



Fluid Dynamics and Transport Phenomena

Numerical Studies of Convective Mass Transfer Enhancement in a Membrane Channel by Rectangular Winglets[☆]

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ARTICLE INFO

Article history:

Received 5 January 2014

Received in revised form 12 June 2014

Accepted 22 August 2014

Available online 6 September 2014

Keywords:

Membrane

Concentration polarization

Mass transfer enhancement

Rectangular winglet

Pumping power

ABSTRACT

Numerical calculations were conducted to simulate the flow and mass transfer in narrow membrane channels with and without flow disturbers. The channel consists of an impermeable solid wall and a membrane surface with a spacing of 2.0 mm. The flow disturbers studied include rectangular winglets, which are often used as longitudinal vortex generators to enhance heat transfer in heat exchanger applications, as well as square prism, triangular prism, and circular cylinder, which are used here to mimic the traditional spacer filaments for comparison of their abilities in enhancing the convective mass transfer near the membrane surface to alleviate the concentration polarization. The disturber performance was evaluated in terms of concentration polarization factor *versus* consumed pumping power, with a larger factor meaning a more serious concentration polarization. Calculations were carried out for NaCl solution flow with Reynolds numbers ranging from 400 to 1000. The results show that the traditional flow disturbers can considerably reduce the concentration polarization but cause a substantial pressure drop, while the rectangular winglets can effectively reduce the concentration polarization with a much less pressure drop penalty. The rectangular winglets were optimized in geometry under equal pumping power condition.

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1. Introduction

Ultrafiltration, nanofiltration and reverse osmosis are typical membrane processes [1,2]. One of the obstacles to more widespread application of these membrane separation processes is the problem of concentration polarization, due to the accumulation of rejected particles/molecules near the membrane surface. Since concentration polarization debases permeate quality and reduces permeate flux, its suppression is of great importance.

In spiral-wound and plate-frame membrane modules, wire meshes are often used to separate adjacent membrane sheets to create flow passage for feed solution, so they are often called spacers, which also act as flow disturbers or turbulence promoters to enhance mass transfer and consequently weaken concentration polarization. In the past decades, many studies have been done to investigate the impacts of various net-type spacers on the flow and convective mass transfer in membrane channels [3–14]. The cross-sectional shapes of the investigated spacer filaments included circle [3–13], square [10,11,13,14], triangle [10,11], as well as some other modifications [12,13]. All results show that spacers augment mass transport but they increase

simultaneously flow resistance. Since net-type spacers generally cause a significantly higher pressure drop increase than the mass transfer enhancement, they are not effective turbulence promoters in terms of mass transfer enhancement relative to pressure drop penalty.

There is an analogous relation between the heat transfer and the mass transfer. Various enhanced surfaces have been developed for the purpose of heat transfer enhancement in heat exchanger applications. Min and Xu compared the performance of the fin with winglet-type longitudinal vortex generators (WLVGs) with that of louver fin, and found that the former had a higher *j*-to-*f* factor ratio than the latter [15]. There are many studies that support the effectiveness and superiority of WLVG in enhancing heat transfer [16–19]. The most attractive character of WLVG is that they can increase the heat transfer coefficient with a relatively low pressure drop penalty, as stated by Webb and Kim [20]. It is thus interesting to know how WLVGs enhance mass transfer if they are used in a membrane channel for mass transfer. We note that net-type spacers are not always necessary to form membrane channels. Geraldine *et al.* [21] and de Pinho *et al.* [22] performed experimental studies of flow transfer and mass transfer in an empty membrane channel in nanofiltration. The channel comprised an impermeable solid wall and a membrane sheet supported by a porous stainless steel plate, so the channel height was maintained without the use of wire meshes. Koutsou *et al.* [23] investigated numerically the flow in a flat channel containing a periodic array of cylindrical turbulence promoters suspended between the two channel walls, the cylinders therefore

[☆] Supported by Tsinghua University Initiative Scientific Research Program (20131089319).

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served only as turbulence promoters rather than spacers. Flow in an empty membrane channel was also studied by Wiley and Fletcher [24].

The present research attempts to introduce the longitudinal vortex enhancement technique into the membrane mass transfer and evaluate the mass transfer enhancement effect of WLVG. It should be noted that the effectiveness of WLVG in augmenting convective mass transfer in a membrane channel is not self-evident, because there are some key differences between the use of WLVGs in heat transfer and that in mass transfer: (1) WLVGs are installed in different geometric configurations, (2) the convective mass transfer boundary layer is substantially thinner than the convective heat transfer boundary layer, and (3) a permeate flux across the membrane exists in contrast to impermeable heat transfer wall. The present work aims to reveal the mass transfer enhancement effects of winglet-type longitudinal vortex generators in membrane processes. Rectangular winglets are used to enhance convective mass transfer to reduce the concentration polarization in a narrow membrane channel. Quadrangular prism, triangular prism, and circular cylinder, which are used to simulate the traditional spacer filaments, are also studied for comparison purpose. Numerical calculations are conducted to simulate the flow and convective mass transfer in membrane channels with and without the abovementioned flow disturbers for channel height based Reynolds numbers ranging from 400 to 1000. The mass transfer enhancement effects are compared in terms of concentration polarization factor *versus* consumed pumping power. The rectangular winglets are further optimized in geometry under equal pumping power condition.

2. Computational Details

2.1. Physical model

The physical model of the feed channel of a typical plate module is a narrow rectangular channel with an impermeable wall and a membrane, with feed solution flowing and separating into two parts – permeate and retentate, as illustrated by Fig. 1. Fig. 2 is a schematic diagram of the basic membrane channel selected for this study, which consists of an impermeable solid wall and a membrane. The channel height is H and the channel length is $L = 35H$. Four kinds of flow disturbers, which include the quadrangular prism, triangular prism, circular cylinder, and rectangular winglets, are mounted on the solid bottom wall and located $5H$ downstream from the channel inlet. The first three strip shape disturbers [(a), (b) and (c) in Fig. 2] have a length equal to the channel width, and they are installed in perpendicular to the entering solution flow, while the rectangular winglets [Fig. 2(d)] are set up with an angle attacking to the entering solution flow, they are arranged in pairs to form V or Λ geometry, as illustrated in Fig. 3. For convenience, the former is called the convex winglet pair and the latter the concave winglet pair. The typical geometry and arrangement of the rectangular winglets are set as follows: the winglet height $h = H/2$, the aspect ratio $\sigma = l/h = 2.0$, the attack angle $\beta = 30^\circ$, and the distance between two adjacent winglets $W = 1.5H$, as summarized in Table 1. The winglet thickness is zero. Fig. 2 shows that the computational domain is taken to include the channel height in the normal

direction (perpendicular to the solid wall and the membrane surface), the entire channel length in the longitudinal (streamwise) direction, and a channel width that just involves one winglet in the transversal (spanwise) direction. The domain width is equal to the winglet interval, W . The coordinate system adopted in this study has an origin locating at the channel inlet on the membrane surface, with the x axis pointing to the streamwise direction, the y axis opposite to the channel height direction, and the z axis to the spanwise direction.

2.2. Numerical simulation

Solution flow in membrane channel is assumed to be steady and incompressible with constant properties. Although the solution feed Reynolds number is low, the flow may show a feature of turbulence because of the existence of flow disturbers in the channel. The re-normalization group (RNG) k - ε turbulent flow model was developed using the RNG method by Yakhot *et al.* [25] to renormalize the Navier–Stokes equations to account for the effects of smaller scales of motion. Such a model is considered to be suitable for modeling flow in channel with disturbers due to its capacity and accuracy for solving eddy activities at relatively low Reynolds number. The basic idea of the RNG method as applied to turbulence modeling is the elimination of small-scale eddies from governing equations by expressing their effects in terms of larger scale motions and a modified viscosity [4]. Summarized below are some key equations governing the solution flow and solute transport in the membrane channel with use of the RNG model.

Continuity equation:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0. \quad (1)$$

Momentum equation:

$$\frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \frac{\partial u_i}{\partial x_j} + \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right]. \quad (2)$$

Convective diffusion equation:

$$\frac{\partial(\rho u_i w)}{\partial x_i} = (\rho D + \frac{\eta_t}{Sc}) \frac{\partial^2 w}{\partial x_i^2}. \quad (3)$$

Transport equation for turbulent kinetic energy per unit fluid mass, k :

$$\frac{\partial}{\partial x_i} (\rho u_i k) = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_k - \rho \varepsilon. \quad (4)$$

Transport equation for the viscous dissipation rate of k , ε :

$$\frac{\partial}{\partial x_i} (\rho u_i \varepsilon) = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} G_k - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \quad (5)$$

Table 1
Typical rectangular winglet parameters

h	β	σ	W
$0.5H$	30°	2	$1.5H$

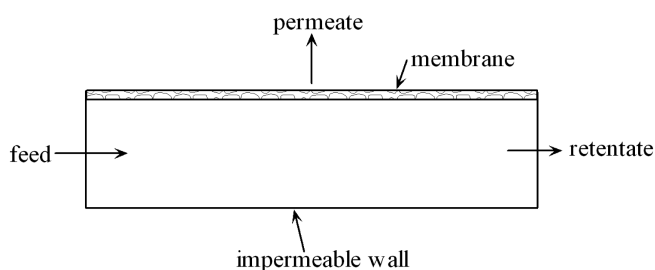


Fig. 1. Solution splitting in a typical plate membrane module.

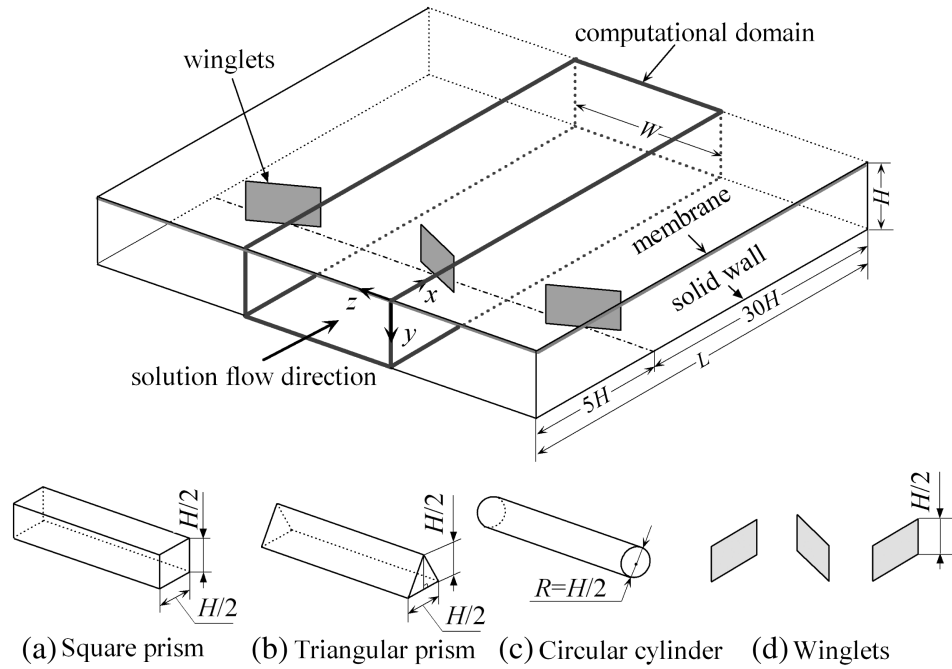


Fig. 2. Membrane channel with various flow disturbers.

where

$$\mu_t = \frac{\rho C_\mu k^2}{\varepsilon}, \varepsilon = c_D \frac{k^{3/2}}{l}, G_k = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_j}{\partial x_i}$$

$$C_\mu = 0.0845, C_{1\varepsilon} = 1.42 - \frac{\eta(1-\eta/\eta_0)}{1+B\eta^3}, C_{2\varepsilon} = 1.68$$

$$\sigma_k = 0.7179, \sigma_\varepsilon = 0.7179, \eta = Sk/\varepsilon$$

$$S = (S_{ij}S_{ij})^{1/2}, \eta_0 = 4.38, B = 0.015$$

$$S_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

In these equations, w is the solute mass fraction, D the solute diffusivity, and Sc the Schmidt number.

As boundary conditions, the fluid inlet velocity is assumed to have a parabolic profile along the channel height direction to reduce the inlet velocity influence on mass transfer. Fluid flowing out of the channel is assumed to exist in a fully developed condition where all changes for

the flow parameters are equal to zero. Symmetry boundaries are used at both sides of the computational domain shown in Fig. 2, with no slip conditions being applied to both the solid wall and the membrane surface. The solute concentration distribution at the membrane surface is determined by the mass balance among the convection, reverse diffusion, and permeate flux.

For channel inlet at $x = 0$:

$$u_x = -\frac{8u_m}{H^2}(y-0.5H)^2 + 2u_m, u_y = 0, u_z = 0, w = w_0 \quad (6)$$

where u_m is the fluid mean velocity and w_0 is the inlet solute mass fraction.

For channel outlet at $x = 35H$, where the flow is considered to be fully developed:

$$\frac{\partial u_x}{\partial x} = 0, \frac{\partial u_y}{\partial x} = 0, \frac{\partial u_z}{\partial x} = 0, \frac{\partial w}{\partial x} = 0. \quad (7)$$

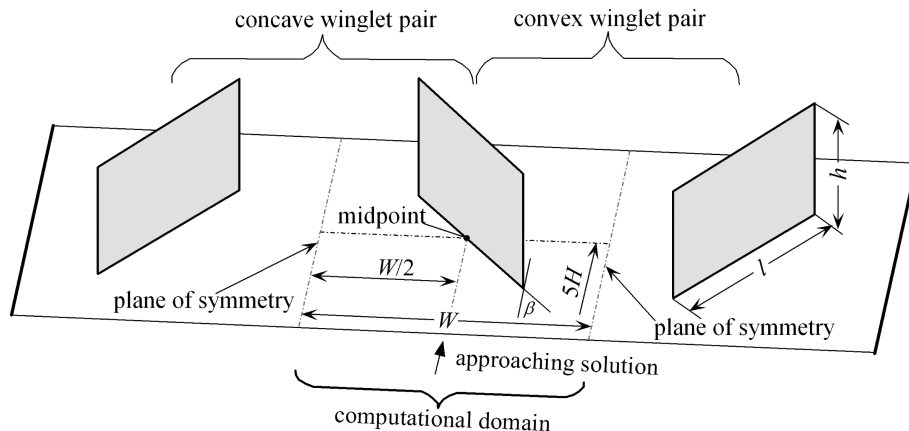


Fig. 3. Geometry and arrangement of rectangular winglets.

For wall surface at $y = H$:

$$\frac{\partial w}{\partial y} = 0, u_x = 0, u_y = 0, u_z = 0. \quad (8)$$

For membrane surface at $y = 0$:

$$Jw = -D \frac{\partial w}{\partial y} + Jw_p, u_x = 0, u_y = -J, u_z = 0 \quad (9)$$

where J is the permeate volumetric flux across membrane or the permeation velocity, and w_p is the solute mass fraction at the membrane surfaces on permeate side or the permeate composition. The equation is obtained from the solute mass balance at the feed solution/membrane interface, that is, the convective flux is the sum of the reverse diffusion flux and the permeate flux.

For each side of the computational domain at $z = 0$ or $z = W = 1.5H$:

$$u_z = 0, \frac{\partial \varphi}{\partial z} = 0 \quad (10)$$

where φ expresses various variables such as velocity, pressure and mass fraction.

The governing equations are solved under the boundary conditions using Fluent V6.3 based on the finite volume method. The mass balance at the solution/membrane interface is realized through the user defined function (UDF) in Fluent. For each simulation, the numerical grids are refined until a grid independent solution is obtained.

2.3. Data reduction

Based on the numerical simulation results, we can calculate the concentration polarization factor, which is defined by

$$\Gamma = \frac{w_w}{w_b} - 1 \quad (11)$$

where w_b is the solute mass fraction of the bulk fluid and w_w is the solute mass fraction at the feed solution/membrane interface. The bulk fluid refers to the solution outside the concentration boundary layer, so w_b is equal to w_0 . The magnitude of the concentration polarization factor reflects the degree of the concentration polarization, the larger the concentration polarization factor the more serious the concentration polarization problem. The concentration polarization factor averaged over a channel width of W along the spanwise direction at position of x can be represented by

$$\Gamma_x = \frac{1}{W} \int_0^W \Gamma dz \quad (12)$$

while the concentration polarization factor averaged over a membrane surface area from x_1 to x_2 can be expressed as

$$\Gamma_A = \frac{1}{(x_2 - x_1)} \int_{x_1}^{x_2} \Gamma_x dx. \quad (13)$$

Considering the position where the flow disturbers are located ($x = 5H$) and the feature of the evolution of concentration polarization along the channel length to be illustrated in the next section (Section 3), the starting and ending points of the above integral are taken to be $x_1 = 3H$ and $x_2 = 13H$ in the present research.

The fluid velocity at the channel cross-section perpendicular to the x axis can be represented by

$$U_x = \sqrt{u_y^2 + u_z^2} \quad (14)$$

which is the local velocity magnitude of the secondary flow.

The total pressure at a channel cross-section perpendicular to the streamwise direction can be calculated from

$$P = \frac{1}{HW} \int_0^W \int_0^H p dy dz. \quad (15)$$

The pressure drop between the two cross-sections at $x_1 = 3H$ and $x_2 = 13H$ is given by

$$\Delta P = P_1 - P_2 \quad (16)$$

while the consumed pumping power corresponding to this pressure drop can be obtained from

$$E = V \Delta P \quad (17)$$

where V is the volumetric flow rate of the feed solution corresponding to a channel width of W .

2.4. Model validation

Calculations were implemented to simulate the concentration polarization in a membrane channel in nanofiltration investigated by de Pinho *et al.* [22], who studied NaCl solution flow and mass transfer in an empty membrane channel having a height of 0.7 mm, a width of 30 mm, and a length of 200 mm. They performed both experimental and numerical studies and obtained the concentration polarization factor by combining the experimental data on the solute mass fraction of the bulk solution and permeate composition with the two-dimensional numerical results on the solute mass fraction at the feed solution/membrane interface. Fig. 4 illustrates the longitudinal concentration polarization profile for $w_0 = 2.0 \times 10^{-4} \text{ kg} \cdot \text{kg}^{-1}$ feed solute mass fraction, $J = 1.36 \times 10^{-5} \text{ m} \cdot \text{s}^{-1}$ permeate flux, and $w_p = 3.7 \times 10^{-5} \text{ kg} \cdot \text{kg}^{-1}$ permeate composition. The feed Reynolds number is $Re = 1300$, which corresponds to an entering velocity of $1.658 \text{ m} \cdot \text{s}^{-1}$, this value is substantially greater than the permeation velocity of $1.36 \times 10^{-5} \text{ m} \cdot \text{s}^{-1}$. Fig. 4 compares our calculation with that in de Pinho *et al.* [22]. Note that our results were obtained by using a grid system of 50×400 grid points for the computational domain. Two grid systems of 50×400 and 80×750 were tested to examine the grid-independence of the numerical result, and the relative error between the two meshes was 1.6% for the averaged concentration polarization factor. Fig. 4 shows that our result is in good agreement with the de Pinho data, supporting the reliability of our numerical procedure.

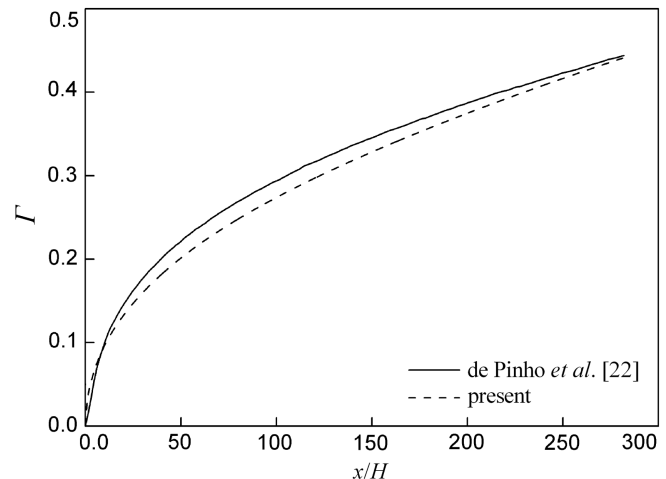


Fig. 4. Comparison of the present results and the literature simulation.

3. Results and Discussion

Consider NaCl solution flow in the present membrane channel that has a height of $H = 2.0$ mm and a length of $L = 35H = 70$ mm. Calculations were first conducted on an empty channel to show the effects of Reynolds number, which is defined by $Re = 2Hu_m\rho/\mu$. The simulations used $w_0 = 0.2 \times 10^{-3} \text{ kg} \cdot \text{kg}^{-1}$, $J = 1.36 \times 10^{-5} \text{ m} \cdot \text{s}^{-1}$ and $w_p = 3.7 \times 10^{-5} \text{ kg} \cdot \text{kg}^{-1}$, with the Reynolds numbers ranging from 400 to 1000, which correspond to the entering solution velocities of 0.1786–0.4464 $\text{m} \cdot \text{s}^{-1}$. The NaCl solution physical and transport properties are given in Table 2.

Fig. 5 depicts the evolution of the concentration polarization along the channel length for Reynolds numbers of $Re = 400, 600, 800$ and 1000, which correspond to the entering solution velocities of 0.1786, 0.2679, 0.3572 and 0.4464 $\text{m} \cdot \text{s}^{-1}$, respectively. The coordinate is the local concentration polarization factor (Γ_x) and the abscissa is the dimensionless longitudinal distance from the channel inlet (x/H). The figure shows that the concentration polarization factor increases with increasing dimensionless distance of x/H , with a larger Reynolds number yielding a smaller concentration polarization factor. This is because a larger Reynolds number means a larger velocity, which causes an enhanced mass transfer and consequently a reduced concentration polarization.

3.1. Performance comparison of rectangular winglets with traditional flow disturbers

Calculations were then conducted to investigate the effects of various flow disturbers, which include the traditional two-dimensional (2D) flow disturbers of square prism, triangular prism and circular cylinder, and the special three-dimensional (3D) flow disturber of rectangular winglets, whose geometry and arrangement are presented in Table 1. Same as above, the simulations used $w_0 = 0.2 \times 10^{-3} \text{ kg} \cdot \text{kg}^{-1}$, $J = 1.36 \times 10^{-5} \text{ m} \cdot \text{s}^{-1}$ and $w_p = 3.7 \times 10^{-5} \text{ kg} \cdot \text{kg}^{-1}$.

Fig. 6 illustrates the evolution of the concentration polarization along the channel length for channels with and without flow disturbers for $Re = 600$. The coordinate is the local concentration polarization factor (Γ_x) and the abscissa is the dimensionless longitudinal distance from the channel inlet (x/H). The data for the empty channel are also incorporated to serve as a baseline to better show the concentration polarization suppressing effects of various flow disturbers. Fig. 6 shows that the three traditional disturbers cause a substantially reduced concentration polarization factor over a region in which the disturbers are located, but their concentration polarization suppressing effect weakens with increasing dimensionless distance of x/H . Although the rectangular winglets cause only a moderately reduced concentration polarization factor over a region in which the winglets are placed, their concentration polarization suppressing effect tends to strengthen with increasing dimensionless distance of x/H . Concretely speaking, in the region of $3 < x/H < 8$, the traditional disturbers yield a lower concentration polarization factor than the rectangular winglets; in the region of $x/H > 10$, however, the rectangular winglets give a lower concentration polarization factor than the traditional disturbers. The three traditional disturbers are basically comparable in reducing concentration polarization.

The solute mass fraction distributions at the feed solution/membrane interface in channels with and without flow disturbers for $Re = 600$ are illustrated in Fig. 7. The channels with the traditional flow disturbers including the square prism, triangular prism and circular cylinder provide a simple mass fraction distribution because these

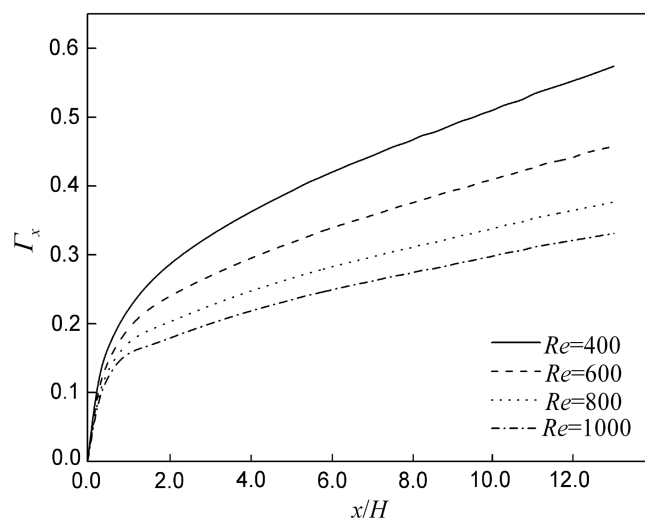


Fig. 5. Longitudinal concentration polarization profiles in an empty channel for various Reynolds numbers.

channels have a configuration that has a 2D feature, while the channel with the rectangular winglets produces a more complicated mass fraction distribution because this channel has a configuration that has a 3D feature. Different mass fraction distributions exist in the regions that contain the convex and concave winglet pairs, which are defined in Fig. 3. A large mass fraction is observed in the region that contains the convex winglet pair while a small mass fraction is seen in the region that contains the concave winglet pair. Note that large mass fraction means serious concentration polarization. The convex and concave winglet pairs work together to yield a longitudinal concentration polarization profile like that shown in Fig. 6.

Fig. 8 illustrates the fluid velocity contours at plane of $z = 0.75H$ for channels with and without flow disturbers for $Re = 600$. Since the traditional flow disturbers including the square prism, triangular prism and circular cylinder considerably block the flow passage, they produce a larger maximum velocity, which appears in a region close to the membrane surface and slightly downstream from the disturbers. A large velocity may cause a small mass fraction as observed in Fig. 7(b), (c) and (d) and further to a reduced concentration polarization as seen in Fig. 6. This trend is also illustrated in Fig. 5. Since the rectangular winglets have only a limited flow blocking effect, they cause only a moderate increase in fluid velocity and yield a maximum velocity significantly smaller than that by the traditional flow disturbers.

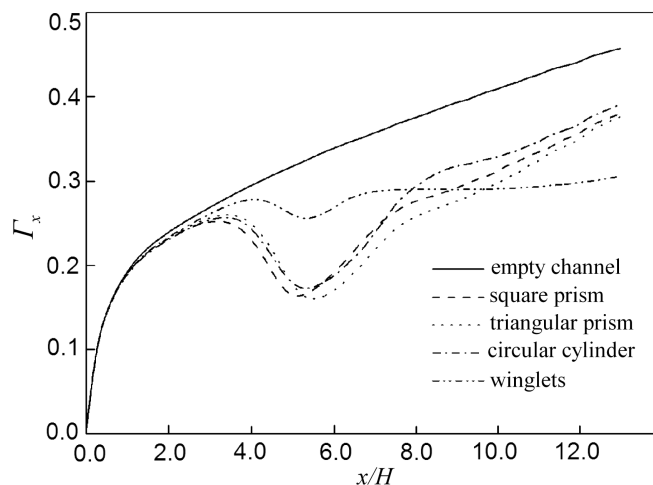


Fig. 6. Evolutions of concentration polarization along channel length for channels with and without flow disturbers ($Re = 600$).

Table 2
NaCl solution physical and transport properties

$P/\text{kg} \cdot \text{m}^{-3}$	$\mu/\text{Pa} \cdot \text{s}$	$D/\text{m}^2 \cdot \text{s}^{-1}$
997.2	0.8903	1.605×10^{-9}

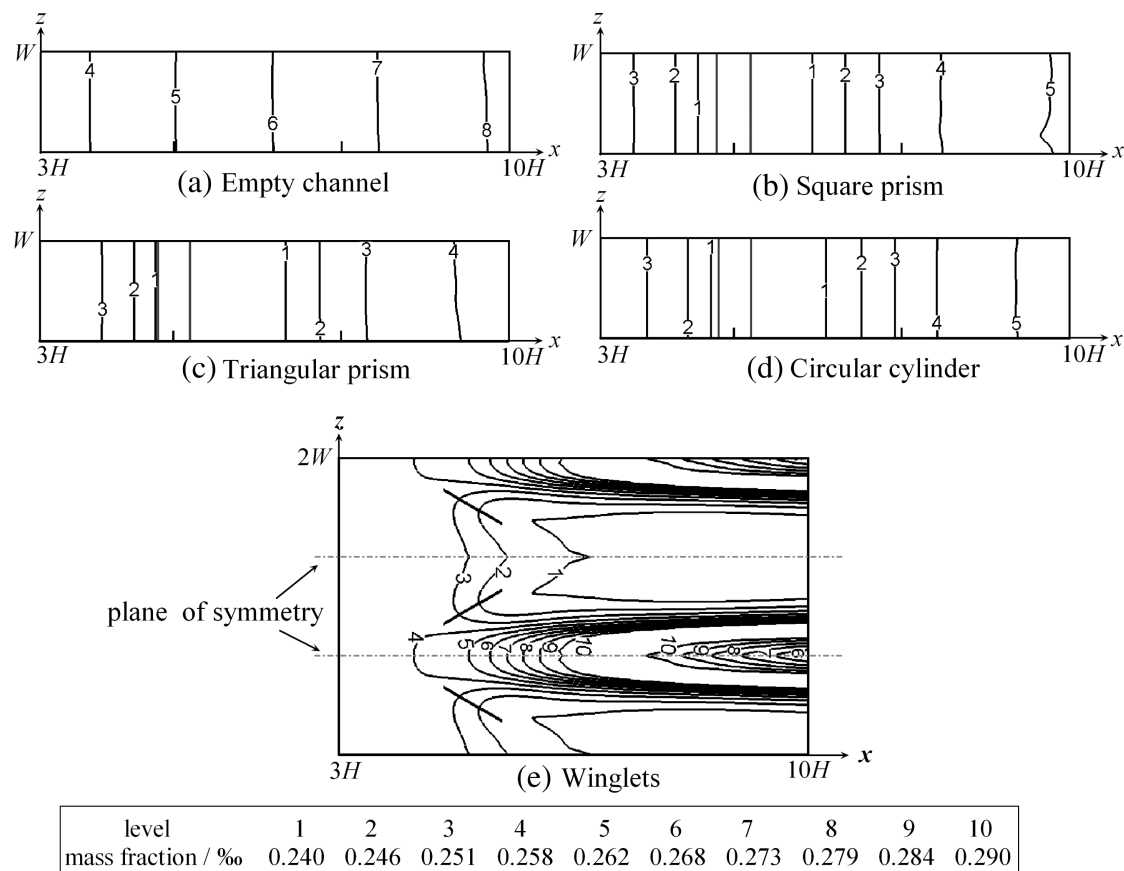


Fig. 7. Solute mass fraction contours at membrane surface for channels with and without flow disturbers ($Re = 600$).

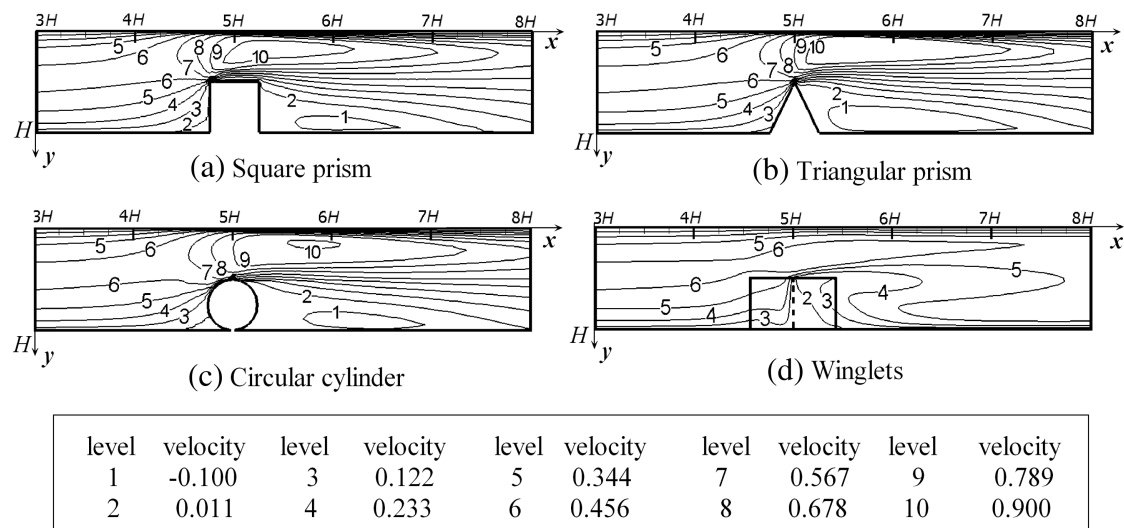


Fig. 8. Fluid velocity contours at plane of $z = 0.75H$ for channels with various flow disturbers ($Re = 600$).

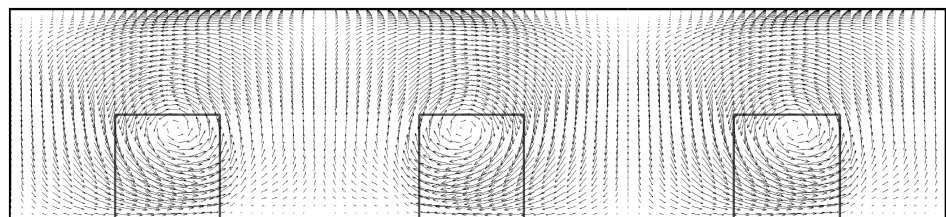


Fig. 9. Fluid velocity vector plot at cross-section of $x/H = 6$ for channel with rectangular winglets ($Re = 600$).

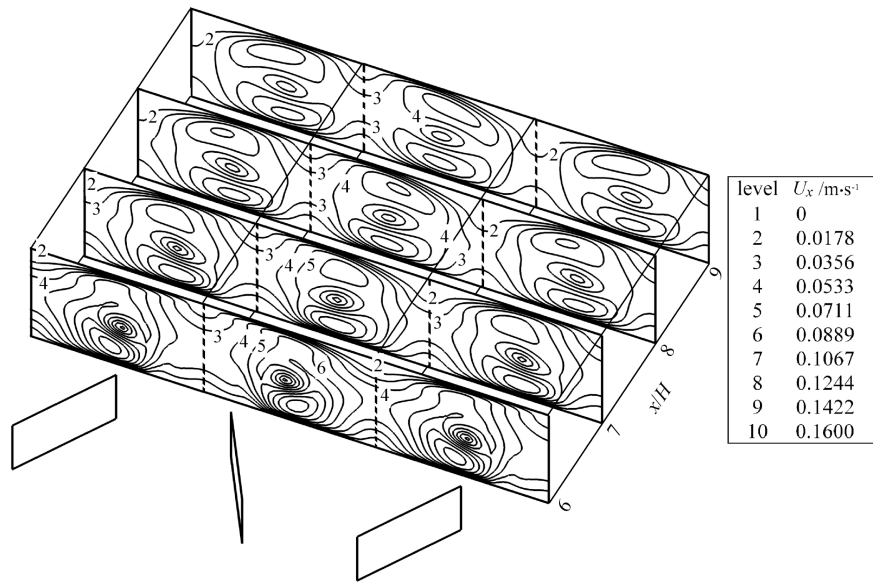


Fig. 10. Fluid velocity contours at cross-sections of $x/H = 6, 7, 8$ and 9 for channel with rectangular winglets ($Re = 600$).

Fig. 9 is a vector plot of fluid velocity at a cross-section of $x/H = 6$ for channel with the rectangular winglets for $Re = 600$. The figure shows that each winglet produces one vortex, with the concave winglet pair generating two counter-rotating vortices that flow up to wash the membrane surface while the convex winglet pair generating two counter-rotating vortices that flow down to wash the solid wall surface. The flow-up vortices thin the concentration boundary layer near the membrane surface, causing an enhanced mass transfer and consequently a small mass fraction at the membrane surface as observed in Fig. 7(e), whereas the flow-down vortices thicken the concentration boundary layer near the membrane surface, causing a reduced mass transfer and consequently a large mass fraction at the membrane surface as seen in the same figure.

Fig. 10 depicts the evolution of fluid velocity contours at a series of consecutive channel cross-sections of $x/H = 6, 7, 8$ and 9 for channel equipped with the rectangular winglets for $Re = 600$. The magnitude of the fluid velocity, which is given by Eq. (14), reflects the strength of the secondary flow. The figure shows that the vortices can effectively move downstream, supporting the fact that the rectangular winglets are able to extend their concentration polarization suppressing effect to a space further away downstream from the position at which they are located, as seen in Fig. 6.

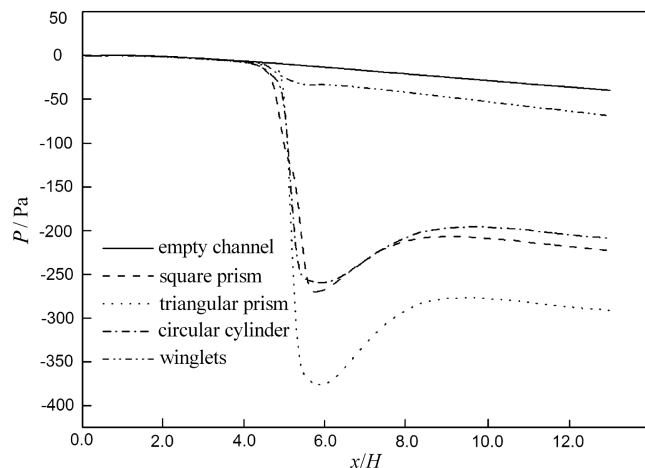


Fig. 11. Evolutions of pressure along channel length for channels with and without flow disturbers ($Re = 600$).

Fig. 11 illustrates the evolution of fluid pressure (P) along the channel length for channels with and without flow disturbers for $Re = 600$. Comparison of the channels equipped with different flow disturbers suggests that the triangular prism yields the maximum pressure drop while the rectangular winglets give the minimum pressure drop. This is consistent with Fig. 8 result, which shows that the triangular prism yields the largest maximum velocity while the rectangular winglets give the smallest maximum velocity.

Fig. 12 is a graph of the area-averaged concentration polarization factor (Γ_A) plotted against the consumed pumping power (E) for channels with and without flow disturbers. For each channel, there are four data points, which correspond to the cases of $Re = 400, 600, 800$ and 1000 , respectively. Fig. 12 shows that for a given pumping power, the channels with the traditional flow disturbers yield the largest concentration polarization factor while that with the rectangular winglets give the smallest concentration polarization factor, with the empty channel providing an intermediate value. The results support that the rectangular winglets are much more effective in suppressing concentration polarization than the traditional flow disturbers.

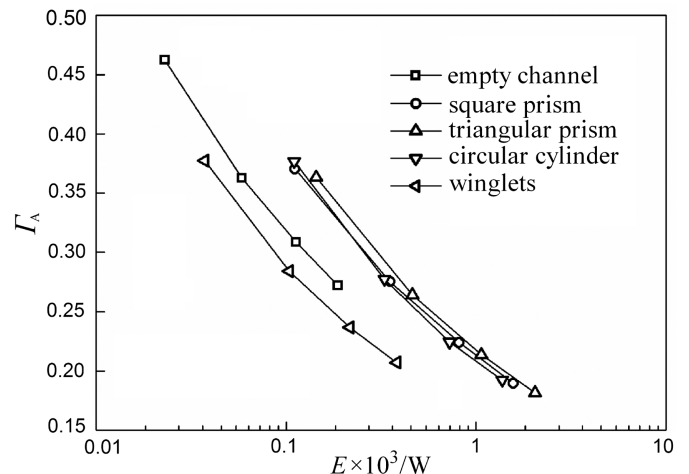
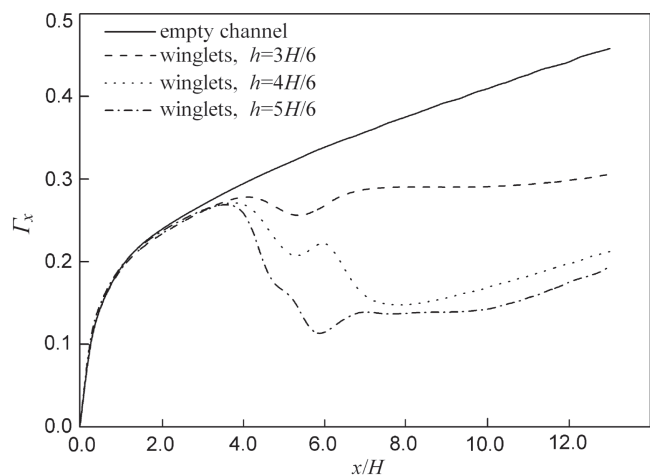
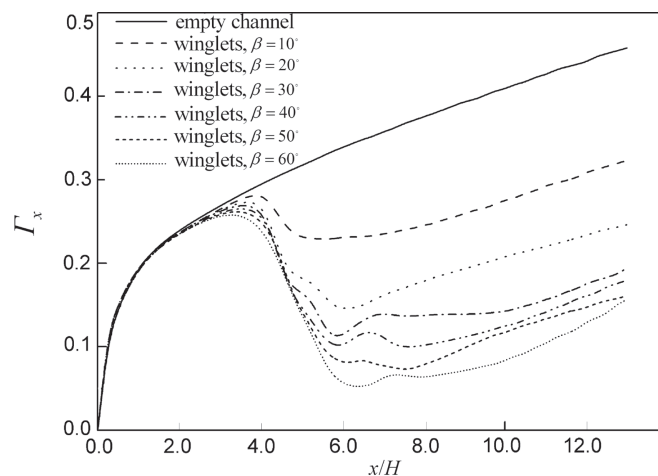


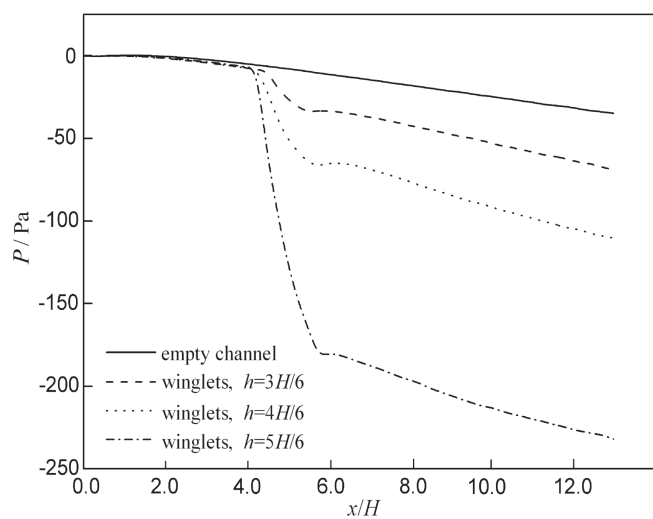
Fig. 12. Variations of area-averaged concentration polarization factor with pumping power for channels with and without flow disturbers ($400 \leq Re \leq 1000$).



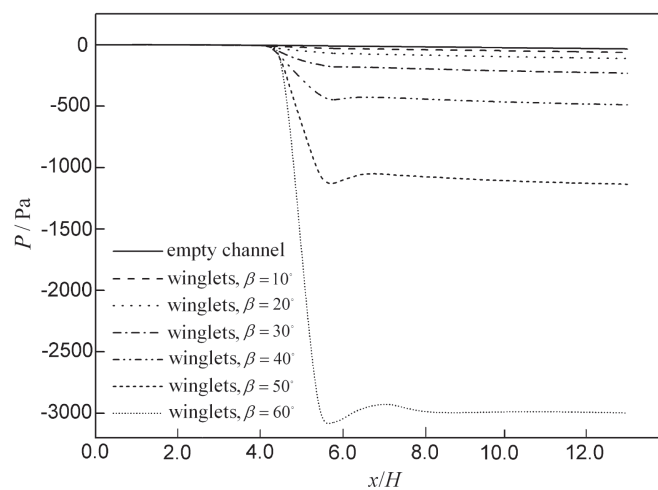
(a) Concentration polarization factor



(a) Concentration polarization factor



(b) Pressure



(b) Pressure

Fig. 13. Effects of winglet height on concentration polarization factor and pressure ($Re = 600$).

Fig. 15. Effects of attack angle on concentration polarization factor and pressure ($Re = 600$).

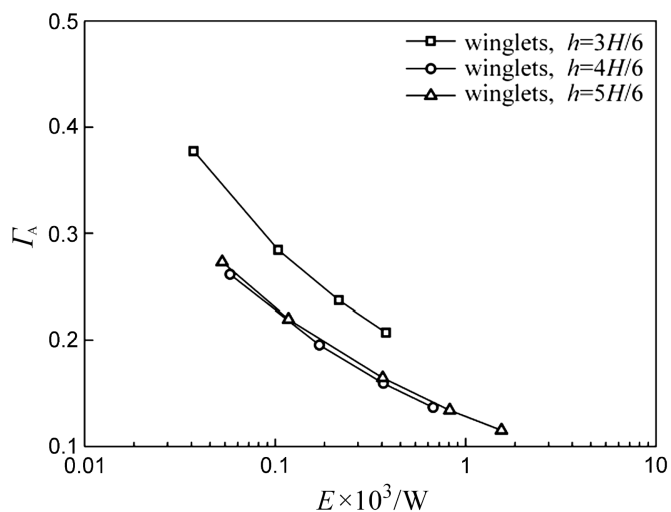


Fig. 14. Variations of area-averaged concentration polarization factor with pumping power for various winglet heights ($400 \leq Re \leq 1000$).

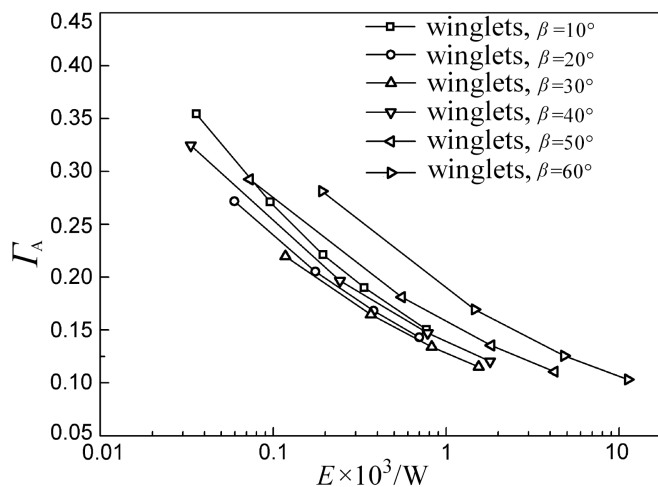


Fig. 16. Variations of area-averaged concentration polarization factor with pumping power for various attack angles ($400 \leq Re \leq 1000$).

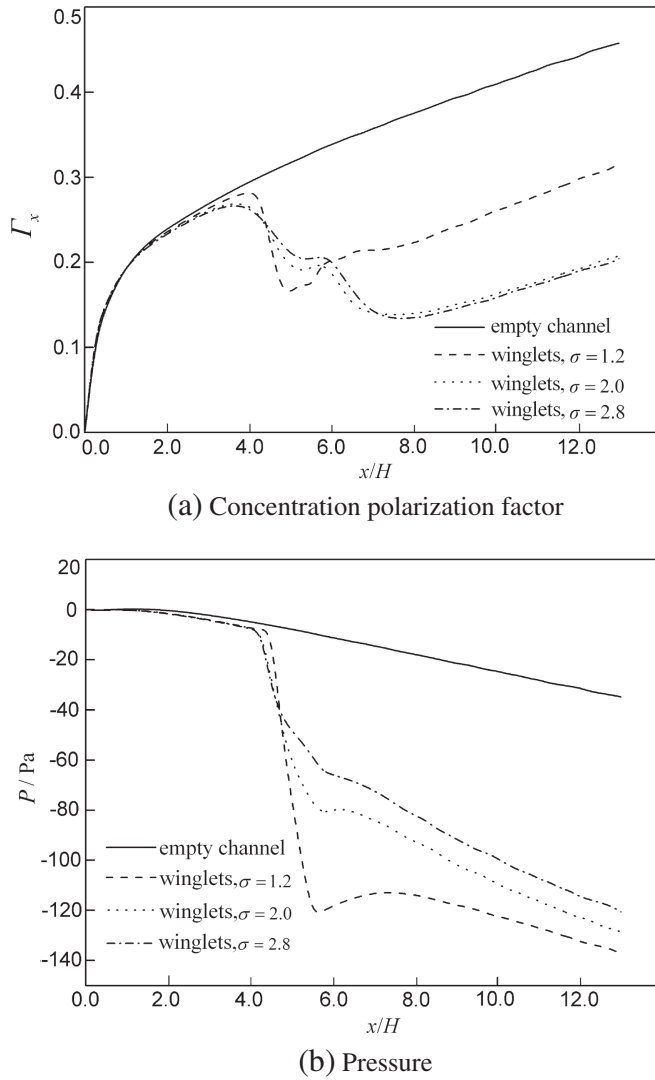


Fig. 17. Effects of aspect ratio on concentration polarization factor and pressure ($Re = 600$).

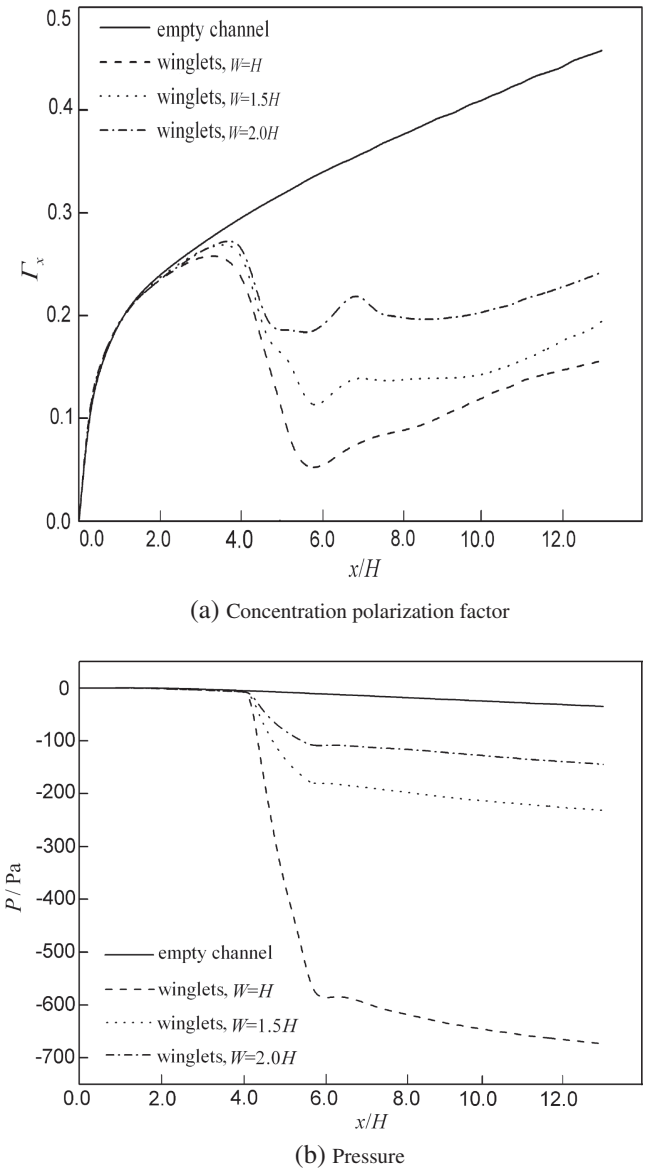


Fig. 19. Effects of winglet interval on concentration polarization factor and pressure ($Re = 600$).

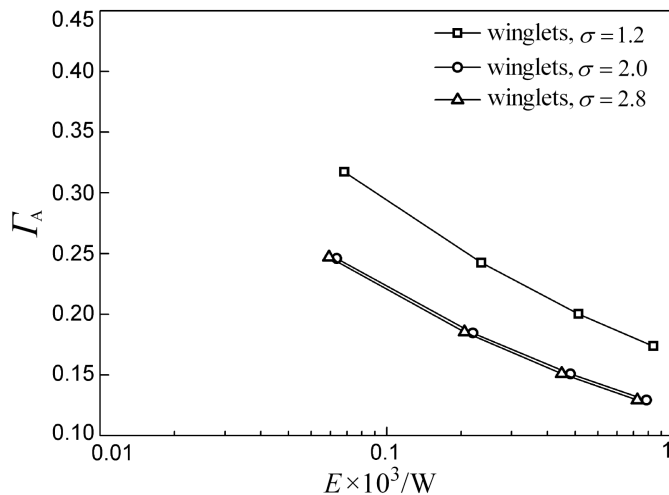


Fig. 18. Variations of area-averaged concentration polarization factor with pumping power for various aspect ratios ($400 \leq Re \leq 1000$).

3.2. Parametric optimization of rectangular winglets

Calculations were finally implemented to investigate the effects of the winglet geometry and arrangement on the winglet performance for the purpose of winglet optimization. As stated previously, there are four key parameters to define the winglet geometry and arrangement, which include the winglet height h , the aspect ratio $\sigma = l/h$, the attack angle β , and the distance between two adjacent winglets W . The values taken for these parameters for typical rectangular winglets are $h = H/2$, $\sigma = 2.0$, $\beta = 30^\circ$ and $W = 1.5H$, as presented in Table 1. Calculations were made with these data as a base. In each calculation, only one parameter was varied with other parameters being unchanged. Also, the simulations used $w_0 = 0.2 \times 10^{-3} \text{ kg} \cdot \text{kg}^{-1}$, $J = 1.36 \times 10^{-5} \text{ m} \cdot \text{s}^{-1}$ and $w_p = 3.7 \times 10^{-5} \text{ kg} \cdot \text{kg}^{-1}$.

Fig. 13 shows the effects of the winglet height (h) on the concentration polarization and pressure drop characteristics for $Re = 600$. As expected, when the winglet height is increased, the concentration polarization factor decreases while the pressure drop increases. Fig. 14 depicts the variations of the area-averaged concentration polarization

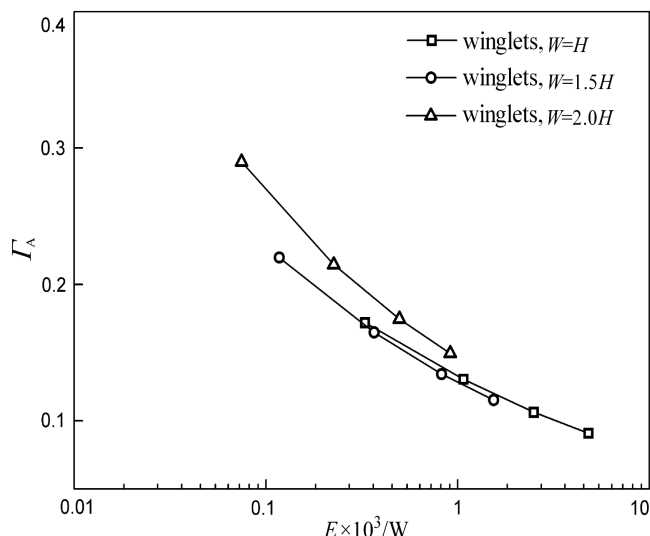


Fig. 20. Variations of area-averaged concentration polarization factor with pumping power for various winglet intervals ($400 \leq Re \leq 1000$).

factor (Γ_A) with the consumed pumping power (E) for various winglet heights. For each height, there are four data points, which correspond to the cases of $Re = 400, 600, 800$ and 1000 , respectively. For a fixed pumping power, comparison of the results for $h = 4H/6$ and $h = 5H/6$ shows that the former gives a slightly lower concentration polarization factor than the latter, suggesting that $h = 4H/6$ is the best winglet height.

Fig. 15 shows the effects of the winglet attack angle (β) on the concentration polarization and pressure drop characteristics for $Re = 600$. As the attack angle increases, the concentration polarization factor decreases while the pressure drop increases. Fig. 16 illustrates the variations of the area-averaged concentration polarization factor with the consumed pumping power for various attack angles. For a fixed pumping power, the winglets having a 30° attack angle yields the smallest concentration polarization factor, suggesting that the best attack angle is $\beta = 30^\circ$. This can be explained as follows. When the angle is small, the increase of the angle is very effective in improving the concentration polarization, at the same time it causes only a moderate increase in the pressure drop; when the angle is large, however, further increase of the angle is not so effective in suppressing the concentration polarization, at the same time it causes a substantial increase in the pressure drop. As a result, the minimum concentration polarization factor takes place at $\beta = 30^\circ$.

Fig. 17 shows the effects of the winglet aspect ratio (σ) on the concentration polarization and pressure drop characteristics for $Re = 600$. Note that the winglet aspect ratio, which is defined as the winglet length-to-height ratio, is varied, with the winglet surface area being kept unchanged in the calculations. Fig. 17 shows that as the aspect ratio increases, the concentration polarization factor tends to decrease while the pressure drop increases. Fig. 18 depicts the variations of the area-averaged concentration polarization factor with the consumed pumping power for various aspect ratios. The figure shows that for a fixed pumping power, the winglets having aspect ratios of $\sigma = 2.0$ and $\sigma = 2.8$ provide almost the same concentration polarization factor, which is much lower than that generated by the winglet having an aspect ratio of $\sigma = 1.2$. Since $\sigma = 2.0$ is a typical value for the winglet aspect ratio, it is thus taken as the best aspect ratio.

Fig. 19 shows the effects of the distance between two adjacent winglets (W) on the concentration polarization and pressure drop characteristics for $Re = 600$. The figure shows that when the winglet interval (W) is reduced, the concentration polarization factor decreases while the pressure drop increases. Fig. 20 illustrates the variations of the area-averaged concentration polarization factor with the consumed pumping power for various winglet intervals. The figure shows that,

for a fixed pumping power, a winglet interval of $W = 1.5H$ yields the lowest concentration polarization factor, suggesting that the best interval is $W = 1.5H$.

The summary of the above results supports that the optimal geometric parameters for the rectangular winglets are $h = 4H/6$, $\beta = 30^\circ$, $\sigma = 2.0$, and $W = 1.5H$. As compared to the typical values listed in Table 1, the only difference is that the winglet height changes from $h = 3H/6$ to $h = 4H/6$. This change leads to a significant reduction in the area-averaged concentration polarization factor under the equal pumping power condition, as shown in Fig. 14.

4. Conclusions

Numerical calculations were carried out to simulate the solution flow and solute transport in narrow membrane channels with and without flow disturbers for reducing concentration polarization under equal pumping power condition. The conclusions are as follows:

- (1) The traditional flow disturbers including the square prism, triangular prism and circular cylinder can considerably reduce the concentration polarization factor but they simultaneously cause a substantially increased pressure drop, while the rectangular winglets can effectively reduce the concentration polarization factor with a much less pressure drop penalty. Under equal pumping power condition, the use of the traditional disturbers worsens the concentration polarization while the use of the rectangular winglets improves the concentration polarization.
- (2) Two adjacent rectangular winglets that form a concave winglet pair generate two counter-rotating vortices flowing up to wash the membrane surface, causing a thinned concentration boundary layer near the membrane surface and consequently a reduced concentration polarization factor, while two adjacent rectangular winglets that form a convex winglet pair generate two counter-rotating vortices flowing down to wash the solid wall surface, leading to a thickened concentration boundary layer near the membrane surface and consequently an increased concentration polarization factor.
- (3) Parametric optimization of the rectangular winglets under equal pumping power condition suggests that the winglet height is $2/3$ of the channel height, the aspect ratio is 2.0 , the attack angle is 30° , and the winglet interval is $3/2$ of channel height.

Nomenclature

D	solute diffusivity, $\text{m}^2 \cdot \text{s}^{-1}$
E	pumping power, W
H	channel height, m
h	height of flow disturber, m
J	permeate volume flux across membrane, or permeation velocity, $\text{m} \cdot \text{s}^{-1}$
k	turbulence kinetic energy, $\text{m}^2 \cdot \text{s}^{-2}$
L	length of channel, m
l	length of rectangular winglet, m
P	pressure, Pa
ΔP	pressure drop, Pa
Re	Reynolds number ($= 2Hu_m/\mu$)
Sc	Schmidt number
U_x	velocity of secondary flow, $\text{m} \cdot \text{s}^{-1}$
u	velocity, $\text{m} \cdot \text{s}^{-1}$
u_m	mean velocity, $\text{m} \cdot \text{s}^{-1}$
V	volumetric flow rate, $\text{m}^3 \cdot \text{s}^{-1}$
W	distance between two adjacent winglets, or width of computational domain, m
w	mass fraction, $\text{kg} \cdot \text{kg}^{-1}$
x, y, z	coordinates, m
β	attack angle, ($^\circ$)
Γ	concentration polarization factor

Γ_A	area-averaged concentration polarization factor
Γ_x	local concentration polarization factor
ε	turbulence dissipation rate
μ	viscosity, $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$
μ_t	turbulence viscosity, $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$
ρ	density, $\text{kg} \cdot \text{m}^{-3}$
σ	aspect ratio ($= l/h$)

Subscripts

b	bulk flow
p	permeate side
w	membrane surface
0	channel inlet

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