R_{CPB} + R_{IPB}} = \frac{1}{(e^\tau + G_2\tau - 1)}\left[\frac{(e^\tau + G_2)(e^\tau + G_2\tau)^2}{G_1 - (e^\tau + G_2)(e^\tau + G_2\tau)}\right] \tag{22}$$

$$\frac{R_{CPB}}{R_{IPB}} = \frac{e^\tau - 1}{G_2\tau} \tag{23}$$

Relative dominance of the each of these resistances can be compared by setting the values of the ratios to be greater or less than unity.

Infeasibility criteria

Infeasible solution will result when $\frac{R_c}{R_{CPB}}, \frac{R_c}{R_{IPB}}, \frac{R_c}{R_{CPB}+R_{IPB}}$ and $\frac{R_{CPB}}{R_{IPB}} < 0$. Considering Eq. (20-23), the necessary and sufficient condition for infeasibility is

$$\frac{G_1}{e^{\tau}+G_2} < e^{\tau}+G_2\tau < 1 \qquad (24)$$

for all positive real solutions of τ from Eq. (17).

Fig.1 shows the infeasibility boundary of τ in the parameter space by solving Eq. (18). The region above the curves shows the realistic solution of τ for different combinations of G_1 and G_2. So, for existence of the fouling mechanisms one has to select G_1, G_2 and J_{ss}/J_0 suitably. Solution of τ in the feasible domain has been present in Fig. 2. Using the values of τ and the parameters (G_1, G_2 and J_{ss}/J_0) relative dominance of the blocking mechanism during filtration can be identified. For the instances of only complete pore blocking followed by cake formation (Mondal and De, 2009) and only intermediate pore blocking followed by cake filtration (Mondal and De, 2010), Fig. 3 represents the regimes of dominant fouling mechanisms. An operator can preset these values of the parameters within the feasible boundary of τ to operate the cross flow filtration in a preferential fouling regime.

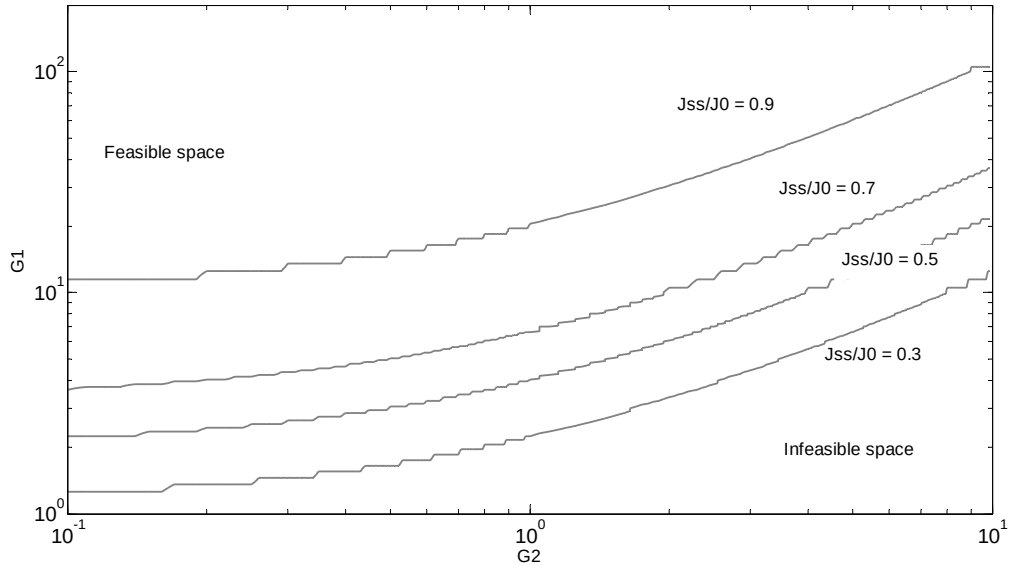


Fig. 1: Infeasibility regimes of solution of τ in the parameter space.

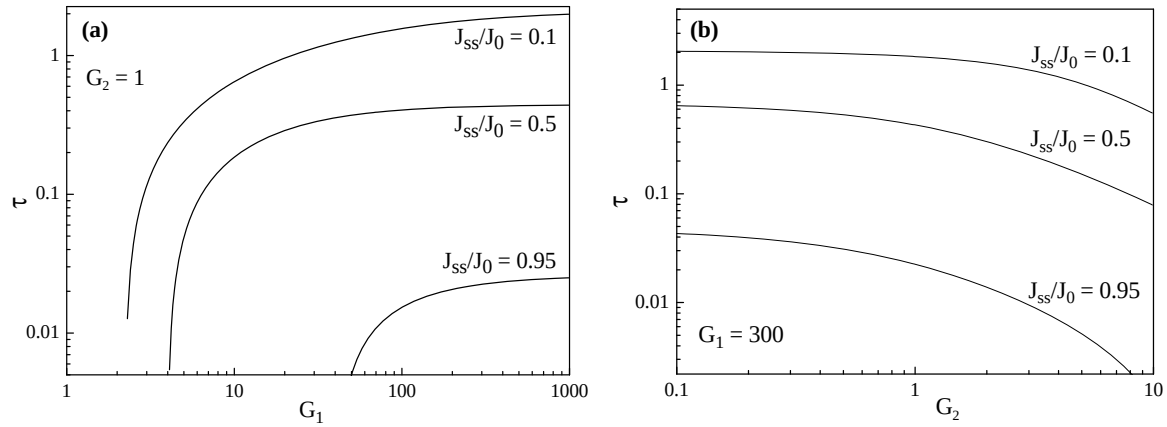


Fig. 2: Real solution of τ in the feasible domain of G_1, G_2 and J_{ss}/J_0.

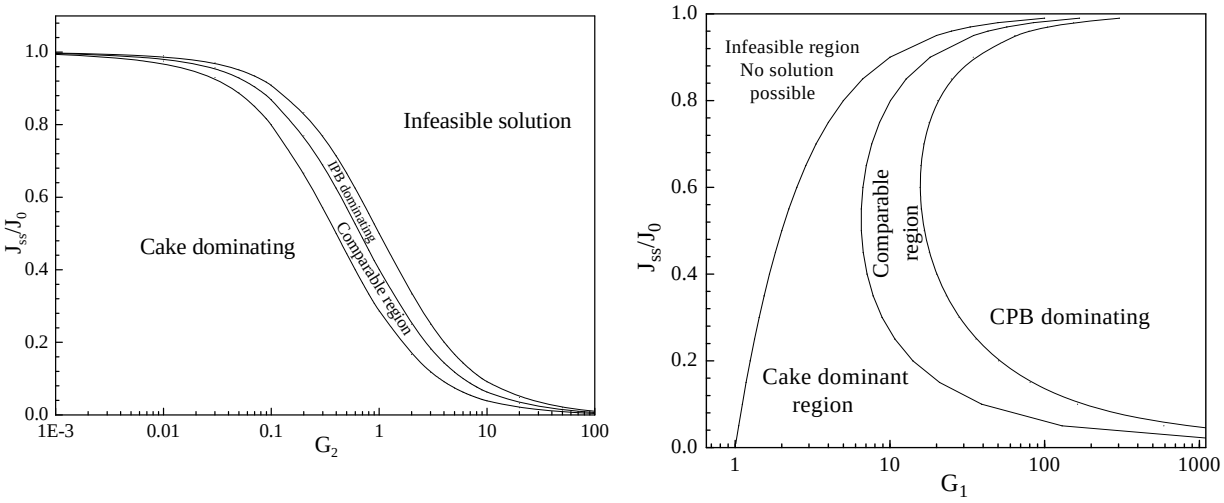


Fig. 3: Dominant filtration regimes in case of intermediate pore blocking followed by cake formation and complete pore blocking followed by cake formation.

References

Bagga, A., Chellam, S., Clifford, D.A. (2008) Evaluation of iron chemical coagulation and electrocoagulation pretreatment for surface water microfiltration, J. Membr. Sci. 309, 82–93.

Barros, S.T.D.d., Andrade, C.M.G., Mendes, E.S., Peres, L. (2003) Study of fouling mechanism in pineapple juice clarification by ultrafiltration, J. Membr. Sci. 215, 213–224.

Bowen, W.R., Calvo, J.I., Hernández, A. (1995) Steps ofmembraneblocking in flux decline during protein microfiltration, J. Membr. Sci. 101, 153–165.

Caro, J., Caspary K.J., Hamel, C., Hoting, B., Kolsch, P., Langanke, B., Nassauer, K., Schiestel, T., Schmidt, A., Schomacker, R., Morgenstern, A.S., Tsotsas, E., Voigt, I., Wang,

H., Warsitz, R., Werth, S., Wolf, A. (2007) Catalytic Membrane Reactors for Partial Oxidation Using Perovskite Hollow Fiber Membranes and for Partial Hydrogenation Using a Catalytic Membrane Contactor, *Ind. Eng. Chem. Res.*, 46, 2286–2294.

Cassano, A., Marcia, M., Drioli, E. (2007) Clarification of blood orange juice by ultra filtration: analyses of operating parameters, membrane fouling and juice quality, Desalination 212, 15–27.

Field, R.W., Wu, D., Howell, J.A., Gupta, B.B. (1995) Critical flux concept for microfiltration fouling, J. Membr. Sci. 100, 259–272.

Hérmia, J. (1982) Constant pressure blocking filtration laws: applications to power-law non-Newtonian fluids, Trans. Inst. Chem. Eng. 60, 183–187.

Hibino, K., Okada, T., Kazno, N., Sahashi, Y. (1990) Enzyme immobilization in an anisotropic ultrafiltration membrane, *US Patent* 4,963,494.

Ho, C.C., Zydney, A.L. (2000) A combined pore blockage and cake filtration model for protein fouling during microfiltration, J. Colloid Interface Sci. 232, 389–399.

Mondal, S., De, S. (2009) Generalized criteria for identification of fouling mechanism under steady state membrane filtration. J. Membr. Sci. 344, 6-13.

Mondal, S., De, S. (2010) A fouling model for steady state crossflow membrane filtration considering sequential intermediate pore blocking and cake formation. Sep. Purif. Technol. 75, 222-228.

Orsello, C.D., Li, W., Ho, C.C. (2006) A three mechanism model to describe fouling of microfiltration membranes, J. Membr. Sci. 280, 856–866.

Rai, P., Majumdar, G. C., Sharma, G., DasGupta, S., De, S. (2006) Effect of various cutoff membranes on permeate flux and quality during filtration of mosambi (Citrus sinensis L.) Osbeck juice, Food Bioprod. Process. 84, 213–219.

Ruohomaki, K., Nystrom, M. (2000) Fouling of ceramic capillary filters in vacuum filtration, Filtr. Sep. 37, 51–57.

Taniguchi, M., Kilduff, J.E., Belfort, G. (2003) Modes of natural organic matter fouling during ultra filtration, Environ. Sci. Technol. 37, 1676–1683.

Yuan, W., Kocic, A., Zydney, A.L. (2002) Analysis of humic acid fouling during microfiltration using a pore blockage–cake filtration model, J. Membr. Sci. 198, 51–62.