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Gas sparging to enhance permeate flux and reduce fouling resistances in cross flow microfiltration

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ABSTRACT

The effects of different two-phase flow patterns on the permeate flux were studied in a microfiltration process. The filtration flux was increased in the slug flow pattern mostly due to the cake reduction and disruption of concentration polarization. Depending on liquid velocity, slug flow enhanced permeability when fouling problem was severe. However, a contrary result was obtained for bubbly flow where gas introduction did almost nothing in higher liquid velocities. Different trends were observed in the dimensionless groups' plane (N_s', N_f), indicating different effects of gas–liquid two-phase flow on the resistances and fouling.

1. Introduction

Whey, a by-product of the dairy industry, is produced during cheese production. After separation of casein and fat during milk coagulation, whey, depending on the kind of produced cheese's properties, is filtered and recovered from the coagulation tanks. Because of their composition, whey proteins have valuable physicochemical properties [1]; however, its biological oxygen demand (BOD) is 32,000–60,000 ppm, which leads to very severe environmental problems [2].

Cross-flow microfiltration (MF) processes, separating particles in the range of 0.1–10 μm, have been widely employed. MF processes reduce the use of heat treatment [3], which is particularly an advantage for products sensitive to high temperature. Furthermore, the microfiltration separation processes, unlike the traditional methods such as acidification and coagulation, do not destroy the proteins' structure in the solution; and also, their inherently high yield makes them suitable for many applications. In the dairy industry, cross-flow microfiltration is used for bacteria removal, fat removal, fractionation of whey proteins and separation of casein micelles [4–6]. Among these, one of the major applications of microfiltration is pretreatment of whey to produce whey protein concentrate (WPC) during ultrafiltration. This results in removal of undesirable components such as fat and casein micelles [2].

Basically, membrane efficiency can be affected by pore blocking where foulants partially occupy the pore space by adsorption and/or deposition which is a function of membrane properties, cake layer formation on the membrane surface which is mostly related to the flow hydrodynamics, and concentration polarization [7]. The latter arises from the nature of microfiltration and ultrafiltration processes causing a back diffusion from the membrane surface to the feed bulk resulting in the permeate flux decline. In almost all purposes, concentration polarization and membrane fouling can significantly reduce the membrane efficiency.

In microfiltration of whey, casein micelles can be responsible for fouling to some extent, while whey proteins such as β-lactoglobulin are the most well-known foulants [8]. The degree of protein fouling and consequent permeate flux are complex phenomena that depend mainly on membrane material [9], membrane morphology [10], solution properties [11], and flow hydrodynamics and operating parameters [12].

To overcome the flux decline problem and to make the membrane process more competitive, many recent studies have been done to minimize fouling. These studies can be classified into different categories including feed pretreatment [13], membrane modification [14], flow manipulation (turbulence promotion, back-flushing, and pulsing) [15], rotating membrane-high shear (dynamic) membranes [16], gas sparging [17], and using some additional force fields like electric and ultrasonic fields [7] as

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Nomenclature

A	total active membrane area (m^2)
J	permeate flux ($m^3\ m^{-2}\ s^{-1}$)
N_s'	shear stress number with gas sparging
N_s	shear stress number without gas sparging
N_f	resistance number
Q_L	liquid flow rate (L/min)
Q_G	gas flow rate (L/min)
Re	Reynolds number
R_f	the overall resistance induced by all the processes (m^{-1})
R_{if}	irreversible fouling resistance (m^{-1})
R_m	membrane resistance (m^{-1})
$R_{rf.}$	reversible fouling resistance (m^{-1})
R_T	total membrane resistance (m^{-1})
t	filtration time (s)
TMP	trans-membrane pressure (Pa)
u_G	superficial gas velocity ($m\ s^{-1}$)
u_L	superficial liquid velocity ($m\ s^{-1}$)
v	permeate volume (m^3)

Greek letters

μ	permeate viscosity (Pa s)
ε	gas injection factor
ρ	density ($kg\ m^{-3}$)
ρ'	equivalent density of the gas–liquid two-phase flow ($kg\ m^{-3}$)

means to enhance turbulence and/or shear stress near the membrane surface. Some of the abovementioned techniques are currently in use and the others show promise for the future to be used in the dairy industry.

Introduction of gas–liquid two-phase flow has been widely used to enhance the membrane efficiencies, mainly for MF and UF processes. It is discussed that the gas sparging technique may disrupt the concentration polarization layer and increases the permeate flux. Imasaka et al., as a pioneer in this field, first used a gas–liquid two-phase cross-flow microfiltration process by injection methane into a ceramic membrane module in 1989 [18,19]. Then, Cui et al. reported 175% enhancement in permeate flux for microfiltration of yeast and a noticeable permeate flux enhancement for dextrans and BSA solution [20]. Mercier et al. also introduced slug-flow to achieve a significant increase in MF and UF in different works [21–23] and theoretically addressed how slug flow can enhance the ultrafiltration flux in tubular membranes [24]. The same was done where Cabassud et al. [25] used gas bubbling to achieve better filtration of clay particle suspensions using UF hollow fibers for water treatment. Some other works have been also done in submerged membrane bioreactor [26,27].

In a relatively recent work, the use of gas bubbling to enhance membrane processes was reviewed by Cui et al. [17]. They reported that the mechanism of fouling control by the gas–liquid two-phase flow involves bubble induced secondary flow, physical displacement of concentration polarization layer, pressure pulsing, and increase in superficial cross-flow velocity. They also discussed some applications in biotechnology, bioseparations and water and wastewater treatment [17].

From then on, gas injection into membrane modules has been investigated in much more detail. Hwang et al. [28] studied the influence of air-sparging on the performance of cross-flow microfiltration of yeast suspension. They measured and discussed the pseudo-steady filtration flux and the cake properties under various operating conditions. It was observed that the cake mass was markedly reduced by increasing the wall shear stress in the slug flow pattern. On the contrary, it is reported that the average specific cake filtration resistance increased with increasing the wall shear stress due to more compact cake structure for the bubbly flow regimes.

Drews et al. [29] investigated the bubble movement, exerted shear and particle classification in membrane modules and reported that air sparging can have advantageous but also detrimental effects. They concluded that depending on membrane plate spacing, wall shear can decrease with bubble size. In addition, some parameters like particle classification or segregation can increase the cake resistance which must be taken into account. Some negative effects of gas sparing have been reported elsewhere [30].

In a recent work, influence of gas sparging on microfiltration of pineapple wine was investigated [31]. It was found that a relatively low gas sparging rate could increase permeate flux up to 138%, while further increase of the gas sparging rates showed a negative effects on the permeate flux. They also observed the effects of gas sparging on the density of cake layer, in which increasing gas sparging rate led to an increase in specific cake resistance and consequently membrane performance decreased.

Laorko et al. [32] applied the gas sparging method for the clarification of pineapple juice by microfiltration, enhancing the critical and limiting flux. They reported that the use of gas sparging not only could reduce the reversible fouling and external irreversible fouling, but also did not affect the pH, total soluble solid, color, and antioxidant capacity of clarified juice. Based on their results, slug flow pattern appeared to give the highest improvement than bubble patterns.

Up to now, gas sparging has proved to be an effective method to control membrane fouling in most cases; however, it is also possible to observe detrimental effects of gas sparging on the membrane performance [29–31]. To the best of our knowledge, gas sparging method has been used in various applications, but there are no reported results for whey as the feed.

The governing fouling mechanisms and the effect of operating conditions on these mechanisms in cross-flow microfiltration of whey were investigated in previous work [33]. It was shown that different kinds of fouling occur depending on different operating conditions. It was thus expected that gas–liquid two-phase flow could be efficient. Continuing our activities in this direction, the present study is aimed at determining the influence of gas–liquid two-phase flow, including bubbling and slug flow, on different resistances, fouling type, and the permeate flux in the case of microfiltration flat sheet membranes. In addition, the effects of gas sparging on the fouling resistances was studied. It was also tried to use the dimensionless approach to understand the permeate flux and fouling.

1.1. Gas–liquid two-phase flow in a channel

When a gas/liquid two-phase flow is injected inside a channel, different flow patterns can be observed according to the respective values of the gas and liquid velocities or the corresponding flow rates [24]. Basically, the flow pattern of a gas–liquid two-phase flow can be stated by the gas injection factor defined as:

$$\varepsilon = \frac{u_G}{u_G + u_L} \qquad (1)$$