Force Balance of Particles in Water During Ultrafiltration Membrane Process

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Abstract—Membrane filtration is vital in our daily lives to extract fresh water from contaminated water. However, membrane filtration is suffering from fouling, which is induced by accumulations of particles on membrane surface. Due to the hydraulic field and electrical field (from functional groups of membranes) near membrane surface, particle will be exerted by different forces. The intermolecular forces such as the Lateral lift force, Brownian force, shear-induced force, Van Der Waal force and electrostatic repulsion force may affect the fouling process, and the water flux inside the system cab exert permeance drag force to the particles near the surface of membrane. In order to figure out the forces that may affect the filtration process, a model was established about the filtration process. In the model, the velocities of the each forces are listed and calculated in this paper. From the analysis, the relations between the particle velocities, which represents the filtration efficiency, and the forces, such as lift or shear forces, are well illustrated. This article shows the importance of potentially understanding the fouling process and providing insight of fouling mitigation for the membrane filtration process.

1. Introduction:
Membrane filtration is an effective way to remove the contaminant in the solution, then stimulate the efficient recycle of water. Water is a kind of vital liquid in our daily lives, so keeping it excess is necessary. The proper construction of membrane filtration system will provide us with a stable fresh water supply.

Ultrafiltration process [1] contains several types of system setups such as cross flow and dead-end flow, and it has several advantages. Cross flow system, usually with the pressure loss, has a higher efficiency of transporting though it consumes more energy, and it is long-lasting so the cost is decreased. As a result, cross flow has been widely used in industries to purify the water or other liquids. Since the axial pressure loss exist while water flow through the flow cell channel, the filtration efficiency will decrease. Dead-end flow, the most common ultrafiltration, usually with the pressure gathered, has smaller foot print and no recirculation though it has weak endurance, and it is energy conservative. The dead-end filtration is a batch process as accumulated matter on the filter decreases the filtration capacity, due to clogging. A next process step to remove the accumulated matter is required. Dead-end filtration can be a very useful technique for concentration compounds. (1)

Ultrafiltration has both advantages and disadvantages. Generally, polymeric membranes were used predominantly during the ultrafiltration (UF) of waste water. [2] The development of inorganic membranes started in France 20 years ago. (2) Ultrafiltration membrane has fascinating advantages to filtrate the solution. The main advantage is that ultrafiltration does not involve a phase change or interphase mass transfer. Although ultrafiltration membrane plays a vital role in filtrating the waste water, it has drawbacks that it is easy to be affected by fouling.
As forces applied on particles and pressure being altered in the filtration process, some impurities may be retained in the waste stream. In order to ameliorate the filtration efficiency, it is necessary to solve the problem of ultrafiltration membrane fouling. Fouling process come into being due to the unbalanced conditions in the filtration system. When the sum of forces exerted on the particle are attractive (i.e. toward to membrane surface), it is really easy that the pores on the membrane will be gradually blocked during operation. Additionally, long-term operation of the membrane will cause the accumulations of impurities in the pores, and that is how fouling phenomenon occurs. Owing to that, the performance of the membrane is affected. Fouling will increase the cost because the frequent cleaning of the membrane is required to maintain the system stability, which also deteriorate the filtration performance of the ultrafiltration process. The intermolecular forces such as Van der Waal’s force, or the attraction or repulsion forces induced by fluid will significantly affect the particles trajectory, thus influencing the membrane filtration performance, and determining the frequency of periodic cleaning. There are four types of fouling, chemical, biological, deposition and corrosion. Those accumulations on the membrane may cause problems in the process. In this condition, it is necessary to find a way to remove those accumulations then increase the filtration efficiency. In order to do that, understanding of force balance from different directions is vital. The interaction forces between each molecules when molecules accumulated are either repellent or attractive, and the sum of forces will affect the overall propensity of membrane fouling.

A model can be used to demonstrate the forces. Velocities are induced form the forces, so they were used in this work to explain the relations. Different forces given by earth or molecules will all affect the filtration efficiency. In the model, the velocities of different forces such as lateral lift force, shear-induced force and some intermolecular forces are displayed. Several formulas are used to calculate the velocities, so it is more obvious to justify the relations between filtration efficiency and forces.

2. Theory:

Constant or symbol definitions:

In the model, several symbols will be shown to represent different data used in the model. \( J_v \) represents filtration water flux \([3]\), which is the amount of liquid that passes the membrane. \( J_w \) represents water flux either. \( D_{tube} \) presents the tube height, which is the height between membranes. \( U_0 \) stands for cross flow rate, which is the flux caused by pressure and forces. \( z_p \) is the zeta potential. \( d_{EL} \) is the thickness of electrical double layer, which is related to ionic strength (IS). \( A_h \) is the hamaker constant, which correlates the Van Der Waal forces. \( \rho \) means the water density, which is as usual 1000kg/m\(^3\). \( U \) is the viscosity of the membrane structure. Additionally, dielectric constant of water and \( h \) (separation distance) are also shown in the model. By using the formulas in the published paper(3), we can formulate the relationship between variables and velocities. For the lift velocity, it is a force exerted upward, and relate to water flux and water density. What’s more, the height of the channel (\( D_{tube} \)) and cross flow rate (\( U_0 \)) will also affect the lift velocity. Brownian velocity is correlated with temperature and radius, and the Net velocity is the sum of aforementioned three velocities. permeance drag velocity is related to water flux (\( J_v \)), radius and membrane resistance (\( R_m \)). DLVO velocity can also be calculated by the given formula(4) which is related to viscosity (\( U \)), dielectric constant of water, hamaker constant (\( A_h \)), zeta potential (\( z_p \)) and the thickness of electrical double layer (\( d_{EL} \)). Owing to the aforementioned relations, different velocities can be calculated with these following formulas.

In the model, these forces will be analyzed: lift force, shear force, Brownian force, Perm-Gorren force and DLVO.

Lift force (define) is related to \( U_0 \) (cross flow rate), water density, particle radius, viscosity, and \( D_{tube} \) as shown in eqn. 1

\[
\text{Lift velocity} = \frac{2.64 \cdot \sum_j (2R)^2 \cdot \rho \cdot U_0}{16 \cdot \mu \cdot \sum_j (D_{tube})^2}
\]

Shear velocity:

\[
\text{Shear velocity} = \frac{\sum_j (2R)^2}{20 \cdot (D_{tube})^2}
\]
Brownian velocity: \[ \frac{298.15 + 1.3807E^2}{3 + \pi + 0.001 + (2R)^2} \]  
(3)

Net Hyd velocity: Lift + Shear + Brownian

Perm-Gorren corrected velocity: \[ \sqrt{\frac{J_v^2 R_m^2 R^2}{3} + 1.072^2} \]  
(4)

DLVO velocity: \[ \frac{1}{u} \left( \frac{2\varepsilon_0 \zeta^2}{4 \pi \lambda_d} - \frac{\Delta H}{36 \pi \lambda_d^2} \right) \]  
(4)

\( \zeta \) represents the zeta potential, \( \varepsilon_0 \) is the hamaker coefficient, \( \lambda_d \) is the electrical double layer thickness

Total velocity: Perm-Gorren – Net Hyd

3. Results and Discussion:

The data in the model will be tested and demonstrated in graphs, to indicate the efficiency between explanatory variables such as water flux, dtube, and cross flow rate and the filtration efficiency.

Water flux has great effect on velocities. When the water flux increases, more particles are carried, so the drag force exerted on the membrane will increase, and the filtration efficiency will increase at the same time. The phenomenon is caused owing to the drag force. If the drag force increases, the quantity of particles removed will increased accordingly. What’s more, stronger strike on the membrane can rush some of the accumulations, which is the same as fouling things, so the pores on the membrane can work effectively. As the water flux increases, the velocity of Permeance drag force increases. At first, when \( J_v \) is 1e-06, Permeance drag force has the tendency to increase as the particle radius increases. If the value is maximized by 5 times, the increasing tendency will increase for a little owing to the relations between water flux and Permeance drag force. The velocity of the Net Hyd and DLVO has a constant variation no matter how the water flux changes since the formula used to calculate them has no relationships with water flux. The velocity of Perm-Gorren is affected by \( J_v \), which turns to an increasing tendency. Since the water passes vertically and horizontally through the membrane, it will have the drag force to the membrane. If \( J_v \) is increased to 50 times of 1e-06, the line that represents Permeance drag force lifts due to the aforementioned relations between water flux and Permeance drag force. Obviously, larger water flux can carry out more particles at once, so these particles will provide larger forces to the membrane. As the velocity increases, the efficiency of filtration is ameliorated either. As a result, though water flux filtration does not have relations to Net Hyd and DLVO velocity, it has relations to Permeance drag forces, which is the drag force exerted on the membrane. So, this graph correctly related to the variation of Permeance drag force with the change as the water flux changes, which provides the accuracy of the model.
When the height of the flow cell channel changes, the velocities of lift force and shear force alters either. If the gap between membranes is larger than before, the liquid can have a larger space to move freely. As a consequence, the lift and shear force will decrease as the gap increases owing to the aforementioned formula. At first, when dtube is designated as 0.00001m, which is a quite small number, the velocity of the lift and shear forces should be in a drastic increasing tendency. If the dtube increases gradually, the slopes of the lines that represents the lift and shear forces should decrease gradually at the same time. If the dtube changes from 0.00001m to 0.0001m, which is ten times larger, there will be an obvious drop of the position of two lines. Due to the effect of the decrease of lift and shear forces, the Net Hyd will become difficult to increase if the particle is not large enough. It is easy to infer that Brownian force has no relationships with the height of the structure since Brownian force can be ignored when the particle diameter was above 0.3 µm. Brownian force is related to particles moving, so it is actually negligible with space that left for particle movement. However, if the space is expanded in the membrane system, the increasing filtration flux will cause a weakness of the lift and shear force provided by membranes, and that causes the slow increase of the Net Hyd. As we can see in figure 2, the lines that represent lift force, shear force, Brownian force and the Net Hyd reasonably correlated with the aforementioned hypothesis.

To some extent, the distance between membrane and channel ceiling will affect the Net Hyd Force by changing the lift and shear force, which may weaken the efficiency.
Figure 2: (Jv=1e-05; U0=2.67e-02; Rm=7.69e+11; zp =-0.015; IEL =1.75e-09; IS=30; Ah=7.53e-21; Rou=1000; u=1e-03; dielectric water constant=6.93e-10; h=4.5e-09)(a) dtube=0.00001m (b) dtube=0.000025m (c) dtube=0.000075m (d) dtube=0.0001m

As U0(cross flow rate) changes, the velocity of total Net Hyd changes accordingly, owing to the relations between DLVO and U0. As U0 increases, the velocities of lift and shear force will increase at the same time. Cross flow rate can cause horizontal forces to the membrane. And due to the effect of gravity, the vertical direction will be affected either. As a result, if the cross flow rate is large enough, it is difficult for the accumulation of fouling.[4] Since there are less accumulations, the efficiency of filtration is ameliorated. Due to figure 3, it is obvious that the orange and blue lines that represent shear and lift forces are related with the variation of U0.

Figure 3: relations between the velocity of U0(cross flow rate) and different velocities of forces. (Jv=1e-05; dtube=5e-04; Rm=7.69e+11; zp =-0.015; IEL =1.75e-09; IS=30; Ah=7.53e-21; Rou=1000; u=1e-03; dielectric water constant=6.93e-10; h=4.5e-09)
(a) U0=0.01m/s (b) U0=0.025m/s (c) U0=0.075m/s (d) U0=0.1m/s
4. Conclusion
Forces such as lift, shear, Brownian, Permeance drag force and DLVO induced by membrane structure forces and intermolecular forces. The model is constructed to investigate the filtration efficiency and forces exerted on membrane, which is obvious that if the water flux increases, the related velocities of lift and shear forces increases either, so the particles will have a faster filtration speed in the same condition. If the height of the tube is altered, owing to particles will move freely, it will cause the decline of the filtration efficiency. When the cross flow rate is increased, the particle movement will be affected by the increased lift and shear forces. To some extent, increased rate will ameliorate the filtration efficiency either. By analyzing the velocities of the forces inside the model, the possibilities of alleviating membrane fouling accumulations are approached. Humans have probabilities to deal with the efficiency of the filtration system, so more water can be filtrated at once, and that will ensure the daily water usage in humans’ daily lives.

References
[1] Bowen WR, Mongrue A, Williams PM. Prediction of the rate of cross-flow membrane ultrafiltration: a colloidal interaction approach. Chemical Engineering Science. 1996;51(18):4321-33.
[2] Reimann W, Yeo I. Ultrafiltration of agricultural waste waters with organic and inorganic membranes. Desalination. 1997;109(3):263-7.
[3] Hwang S-J, Chang D-J, Chen C-H. Steady State permeat flux for particle cross-flow filtration. The Chemical Engineering Journal and the Biochemical Engineering Journal. 1996;61(3):171-8.
[4] Cohen R, Probstein R. Colloidal fouling of reverse osmosis membranes. Journal of Colloid and Interface Science. 1986;114(1):194-207.