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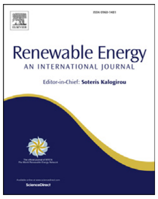

Recovery of ethanol from scrubber-water by district heat-driven membrane distillation: Industrial-scale technoeconomic study

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ABSTRACT

Membrane distillation (MD) integrated with a district heating network (DHN) to supply the heat demand has been investigated in a bioethanol production plant (BP). The specific application considered here is ethanol recovery from fermentation off-gas (CO_2) scrubber water, where the main objective of this study was to develop an air gap MD system that is driven by heat from DHN, thereby offloading the steam-driven distillation column. Experiments conducted on an MD laboratory facility combined with data from the bioethanol industry were used to assess the technological and economic feasibility of this integrated MD-DHN-BP system. Comparisons were also made between the distillation column and MD units regarding heat demand and economic savings. Results of the study showed that MD could be a competitive technology for ethanol recovery given that low-grade heat such as from district heating network or waste heat is accessible.

1. Introduction

The Renewable Energy Directive sets general strategies for the production and promotion of energy from renewables in the EU. It states that by 2020 the EU should fulfill at least 20% of its total energy requirements with renewables, which is to be achieved through the realization of individual national targets. All EU countries must also ensure that at least 10% of their transport fuels come from renewable sources by 2020 [1]. In November 2016, the Commission issued a revised Renewable Energy Directive targeting a minimum of 27% renewables in the total EU energy demand by 2030 [2]. Ethanol production from renewable energy is a promising biofuel supply for the future, especially for transportation. The annual global bioethanol production has almost doubled from 45 000 000 m^3 in 2007 from 87 000 000 m^3 in 2014 [3]. The environmental and economic benefits (including subsides) are the main reasons for the increasing supply of bioethanol, leading to a reduction in petroleum demand [4]. Bioethanol is a fuel which can be derived from sugar cane, sugar beet and other starch-containing plants such as wheat, corn, straw, and wood [5]. The majority of the large scale production of bioethanol currently employs yeast fermentation of sugars extracted from crop-based feedstock, followed by separation of the bioethanol from the fermented broth by distillation [6]. Large scale bioethanol production processes often require significant amounts of energy, especially heat in the form of steam for the heaters, evaporators, and distillation [7]. The costs related to this heat supply have a direct impact on the economic feasibility. To produce economically competitive ethanol, lowering the energy demand and hence the associated costs must be taken into consideration.

Research and development in Sweden and the wider Nordic region are pushing for commercialization of advanced bioethanol production plants. A demonstration pilot plant for hemicellulose-derived bioethanol production has been in operation in Örnsköldsvik, Sweden since 2004. The plant has a capacity of 2 tons of dry raw material per day; ethanol is concentrated up to 90% in a single distillation column [8] with a yearly production of 18 million litres per year [9]. In 2015, St1 Nordic Oy built a bioethanol plant in Gothenburg with biowaste as a feedstock. This bioethanol plant is the fifth in addition to four similar units in Finland, and has an annual production capacity of 5 million litres 100% wt. ethanol from 18 thousand tons of bakery waste [10]. St1's Norwegian subsidiary has also planned to invest in a 50 million litres per year bioethanol

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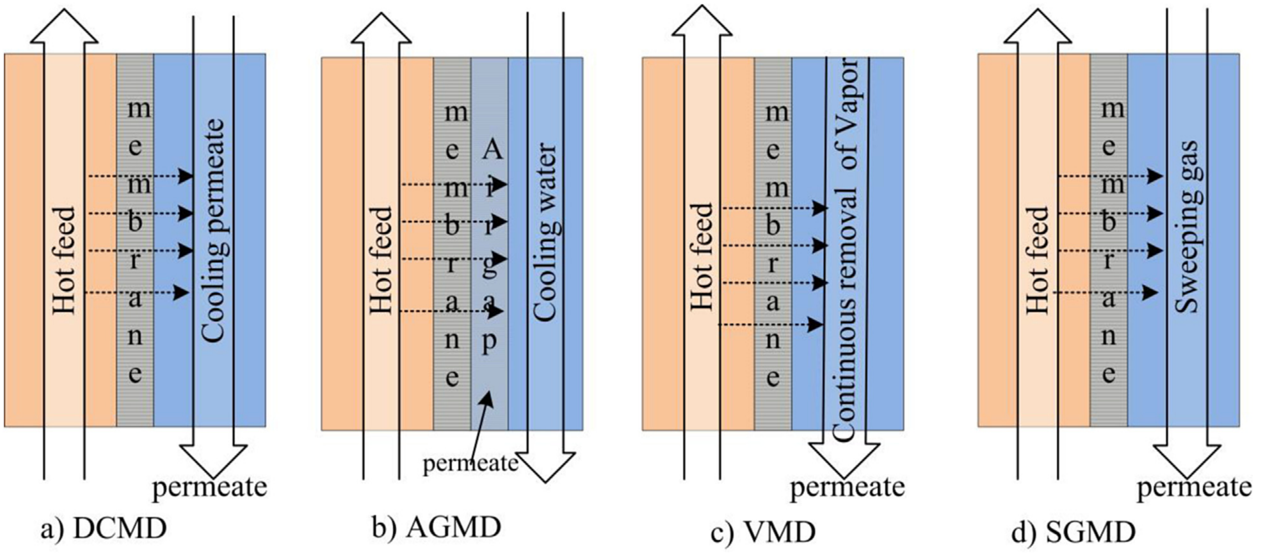
production plant in Norway to be operational by 2021. The raw materials for this plant intended to be sawdust and wood chips. In comparison the Lantmännen bioethanol facility in Norrköping, Sweden represents an example of a fully commercial operation with 250,000 m^3/yr ethanol production from crop feedstocks (more on this facility to follow).

Membrane distillation (MD) is a developing separation technology in which a hydrophobic microporous membrane separates out a volatile liquid or gaseous component from a hot feed. The MD process requires thermal energy to heat up the feed solution (the one to be treated) and cooling water circulation on the other side of the membrane for cooling the vapor. Hence, the temperature difference across the membrane causes vapor pressure gradient, resulting in vapor transfer through the pores from the hot side to the cooling part of the membrane [11]. Four common MD system configurations, as shown in Fig. 1, have been in use since the inception of the technology a few decades ago. The hot feed side is maintained in direct contact with one side of the membrane in all types, with variations made only on the permeate side. Direct Contact Membrane Distillation (DCMD) places the membrane in direct contact with permeate water. DCMD is the simplest design capable of producing reasonably high flux, and is suitable for applications such as desalinating sea water and concentrating aqueous solutions. Air Gap Membrane Distillation (AGMD) interposes an air gap between the membrane and a condensation plate. This configuration is known to have the highest energy efficiency, but the flux obtained is generally lower [12]. Vacuum Membrane Distillation (VMD) and Sweep Gas Membrane Distillation (SGMD) alter the pressure or convective state to enhance volatile removal. AGMD can be widely used for most membrane distillation applications, especially when energy availability is low, and is judged to be the most suitable technology for this application.

MD has been mostly investigated for water purification, desalination, and for concentration or recovery of aqueous-borne compounds in various industrial applications. This separation has some advantages over conventional approaches: relatively lower thermal energy costs due to the possibility of driving the process using low-grade heat/waste heat from industries and reduced vapor space compared to conventional distillation; a complete rejection of dissolved, non-volatile species to produce ultrapure water (electrical conductivity below 5 μS/m); much lower membrane fouling as compared with microfiltration, ultrafiltration, and reverse osmosis; lower operating pressure than pressure-driven membrane processes and lower operating temperature (60^{o}C-90 °C) as compared with conventional evaporation [13]. Hence, MD can be integrated with low-grade heat sources such as waste heat in power plants and related industries, solar thermal collectors and geothermal heat sources. This enables MD to be installed at different scales and applications, from solar-driven desalination [13–15], household drinking water and hot water supply [16] to large scale water purification in semiconductor industries [17].

Previous studies on separation of ethanol-water mixtures by membrane distillation reported promising results mainly regarding separation efficiencies. A study of AGMD for reclaiming fermentation products including acetone, n-butanol, and ethanol (ABE) from aqueous solutions was investigated by Banat and Al-Shannag [18] who found that the most effectively removed compound was n-butanol; and temperature, air gap width, and alcohol concentration all affect the flux and selectivity of compounds recovery. Garcia-Payo et al. [19] used different membrane materials and operation parameters including feed temperatures, flow rates, and different ethanol concentrations to evaluate AGMD separation efficiency. The authors reported increases in permeate fluxes with an increase in temperature and rate of the feed solution and decrease in the air gap. Banat and Simandl [20] studied AGMD for ethanol–water separation process by using PVDF membranes. The authors reported that from a maximum feed concentration 10 wt% ethanol and feed temperature ranges of 40–70 °C, and ethanol selectivity 2–3.5 was achieved [20]. Membrane distillation integration with fermentation process in ethanol production has been investigated as well. Gryta et al. [21,22] have studied the fermentation of sugar using a tubular bioreactor integrated with an MD system. The removal of fermentation broth by-products by MD was found to increase the efficiency and the rate of sugar conversion to ethanol. In a related investigation, MD integration with fermentation enabled to achieve a higher content of ethanol in the broth due to continuous removal of ethanol and other products which otherwise would inhibit the fermentation [22]. Similarly, other researchers [23] reported the effect of MD integrated continuous ethanol recovery on the effect of fermentation degree of sugars in the broth and total ethanol production in comparison between batch



a) DCMD b) AGMD c) VMD d) SGMD

Fig. 1. The four most common MD module configurations.

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