Separation and Purification Technology 190 (2018) 9–24

Contents lists available at ScienceDirect

Separation and Purification Technology

journal homepage: www.elsevier.com/locate/seppur

Ceramic membrane fouling and cleaning during ultrafiltration of limed sugarcane juice

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ARTICLE INFO

Keywords:
Ceramic membrane
Ultrafiltration
Sugarcane juice
Fouling
Cleaning

ABSTRACT

A ceramic membrane is applied to improve the clarification of sugarcane juice and reduce or eliminate the usage of chemicals in sugar industry. Although membrane fouling is unavoidable, fouling can be solved by understanding its mechanism and developing an effective approach to regenerate membranes. Mathematical model prediction, scanning electron microscopy (SEM), and atomic force microscopy (AFM) during membrane fouling indicated that the dominant fouling during ultrafiltration of limed raw sugarcane juice was caused by cake formation on the membrane surface. Energy-dispersive X-ray spectrometry (EDX) and Fourier-transform infrared spectrometry (FTIR) revealed that polysaccharides, proteins, aliphatics, sucrose, phenols, phosphorus, silicon, and few metal elements, such as calcium, magnesium, aluminum, potassium, and sodium, were the compositions of foulants primarily responsible for fouling. An effective membrane cleaning method was proposed on the basis of these findings. The fouled membrane was successively cleaned with tap water, 1.0% NaOH and 0.5% NaClO mixture, and 0.5% HNO_3 solution. The flux recovery ratio was higher than 96.6%, and this value indicated the high repeatability, efficiency, and feasibility of this cleaning method. This method has also helped identify the compositions of foulants on membranes and vice versa.

1. Introduction

Efficient clarification methods for sugarcane juice are necessary to improve the quality of juice and reduce or eliminate the use of chemicals in the sugar industry [1]. An alternative to conventional processes is the application of ceramic membranes, which can save energy, provide high-quality clarified juice, ease operations, and reduce or eliminate chemical consumption [1,2]. Ceramic membrane is a precise filter sintered from Al_2O_3, TiO_2, or ZrO_2 at ultra-high temperature. Ceramic membranes are widely used in various fields to physically remove particles with sizes from 0.005 μm to 10 μm in liquid because of their potential advantages, such as chemical and thermal stability, physical strength, and long service life [3]. Numerous laboratory-scale studies on the treatment of sugarcane juice by ceramic membranes and few pilot-scale and industrial studies have been conducted [4–14].

However, membrane performance deteriorates during the time because of membrane fouling caused by the deposition of suspended or dissolved matters on its external surfaces, at pore openings or within pores. Ceramic ultrafiltration membranes (0.02 μm) have been used to filter the clarified juice (lime defecation) in a sugar mill, wherein 65% of the total clarified juice is subjected to the membrane system [7,8]. Desirable results have been obtained, but flux has gradually reduced because of severe fouling and unsatisfactory membrane cleaning. Fouling is inevitable during membrane filtration and substantially limits the treatment capacity of a membrane system. The fouling and cleaning of membranes are among the main problems impeding membrane applications. Thus, a detailed understanding of the fouling mechanism and an efficient and feasible membrane cleaning method are urgently needed. Jegatheesan et al. [6] employed four mathematical models, namely, cake filtration model, pore narrowing model, combination of external and progressive internal fouling model, and complete pore blocking model, to investigate the fouling mechanisms during the micro- and ultrafiltration of limed and partially clarified sugarcane juice with ceramic membranes. Appropriate methods have also been developed to regenerate fouled membranes. The performance of ceramic membrane filtration of limed and partially clarified sugarcane

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http://dx.doi.org/10.1016/j.seppur.2017.08.046
Received 29 January 2017; Received in revised form 4 July 2017; Accepted 16 August 2017

Nomenclature

List of symbols

UF	ultrafiltration
SEM	scanning electron microscopy
AFM	atomic force microscopy
EDX	energy-dispersive X-ray spectrometry
FTIR	Fourier-transform infrared spectrometry
TMP	transmembrane pressure
CFV	cross-flow velocity
T	temperature
A_s	absorbance at 560 nm
b	cell length (cm)
RDS	refractometric dry substances (°Brix)
ρ	density of the solution (kg/m^3)
t	filtration time (min)
V_f	volume of filtered juice (L)

J_0	initial permeate flux (L/m^2 h)
A_0	total membrane surface area (m^2)
J	permeate flux of time t (L/m^2 h)
J_1	permeate flux of the fouled membrane during sugarcane juice filtration (L/m^2 h)
K_c	cake filtration constant
K_n	pore narrowing constant
K_b	pore blocking constant
J_c	pure water flux of the cleaned membrane (L/m^2 h bar)
J_n	pure water flux of the new membrane (L/m^2 h bar)
ΔP	transmembrane pressure (Pa)
μ	viscosity of the permeate (Pa s)
R_t	total membrane resistance (1/m)
R_m	intrinsic membrane resistance (1/m)
R_f	fouling resistance (1/m)
J_w	pure water flux of the new membrane (m^3/m^2 s)
μ_w	viscosity of the pure water (Pa s)
m	flux decay coefficient (%)

juice has been thoroughly investigated, and significant theoretical and practical contributions have been provided. However, the following limitations were observed in previous studies: (1) Classical fouling models have been used to analyze the decline in flux, but physicochemical analyses, such as SEM, AFM, EDX, and FTIR analysis of membranes or chemical composition changes after cleaning, have yet to be conducted. (2) Partially clarified juice, which is non-limed raw sugarcane juice, has been treated. (3) The obtained cleaning results are based on membranes subjected to slight fouling. Each experimental run of sugarcane juice filtration has been conducted for 4 h. Nevertheless, the membrane cleaning frequency is 12–72 h or even longer in actual applications. Thus, more efficient and feasible cleaning methods should be developed.

Similar reports on ceramic membrane application are mainly based on the filtration of clarified sugarcane juice [6–13]. A high flux can be reached and maintained by low impurity loading in clarified juice, but conventional sugarcane juice treatments should be retained and clarification should be prolonged [12]. Membrane characteristics have been remarkably improved, and the clarification of limed raw sugarcane juice has been achieved [4,5]. In a previous study, mixed juice (limed raw sugarcane juice) has been treated with a 0.05 μm ceramic membrane in a pilot scale, and results have indicated that membrane modules are satisfactory for sugarcane juice clarification. These modules also yield an average flux of 119.1–142.4 L/m^2·h and produce high-quality clarified juice with an increased purity of greater than 1.2 units, a 99.96% reduction in turbidity, and a 10.42% removal of color. A high-quality product with high Pol, low color, and low ash content is also obtained when permeate juice is concentrated and crystallized to form sugar [4]. Nevertheless, insights into this field are limited to observations, and the significance of previous studies is more practical than scientific. Membrane fouling and cleaning during sugarcane juice ultrafiltration have yet to be thoroughly investigated.

Although ceramic membranes have been examined to treat limed raw sugarcane juice in the sugar industry, the sustainable use of these membranes remains unclear. Membrane fouling mechanisms should be elucidated to promote their sustainable use. In our study, the fouling mechanism was systematically explored through model prediction and instrumental analysis during the ceramic membrane ultrafiltration of limed raw sugarcane juice. An effective membrane cleaning method was also proposed to regenerate the fouled membrane. This study aimed to provide a basis for ceramic membrane fouling and cleaning during the ultrafiltration of limed raw sugarcane juice. This work presented basic research on the application of ceramic ultrafiltration membrane to treat limed raw sugarcane juice, and our findings could be used as a reference for future research and practice.

2. Materials and methods

2.1. Sugarcane juice

Raw sugarcane juice (mixed juice) was collected from a local sugar mill (Guangxi, China). The juice was filtered through a 100-mesh stainless steel screen to remove large fibers, treated with milk of lime, and thoroughly mixed with a stirrer to increase pH from 5.2–5.7 to 7.4–7.6 to prevent the conversion of the sucrose fraction into other sugars under sub-acidic conditions. The limed juice was subsequently

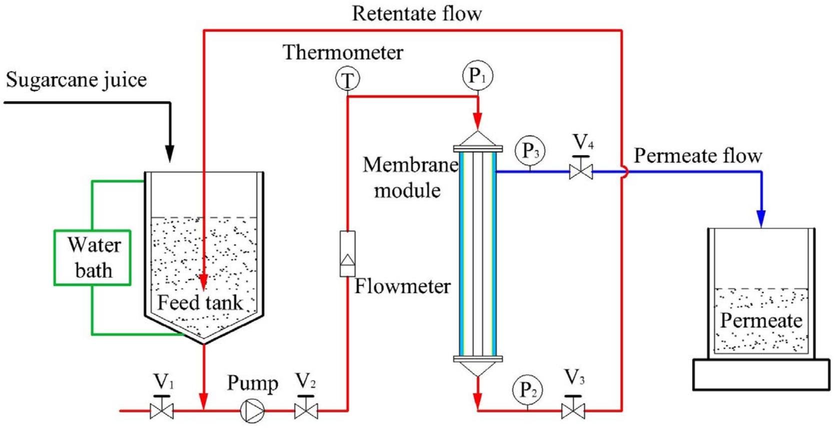

Fig. 1. Schematic of the laboratory set-up.