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Computational fluid dynamics modeling and experimental study of continuous and pulsatile flow in flat sheet microfiltration membranes

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ABSTRACT

Due to the significance of fluid flow hydrodynamics on the membrane surface, pulsatile flow was investigated as a functional approach to promote membrane performance. As a turbulence promoter, pulsatile flow in the membrane channel and its effects on the membrane performance were experimentally and numerically studied. A three-dimensional computational fluid dynamics (CFD) model was used to simulate cross-flow microfiltration process and fluid flow, including porous media by solving Navier-Stocks equations coupled with the Darcy's law. Two different boundary conditions were imposed at the module entrance: simple continuous fluid flow and pulsatile flow. Permeate flux, resistances, and shear forces were calculated in different operating conditions in which the experimental and simulated data showed a good agreement. It was found that shear force was the highest at the entrance region and then decayed along the flow direction for both continuous and pulsatile flow. Besides, two different types of pulsatile flow were considered; sinusoidal pulse flow and step function flow in which the latter led to higher shear forces and consequently higher permeate flux was obtained.
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1. Introduction

Cross-flow microfiltration processes, as an efficient method, have been widely used in different industries and various applications of technology such as clarification, drinking water production, wastewater treatment, food processing, pharmaceutical industry, biotechnology, and biomedicine [1,2].

Concentration polarization and particle deposition on the membrane surface lead to membrane fouling which affects membrane performance. Therefore, many approaches have been proposed to solve this problem and increase the process efficiency. Several experimental and computational studies have been done to access more efficient separation in different membrane application [3–11]. Recently, Computational Fluid Dynamics (CFD) as a practical technique has been widely used to simulate fluid hydrodynamics on the membrane surface, modeling the mass transfer rate and predicting the concentration polarization layer [11–13].

Besides, there are additional new approaches to improve membrane operation and phenomena occurring in the membrane chamber. In this regard, CFD studies in membrane technology can be divided into two categories: one has conducted experiments in membrane operation and concentration polarization phenomenon and the other has focused different methods to increase shear stress on membrane surface in order to enhance membrane efficiency and also minimize fouling.

To begin with, in regard to the first group, some studies have focused on the concentration polarization [6,13–15]. Wiley and Fletcher [16,17] were pioneer in using CFD to model flow and concentration polarization in membrane feed and permeate channel, simultaneously. Ahmad et al. [13] conducted CFD simulation in different operating conditions to predict the concentration polarization profile, mass transfer coefficient and wall shear stress in an empty membrane channel. Similar results were obtained by Zare et al. [14] in which fluid hydrodynamics and concentration polarization of an oil-in-water emulsion were modeled by a novel Eulerian approach in a flat sheet microfiltration. In addition, the effect of different operating conditions on the growth of concentration polarization layer along the membrane surface was studied [2]. Pak et al. [2] solved the two-dimensional diffusion equations for particle transport to model flow field in laminar flow in a tubular permeable membrane. Most of these studies were done without considering the effect of spacers on concentration polarization.

In regard to the second group, different techniques in which CFD have been used to improve membrane performance was comprehensively reviewed by Ghidossi et al. [11]. It was concluded that CFD allows researchers to determine, describe, and optimize the complex hydrodynamics generated by different types of flow regimes; like gas–liquid two phase flow created by gas sparging [18–20], Dean and Taylor vortices [21–23], membranes modules with baffles, spacers, and different geometries [10,24–32]. It is

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now well accepted that an increase in the shear stress induces a decrease in cake layer thickness, and in turn, creates a greater permeate flow rate and higher and more precise selectivity for membrane.

Some researchers [15,26,32,33] reported 2D and 3D CFD modeling by investigating the fluid flow behavior in a spacer filled rectangular or slit membrane channel. They studied the effect of different types of filament and spacers on shear stress distribution and mass transfer coefficient as well as pressure distribution inside the channel. Ranade and Kumar [25] compared the flow in a spacer-filled flat channel with the curvilinear one; they evaluated and demonstrated the applicability of a 'unit cell' approach in understanding influence of spacer shapes on fluid dynamics of channels. It was concluded that hydrodynamics in the two systems were quite similar and shapes of spacer strands influence the fluid flow behavior significantly.

Tung et al. [34] attempted to study fluid flow through a spacer-filled membrane module in order to select suitable cell types for periodic boundary conditions (PBC). They concluded that as angle, mesh size and filament diameter of the spacer and height, width, length, and voidage of the channel vary the pressure drop through spacer-filled channel changes.

Schwinge et al. [35] reviewed different experimental and computational techniques and analyzed the effect of operating conditions which significantly influence the performance of spiral wound modules. Li et al. [28] studied a 3D CFD simulation to consider the effect of spacers in the spiral wound module on flow patterns and mass transfer enhancements. They also tried to optimize the commercial net spacers for membrane modules. Besides, the effects of spacer geometric parameters; such as, filament spacing, thickness and flow attack angle on fluid dynamics, wall shear rates, and mass transfer coefficients in feed channels of spiral wound membranes were studied by Hasani and shakaib [36].

Rahimi et al. [37] reported a 3D CFD modeling on microfiltration fouling which was carried out using a commercial CFD code. The shear stress distributions upon the membrane were predicted and then used to explain the observed fouling. In addition, the discrete phase modeling was also used to predict the particles deposition pattern upon the membrane surface.

It is stated that the permeate flow is almost negligible in comparison to the concentrate flow, then membrane can be modeled as an impermeable wall. It has been considered as an acceptable assumption in some studies, but lead to more errors in modeling results. Lee et al. [38] simulated cross-flow microfiltration of water flow through a porous medium. The shear force analysis on the membrane surface was used to improve the efficiency of the cross-flow microfiltration in different steady-state flows.

As discussed, the effects of turbulancy promoter methods including mixers, baffles, spacers, and gas sparging on the membrane filtration have been experimentally and numerically investigated. A good knowledge has been acquired in recent years, but it needs more investigations in some aspects to overcome the bottlenecks and design more efficient processes. To the best of our knowledge, no study has been reported on using pulsatile flow in membrane filtration as a method to enhance flux and reduce fouling, neither experimentally nor mathematically. In this study, the effects of pulsatile flow on cross-flow microfiltration of whey in a rectangular channel were studied. A non-commercial CFD package based on the finite volume method was used to model flow in the membrane channel. As an important parameter, shear force on the membrane surface was calculated in different types of flow and velocities and, finally, the effects of pulsatile flow on fouling and flux improvement was investigated.

2. Experimental setup

A 0.45 μm mean pore size hydrophilic flat sheet Polyethersulfone (PES) membrane (Membrane Solution Co, USA) with the porosity of 80% and thickness of 120 μm was used for experiments in this study. The advantage of the surface-modified PES membrane used in this study was its low interaction with the protein included in the whey and low protein binding characteristics.

A schematic flow diagram of the cross-flow microfiltration experimental setup is shown in Fig. 1. The system was able to adjust and control the operating pressure and liquid velocity in the system. A variable-speed speed rolling pump provided the required power to maintain the operating pressure of the feed solution constant. By adjusting two needle valves, installed on the two sides of the membrane module, the feed velocity was varied from 0.12 to 0.44 m s^{-1}. Furthermore, two pressure gauges were placed directly before and after the membrane holder in order to calculate the trans-membrane pressure (TMP) which varied from 0.5×10^5 to 2×10^5 Pa for different experiments. Filtration experiments were carried out at room temperature (22 ± 1 °C).

2.1. Feed preparation

The feed was prepared by magnetically stirring 500 g of whey powder, supplied by Kalleh Dairy Co., Iran, in 10 L of distilled water for 30 min in the ambient temperature (~22 °C). The

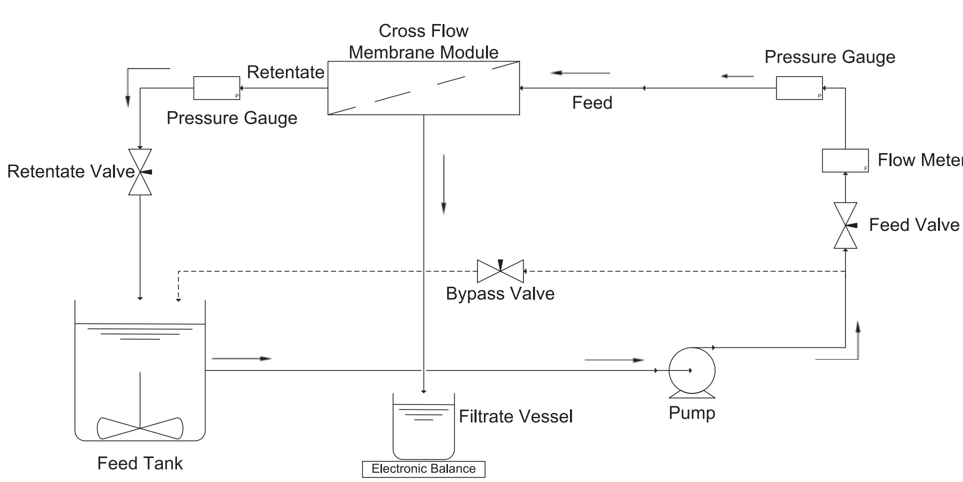

Fig. 1. Schematic figure of the laboratory scale microfiltration setup.

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