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Energy Saving Processes of Biofuel Production from Fermentation Broth

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The energy used for distillation in bioethanol production reaches the 40 % of the total energy demand. The pervaporation is an important alternative process to distillation that can be applied as a hybrid process or even as a single process to produce high quality biofuel. It will be shown how the energy demand, $MJ/kg_{Ethanol}$ energy, can be saved applying pervaporation process with different separation factors and operating modes. It is stated that relatively high separation factor is needed to lower the energy demand below a simple distillation column.

1. Introduction

Bioenergy from renewable 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 e.g. bioethanol and biogas and several biorefinery technologies (dry-milling-, wet-milling technologies, applying lignocellulosic biomass, etc.) can be applied. Bioethanol is regarded as one of the main biofuels for application in the transport sector. In this paper the bioethanol production followed by enzymatic hydrolysis, fermentation and distillation or as alternative method by pervaporation has been briefly discussed. Main points of this paper are to show how energy or cost can be saved during the production of biofuel from the fermentation broth. It will be tried to show whether the pervaporation offers a real alternative to distillation.
Several processes exist for the production of bioethanol. Currently processes using grains or sugar beets as raw material are used, but using various lignocellulosic materials such as straw, wood and waste (Solomon et al., 2007; Petersson et al., 2007) is gaining increased attention. The ethanol production from lignocellulose creates severe technical challenges, such as a need for efficient pretreatment. In lignocellulosic materials, cellulose as a linear polymer of glucose is associated with hemicelluloses and surrounded by lignin seal. The pretreatments are still mostly thermal, thermo-mechanical or thermo-chemical and require a considerable input of energy (Kamm and Kamm, 2004). The lignocellulosic biomass conversion can have several steps, from that the main steps of the biofuel production are: pretreatment (in case of lignocellulosic biomass), hydrolysis, fermentation and concentration and purification of ethanol obtained during the fermentation up to the biofuel quality, i.e. the ethanol concentration should be larger than 99 %.
Downstream from the fermentor is usually dilute aqueous solution containing 5-12 wt% ethanol. 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 (Huang et al., 2008), it needs about 40 % of the total energy demand. In general, for the solution containing 10-85 wt% ethanol, distillation is effective, while for the mixture containing more than 85 wt% ethanol, distillation becomes

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expensive. Recently, the separation of dilute ethanol-water mixture is usually divided into two steps: approximately 92.4 wt% ethanol is firstly obtained from dilute aqueous solution by using ordinary distillation then the resulting ethanol is further dehydrated in order to achieve anhydrous ethanol. Galbe and Zacchi (2002) stated that the energy demand in a single distillation unit changes between about 7 to 10 MJ/kg ethanol, in the feed ethanol concentration range of 3 to 10 w%. Similar results were published by Vane (2005). Recently Huang et al. (2010) discussed how can be lowered the energy demand combining distillation and membrane vapor permeation. The process described has the potential to cut the energy used in distillation operations by more than 50 % in comparison with conventional distillation technology.

The pervaporation process is considered as one of the most effective and energy-saving process for separation of azeotropic mixtures (Huang et al., 2008; Wee et al., 2008). In general, there are two different pervaporation processes: vacuum and sweep gas pervaporation. Membranes can be hydrophobic, i.e. ethanol permselective, or hydrophilic, i.e. water permselective. Based on materials used for membrane production there are inorganic, polymeric and composite membrane (Huang et al., 2008). Vane (2005) compared the energy demand of pervaporation with different separation factor to distillation process. He found that the pervaporation needs lower energy that that of distillation when the separation factor is larger than about 50, depending on the ethanol concentration in feed.

The main task of this study is to predict the energy demand of pervaporation under different concentrations and separation factor and to show under what conditions can be the pervaporation an alternative process to distillation producing ethanol with the same quality by both processes.

2. Theoretical considerations

In this paper the energy demand of pervaporation with different membrane selectivity (ξ) and module configuration will be analyzed and shown. The energy required to evaporate will be taken into account, the heat for condensation and its recovery during the process will not considered here. Accordingly, the necessary energy, given in MJ/kg_{Et} involves the evaporation heat, only. The energy required to evaporate permeate in a pervaporation process, normalized per unit of ethanol permeated (Q) is calculated as follows (Vane, 2005):

$$Q = \frac{H_w J_w + H_{Et} J_{Et}}{J_{Et}} \equiv H_w \frac{J_w}{J_{Et}} + H_{Et} \tag{1}$$

where H_i is the heat of evaporation of species i (=water, ethanol). According to Eq. (1), the ratio of the mass transfer rates, namely J_w/J_{et} should be known in order to be able to calculate the energy demand for the pervaporation process. This ratio can be obtained by means of the separation factor (ξ). Its value can be defined as (Baker, 2004; Nagy, 2004):

$$\xi = \frac{[C_w / C_{Et}]^G}{[C_w / C_{Et}]^L} \tag{2}$$

Considering that the permeate concentration ratio of the component is equal to their mass transfer rates' ratio, namely $J_{Et}/J_w = [C_{Et}/C_w]^G$, Eq. (2) can be rewritten as:

$$\frac{J_w}{J_{Et}} = \frac{[C_w]^L}{\xi [C_{Et}]^L} \tag{3}$$

Accordingly, in the knowledge of the ξ value, the energy demand for evaporation can be estimated, during pervaporation. Knowing the ratio of the permeation rates, the concentration of the liquid permeate can easily be predicted, namely e.g.:

$$[C_{Et}]^G = \frac{J_{Et}}{J_{Et} + J_w} \equiv \frac{1}{1 + J_w / J_{Et}} \tag{4}$$

Note that during our calculation the average value of the mass transfer rates can be applied. The differential mass balance equation on species i over a differential area of membrane module can be given as:

$$FdC_i = J_i dA \equiv P \Delta C dA \tag{5}$$

After solution one can get as:

$$\ln \frac{\Delta C_{out}}{\Delta C_{in}} = \frac{P}{F} A \qquad (6)$$

According to Eq. (6), during our calculation the log-mean ethanol concentration was used to represent the pervaporation feed system.

3. Results and discussion

Energy required to be removed the ethanol from the fermentation broth illustrated in Figure 1. It is assumed that the bottom residual stream contains 0.02 w% ethanol. This should mean that less than, depending on the feed concentration 0.67 % of ethanol, remained in the rest of the feed stream. Note that the permeate

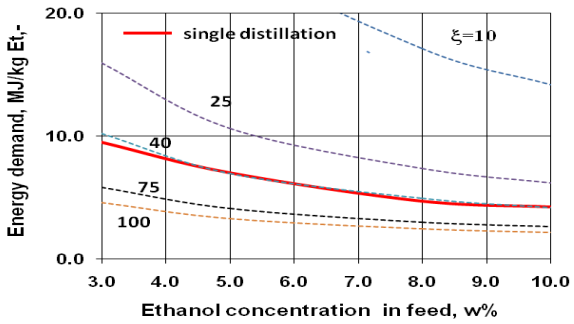

Figure 1: Energy required to remove the ethanol from the fermentation broth with different initial concentration depending on the value of the separation factor (ξ)

concentration obtained can strongly depend on the values of the separation factor as will be shown later. The red line represent the energy demand a single distillation (Galbe and Zacchi, 2002; Vane, 2005) where the overhead product contains about 94 w% ethanol, which can essentially differ from that of pervaporation. As can be seen, if the separation factor is higher than 40 then the pervaporation can have lesser energy demand as that of the single distillation. Note that the heat of combustion of ethanol is 30 MJ/kg. The question to be answered is value of the ethanol concentration of the permeate during pervaporation in one stage at defferent values of ξ. This is plotted in the Figure 2. As can be seen the water concentration of the permeate is rather high, strongly depending on the separation factor. Accordingly the ethanol concentration is much lower than that in case of the distillation. Thus further separation is needed to get product with 94 w% ethanol concentration, which needs additional energy. The dotted line represents the target concentration. To reach it in a single stage, one should have a membrane with very high separation factor, namely ξ= about 1000 or more, depending on the feed concentration. The ratio of the mass transfer rates is illustrated in Figure 3 as a function of the ethanol concentration in feed. The water permeation rate can be higher than that of ethanol even at ξ=100 depending on the feed concentration (note $J_{Et} / J_w = [C_{Et} / C_w]^G$). As a consequence, permeate has large water content as it shown in Figure 2.

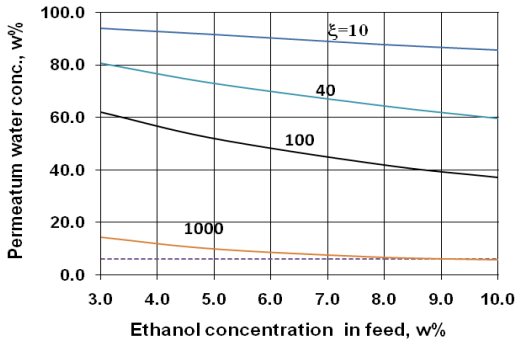

Figure 2. The permeate water concentration at different values of the separation factor, ξ

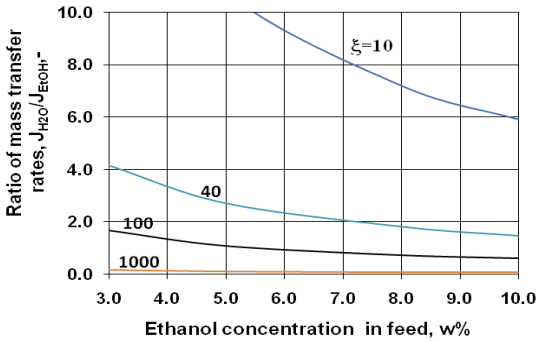

Figure 3: The ratio of permeation rates of components as a function of the feed concentration at different values of separation coefficient

3.1 Separation factor to reach the desired permeate concentration

As it was shown in previous figures, the permeate concentration strongly depend on the ξ value. What separation factor is needed to reach a given permeate concentration in one stage is illustrated in Figure 4 as a function of the feed concentration.

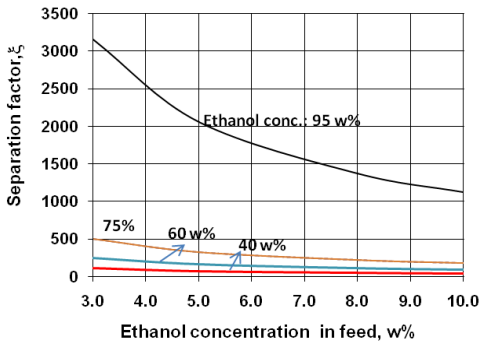

Figure 4. The necessary separation factor for removal of ethanol from fermentation broth in a given concentration

As can be seen it strongly depend on the feed concentration, as well. In order to reach the desired 95 w% ethanol in the permeate, high value of ξ is needed. But its value can essentially decrease with the increase of the feed concentration. The value of ξ varies between 1000 and 3200, in the feed concentration range of 3 w% to 10 w%. Lower permeate concentration needs much lower separation factor as it is also shown in this figure.

3.2 Additional energy demand for concentration up to 94 w% ethanol

The task to realize is the concentration of the fermentation broth from 3 w% ethanol concentration up to its concentration of 94 w% in such a way by pervaporation that about 95 % of its ethanol content should be removed from the initial solution into the end product. It is assumed a relatively low, and in the industrial practice available quality of membrane module, namely ξ=50. With such kind of membrane, the removal and the concentration of ethanol can be realized in 3 stages (Figure 5). If you want to carry out this separation in a one-stage process you needs a membrane module with about ξ=3200. The energy demand of such a separation realized in one stage of concentration from 3 w% up to 94 w% ethanol is altogether 0.98 MJ/kg_{Et}. Commercial membrane with such membrane property is not known until now. The first two membrane modules in Figure 5 will be a hydrophobic membranes which concentrate the starting solution with 3 w% ethanol content up to 65 w%, the third one will be a hydrophilic membrane which have a separation factor 0.02 defined by Eq. (2). In this stage mostly water will permeate through the hydrophilic membrane, the rest of the feed phase will be concentrated up to 94 w% of ethanol. Figure 5 illustrates the inlet and outlet concentrations from stage to stage. During the process 95 % of the starting amount of ethanol will be present in the end product (0.04 w% remains in the rest feed in the first two stages, and about its 4.5 w% transfers into the permeate phase in the 3rd stage; the permeate concentrations of the 3rd stage will be as: 0.913 w% water, and 0.087 w% ethanol will be as well as J_w/J_{Et}=10.5). The ratio of amount of water/amount of ethanol to be evaporated is equal to 4.3 in the whole process. The energy demand of every single pervaporation process is, in increasing order, as: 8.34 MJ/kg_{Et}, 2.86 MJ/kg_{Et} and 1.8 MJ/kg_{Et} .Thus, the additional energy to be consumed in the 2nd and 3rd stages in order to get the target quality of the ethanol, namely ethanol concentration of 94 w% from the concentration of 23 w%, obtained by the 1st stage will be 2.86 MJ/kg_{Et} +1.8 MJ/kg_{Et}= 4.64 MJ/kg_{Et}. That means the real energy demand will be higher than that is given in Figure 1. In this example, at 3 w% feed concentration and with ξ=50 for the membrane, the energy demand is about 55 % of that given in Figure 1. Note that the application of the three membrane processes needs further additional energy, e.g. vapor condensation, etc. But, it is easy to see from the Figure 1 that the energy demand can significantly be decreased below that of a single distillation, with the increase of the separation factor.

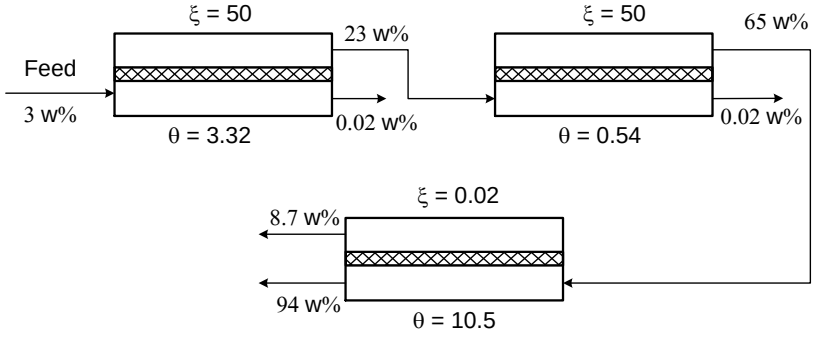

Figure 5 Multistage separation of the fermentation broth by pervaporation ($\theta = J_W / J_{Et}$)

4. Conclusion

The energy demand of the ethanol concentration of the fermentation broth can be, at least partly, replaced by pervaporation. It has be shown, how strongly depend the outlet concentration, the energy demand of the process on the separation factor of pervaporation the membrane. The application of the pervaporation needs very high separation coefficient to reach about 95 w% ethanol concentration, from

the fermentation broth, in a one-stage process. Thus, this target can reach in a multi-stage pervaporation process with commercially available membrane modules. The energy demand of a three-stage process is about 55 % more than that of a single distillation with separation coefficient of 50. Accordingly, the pervaporation process can economically applied only as a hybrid process with membranes modules currently available in the market.

5. Nomenclature

A membrane area, m^2
C concentration, mol/m^3, w%
F liquid flow rate, m^3/s
Hheat of evaporation, KJ/kg
J permeation rate, mol/m^2s, kg/m^2s
P permeability coefficient, m/s
Q energy demand for unit oh ethanol permeated, KJ/mol, KJ/kg
Ξ separation factor (Eq. 2)
θ ($\theta = J_W / J_{Et}$)

Subscript
Et ethanol
W ater

Supperscript
L feed
G liquid permeate

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References

Baker R.W., 2004. Membrane Technology and Applications, 2nd Ed., Wiley & Sons, Chichester, England, 2004

Galbe M., Zacchi G., 2002. A review of the production of ethanol from softwood, Appl. Microbiol. Biotechnol., 59, 618-628.

Huang H.J., Ramaswamy S., Tschirner U.W., Ramarao B.V., 2008. A review of separation technologies in current and future biorefineries, Sep. Purif. Technol., 62, 1-21.

Huang Y., Baker R.W., Vane L.M., 2010. Low-energy distillation-membrane separation process, Ind. Eng. Chem. Res., 49, 3760-3768.

Kamm B., Kamm M., 2004. Principles of biorefineries. Appl. Microbiol. Biotechnol., 64, 137-145.

Nagy E., Basic equation of mass transport through a membrane layer, Elsevier, New York, 2012).

Petersson A., Thomsen M.H., Hauggard-Nielsen H., Thomsen A.B., 2007. Potential bioethanol and biogas production using lignocellulosic biomass from winter rye, oilseed rape and faba bean. Biomass and Bioenergy, 31, 812-819.

Solomon B.D., Barnes J.R., Halvorsen K.E., 2007. Grain and cellulosic ethanol: History, economics, and energy policy. Biomass and Bioenergy, 31, 416-425.

Vane L.M., 2005. A review of pervaporation for product recovery from biomass fermentation processes, J. Chem. Technol. Biotechnol., 80, 603-629.

Wee S.L., Tye C.T., Bhatia S., 2008 Membrane separation process-Pervaporation through zeolite membrane, Sep. Purif. Technol., 63, 500-516.