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Assessment of combination of pressure-relief pulsation flow and diatomite filter-aid in membrane fouling control

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ABSTRACT

Alleviation of membrane fouling in a convenient process design of pressure-relief pulsation flow coupled with diatomite filter-aid has been researched both theoretically and experimentally. On the one hand, the cake-layer of diatomite particles serves as a dynamic membrane, which acts as a deep-bed filter and catches some small particles before they contact to the membrane surface. On the other hand, the diatomite particles in cake layer may return to the feed solution under the condition of high shearing force produced by pulse flow. The membrane flux in the four processes (non-pulsation, with pulsation, with diatomite, and with pulsation + diatomite) was studied, and the filtration resistance during the processes was also evaluated. The results showed that the flux increased by 33.3% and the cake layer resistance decreased by 24.5% in the coupled process, though the average operating pressure was 22.5% lower than conventional non-pulsation process. Therefore, the coupling process is expected to be a practical and realizable technology applying in membrane separation process.

1. Introduction

Ultrafiltration (UF) has aroused board attention in academy and industry due to its high efficiency and stable performance [1,2]. However, membrane fouling is still a major drawback that hinders the wide use of UF membrane. It has been proved that fouling can be effectively reduced by pre-treatment, backwash, selection and modification of membrane materials and optimization of operation conditions [3–5]. In particular, an increase in fluid disturbance on membrane surface is an effective method of mitigating membrane fouling.

Most of the developments in fluid dynamics in the field of membrane separation have concentrated on increasing mass transfer through surface shear with *e.g.* pulsation flow, turbulence promoters (TP) and generation of Taylor vortices, Dean vortices and oscillating flow. Zhang et al. [6] applied TP with inserting baffles to increase the wall shear stress, they found the mass transfer resistance significantly reduced after TP condition being optimized, and the permeate flux increased more than 60%. Finnigan and Howell [7] found that geometric inserts in the form of periodically spaced disc and doughnut baffles will increase fluxes by up to 127% and 250% in UF process for whey protein solution treatment, respectively. Bertram et al. [8,9] used flexible tubing as pulsation generator, and achieved 60%–450% flux increases under different testing conditions. Gupta et al. [10] produced the pulsed flow by reciprocating motion of a piston, which improved flux by 60% to 70%. Pourbozorg et al. [11] investigated the influence of a turbulence generator using a vibrating perforated plate on submerged hollow fiber membrane filtration, and the experimental results showed that the presence of turbulence had a significant improvement in membrane fouling. Ziskind et al. [12] studied the influence of mean and fluctuating shearing force components upon the particles removal from the wall. They have shown the interest of oscillating flows in particles removal when the mean shear stress is not high enough. Gillham et al. [13] also found that the cleaning rates of the deposited protein had an enhancement by laminar pulse flow at large-amplitude and low-frequency (≤ 2 Hz) of pulsations, which proved that pulsations could induce the breaking of the deposition matrix. All these measures are effective in increasing mass transfer and thereby increasing permeation flux. However, the membrane module types described above most focus on tubular, spiral wound and flat sheet, so it is necessary to develop a membrane process for controlling hollow fiber membrane fouling. In addition, the improvement of hydrodynamics in a membrane module

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List of symbols

F_t	drag forces produced by the suspension flow [N]
F_p	drag forces produced by the permeate flow [N]
F_g	net gravitational force [N]
F_l	inertial lift force [N]
F_i	net interparticle force [N]
F_b	impulsive force produced by pulsing flow [N]
α	Womersley number, defined in Eq. (1)
a	bore radius [m]
ω	angular frequency [/s]
ν	fluid kinematic viscosity or momentum diffusivity [m^2/s]
m	particle mass [kg]
Δt	time of duration [s]
ΔV	velocity variation [s]
R_t	total filtration resistance [/m]
R_c	cake filtration resistance [/m]
R_m	filtration resistance of virgin membrane [/m]
R_a	absorption resistance [/m]
ΔP	transmembrane pressure [Pa]
J_w	filtration flux [L/m^2/h]
μ	fluid viscosity [Pa s]
J	membrane flux [kg/m^2/h]
M	mass of the permeated water [kg]
S	filtration area [m^2]
t	filtration time [s]
R	rejection ratio [%]
C_p, C_f	turbidity of the filtrate and feed solution [NTU]
LPD	low pressure duration [s]
HPD	high pressure duration [s]

without complex module design or complex process operation is expected.

Generally, the fouling is the deposits of rejected macromolecules, colloids, particles, *etc.*, at membrane surface or inside membrane pore. Interestingly, some researchers have found that the rejected particles are wanted and act as a dynamic layer that may prevent primary membrane from polluting by the underlying high pollution substances [14,15]. Davis and coworkers [16–18] proved that the membrane fouling caused by protein could be significantly reduced by forming a yeast cake on the membrane surface. Youn et al. [19] found that pretreating the apple juices with filter-aids (*e.g.* activated carbon, bentonite and polyvinylpolypyrrolidone) can effectively increase the permeate flux without quality compromising. Pontié et al. [20] added clay-particles synthetized from natural bentonite (denoted as Mont-CTAB) into the humic acid (HA) solution, which achieved 25% productivity increase. More importantly, the dynamic layer can be removed and regenerated easily [21].

Diatomite is the sedimentary fossils of ancient diatom (primarily of amorphous SiO_2) and is characterized with high porosity, high compression resistance, good chemical stability, and low cost [22–24]. It was also reported that diatomite could form a dynamic membrane used for long-term water treatment [25,26]. The filtering effect of diatomite filter-aid mainly attributes to the following three aspects: (i) sieving effect: when the fluid flows through the diatomite filter-aid, the pollutants will be retained as its particle size greater than the clearance between the diatomite particles. (ii) Depth effect: during deep filtration, separation process occurs only in the “internal” of the medium, the tortuous pore channel in the internal of diatomite or clearance can retain the small suspended particles through smaller pore in the channel or clearance. (iii) Adsorption effect: the particles smaller than the internal pore will be attracted when contact with the diatomite.

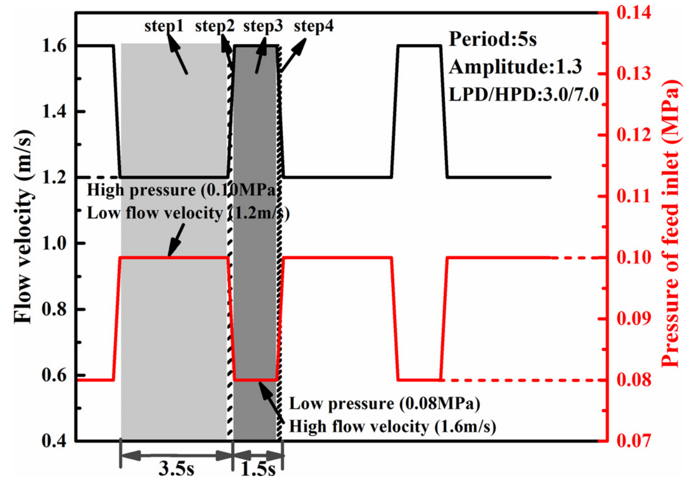

Fig. 1. Specific operating conditions of pulsation process.

In this study, we developed a convenient and practical membrane filtration process that combined pressure-relief pulsation flow and diatomite filter-aid, in which the pulsation flow was used to generate varying wall shear stress and the diatomite was used to form a loosened cake layer due to its bridge effect. The coupling process can be divided into four different phases (as shown in Fig. 1). To be specific, in the stage of low flow velocity (named as step 1), the high pressure produced permeation flux; When the flow velocity changed from low speed to high speed (named as step 2), the transmembrane pressure reduced and the integrity of cake layer would be destroyed by the impulsive force induced by the change of flow velocity. In high flow velocity stage (named as step 3), the outer diatomite in cake layer may return back to the feed solution. When the flow velocity changed from high speed to low speed (named as step 4), the pressure would increase accordingly. Based upon hydrodynamics, the external forces exerted on particles under different conditions were analyzed applying a force balance model. Additionally, the permeate flux and cake-layer resistance were studied to estimate the influence of the coupling process on membrane fouling control.

2. Synergy effect of pressure-relief pulsation flow and diatomite filter-aid

2.1. Modeling of fouling decrease by dynamic membrane

R.H. Davis proposed that the particles in the feed solution can be considered as a bi-dispersed compound of small and large particles [21]. The latter could form a dynamic cake-layer on the membrane surface, which could act as a pre-filter and catch some small particles before they contact the membrane surface. Significantly, a cake-layer formed by large particles may have a low filtration resistance, which could lead to an increase in water flux [21]. As shown schematically in Fig. 2, the water molecules could transport directly through the inner pores or the gaps between the diatomite particles, then pass through the membrane channel.

2.2. Force analysis on a depositing particle

During the filtration process, some of the particles may have the opportunity to get to the membrane surface. It is determined by the resultant external forces whether the particle can deposit stably or not. As shown in Fig. 2, the outer forces acted on the particles including the dragging force attributes to the suspension