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Refining sugarcane juice by an integrated membrane process: Filtration behavior of polymeric membrane at high temperature

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ABSTRACT

Application of membrane filtration to sugarcane juice refining is appealing because it can eliminate the usage of chemicals, achieve continuous and automated production, as well as produce superior quality of juice. However, some technical problems, such as low permeate flux, high sucrose loss in membrane retentate and serious membrane fouling, are impeding this technological upgrading in sugar industry. In this work, an integrated membrane process consisting of a tubular loose ultrafiltration (UF), a spiral-wound tight UF and a spiral-wound NF was developed to refine the raw sugarcane juice at pilot-plant scale. With a super high volume reduction ratio (VRR) of 20, the loose UF was able to be operated at a flux from 30 to 70 L m^{-2} h^{-1}, and the tight UF could run at a flux from 10 to 40 L m^{-2} h^{-1}; at the same time, the color removal kept more than 95%. Moreover, diafiltration operation could recover most of sugar in the UF concentrates, leading to a high sucrose recovery of up to 98% in two-stage UF. A novel cascade diafiltration mode was proposed to save water by 25% compared with the separated diafiltration. Mathematical models could well predict the diafiltration efficiency for the loose UF but not for the tight UF. Permeate flux of the loose UF was dominated by membrane fouling while for the tight UF, osmotic pressure played a more important role in the flux decline. With a suitable cleaning strategy, the performance of this integrated membrane process can be nearly regenerated although the temperature jump between filtration and cleaning (60–30 °C) might result in some foulants accumulating in the membrane system. These results would serve as a valuable guide for process design and practical operation in subsequent industrial application.

1. Introduction

The manufacture of plantation white sugar contains several successive steps: (1) juice extraction from cane or beets by crushing; (2) clarification and decoloration of raw juice; (3) concentration of clarified juice by multi-effect evaporation; (4) syrup sulphitation; (5) crystallization [1–3]. The second step plays a vital role in the sugar quality and productivity [4]. Conventional purification treatment involves addition of lime and sulfur dioxide, followed by boiling the treated juice, and the resulting sludge is then removed by sedimentation and vacuum filtration [2,3]. However, due to the addition of chemicals as well as manual and batch operation, this traditional refining method suffers from inferior and unstable product quality, high operation and reagent costs, and serious environmental problems caused by solid waste [1,4]. Therefore, alternative processes, such as activated carbon adsorption [5,6], electrodialysis [7], ion exchange [8] and membrane filtration [4,9], were explored to solve the above-mentioned problems. Among these methods, membrane filtration, particularly ultrafiltration (UF) is considered as the most promising one because it can eliminate the usage of chemicals, achieve continuous and automated production, and produce superior quality of juice [1,10].

Although research on the purification of sugarcane juice by membrane filtration began in the early 1970s [11], the use of membranes for this application is rare in Chinese sugar mills, and, indeed, the world [1,12]. In fact, there are three technical limitations impeding this technological upgrading in sugar industry. First, there was a trade-off between permeate flux and color removal [13,14]. For instance, Hamachi et al. found that when color removal increased from 37% to 55% by using the membrane with smaller pore size, the steady flux decreased by 69% [13]. In a pilot-plant test, Ghosh and Balakrishnan observed a low permeate flux of 7 L m^{-2}h^{-1} with a color removal of 47% [15]. To break this trade-off, the development of high-performance membrane (higher porosity and stronger antifouling performance) and

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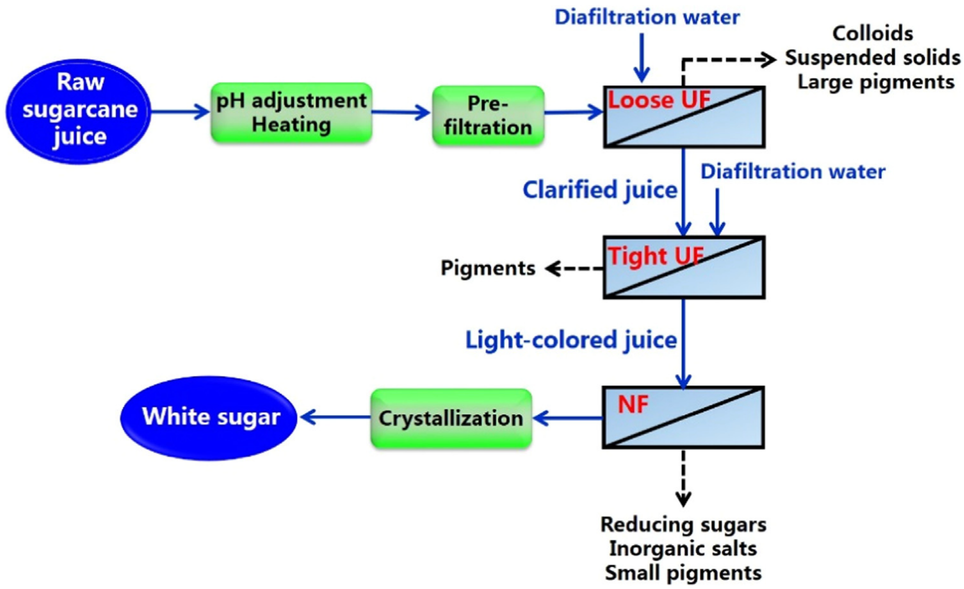

Fig. 1. Schematic diagram of sugar production from sugarcane juice by an integrated membrane process.

Table 1
Characteristics of raw sugarcane juice after pH adjustment and pre-filtration.

Index	Value
Brix (%)	12.9–15.2
Purity (%)	62.7–70.5
Sucrose (%)	8.2–10.4
Color (IU/560 nm)	15000–30000
Turbidity (MAU/560 nm)	21000–41000
Reducing sugar (%)	1.7–3.2
Conductivity ash (%)	0.019–0.020
pH	6.9–7.5
Density (g mL^{-1})	1.07

process integration are required. Second, the sugar loss in the UF concentrate would debase the benefit of this technology since UF membrane could retain some sugar [3,14]. Additional chemical treatment for the UF concentrate would introduce harmful agents into the juice, thus reducing the added-value of the by-products. Diafiltration operation may recover most of the residual sugar without adding chemicals [16], while there has few report yet regarding the sugar recovery from the UF concentrate [9]. Third, due to the high viscosity and complex composition of raw sugarcane juice, severe membrane fouling (e.g. cake layer and pore narrowing) and flux decline would occur with processing time, especially at a high Brix of juice [12,17,18]. Saha et al. claimed that polysaccharide fractions in sugarcane juice mainly contributed to membrane fouling [19], and they also modified commercial UF membranes with poly(ethylene glycol) methacrylate (PEGMA) monomer to control the fouling caused by polysaccharides in sugarcane juice [20]. Moreover, Balakrishnan and co-workers made great efforts to scale up the trials in the sugar mills [2,15,21], and they applied spiral wound UF modules (20 kD, polyethersulphone) to clarify the raw sugarcane juice (10 m^3/h) for more than 180 h, however, the flux is too low to meet the demand of industrialization [15]. Therefore, in order to industrialize this technology, more efforts regarding membrane selection/integration, residual sugar recovery, fouling mechanism and membrane cleaning should be made at pilot-plant scale.

On the other hand, due to the high viscosity of the sugarcane juice and the pretreatment demand, the purification of sugarcane juice by membrane filtration should be carried out at above 50 °C in sugar mills. This provides an opportunity to study filtration behavior of polymeric membrane at high temperature, since the relevant literature was quite scarce. Poly (phthalazine ether sulfone ketone) (PPESK) membrane is thermostable and commonly applied at high temperature. Generally, the permeate flux of PPESK membrane was increasing with temperature, while the retention started to decline when the temperature was more than 60 °C [22,23]. For other membrane materials, such as polyethersulfone, polysulfone, regenerated cellulose and polyamide, Kowalska et al. found that the retention was decreasing when temperature increased from 25 to 55 °C [24]. Manttari et al. claimed that an increase in temperature decreased the retention until a critical temperature of the membrane was exceeded (~60 °C), and after that temperature the flux even decreased and the retention increased [25]. At elevated temperature, the higher permeate flux could be explained by the lower feed viscosity, while the greater diffusion coefficient and larger effective pore diameter of membrane might cause a reduction in retention [26]. However, the concentration polarization would be reduced at higher temperature (faster back diffusion), which might increase the observed retention. Moreover, the severe fouling formation at high temperature was also likely to be responsible for the retention augment mentioned by Manttari et al. [25]. These previous studies mostly focused on the permeate flux and retention of the membranes [10]. To the best of our knowledge, there has been no report regarding the fouling behavior and cleaning strategy when the membrane is operated at high temperature (~60 °C).

The present work aimed at establishing an integrated membrane process to obtain both high color removal and satisfactory permeate flux in refining sugarcane juice. As shown in Fig. 1, a loose tubular UF (with big pore size) was applied to remove colloids, suspended solids and large pigments in sugarcane juice, and a tight spiral wound UF (with small pore size) was employed to further decolorize the clarified juice, and then a spiral wound nanofiltration (NF) was used to concentrate the final UF permeate and at the same time decrease the contents of reducing sugar, salts and small pigments in the syrup. Efforts were also made to recover sugar from the UF retentate by different diafiltration operations. Moreover, flux behavior and fouling mechanisms during the UF/NF concentration process at high temperature were illustrated, and membrane cleaning and long-term operation stability of sugarcane juice refining by membrane filtration at pilot-plant scale were investigated.