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Performance of ceramic micro- and ultrafiltration membranes treating limed and partially clarified sugar cane juice

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ABSTRACT

The performance of ceramic membranes with pore sizes of 0.02, 0.05 and 0.10 μm in clarifying limed and partially clarified raw sugar cane juice was investigated under different operating conditions. For the 0.10 μm membrane, the increase in transmembrane pressure (TMP) from 1 to 3 bar increased the initial flux by 15.5% and increased the average flux over a period of 4 h by 11.9%. The initial flux of the 0.10 μm membrane increased dramatically at a TMP of 1 bar when the membrane underwent a chemical cleaning with 1% NaOH and NaOCl equivalent to 3000 ppm free chlorine for 1 h and the average flux over a period of 4 h was also increased. Among the three membranes tested 0.05 μm membrane performed better than the other two membranes and yielded higher initial and average fluxes. Out of the four fouling models used to fit the experimental data, the cake filtration model predicted the initial fluxes of 0.02 and 0.05 μm membrane more accurately. On the other hand, the combination of external and progressive internal fouling model predicted the performance of 0.10 μm membrane better compared to the others. Intermittent air back flushing improved the performance of 0.10 μm but did not have any effect on the performance of the other two membranes. However, all the membranes produced high quality filtered juice.

1. Introduction

The sugar industry needs to find efficient methods in clarifying the raw sugar cane juice in order to improve the quality of the clarified juice and to reduce or eliminate the usage of chemicals (lime). Conventional clarifiers use heavy equipments which lead to high operating costs and associated environmental problems. Further, the mud produced in a conventional clarifier is sent to a rotary vacuum filter to recover the sugar. However, the filtrate from the vacuum filter generally contains impurities and will not be able to enter the evaporation station directly and should be returned to the clarifier. This will increase the loading to the clarifier.

In sugar mills, ensuring the production of juice of consistently high clarity and low color through the clarification process is a challenging task. The variations in the incoming juice characteristics due to differences in cane variety, soil and growing conditions, weather patterns and season makes this task even more challenging. The membrane filtration promises superior quality juice with better clarity, much lower viscosity and noticeable color removal [1–3]. Ultrafiltration of clarified sugar cane juice can be done through spiral wound or flat sheet filtration system using polymeric membranes or tubular filtration system using ceramic membranes [4]. The filtrate from the membrane has an increase of 1.5–3 unit of juice purity, which is a remarkable improvement compared to the increase of 0.5–1 unit obtained in the liming-sulphitation process [5]. Membrane clarification yielded multi-fold improvement in juice clarity with nearly 60% reduction in color [6] as well as reduction in the inorganic contents of the juice.

In a study conducted with 0.02 μm ceramic membrane treating brown sugar solution of 28 °Brix at 60 °C produced 148 and 198 L/(m^2 h) of steady state fluxes at a TMP of 3 bar and cross flow velocities of 5.4 and 7.7 m/s, respectively. When the TMP was increased to 5 bar, the corresponding fluxes were 183 and 217 L/(m^2 h), respectively [7]. The steady state flux was reached within 10 min of the commencement of the experiments. Similarly, in another study, 230, 260 and 150 L/(m^2 h) of fluxes were obtained when treating 20 °Brix solution at 90 °C with 0.14, 0.20 and 0.45 μm membranes [8]. When 50 °Brix solution at 85 °C was treated with 0.1 μm membrane, the flux was around 50 L/(m^2 h) [9]. The 0.1, 0.2, 0.5, 0.8 and 1.4 μm membranes produced 38.0, 27.0, 30.0, 52.0 and 62.7 L/(m^2 h) of fluxes when treating 60 °Brix solution at 80–90 °C [10].

However, application of membranes in clarifying raw sugar cane juice to produce raw sugar using membranes is lacking in sugar mills. Thus, this study is aimed at investigating the performance of a laboratory scale ceramic membrane system in treating limed

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Table 1
Material characteristics and module details of the membrane system used in this study.

Item	Description
Manufacturer	Jiangsu Jiuwu HiTech, Nanjing, China
Membrane type	Tubular
Membrane material	ZrO_2
Membrane support material	α-Alumina oxide
Pore size	0.02, 0.05 and 0.1 μm
Pure water permeability	316 L/(m^2 h bar) (0.02 μm) 597 L/(m^2 h bar) (0.05 μm) 533 L/(m^2 h bar) (0.10 μm)
Porosity	35%
Length	500 mm
Number of channels	19
Channel diameter	4 mm
Surface area	0.1193 m^2

sugar cane juice. The aims of this study are to (i) evaluate the flux obtained for membranes with different pore sizes under different operating conditions such as transmembrane pressure (TMP) and air back flushing, (ii) evaluate the rate of fouling of membrane under the operating conditions mentioned above, (iii) selecting an appropriate mathematical model to predict the performance of the membranes and (iv) identifying appropriate chemicals for cleaning the fouled membrane and quantify the corresponding membrane resistance.

2. Materials and methods

Ceramic membranes with three different pore sizes (0.02, 0.05 and 0.10 μm) were used to filter the limed and partially clarified sugar cane juice under different operating conditions. The specifications of membranes are given in Table 1 and the operating conditions of each experimental run are given in Table 2. The experimental setup of the system is shown in Fig. 1.

Sugar cane variety Q200 was collected from Paluma (Queensland, Australia) and stored inside a large cold room at the Mechanical Engineering workshop of James Cook University at 10 °C for experiments. Raw sugar cane was crushed using the sugar cane miller. The raw sugar cane juice was then filtered through a 250-μm sieve to remove large fibers. Around 40 L of raw sugar cane juice was treated with $Ca(OH)_2$ and mixed by a stirrer to raise the pH from 5.2–5.5 to 7.5. The treated juice was kept unstirred for 1 h for the flocculated solid particles to settle. Supernatant juice was siphoned, filtered through a 125-μm sieve and diluted with DI water to adjust the sucrose content to be around 16 °Brix. The diluted solution (around 50 L) was then used as the feed for experiment. The above pre-treatment was used in order to simulate the conditions applied in sugar mills.

The juice volume in the feed tank was kept constant at 20 L throughout experiment by pumping the juice (30 L) from the limed juice tank with a peristaltic pump continuously. Sugar cane juice in the feed tank was maintained at 60 °C by a water bath. The juice was circulated through the membrane module by the centrifugal pump for juice filtration. The valves before (V1) and after (V2) the membrane module were adjusted to obtain the desired operating transmembrane pressure and crossflow velocity. The cross flow velocity was maintained at 3 m/s in all experiments. The retentate was recycled to the feed tank while the permeate was collected in a vessel placed on an electronic balance (Ohaus-CD33) connected to a computer that received weight data at 5 min intervals. To compute the flux, the weight was converted to volume based on specific weight of the permeate. For experiments with air back flushing mode in runs 5, 7 and 9, compressed air at 5 bar was applied from the permeate side to feed side to evaluate the effect of compressed air on membrane fouling. In this mode the filtration was conducted in a cycle of three periods controlled by solenoid valves and timers: (1) filtration period: 5 min during which the permeate valve (V3) was opened, compressed air valve (V4) and air exhaust valve (V5) were closed; (2) air back flushing period: 4 s with permeate valve and air exhaust valve closed and compressed air valve open; (3) air exhaust period: 4 s where the permeate valve and compressed air valves were closed and the air exhausted valve was opened. Each experimental run was conducted for 4 h. The flux generally reached a steady state condition in 4 h in all experiments and thus the results obtained in those experiments are comparable.

Samples from both the feed tank and permeate stream were collected at initial, after 30 min, 1, 2 and 3 h for analyses. The sample volume collected was recorded and added to the total filtrate volume calculated from the weight data for the flux computation.

After every experiment, the sugar cane juice is drained from the membrane system. The membrane was then rinsed with de-ionized water and then cleaned with chemicals as given in Table 2. Membrane resistance was checked before and after every experiment by measuring the pure water flux at 30 °C and at different TMPs.

3. Analytical methods

Brix is a measure of refractometric dry substance (RDS). The juice was filtered through Whatman filter paper and measured Brix by a digital refractometer (Palette PR-101, Atago).

The Pol is a measurement of the total polarized substances in the juice, which is used to represent the sucrose content in the juice. The dry lead method [11] was used to measure the Pol. A 2-g of subacetate of lead was mixed with 200 mL of juice and mixed thoroughly. The solution was let several minutes for the precipitate to settle and the supernatant was filtered through Whatman filter paper. A polarimeter (SQF-WXG4, Vanco) calibrated in sugar degree (°Z) was used to measure the Pol reading of the filtered supernatant. The

Table 2
Operating and cleaning conditions of the experimental runs.

Run no.	Membrane pore size (μm)	TMP (bar)	Air back flushing	Cleaning chemicals[a]	Cleaning time
1	0.10	1.0	No	2% HNO_3 followed by 2% NaOH	40 min each
2	0.10	2.0	No	2% HNO_3 followed by 2% NaOH	40 min each
3	0.10	3.0	No	2% NaOH, 1% NaOH + 3000 ppm free chlorine	1 h, 1 h
4	0.10	1.0	No	1% NaOH + 3000 ppm free chlorine	1 h
5	0.10	1.0	Yes	1% NaOH + 3000 ppm free chlorine	1 h[b]
6	0.05	1.0	No	1% NaOH + 3000 ppm free chlorine	1 h
7	0.05	1.0	Yes	1% NaOH + 3000 ppm free chlorine	1 h
8	0.02	1.0	No	1% NaOH + 3000 ppm free chlorine	1 h
9	0.02	1.0	Yes	1% NaOH + 3000 ppm free chlorine	30 min

[a] Cleaning was carried after each run; the membrane was first cleaned with pure water and then with the chemicals.
[b] Used cleaning solution was replaced four times by fresh cleaning solution during this cleaning.