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Characterization and modeling of radial flow membrane (RFM) module in ultrafiltration

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HIGHLIGHTS

- Design of a novel radial flow membrane (RFM) module
- Performance characterization of the module in ultrafiltration of BSA
- Average permeate flux enhancement is 0.06×10^{-6} m^3 m^{-2} s^{-1} per unit kPa rise of TMP.
- Mathematical model to predict the steady permeate flux
- Maximum absolute deviation of the model is well within 7%.

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ABSTRACT

Design, characterization and modeling of a novel radial flow membrane (RFM) module is reported in the present study. The module has been investigated in ultrafiltration of bovine serum albumin (BSA) with a 30 kDa polyethersulphone (PES) membrane under steady state. The proposed semi-empirical, steady state model was validated under different parametric conditions of transmembrane pressure and bulk concentration. The model may be viewed as an extension of the well known osmotic pressure model in conjugation with Spiegler–Kedem black box model and a system specific, steady state solute balance equation. Model empiricity was introduced primarily to account for unknown entrance–exit effects and effects of membrane roughness on hydrodynamic profile. The empirical parameter was evaluated by minimizing a global objective function. The maximum absolute deviation of the model with respect to the experimental data of permeate flux was found to be well within 7%.

1. Introduction

Membrane separation technology is an energy efficient downstream process either to separate valuable components from an intermediate process stream or to treat the far downstream effluents in order to meet the discharge standards [1–3]. However, rapid flux decline due to (i) reversible concentration polarization and (ii) irreversible membrane fouling restrict the growth of membrane based techniques as an alternative to the conventional energy intensive separation processes. These non idealities triggers higher energy consumption and additionally reduce the effective membrane life [4]. In general, concentration polarization can be partially controlled by the use of periodic pulsation, electric field, gas sparging or ultrasound [5–10]. On the other hand, membrane fouling is a complicated physicochemical phenomenon, which leads to an irreversible loss of membrane permeability [11]. Different remedial techniques ranging from feed pretreatment to force field assisted filtration have been proposed to counter fouling phenomenon. Recently, in a review article, Hilal et al. [12] have presented a root cause analysis and necessary remedial techniques of fouling in details. It has been also established that to limit the membrane fouling, concentration polarization must be reduced to its lowest possible threshold [13].

It is well recognized that high membrane shear arrests the growth of polarized layer and the therefore enhances the permeate flux. To create a high membrane shear, it is necessary to circulate the fluid at high speed i.e. in the range of 3–6 m s^{-1} [14] in a standard cross flow module. This leads to a higher pumping cost. Over the last two decades, different types of cross flow modules with varied geometry and/or shear enhancing accessories were proposed [15–20]. Alternative to passive enhancement strategies, active use of external force fields, for example ultrasound to enhance the permeate throughput are also reported [21, 22]. Dynamic shear enhanced (DSE) modules, which consist of rotating or reciprocating parts like rotating, spinning or vibrating disks and/or

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membranes were introduced in late 1980s to further intensify the membrane shear independent of feed flow rate [23–27]. However, the specific membrane surface area ($m^2\ m^{-3}$) of even the most advanced DSE module is practically insignificant compared to the standard cross flow units. For example, in a typical plate and frame module (the oldest cross flow unit commercialized), the surface to volume ratio is around 350–500 m^{-1}, whereas the same for the well known hollow fiber modules is as high as 7000–13,000 m^{-1} [28,29]. Naturally the permeate throughput becomes much higher in cross flow devices compared to the equivalent DSE units of same size. Instead of several advantages, enhanced axial pressure drop in a cross flow module leads to a progressive reduction of transmembrane pressure. Therefore, it is necessary to introduce a cross flow design with reduced pressure drop so as to optimize the membrane area usage in terms of uniform TMP distribution.

It is well known that in a radial flow channel with central inlet and peripheral outlet (source flow type), the pressure drop is lower than a rectangular/cylindrical conduit of same internal volume and surface area. Based on this idea, the present work has been undertaken in an attempt to develop and characterize a radial flow module in ultrafiltration of bovine serum albumin (BSA). Moreover, a semi-empirical model was proposed to simulate the present radial flow membrane (RFM) module under steady state.

2. Materials and methods

2.1. Materials

Bovine serum albumin (BSA) with an average molecular weight of 66,000 g mol^{-1} was supplied by E. Merck, Mumbai, India. Moist, semi-permeable, asymmetric polyethersulphone (PES) membrane with a molecular weight cut off (MWCO) of 30 kDa was obtained from Spectrum Medical Industries (USA). The flat disk membrane (diameter: 0.045 m) was operable in the pH range of 2–10 and temperature range of 5–54 °C.

2.2. Filtration system

The present module was designed to ensure smooth radial flow of the feed over a flat circular membrane. Therefore, the corresponding kinematic pattern must either be source or sink flow type. The primary drawback of sink flow is the heavy impact of incoming radial jets over the central region. This may create flow reversal and may hinder the outflow of the retentate. Accordingly, source flow type feed inlet and retentate withdrawal system was chosen for the present work. Fig. 1 represents the sectional view of the module along with the snapshots of the membrane holder and the top lid. The membrane holder is a perforated disk through which permeates flows out. This also acts as a mechanical support of the membrane. Permeate can be collected through a radial tube fitted below the holder. The feed is delivered to the module through a central opening on the top lid. Just below the opening, a circular impingement plate of 0.016 m radius (r_i) is fixed to top lid in order to avoid the feed jet impact on the membrane. Essentially, the feed enters the module through a narrow channel of 0.001 m depth between the impingement plate and the top lid. The retentate flows out of the module through nine peripheral holes of diameter 0.005 m, drilled through the lid. The clearance between the top lid and the membrane (z_t) is 0.014 m, as shown in Fig. 1. An O-ring was used to fix the membrane over the porous membrane holder. This eventually reduces the effective diameter of the membrane diameter (r_o) to 0.041 m. For the present work, the RFM module, made of SS-316 was fabricated by Concept International, Kolkata, India as per the specified design. SS-316 was selected as the material of construction.

The schematic of the entire filtration bench is shown in Fig. 2. The feed tank is fitted with a coolant circulation system. The feed is

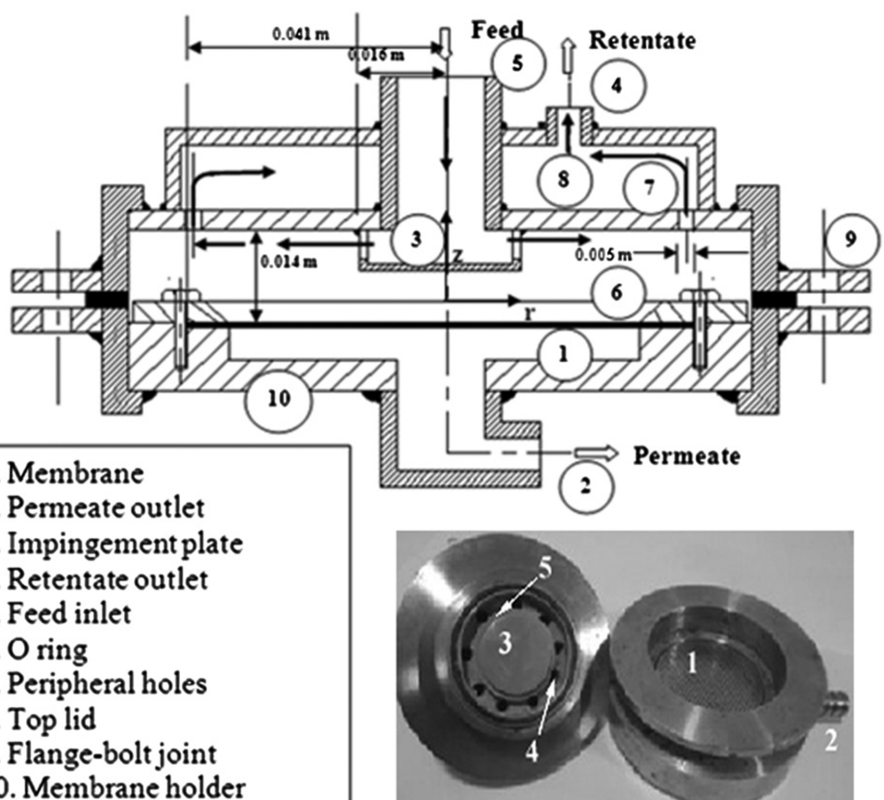

Fig. 1. Sectional view of the radial flow membrane (RFM) module (insert showing the photograph of the module internals).