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Analysis of energy saving by combination of distillation and pervaporation for biofuel production

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ABSTRACT

Energy consumption of distillation needs high portion of the total energy demand of the fuel-grade bioethanol production. Pervaporation, being a membrane separation process, is a promising alternative process to distillation. A detailed analysis was performed considering the energy demand of concentration of ethanol solution obtained during fermentation up to the fuel-grade quality applying both hydrophilic and hydrophobic membranes. It was also discussed how the specific energy demand of the process varies during the pervaporation process and how energy consumption can be reduced applying pervaporation process with different operating modes. It was stated that standalone pervaporation process can provide fuel-grade quality biofuel at very high separation coefficient, only, using consecutively switched hydrophobic and hydrophilic membranes. Three-stage pervaporation process is needed at separation coefficient of 50, and two-stage one at separation coefficient of 100 to achieve the desired quality. Application of a hybrid process with lower membrane separation coefficient can give the desired quality by lower energy than that the distillation alone. Thus, the hybrid process can provide saving of essential amount of energy comparing it with the energy demand of distillation. However, the commercially available membrane, at present, has not the desired selectivity for replacing, at least partly, the distillation.

1. Introduction

Bioenergy from renewable, agricultural resources is already today a viable alternative to fossil fuels. However, to meet the increasing need for bioenergy several raw materials have to be considered for the production of biofuel as first-, and second generation bioethanol or biomass. Several biorefinery technologies can be applied [1], e.g. dry-milling-, wet-milling technologies for grain resources or application of lignocellulosic biomass as potential alternative bioenergy resources.

Several processes exist for the production of bioethanol as transportation fuel. Currently, processes using grain or sugar beet as raw material are used, but using various lignocellulosic raw materials such as straw, wood and waste [2–4] is gaining increased attention. Lignocellulosic biomass conversion to biofuel involves several steps [1,5,6]. From those the main ones are: pre-treatment, hydrolysis, fermentation, dehydration of ethanol of fuel-grade quality, namely more than 99.5 wt% ethanol [7]. The fermentation product is usually a dilute aqueous solution containing 3–12 wt% of ethanol. Especially, low ethanol concentration of the fermentation broth, about 3–5 wt%, can be obtained applying lignocellulosic raw material [4]. Separation of ethanol from the fermentation broth is an energy-intensive process. It usually takes up a large fraction of the total energy requirement for the whole biorefinery [5]. In general, ethanol distillation up to 85 wt% overhead product is effective, while for the feed containing more than 85 wt% ethanol, distillation becomes expensive. Galbe and Zacchi [8] stated that the energy demand in distillation unit changes between about 7 to 10 MJ/kg$_{Et}$, in the feed ethanol concentration range of 3–10 wt%. Similar results were published by Vane [9]. Later Huang et al. [5] discussed how the energy demand of ethanol purification can be lowered by combining distillation and membrane vapour permeation. Economic analysis of corn-based bioethanol production by means of continuous fermentation–pervaporation process was

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Nomenclature

A Membrane area (m^2)
C Concentration (mol/m^3), (wt%)
F Liquid flow rate (m^3/s)
H Heat of evaporation (MJ/kg)
J Permeation rate (mol/m^2s), (kg/m^2s)
P Permeability coefficient (m/s)
Q Energy demand for unit of ethanol permeated (MJ/mol), (MJ/kg)
V Volumetric velocity (m^3/s)

Greek symbols
ξ Separation coefficient hydrophobic membrane (Eq. (2))
ξ^* Separation coefficient for hydrophobic membrane ($\xi = 1/\xi^*$, Eq. (3))
θ ($\theta = J_w/J_{Et}$)

Subscripts
Et Ethanol
in Inlet
out Outlet
p Permeate
w Water

Superscript
L Feed
G Liquid (condensed) permeate

analyzed by O'Brien et al. [10]. The continuous removal of the fermentation product enables the user to lower the production costs. They stated that the production cost by conventional fermentation-distillation system (0.226 $/L_Et) is 19% cheaper than fermentation–pervaporation–distillation operation (0.27 $/L_Et). Note the ethanol content of fermentation, the permeation rate, the permeate concentration was 7.1 wt%, 0. 15 $kg/m^2/h$, and 42 wt $\%_{Et}$ ($\xi = 9.5$), respectively. They concluded that this new process could achieve break-even with the conventional case if either the flux could be increased to 0.2 $kg/m^2/h$ or the permeate concentration raised to 0.55 ($\xi = 16$). Analysis of production costs of the lignocellulosic biomass came in focus of researchers in the last decade [11–14]. According to calculation of Gnansounou and Dauriat [11], the production cost of ethanol from straw is about 0.73 $/L_Et, from which the distillation cost accounts 0.042 $/L_Et which is 11.67 % of the total non-feedstock cost, namely 0.36 $/L_Et. According to the International Institute of Sustainable Development's report [13], the production cost of lignocellulosic bioethanol is predicted to be 0.76 Euro/L_Et. The recent report of NREL of US Department of Energy [14] predicted the minimum ethanol selling price to be 0.57 $/L_Et (calculated by 2007$) applying 231 Million L_Et/y capacity (from which the cost distributions are: feedstock: 0.195, enzymes: 0.09, conversion: 0.285 $/L_Et). Distillation accounts 0.032 $/L_Et from this sum, which is 18.3 % of the total manufacturing costs of 0.175 $/L_Et, namely the sum of pretreatment (0.09 $/L_Et), saccharification-fermentation (0.053 $/L_Et) and distillation.

The main question to be answered is whether the application of the membrane separation process, namely the pervaporation as a promising separation process, offers a real alternative to conventional distillation and also whether its standalone or combined application with distillation can really lower the energy demand of biofuel production and accordingly its production costs. Increase of the ethanol concentration, from that in the fermentation broth up to the biofuel-grade (more than 99.5 wt%), is mostly carried out by distillation in conventional ethanol separation processes. The distillate stream (approximately 90 wt% ethanol) then undergoes dehydration (commonly adsorption, pervaporation, and vapour permeation) to produce anhydrous ethanol product of fuel grade [15]. Nowadays, the application of the so called hybrid process, namely combination the distillation with pervaporation, as a potential combined process of the next future, could come to the front due to the relatively high permeation rate and selectivity of the pervaporation [16]. Vane [9] reviewed various approaches to integrate pervaporation recovery of ethanol from fermentation broth. He compared the energy demand of distillation and one-stage pervaporation, applying membrane with different separation factor. But this comparison did not mention the insufficient, much lower than the demand, fuel-grade quality, product concentration of the one-stage pervaporation. The additional purification of this product needs, as will be shown in this paper, additional energy supply. More recently Huang et al. [17] and Vane et al. [18] proposed a process which combines distillation and vapour permeation to improve the energy efficiency of the process. The economical applicability of pervaporation depends strongly on the efficiency of the separation of ethanol–water binary mixture [19,20]. Shao and Huang [21] reviewed the applicability of polymeric membranes for concentration of ethanol up to fuel grade from 90 wt% ethanol. Accordingly, the selectivity changed between 100 to more thousand using e.g. alginate, chitosan or other membranes. Recently, extensive research has been carried out for concentration of the azeotropic mixture of ethanol–water [22–25]. Applying NaX [22], or Faujasite zeolites [26], or very thin zeolite [27,28] nanocomposite [29], silica [30], modified PDMS {poly(dimethyl siloxane)} [24], separation coefficient of more hundreds could be reached. Several papers have also been published for concentration of ethanol from fermentation broth, mostly applied different construction of cross-linked alginate [30,31], cross-linked chitosan [32] or modified PDMS membranes [22]. The separation factor, ξ, can reach 1000 by these membranes which, as will be shown, can provide ideal means for separation of ethanol-water mixtures. In general, the ethanol–water separation factors of hydrophobic membranes are approximately ranked in the following order: PDMS < composite membranes < zeolite membranes [5].

No detailed analysis has been found of the energy consumption of pervaporation depending on its selectivity regarding the desired product concentration. The analysis of Vane [9] did not give adequate data for energy demand of a pervaporation process

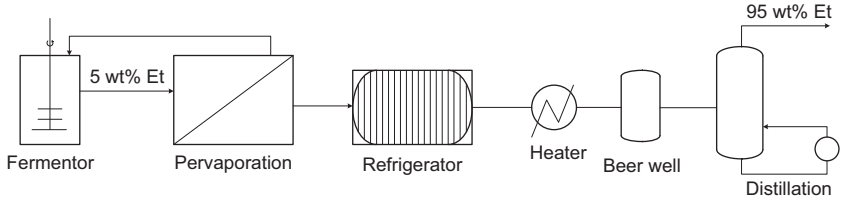

Fig. 1. Schematic diagram for fermentation–pervaporation and distillation for producing bioethanol of fuel grade.