Separation and Purification Technology 149 (2015) 322–330

Contents lists available at ScienceDirect

Separation and Purification Technology

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

Short Communication

Hybrid operation of the bio-ethanol fermentation

Qian Kang [a], Bart Van der Bruggen [b], Raf Dewil [c], Jan Baeyens [a], Tianwei Tan [a,*]

[a] Beijing University of Chemical Technology, College of Life Science and Technology, Beijing Key Lab of Bioprocess, Beijing, China
[b] KU Leuven, Department of Chemical Engineering, Process Technology for Sustainable Systems Division, W. De Croylaan 46, 3001 Leuven, Belgium
[c] KU Leuven, Department of Chemical Engineering, Process and Environmental Technology Lab, J. De Nayerlaan 5, 2860 Sint-Katelijne-Waver, Belgium

ARTICLE INFO

Article history:
Received 5 January 2015
Received in revised form 6 May 2015
Accepted 8 May 2015
Available online 20 May 2015

Keywords:
Bio-ethanol
Inhibition
PDMS membrane
Separation
Flux
Economy

ABSTRACT

Bio-ethanol is a clean and renewable fuel of increasing importance. It is biochemically produced by fermentation of different feedstock in an aqueous broth. Its purification is generally achieved by distillation (till the water/ethanol azeotropic mixture of ~95 wt% ethanol is reached), followed by molecular sieve or membrane dehydration to obtain anhydrous ethanol. Drawbacks of the current production process are the high energy consumption of the distillation and dehydration, and the potential inhibition of the fermentation at high ethanol concentrations. To reduce the impact of both drawbacks, the use of pervaporation in the fermenter broth offers a significant potential. The present paper assesses this hybrid operation mode and its potential in large-scale applications. The experimental results demonstrate a high permeate flux and a good membrane selectivity. At a feed temperature of ~70 °C, a membrane unit of ~900 m^2 can reduce the steam requirements, whilst also lowering the effective ethanol concentration in the fermenter to below the inhibition threshold. Overall operating costs are reduced by nearly 20 €/ton bio-ethanol.

1. Introduction

Bio-ethanol is considered as the alternative renewable fuel with the largest potential to replace fossil-derived fuels, with a world production in excess of 100 million m^3 in 2012 [1], and with a potential for a significant reduction of greenhouse gas emissions [2]. The vast majority of ethanol for use as bio-fuel, is produced by fermentation [3–6], where certain species of yeast (e.g., *Saccharomyces cerevisiae*) or bacteria (e.g., *Zymomonas mobilis*) metabolize sugars in oxygen-lean conditions and produce ethanol and carbon dioxide. The general flow sheet of the fermentative bio-ethanol production, including the successive processing steps, is illustrated in 1. The difference between 1st, 2nd and 3rd generation raw materials (sugar-based, lignocellulosic-based or algal-based, respectively) is also indicated, together with the possible use of membrane separations. The processing steps of Fig. 1 and their principles were assessed by Kang et al. [6]. Whereas food-related feedstock was traditionally used in the 1st generation processes (sugar cane, e.g. Brazil; corn and wheat, e.g. USA and China), this feedstock is now replaced by non-food raw materials, such as sweet sorghum or cassava [7]. The world's first large-scale cassava ethanol plant was built in China by Cofco in 2007, with an annual production capacity of 200,000 tons [8].

Membrane techniques can be integrated in the process, and some relevant applications are illustrated in Table 1, where each membrane technique targets specific objectives.

The importance and potential of bio-ethanol in general, and of the associated technologies, are highlighted in the literature, with recent exponential research efforts illustrated in Fig. 2.

Clearly, the use of membrane technology in the production of bio-ethanol is gaining increased attention.

Whether first, second or third generation feed stock is used, fermentation produces an alcohol-lean broth only (~12 vol%). The ethanol must hence be purified. Fractional distillation can concentrate ethanol to 95.6 vol% (89.5 mol%), the azeotrope with a boiling point of 351.2 K. Several distillation flow sheets have been presented in the literature, with minor process-specific differences (2 or 3 distillation columns), but with an overall equivalent mode of operation. Flow sheets and operating data of the Cofco (3 column) and Lurgi (2 column) concepts have been compared by Kang et al. [6], and their analogy is outspoken since the first Cofco column does not considerably enrich the top and side streams, but mostly eliminates the fine suspended solids of the broth, evacuated in the bottom stream. Kang et al. [6] assessed the energy balance of the processes, both as lean fermentation (11–12 wt%) and as Very High Gravity (VHG) fermentation

---

* Corresponding author.
E-mail addresses: kqgrace@126.com (Q. Kang), twtan@mail.buct.edu.cn (T. Tan).

http://dx.doi.org/10.1016/j.seppur.2015.05.007
1383-5866/

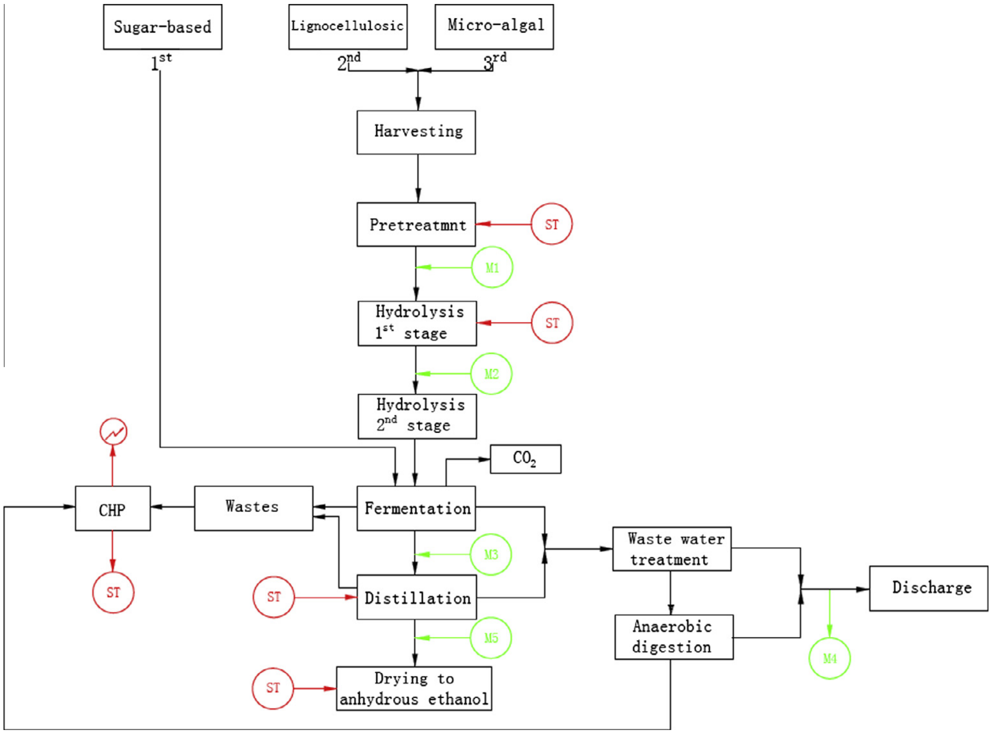

Fig. 1. Bio-ethanol production and potential membrane applications (ST: steam; M1: ultra- and nanofiltration, reverse osmosis; M2: microfiltration; M3: M2 and subsequent pervaporation by hydrophobic membrane; M4: combined membrane processes; M5: hydrophilic membrane).

Table 1
Possible membrane applications in bio-ethanol production.

Membrane technique	Application
Microfiltration [9–13]	– In microalgae harvesting – To replace the traditional broth mechanical separation – To protect subsequent membrane techniques, distillation columns and heat exchangers from fouling – In the treatment of effluent streams
Pervaporation [14–20]	– To reduce the distillation energy consumption, often as hybrid operation – To dewater ethanol after the 95 wt% azeotrope
Reverse osmosis/ nanofiltration [21–26]	– In removing inhibitors after saccharification – For sugar concentration
Ultrafiltration [27–29]	– To recycle micro-organisms, or other value-added chemicals such as cellulase in the enzymatic hydrolysate

(15–19 wt%): the results demonstrate that the production costs of fermentative bio-ethanol are significantly determined by the steam consumption, varying from ~3.0 kg steam/kg bio-ethanol, to 1.9 kg steam/kg bio-ethanol when reboilers and condensers are integrated, and as low as 1.7 kg steam/kg bio-ethanol for VHG fermentation at 19 vol%. The molecular sieve dehydration of the azeotropic ethanol/water phase represents 0.5 kg steam/kg bio-ethanol in the above steam consumption. This dehydration steam requirement can be omitted by replacing the molecular sieve dehydration by hydrophilic membranes [20]. The major drawbacks of the current production remain related to this significant energy-intensive distillation/dehydration stages; and to the possible limitation of the ethanol yield in the fermenter due to ethanol inhibition, responsible for the low achievable ethanol concentrations (11–12 wt% only). To reduce the impact of these drawbacks, pervaporation of the fermenter broth has been advocated in the literature, as illustrated in Section 2: not only can the distillation requirements be reduced, but ethanol can be continuously extracted from the fermenter broth, thus avoiding the problem of ethanol-based inhibition. Further advantages of continuously removing ethanol from the fermentation broth include a slightly higher conversion of sugars to ethanol, and a higher production capacity of the fermenter per unit volume, especially if the VHG operating mode is selected and ethanol inhibition is overcome.

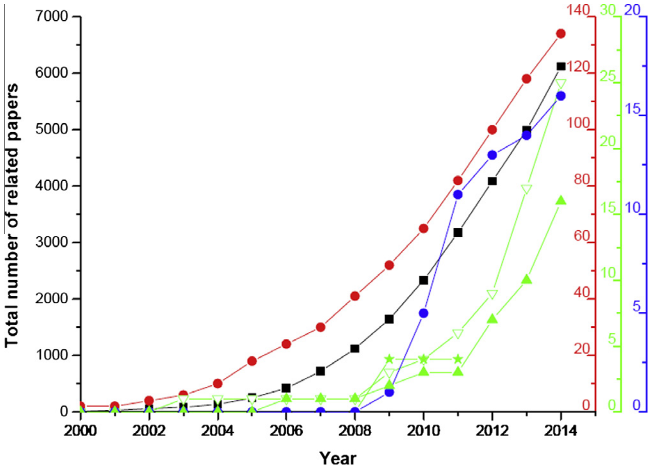

Fig. 2. Literature (2000–2014) concerning bio-ethanol SCOPUS with keywords (left: ■ bio-ethanol general; right: ● fuel-application; ▲ simulation and separation; ▽ membrane technology; ● Very High Gravity fermentation (VHG)).

The present paper will, therefore, investigate the use of a commercial pervaporation membrane to selectively permeate ethanol from the aqueous fermenter broth. Experimental results will be