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Fluid Dynamics and Transport Phenomena

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

Jingchun Min *,1, Bingqiang Zhang [2]

[1] School of Aerospace, Tsinghua University, Beijing 100084, China
[2] Beijing Key Laboratory of Space Thermal Control Technology, Beijing 100094, China

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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.

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. Geraldes *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

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* Corresponding author.
E-mail address: minjc@tsinghua.edu.cn (J.C. Min).

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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 $\beta = 30°$, 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.

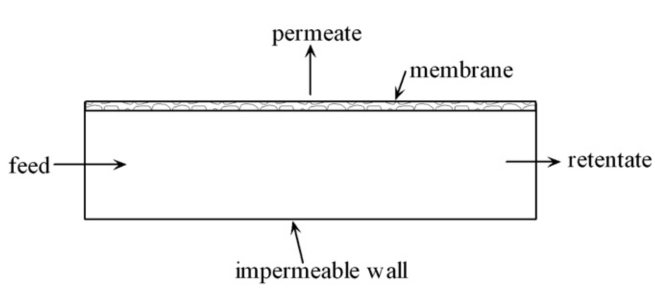

Fig. 1. Solution splitting in a typical plate membrane module.

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 renormalization 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:

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

Momentum equation:

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

Convective diffusion equation:

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

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

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

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

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

Table 1
Typical rectangular winglet parameters

h	β	σ	W
0.5H	30°	2	1.5H