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Fluid Dynamics and Transport Phenomena

Convective mass transfer enhancement in a membrane channel by delta winglets and their comparison with rectangular winglets☆

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ABSTRACT

Numerical calculations were conducted to simulate the flow and mass transfer in narrow membrane channels equipped with delta winglets, which are often used as longitudinal vortex generators to enhance heat transfer in heat exchanger applications. The channel consists of an impermeable solid wall and a membrane. The delta winglets are attached to the solid wall surface to enhance the mass transfer near the membrane surface and suppress the concentration polarization. The winglet performance was evaluated in terms of concentration polarization factor *versus* consumed pumping power. Calculations were implemented for NaCl solution flow in a membrane channel having a height of 2.0 mm for Reynolds numbers ranging from 400 to 1000. The delta winglets were optimized under equal pumping power condition, and the results of optimization suggest winglet height of 5/6 of the channel height, aspect ratio of 2.0, attack angle of 30°, and a winglet interval equal to the channel height. The optimal delta winglets were compared with the optimal rectangular winglets we found previously, and it is shown that the rectangular winglets yield a somewhat better performance than the delta winglets.

1. Introduction

Ultrafiltration and nanofiltration are typical pressure-driven membrane separation processes [1,2]. In such processes, there exist so-called concentration polarization phenomena that deteriorate permeate quality and reduce permeate flux, so the suppression of concentration polarization is of practical importance.

The present research continues our previous work [3], in which we numerically simulated the flow and mass transfer in narrow membrane channels equipped with various flow disturbers aiming at enhancing the convective mass transfer near the membrane surface by suppressing the concentration polarization. We compared the rectangular winglets with the traditional flow disturbers including circular cylinder [4–11], four-prism [9–11] and tri-prism [9,10], which were employed to mimic the traditional spacer filaments in a membrane module, and found that the former was more effective than the latter three in reducing the concentration polarization under equal pumping power condition.

There are many studies that support the effectiveness and superiority of the winglet-type longitudinal vortex generators (WLVGs) in enhancing heat transfer in heat exchanger applications [12–19]. The most attractive character of such vortex generators is that they can increase the heat transfer coefficient with a relatively low pressure drop penalty. There are two typical types of WLVG: one is the delta winglet and the other is the rectangular winglet. Extensive studies have been done to investigate the heat transfer enhancing effects of WLVGs, most of them are on delta winglets [12–15] and others on rectangular winglets [16] or both [17–19].

Although the effects of WLVG in augmenting heat transfer have been fully confirmed, little information is available on their effects in augmenting mass transfer in a membrane channel, except for our previous work [3]. It should be noted that such effects are not self-evident, because there are some key differences between the use of WLVGs for heat transfer enhancement and that for mass transfer enhancement. For instance, when WLVGs are used in a finned tube heat exchanger, they are set up on the fin surface to enhance the convective heat transfer near the fin surface on which they are mounted; when WLVGs are employed in a membrane module, however, they are set up on the solid wall to augment the convective mass transfer near the membrane surface opposite to the wall. Besides, since the Schmidt number is much larger than Prandtl number, the convective mass transfer boundary layer is substantially thinner than the convective heat transfer boundary layer, implying that the mass transfer enhancement is more difficult than the heat transfer enhancement.

In our previous work [3], we tried to introduce the WLVG technique into the enhanced mass transfer area and chose to use the rectangular winglets to enhance the convective mass transfer in a membrane channel. We evaluated their mass transfer enhancing effects in terms of

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concentration polarization factor *versus* consumed pumping power and found that they had better performance than the traditional flow disturbers. In the present research, we devote to investigate the effects of the delta winglets, which are one of the abovementioned two typical types of WLVGs, in augmenting the convective mass transfer to reduce the concentration polarization in a membrane channel having a height of 2.0 mm for Reynolds numbers ranging from 400 to 1000. Delta winglets are first optimized in geometry and arrangement under the equal pumping power condition, and then compared with the rectangular winglets optimized in our previous research [3].

2. Calculation Method

2.1. Physical model

Fig. 1 shows the basic membrane channel used in this study, which consists of an impermeable solid wall and a membrane. The channel height is H and the channel length is $L = 35H$. Delta winglets are installed on the solid wall and locate $5H$ downstream from the channel inlet. Fig. 2 depicts the geometry and arrangement of the delta winglets, all of which are set up with an angle attacking to the entering solution flow. Winglets are arranged in pairs to form alternate V and Λ configuration, with the former being called a convex winglet pair and the latter a concave winglet pair. Because of symmetry in geometry, the computational domain is chosen to include one channel height, the entire channel length, and a channel width that just involves a single winglet, as illustrated by Fig. 1, which also shows the coordinate system adopted in this study. The domain has a height of H, a length of L, and a width of W, which is equal to the winglet interval. The representative geometry and arrangement of the delta winglets are set as follows (Fig. 2): the winglet height $h = H/2$, the winglet aspect ratio $\sigma = l/h = 2.0$, the winglet attack angle $\beta = 30°$ and the winglet interval $W = 1.5H$, as summarized in Table 1. Note that the winglet thickness is zero.

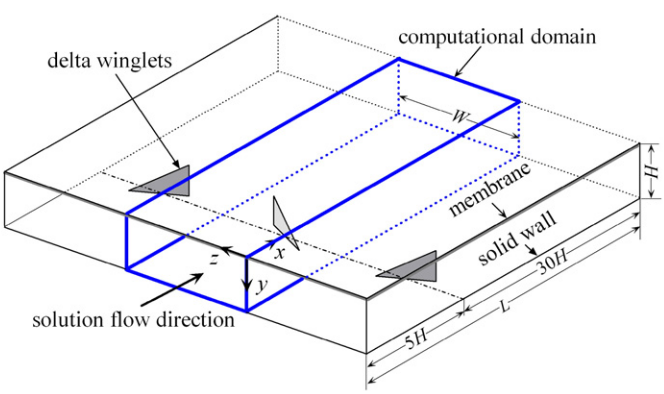

Fig. 1. Membrane channel with delta winglets.

Table 1
Representative delta winglet parameters

h	σ	β	W
$H/2$	2	30°	$1.5H$

2.2. Numerical simulation

Solution flow in membrane channel is assumed to be steady and incompressible with constant properties. RNG k-ε model is used to simulate the flow in channels. As boundary conditions, symmetry boundaries are employed on both sides of the computational domain shown in Fig. 1, with no slip conditions being applied to both the solid wall and the membrane surface. The fluid inlet velocity is assumed to have a parabolic profile over the channel height 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. The solute concentration distribution at the membrane surface is determined by the mass balance among the convection, reverse diffusion, and permeate fluxes. Equations governing the solution flow and solute transport as well as those formulating the boundary conditions are described in details in our previous paper [3].

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

The concentration polarization factor is defined by [9,10,21,22]

$$\Gamma = \frac{w_{\mathrm{w}}}{w_{\mathrm{b}}} - 1. \tag{1}$$

The local concentration polarization factor at position of x is calculated from

$$\Gamma_x = \frac{1}{W}\int_0^W \Gamma \mathrm{d}z \tag{2}$$

where w_{b} is the solute mass fraction of the bulk solution and w_{w} is the solute mass fraction at the feed solution/membrane interface. The

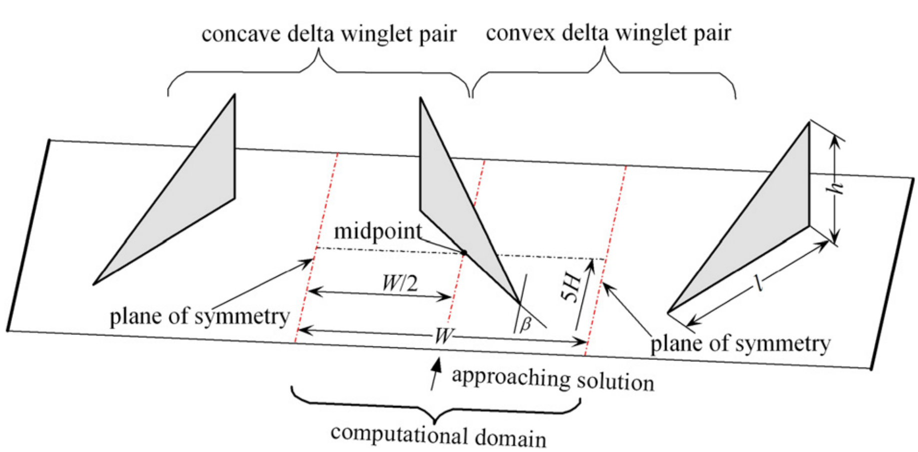

Fig. 2. Geometry and arrangement of delta winglets.