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Optimum design for cylindrical-shaped nanoporous filtration membrane

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ABSTRACT

The design of cylindrical-shaped nanoporous filtration membranes is optimized. Across the membrane thickness, two kinds of concentric nanopores respectively with the radii R_0 and R_1 ($R_0 \leq R_1$) are manufactured. The nanopore with the radius R_0 is for filtration, while the nanopore with the radius R_1 is for reducing the flow resistance and increasing the flux of the membrane. The optimum R_1/R_0 value was obtained for yielding the smallest flow resistance of the membrane. This optimum R_1/R_0 value is dependent on the radius R_0, the depth of the filtration pore and the passing liquid-pore wall interaction. For increasing the flux of the membrane, the depth of the filtration pore should be as small as possible.

1. Introduction

One of the nanopore applications is for filtration. Because of the very small size of the nanopore, only sufficiently small substances can pass through the pore, while others can not [1]. Nanoporous filtration membranes have wide applications such as in water purification, hemofiltration and drug delivery [2, 3]. The performances of this membrane are evaluated by its filtration ability (determined by the pore size) and the flux through it (determined by both the pore size and the membrane thickness). Normally, these two membrane performances can not be easily reconciled. The nanoscale pore size can greatly slow the flow through the pore driven by the pressure because of the significantly increased fluid viscosity, the strong fluid non-continuum effect and the very small pore size [4]. For increasing the flux of the membrane, the membrane thickness should be as small as possible. Cadotte et al. [5] tested the performance of a thin film composite membrane and found its high flux in water treatment; Their membrane was formed by depositing a proprietary thin polymer coating on a microporous polysulfone support layer. Surwade et al. [6] found that a nanoporous membrane made of a mono layer graphene can yield a high flux in water desalination. Li et al. [7] found that a conical-shaped nanopore is advantageous over a cylindrical-shaped nanopore for a high membrane flux. Yang et al. [8] proposed a mixed membrane in which the top layer has cylindrical nanopores while the bottom layer is full of micropores. They found that by this way the virus can be effectively blocked while the protein can freely pass. Kang et al. [9] proposed a method of surface modification on the pore surface of a thin film composite membrane by grafting hydrophilic poly chains to the surface; They found that this surface modification improved the membrane antifouling property. Tang et al. [10] also experimentally studied the possibility of covering specific coatings on the pore surface of a thin film composite membrane. Yip et al. [11] developed a thin film composite membrane consisting of a selective layer and the supporting microporous layer; They found the significantly increased flux of this membrane, which depended on the thickness, porosity and pore structure of the supporting layer. Tiraferri et al. [12] investigated the influence of the supporting layer on the performance of a thin film composite membrane; Their membrane consisted of a selective layer on the top of the supporting layer; Their study confirmed that the optimal membrane should consist of a mixed-structure support layer where a thin sponge-like layer sited on the top of highly porous macrovoids; They found that both the selective layer transport properties and the supporting layer structure characteristics needed to be optimized for a high performance membrane. Tong et al. [13] manufactured a silicon nitride nanosieve membrane in which the cylindrical nanopores were uniform. They said that the pore size can be further reduced by coating another silicon nitride layer; The mechanical strength of their membrane was adequate. Lin and Buehler [14] studied by molecular dynamics simulation the performance of graphene nanoweb membranes in water purification. They found the optimal case for water purification.

According to the design method proposed recently for nanofluidic circuits [15], the present study addresses a new cylindrical-shaped nanoporous filtration membrane in which two kinds of concentric nanopores with different radii are manufactured across the membrane thickness. The smaller pore with the radius R_0 is for filtration, while the larger pore with the radius R_1 is for reducing the flow resistance and increasing the flux of the membrane. By this way, the mechanical strength of the studied membrane can be substantially improved because of a relatively high membrane thickness. By taking the analytical

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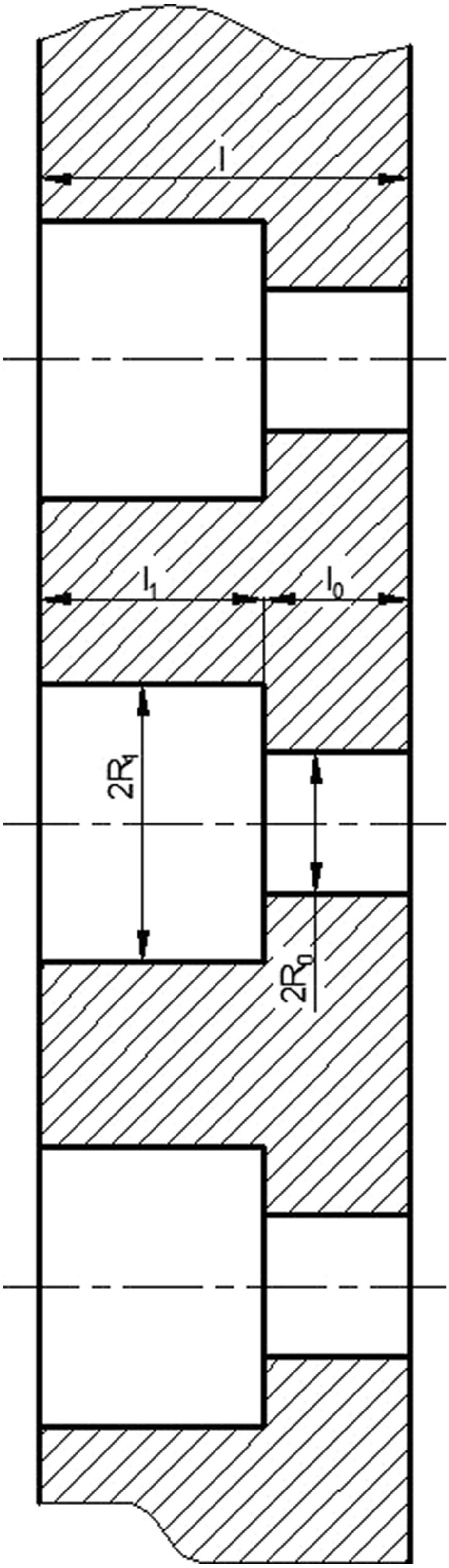

Fig. 1. The studied nanoporous filtration membrane.

approach for nanofluidic circuits in Ref. [15], the flow resistance of the studied membrane was calculated. It was found that there exists the optimum R_1/R_0 value which gives the smallest flow resistance of the membrane and thus the highest membrane flux.

As shown by the analytical results, the filtration pore can be very small, but its depth should be as small as possible for the lowest flow resistance of the membrane. The other larger pore with the radius R_1 is optimized for the smallest flow resistance of the membrane. In this circumstance, the membrane can have a sufficient thickness to hold its mechanical strength. The overall performances of the studied membrane should be substantially improved.

2. Studied membrane

Fig. 1 shows the studied filtration membrane in which are uniformly distributed numerous cylindrical nanopores. Across the membrane thickness l are manufactured two kinds of concentric pores respectively with the radii R_0 and R_1 ($R_0 \le R_1$). The pore with the radius R_0 is for filtration. The value of R_0 is determined by the filtration requirement. The depth l_0 of the filtration pore should be as small as possible for the lowest flow resistance of the membrane; It may be determined according to the requirement of the strength of the filtration pore. The other larger pore with the radius R_1 occupies the remaining membrane thickness; This pore is for reducing the flow resistance of the membrane and should be manufactured as optimum for the highest membrane flux; Its depth l_1 should be determined according to the requirement of the mechanical strength of the membrane.

The membrane in Fig. 1 can be understood as consisting of a selective layer with small pores and the supporting layer with bigger pores. However, its configuration is different from the configurations of the thin-film composite membranes studied before [5,9,11,12], where the selective dense layer was coated on the supporting looser layer and there was less demanding on the relationship between the selective layer pores and the supporting layer pores. The present membrane is an integrated body; The positions and sizes of the pores with different radii in this membrane are intimately related and well controlled.

3. Analysis

3.1. Basic equations

The analysis for the liquid flow in the membrane nanopores in Fig. 1 is based on the flow equation for a nanoscale fluid flow [16]. According to this flow equation, in Ref. [15] has been presented a design method for nanofluidic circuits, in which a section of nanochannel was considered as a flow resistance. According to this design method, in Fig. 1, the single pore with the radius R_0 has the flow resistance $i_{f,\,0}$, and the single pore with the radius R_1 has the flow resistance $i_{f,\,1}$; Across the membrane thickness, the two flow resistances $i_{f,\,0}$ and $i_{f,\,1}$ are in series connection. While, within the whole membrane, the pores distributed on the membrane surface are in parallel connection. Fig. 2 shows the nanofluidic circuit chart of the studied membrane.

In Fig. 2, the mass flow rate through a single pore is [15]:

$$q_{m,b} = \frac{\Delta p}{i_{f,0} + i_{f,1}} \tag{1}$$

where Δp is the pressure drop across the membrane thickness. The total mass flow rate through the whole membrane is: $q_m = N \cdot q_{m,\,b}$, where N is the total number of the pores with the radius R_1 distributed on the whole membrane surface. Thus, the flow resistance of the whole membrane is [15]:

$$i_f = \frac{\Delta p}{q_m} = \frac{i_{f,0} + i_{f,1}}{N} \tag{2}$$

It can be written that $N = \lambda_N \cdot A_m$, where λ_N is the number density of the pore with the radius R_1 on the membrane surface (in/m^2) and A_m is the area of the whole membrane surface. The surface area occupied by each pore is $1/\lambda_N$. If the pore production rate on the membrane surface isχ, it is written that: