CFD analysis of particle deposition in the spacer-filled membrane module

Yu-Ling Li, Ting-Hsiang Chang, Chung-Yeh Wu, Ching-Jung Chuang and Kuo-Lun Tung

ABSTRACT

Particle deposition in spacer-filled membrane modules is investigated using a computational fluid dynamic (CFD) technique. The flow field and particle transport in the channels with permeable membrane surfaces are calculated using the commercial available CFD software FLUENT®. A scheme similar to the Eulerian–Lagrangian numerical method is adopted for the two-phase flow simulation. Particle transport in three spacer-filled channel configurations is analyzed by considering fluid drag, body force, and lift force exerted on the particles. Feed velocity, permeation flux, and spacer arrangement effects on particle deposition are discussed comprehensively. Based on conclusive preliminary study results, multi-phase flow simulation can provide microscopic understanding of the fouling mechanism in the spacer-filled channel and prove to be a powerful tool to aid in membrane module design.

Key words | computational fluid dynamics, membranes, particle deposition, spacer, spiral-wound membrane module

INTRODUCTION

New technological developments for overcoming water scarcity and quality constraints have appeared since the 1960s to help fulfill future demands. In the field of drinking water treatment, new filtration and disinfection regulations have generated considerable interest in using membrane processes for particle and organic materials removal (Mallevaille et al. 1996; Huang et al. 2000). Among a variety of commercially available membrane modules, the hollow fiber and spiral wound modules are most common due to their higher packing density (Crowder & Gooding 1997; Schwinge et al. 2002b). The hollow fiber module is widely used in wastewater treatment, while the spiral wound module is prevalent in water supply ranging from RO to UF. However, all membrane filtration processes face the inevitable flux decline problem due to concentration polarization and membrane fouling caused by particles and/or organic materials. How to prevent membrane fouling and hence improve module performance is always a main concern for module design. In the case of the spiral wound module, the spacers are mostly used to promote turbulence to prevent particle deposition or organic materials precipitation and are also used to separate the feed/permeate channels.

Numerous attempts made by previous researchers investigated mass transfer (Ohya & Tanaguchi 1975; Tweddle et al. 1980; Schwinge et al. 2002b), hydrodynamics (Belfort 1988; Farkova 1991; Da Costa et al. 1994a,b; Gauwbergen & Baeyens 2000), or particle deposition (Schwinge et al. 2002b; Neal et al. 2003; Moon et al. 2005) in the spacer-filled channel or to improve the spacer design (Sirkar et al. 1982; Li et al. 2002; Schwinge et al. 2004b) through various techniques. The techniques can be classified into experimental and theoretical approaches. The limiting current method was adopted in experimental approaches to measure flow pattern, shear stress, and mass transfer (Li et al. 2004). Several non-intrusive methods were devised for cake layer thickness detection (Pope et al. 1996; Tung et al. 2001; Chen et al. 2004) and membrane
direct observation was used to observe particle deposition (Neal et al. 2003). Analytic solutions have been derived from theoretical approaches for simplified geometry to predict pressure drop and mass transfer coefficient (Sirkar et al. 1982), while the computational fluid dynamic (CFD) technique was widely utilized recently for more complicated systems (Schwinge et al. 2002a–c). In the CFD approach, a unit cell in the full-scale 3D module system has been chosen to predict the flow pattern, pressure drop, and mass transfer in the spacer-filled channel in order to reduce computational time. The cell boundary then was set to be a periodic boundary condition. However, no efforts have been made to investigate particle deposition onto the membrane by the CFD simulation technique. Many papers have discussed channel flow field without considering permeate flux through the membrane, but the particles trajectory could be affected by suction force caused by permeate flux. Analyzing particle trajectory and deposition position according to various membrane resistances by CFD simulation in the spacer-filled membrane module in order to reveal how the membrane is fouled by particles is the purpose of this study.

THEORETICAL MODELS

Spiral wound modules are constructed of two flat membranes placing together with their active sides facing away from each other as shown in Figure 1. They are separated by a sheet of permeate collection material. Another feed channel spacer is placed on either side of the envelope. Then, this whole assembly is rolled around a perforated center tube in a spiral or “jelly-roll” assembly. The feed solution is then pumped from one side along the tube while the permeate and the concentrate leave from the other side. The commercial mesh-type spacers in Figure 2 consist of two layers of filaments forming a diamond-type or ladder-type spacer.

Figure 1 | Schematic representation of the spiral wound membrane module.

Figure 2 | Schematic diagrams of the (a) diamond and (b) ladder configurations of mesh type spacers.
Three different spacer configurations – zigzag, cavity, and submerged types, defined by Schwinge et al. (2002a) – were adopted in this study. Figure 3 illustrates the simulation system, schematic diagrams of the different spacer configurations and empty channel with permeable membrane surfaces. In these two-dimensional \((x-y)\) arrangements of filaments in spacer-filled membrane modules, the lateral movement of depositing particle and wall effects in the \(z\) direction can be neglected. The entrance distance of the channel was at least 10 times the cylindrical filament diameter to form the fully developed flow, while the exit distance was at least twice the entrance distance to avoid any effects of the channel exit on eddy formation behind the cylindrical filaments (Schwinge et al. 2002a).

The geometry of the empty channel and different spacer-filled channels is shown in Table 1. The height of the channel \(h_{\text{ch}}\) is 1 mm \((y = 0 \text{ to } y = 1 \times 10^{-3} \text{ m})\) and the length is 40 mm \((x = 0 \text{ to } x = 4 \times 10^{-2} \text{ m})\). The length \(L_m\) and thickness \(h_m\) of the membrane are 24 mm and 0.01 mm. The diameter \(d_f\) and spacing \(l_f\) of the filaments in the spacer-filled channels are 0.5 mm and 4.0 mm. The channel Reynolds number of the spacer-filled system was set in the range of 100–300. Schwinge et al. (2002a) pointed out that each filament attached to the membrane wall was separated into three areas with 90% angular resolution covering 45° to 315° in order to generate superior grids, and the grid created around a cylindrical filament adjacent to a membrane surface and submerged in the center of the membrane channel is shown in Figure 4.

### Governing equations for fluid flow

In the continuous phase simulation, the flow field was calculated based on fluid phase continuity and momentum equations by a finite volume method on an Eulerian grid. The flow of field in the domain of this work is assumed laminar, steady state, and isothermal at low Reynolds number (Schwinge et al. 2002a; Geraldes et al. 2002). There is fairly low volume fraction of particles in the feed solution, so the flow field can be obtained by the equation of continuity and the Navier–Stokes Equations (1) and (2):

\[
\nabla \mathbf{u} = 0
\]

### Table 1 Geometric parameters of the channels with various spacer arrangements

<table>
<thead>
<tr>
<th></th>
<th>Empty channel</th>
<th>Submerged type</th>
<th>Cavity type</th>
<th>Zigzag type</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_m^a) (mm)</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>(d_f^b) (mm)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>(l_f^c) (mm)</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>(h_m^d) (mm)</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>(h_{\text{ch}}^e) (mm)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

*a* Membrane length.

*b* Filament diameter.

*c* Distance between filaments.

*d* Membrane thickness.

*e* Channel height.
Force analysis on particles transport and deposition

The channel flow field and particle transport with permeable membrane surfaces were calculated using the discrete phase model of FLUENT. The scheme similar to the Eulerian–Lagrangian numerical method (Hu et al. 1992; Lu et al. 1997; Hwang et al. 2005; Tung et al. 2006; Rief et al. 2006) was adopted for the two-phase flow simulation. In dispersive phase simulation, particle motion is governed by Newton’s second law, thus following the Lagrangian approach. For low volume fraction of particles, dispersive phase existence in the continuous phase will not noticeably affect fluid physical properties. This model limits the volume fraction of particles to be less than 10%. Thus, momentum exchange from the particle to fluid is neglected in this preliminary study. A particle size of 1 μm was selected for this work. Here particle transport by Brownian motion is small and neglected compared to other particle transport mechanisms. It is also assumed that the particles have no or little surface charge so electrical double layer effects are ignored. Therefore, suspended particle motion was tracked by considering forces which include net gravitational force, hydraulic drag force, and lift force:

\[
\frac{D\mathbf{u}}{Dt} = -\nabla P + \mu \nabla^2 \mathbf{u} + \rho g
\]  

(2)

\[
F_G = g \frac{(\rho_p - \rho_p)}{\rho_p}
\]  

(4)

where \( F_G \), \( F_D \), and \( F_L \) are net gravity force, particle drag force and Saffman lift force, respectively. These forces are based on per unit particle mass. The net gravitational force exerted on a deposited particle can be evaluated by

\[
F_G = g \frac{(\rho_p - \rho)}{\rho_p}
\]  

(4)

where \( \rho_p \) (1210 kg/m³) and \( \rho \) (998 kg/m³) are the densities of the particle and the water, respectively. The drag force can be derived as

\[
F_D = \frac{3 \mu C_D R e_p}{4 \rho_p d_p^2} (u - u_p)
\]  

(5)

in which \( d_p \) is the particle diameter, \( u \) is the water velocity and \( u_p \) is the particle velocity. In addition, \( R e_p \) is the Reynolds number based on the particle described as

\[
R e_p = \frac{\rho_p d_p (u - u_p)}{\mu}
\]  

(6)

where \( \mu \) is the viscosity of water. \( C_D \) is the drag coefficient evaluated by

\[
C_D = a_1 + \frac{a_2}{R e_p} + \frac{a_3}{R e_p^2}
\]  

(7)

where \( a_1, a_2 \) and \( a_3 \) are constants that apply to smooth spherical particles over several ranges of \( R e_p \) (Morsi & Alexander 1976). The Saffman lift force can be derived as

\[
F_L = \frac{3.1 \rho d_p^{0.5} (du/dy)^{0.5}}{d_p \rho_p} (u - u_p)
\]  

(8)

where \( \nu \) is the kinematics viscosity. The major simulation processes are:

1. To solve the continuous phase flow field.
2. To set particle physical models, including particle basic physical properties and a suitable force model.
3. To calculate particle trajectories for dispersive phase injections with the continuous phase.
4. To analyze particle trajectories and position of particles trapped by the membrane.

The particles were uniformly released at the feed channel inlet between \( y = 0 \) to \( y = 1 \times 10^{-3} \) m. It should be noted that particle position obtained by the CFD
simulation was taken as the particle center and real particle size was neglected in the CFD code (Lehmann 2006). In order to overcome this limitation, the user defined subroutine function (UDF) provided by FLUENT® was adopted to take the particle radius into consideration during particle attachment detection onto membrane or filament surfaces.

RESULT AND DISCUSSION

The effects of feed velocity, permeation flux, and spacer arrangement on particle deposition are discussed in the following sections.

Trajectory of particle in the feed channels

Particles are released uniformly at the inlet of the channel. Trajectory comparison of two positions at $y/h_{ch} = 0.10$ and $y/h_{ch} = 0.90$ in various spacer configurations are shown in Figure 5. The abscissa and coordinate in Figure 5 are the normalized membrane length along the feed transport direction ($x$ direction) and the normalized channel height, respectively. Simulation operation conditions were set as: feed velocity $u_f = 0.1 \text{ m/s}$, resistance of clean membrane $R_m = 1.0 \times 10^{12} \text{1/m}$ and permeation rate $q = 4.7 \times 10^{-4} \text{ m/s}$.

Particle movement is mainly governed by normal drag force toward the top and bottom membrane surfaces. At the beginning, the particle moves along the field line until impacting spacer or membrane surface. The loci of the particles toward the top and bottom membrane surfaces are symmetric in the empty channel. This means that gravity plays a minor role for micron-sized particle motion toward a permeable surface. Examining the order of magnitude of forces exerted on the suspended particle showed that the normal drag force resulting from permeation flux of $q = 4.7 \times 10^{-4} \text{ m/s}$ for a micron-sized particle is two orders of magnitude larger than the gravity force.

In the case of particle transport in the submerged configuration channel, fluid flow space is reduced to one-fourth of flow channel height under each filament. The particles are forced toward the membrane surface due to increased $y$-component fluid velocity under each filament ($x/L_m = 0.083$, 0.25 and 0.417). On the other hand, particle trajectories clearly showed transient behavior along the spacer-filled channel when passing multiple filaments. The computational domain must notably contain multiple filaments, and these cannot be approximated by using periodic boundary conditions (PBCs). In view of particle trajectories in the submerged configuration spacer-filled channel, the particle rebounded back to the bulk flow along the fluid stream after the first ($x/L_m = 0.083$), second ($x/L_m = 0.25$) filaments and third ($x/L_m = 0.417$). Then the particle was trapped at $x/L_m = 0.48$ in front of the fourth filament ($x/L_m = 0.583$). Comparison of particle deposition position along the feed channel (in the $x$ direction) between two cases of empty channel and submerged spacer-filled channel showed that the submerged channel results in an earlier particle deposition than the empty channel. Furthermore, the loci of particles in the submerged configuration channel are always closer to the membrane surface when compared to those in the empty channel. This is mainly due to the increase of the $y$ component fluid velocity in front of and under each filament. The velocity component forces the particle toward the permeable membrane surface, and thus results in an earlier deposition in the case of submerged configuration. If the velocity component in a downward direction is larger than that in a transverse direction, and the
spacing between particle and permeable membrane surface is far enough for particles to escape, the particle will rebound back to the flow stream after passing through the narrows in both filament sides. On the contrary, if the spacing between particle and permeable membrane surface is not far enough for particles to escape, the particles will impact or be intercepted by the permeable membrane surface.

When particles transport in the cavity configuration spacer-filled channel with all filaments placed adjacent to the bottom wall, the particle close to the top wall will be trapped earlier than that close to the bottom wall as indicated by the solid curves in Figure 5. This is mainly due to increased $y$-component fluid velocity between the filament and top wall caused by the filaments placed adjacent on the opposite bottom wall. In view of the particle locus indicated by the lower solid curve in Figure 5, the particle was trapped behind the fourth filament, and a locus undertow observed before the particle was trapped by the bottom permeable wall. This indicates that the particle will lapse into the recirculation region between sequential filaments before attaching onto the permeable wall.

For the last case of particle transport in the zigzag spacer-filled channel, since the geometrical arrangement of the first filament in the zigzag configuration is the same as that in the cavity configuration, the particle locus close to the bottom wall around the first filament is similar to that in the cavity configuration with filaments placed adjacent to the bottom wall. After the particle passed through the upstream filament, it is forced to change direction because of the sequential downstream filament at the opposite wall. The particle close to the bottom wall will attach onto the permeable bottom wall earlier than that in the cavity configuration. Comparison of the particle loci close to the top and bottom permeable walls in the zigzag configuration channel depicts that the particle locus close to the upstream filament kept a longer route behind the filament than that close to the sequential filament.
This is mainly caused by the fact that feed velocity decreases along the spacer-filled channel due to fluid suction through the permeable walls; the particle will bear a larger than normal transverse drag force ratio behind the sequential filament than that behind the upstream filament.

Effect of feed velocity and permeation flux on particle deposition

For a fluid flow in a parallel plate channel with permeable walls, the feed velocity will decrease along the channel due to fluid suction toward the permeable walls. The fluid flow pattern in the empty channel with permeable membrane surfaces is illustrated in the center of Figure 6. The fluid velocity contour depicts decreasing feed velocity along the channel with a reduction ratio of \( \frac{2q}{u_f} = \frac{(2 \times 4.7 \times 10^{-4})/0.1}{0.0094} \) in the \( x \) direction according to mass conservation law. In this simulation study, the channel along the \( x \) direction was divided into 24 zones (1C, 1D, 2A–2D, …, 6A–6D, 7A and 7B) for interpretation feasibility and particle deposition comparison among different spacer configurations. In the case of particle transport in an empty channel with permeable walls, particle deposition position will be affected by injection position (\( y \) coordinate), feed velocity \( u_f \) and permeation flux \( q \). If particle collision is not considered, particle deposition position along the feed channel is totally dependent on injection position (\( y \) coordinate) for a specified flow condition. For a specified flow condition, say \( u_f = 0.1 \text{ m/s} \) and \( q = 4.7 \times 10^{-4} \text{ m/s} \), nearly 80% of particles escaped out of the empty channel with two permeable membrane surfaces of \( L_m = 24 \text{ mm} \) in length. A large number of particles attached onto the membrane entrance region, and kept a deposition ratio of 0.3–0.4% of the totally released number after zone 5. To compare the particle transport in the spacer-filled channel, particle deposition ratio in the spacer-filled channel is smaller than that in the empty channel as depicted in Figures 7 and 8 and Table 2 since the spacer placed adjacent to the permeable walls serves as turbulence promoter, thus reducing the probability of particle attachment onto the membrane surface.

Figure 7  Deposition ratios at the different positions of the top and bottom membrane for the submerged channel \( (R_m = 1.0 \times 10^{12} \text{ m}, u_f = 0.1 \text{ m/s}, q = 4.7 \times 10^{-4} \text{ m/s}) \).

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Comparison of the deposited particle profile on the membrane surface between the feed velocity \( u_f = 0.1 \text{ m/s} \) (Figure 7) and \( u_f = 0.23 \text{ m/s} \) (Figure 8) showed that, as feed velocity increases, shear wall stress increases as well with the Reynolds number and thus resulted in a decreased number of deposited particles in each zone, from zone 1C to zone 7B. On the other hand, comparison of deposited particle profile on the membrane surface between the permeation rate of \( q = 4.7 \times 10^{-4} \text{ m/s} \) (Figure 8) and \( q = 9.4 \times 10^{-3} \text{ m/s} \) (Figure 9) depicted a decreasing permeation rate. This causes a decreased normal drag force exerted on the particles, resulting in a decreased number of deposited particles in each zone.

### Effect of spacer configurations on particle deposition

The effect of spacer configurations on particle deposition were interpreted and compared in Figures 7 through 13. In the case of particle transport in the submerged configuration channel as illustrated in Figures 7 and 8, there are local maxima of particle deposition quantities in front of each filament (in each zone D) after the first filament. Because particles were forced toward the membrane surface due to the increased \( y \)-component fluid velocity in front of each filament, resulting in a larger particle deposition amount. It is also significant that the deposition ratio decreases noticeably under the filament (1D to 2B, 2D to 3B and 3D to 4B)

### Table 2

<table>
<thead>
<tr>
<th></th>
<th>Empty channel</th>
<th>Submerged type</th>
<th>Cavity type</th>
<th>Zigzag type</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta_t ) (%)</td>
<td>14.3(^a)/9.2(^b)</td>
<td>14.6(^a)/9.0(^b)</td>
<td>14.0(^a)/9.1(^b)</td>
<td>12.5(^a)/6.6(^b)</td>
</tr>
<tr>
<td>( \eta_b ) (%)</td>
<td>14.3(^a)/9.2(^b)</td>
<td>14.6(^a)/9.0(^b)</td>
<td>11.0(^a)/4.7(^b)</td>
<td>13.2(^a)/6.6(^b)</td>
</tr>
<tr>
<td>( \Delta P_{ch} ) (N/m(^2))</td>
<td>51(^a)/122(^b)</td>
<td>195(^a)/652(^b)</td>
<td>95(^a)/272(^b)</td>
<td>95(^a)/278(^b)</td>
</tr>
</tbody>
</table>

\(^a\)based on \( u_f = 0.1 \text{ m/s} \); \(^b\)based on \( u_f = 0.23 \text{ m/s} \).

where \( N_t \) the sum of discharging positions for feed particles, \( N_c \) the sum of discharging positions deposited onto the top membrane, \( N_b \) the sum of discharging positions deposited onto the bottom membrane.
and increases slightly between the filaments (2B to 2D, 3B to 3D and 4B to 4D). Since there are recirculation regions formed in back of the filament, fluid will be forced toward the membrane surface so as to enhance the velocity near the membrane surface. The recirculation region is about each zone A and zone B, so the velocity near the membrane face will be decreased after each zone B.

The particle deposition profiles in the cavity configuration are shown in Figures 10 and 11. It is notable that almost no particle deposition in each zone A deposits on the bottom membrane surface wall. This is largely due to a recirculation region existing behind the transverse filament adjacent to the membrane which prevents particle deposition onto the bottom wall. Neal et al. (2003) have also observed this phenomenon by using direct observation through the membrane (DOTM) technique. In their experimental study, the 90° orientation net spacer gives a deposition field offset from the upstream transverse filament, extending from a clearly defined leading edge, and becoming more diffused across the cell until it reaches the next filament. Furthermore, increased feed velocity, i.e. the Reynolds number, will form a larger recirculation behind the filament, resulting in a much smaller particle deposition amount onto the wall. A comparison between Figures 10 and 11 demonstrated that the zone without particle deposition (clear zone) extends from zone A to zone C while feed velocity increases.

The last case of zigzag configuration advantageously includes both cavity and submerged configurations. The flow pattern in the zigzag configuration, spacer-filled channel looks somewhat like a cavity superposition and submerge configurations. As can be seen in Figures 12 and 13, a recirculation region can be found behind each filament. The recirculation causes a high shear stress and prevents particle deposition; thus, there are clear regions behind each filament on either side of the channel wall (at zones 2A, 4A and 6A on the bottom wall and at zones 3A, 5A and 7A on the top wall). Furthermore, increased feed velocity, i.e. the Reynolds number, will form a larger recirculation behind the filament, resulting in a much smaller particle deposition amount onto the wall. A comparison of Figures 12 and 13 demonstrated that the clear zone extends from zone A to zone D while feed velocity increases.
Figure 10 | Deposition ratios at the different positions of the top and bottom membrane in the cavity configuration spacer-filled channel ($R_m = 1.0 \times 10^{12} \text{ m}^{-1}$, $u_i = 0.1 \text{ m/s}$, $q = 4.7 \times 10^{-4} \text{ m/s}$).

Figure 11 | Deposition ratios at the different positions of the top and bottom membrane in the cavity configuration spacer-filled channel ($R_m = 1.0 \times 10^{12} \text{ m}^{-1}$, $u_i = 0.23 \text{ m/s}$, $q = 4.7 \times 10^{-4} \text{ m/s}$).
Figure 12 | Deposition ratios at the different positions of the top and bottom membrane in the zigzag configuration spacer-filled channel ($R_m = 1.0 \times 10^{12} \text{1/m}, u_f = 0.1 \text{m/s}, q = 4.7 \times 10^{-4} \text{m/s}$).

Figure 13 | Deposition ratios at the different positions of the top and bottom membrane in the zigzag configuration spacer-filled channel ($R_m = 1.0 \times 10^{12} \text{1/m}, u_f = 0.23 \text{m/s}, q = 4.7 \times 10^{-4} \text{m/s}$).
CONCLUSION

In this simulation, particle depositions in spacer-filled membrane modules are examined using a computational fluid dynamic (CFD) technique. The flow field and particle transport in the channels with permeable membrane surfaces are calculated using FLUENT®. A scheme similar to the Eulerian–Lagrangian numerical method is adopted for the two-phase flow simulation. Forces acting on the particles include fluid drag, body force, and lift force. Three configurations of the spacer-filled channel – submerged, cavity, and zigzag – proposed by Schwinge et al. (2002a) are adopted for analysis. The effects of feed velocity, permeation flux, and spacer arrangement on particle deposition are discussed. Simulated results show that recirculation behind the filament placed adjacent to the membrane surface causes a high shear stress and prevents particle deposition; thus there are clear regions behind each filament. Furthermore, increased feed velocity will form a larger recirculation behind the filament which results in a much smaller particle deposition amount onto the membrane. Comparison of particle deposition profile and deposition ratio among submerged, cavity, and zigzag configuration spacer-filled channels depicted that the capability for preventing particle fouling onto the membrane is in the order of zigzag type > submerged type > cavity type under the same feed velocity and permeation rate. Based on this preliminary study, it is concluded that multi-phase flow simulation can provide a microscopic understanding of the fouling mechanism in the spacer-filled channel and prove to be a powerful tool to aid in membrane module design.

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