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Design of a Novel Pass-Through Distillation Process for Bioethanol Recovery

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Abstract

Pass-through distillation (PTD) is a novel separation technology that can effectively overcome challenges related to using vacuum distillation in bio-based processes (defined temperature limit for evaporation that might result in very low condensation temperature). This method allows evaporation and condensation to be performed at different pressures by decoupling them using an absorption-desorption loop with an electrolyte absorption fluid. This original paper presents a process design for large-scale bioethanol recovery from fermentation broth (production capacity ~100 ktonne/y) by PTD. The flexibility of the novel PTD technology is expanded by combining it with heat pumps (PTD-HP) and multi-effect distillation (PTD-MED). Total cost and energy requirements for the recovery of high-purity bioethanol (99.8 wt%) are respectively 0.122 $/kg$_{EtOH}$ and 1.723 kW$_{th}$h/kg$_{EtOH}$ for PTD-HP, and 0.131 $/kg$_{EtOH}$ and 1.834 kW$_{th}$h/kg$_{EtOH}$ for PTD-MED, proving the effectiveness of the newly designed recovery processes for concurrent alcohol recovery and fermentation.

Keywords: bioethanol, pass-through distillation, industrial fermentation

1. Introduction

The need to transition from fossil fuels to more sustainable alternatives is rapidly gaining significance due to increasing concerns about climate change, environmental pollution and energy security. Biofuels and biochemicals potentially present a renewable replacement for conventional fossil-derived chemicals. In particular, a lot of research emphasis has been put on the fermentative production of lower alcohols, such as ethanol. A major limitation of the industrial production of bioethanol is the low product concentration that can be obtained due to inhibitory effects on microorganisms. Consequently, the downstream processing part of the bioethanol production process is especially challenging. Implementing a concurrent alcohol recovery and fermentation (CARAF) process is one way to improve the competitiveness of the overall bioethanol production process (McGregor and Furlong, 2017).

Conventional vacuum distillation can be used to separate valuable products from the rest of the fermentation broth while maintaining operating conditions appropriate for the present microorganisms. However, the selection of operating pressure in classic distillation determines both the reboiler and the condenser temperatures, and accordingly, the types of external utilities that are needed. Consequently, reducing operating pressure so that evaporation temperature does not exceed a certain limit might easily result in a very low condensation temperature that requires the usage of expensive refrigeration. Described limitations of applying conventional distillation on biobased

systems can be conveniently addressed using pass-through distillation (PTD). This relatively new separation technique decouples evaporation and condensation steps with an absorption-desorption loop (McGregor and Furlong, 2017). PTD has already been proven effective by Drystill at lab and pilot scale (Kiss et al., 2014), but further scale-up has not been attempted. Therefore, this original paper contributes to sustainable development by providing an eco-efficient process design for large-scale bioethanol recovery (~100 ktonne/y) from the fermentation broth using a novel PTD technique.

2. Working principle

The working principle of PTD is presented in Figure 1. Firstly, bioethanol product, together with some water, is evaporated from the fermentation broth. Formed vapor is later absorbed by electrolyte absorption fluid, commonly concentrated lithium-bromide (LiBr) solution. The heat released during the exothermic absorption can be transferred to the evaporation part by heat pipes in an integrated process equipment unit called a stripping-absorption module (SAM) (McGregor and Belchers, 2014). Ethanol and water are further desorbed from the diluted brine and condensed. Recovered concentrated electrolyte solution can be recycled and reused in the absorption step. The major benefit of PTD is decoupling the evaporation and condensation steps, allowing operation at different pressures. This means that the evaporator can operate at a lower pressure and a temperature below thermal limits, while the condenser can operate at ambient pressure and a temperature suitable for cheaper cooling utilities (McGregor and Furlong, 2017).

3. Results and discussion

This section contains the main results related to design of large-scale bioethanol recovery process from the fermentation broth by using a novel PTD method. Rigorous simulations for every part of process were designed in Aspen Plus. The main challenges for developing a cost- and energy-effective recovery process are highly diluted feed stream (5 wt% ethanol), presence of living microorganisms, modeling physical properties due to used electrolyte absorption fluid and thermodynamic limitations due to formation of ethanol-water azeotrope (95.57 wt% ethanol).

3.1. Property method development

Aspen Plus and MATLAB were used as CAPE tools to develop a reliable property model employing the electrolyte-NRTL model coupled with the Redlich-Kwong equation of state (ElecNRTL-RK) (Aspen Technology, 2023). Since this model describes complex systems using only binary interactions, experimental data for binary systems (Nasirzadeh et al., 2004; Patil et al., 1990; Perry and Green, 1997) were used to determine the values of binary interaction parameters. The total deviation of the obtained property model from the experimental data is 0.5%, 6.5% and 3.2% respectively for systems water-ethanol, LiBr-water and LiBr-ethanol. Therefore, the property method takes into account the complex interactions between electrolyte and two polar solvents (water and ethanol), as well as interactions among water and ethanol.

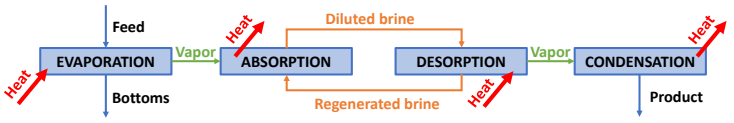

Figure 1. Working principle of pass-through distillation

3.2. Pass-through distillation part of the bioethanol recovery process

A recovery process was designed in Aspen Plus for an industrial-scale bioethanol production process with a production capacity of about 100 ktonne/y. The feed stream for this process is taken from the fermenter (37 ˚C, 1 bar) and contains about 5 wt% of ethanol and 0.1 wt% of CO_2, while the rest is water with some microorganisms. The first step is removing some of the initially present CO_2 in the degasser unit under reduced pressure. Some of the ethanol is also evaporated together with CO_2 but is later captured in a striping column and recovered.

After the degassing step, the fermentation broth is sent to the SAM unit. As this equipment unit is not available in Aspen Plus, equivalent operations are used (see Figure 2 and Figure 3). The operating pressure for evaporation and absorption parts of PTD (0.054 bar) was chosen such that total vaporization can happen while maintaining temperature below the fermentation temperature. The required flowrate of LiBr absorbent fluid was determined such that the heat content of diluted brine after absorption is sufficient to cover the heat demand of the evaporation part. This led to an absorbent-to-feed ratio of 1.4 on a mass basis. Diluted LiBr after the absorption step is sent to desorption and condensation. The remaining liquid fermentation broth after the evaporation step contains microorganisms and most of the present water, and can be recycled to the fermentation to avoid loss of biomass, allowing the upstream process to operate in a closed loop and to reduce fresh water requirements (Daniell et al., 2012).

Furthermore, the stripping column C1 was included prior to the SAM unit to increase ethanol concentration in formed vapor (from 19 wt% to 30 wt%), reduce ethanol losses in the stream that is being recycled to the fermenter and decrease ethanol concentration in this stream (from 2 wt% to 0.2 wt%). Vapor fraction in the evaporation part of the SAM unit was selected to allow ethanol recovery higher than 90%.

In order to recover and recycle the absorbent fluid, previously absorbed products must be desorbed. Since, this desorption step requires external heating, two process configurations were considered to reduce the overall energy requirements: desorber unit enhanced with heat pumps (PTD-HP) and multi-effect distillation (PTD-MED).

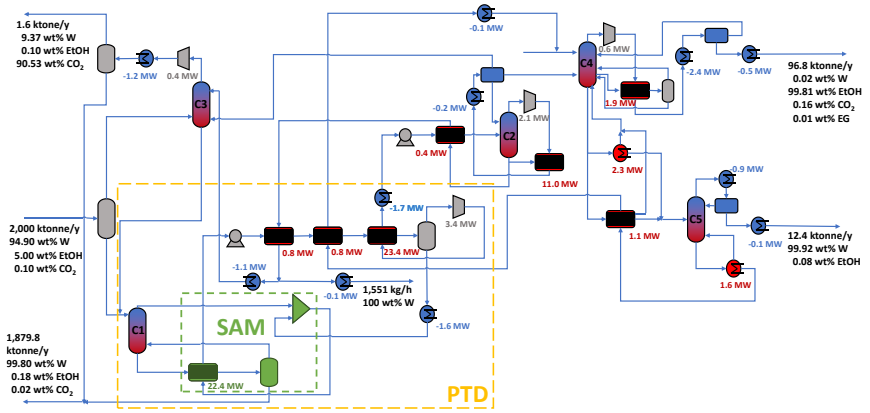

Figure 2. Flowsheet of bioethanol recovery process, PTD-HP configuration

The first process configuration (PTD-HP, see Figure 2) implies using a heat pump system based on vapor recompression to enhance the desorption part of PTD. After the SAM unit, the diluted LiBr needs to be pumped to an appropriate pressure for the following desorption and condensation steps. As the desorption step is very energy-consuming (about 25 MW), heat pumps were implemented to reduce energy requirements. More precisely, the desorbed water-ethanol vapor is compressed and used to provide heat to the diluted LiBr. Consequently, very high amounts of thermal energy are substituted with a much smaller amount of electrical energy. The operating pressure for the desorption and condensation parts (0.2 bar) was determined to minimize total energy requirements, while also allowing condensation with cheaper cooling utilities.

The second process configuration (PTD-MED, see Figure 3) replaces desorption and condensation steps with multi-effect distillation (MED). In this design, diluted brine is separated into high-pressure (HP), medium-pressure (MP) and low-pressure (LP) parts, whereby hot higher-pressure streams provide heat to lower-pressure streams. The split ratio (ratio between flowrates of HP and MP, as well as between MP and LP) determines the required operating pressures needed for efficient heat transfer. The pressure of LP was chosen to allow the following condensation using cheaper cooling utilities. The split ratio of 1.05 was determined to minimize total energy requirements for the PTD part of the bioethanol recovery process while keeping required pressures at reasonable levels. Therefore, pressures of HP, MP and LP are 2.0 bar, 0.5 bar and 0.09 bar, respectively. Replacing desorption and condensation parts with MED results in about 64% reduction in external requirements.

3.3. Further ethanol purification

As a result of PTD, the ethanol concentration increased from 5 wt% to about 30 wt%. However, additional treatment is needed to obtain a high-purity end product. Further processing consists of several steps due to the water-ethanol azeotrope. Firstly, a stream containing separated products from the PTD was preconcentrated, in column C2, to obtain 91 wt% ethanol in distillate since this concentration was determined to minimize total energy requirements (Kiss and Ignat, 2013).

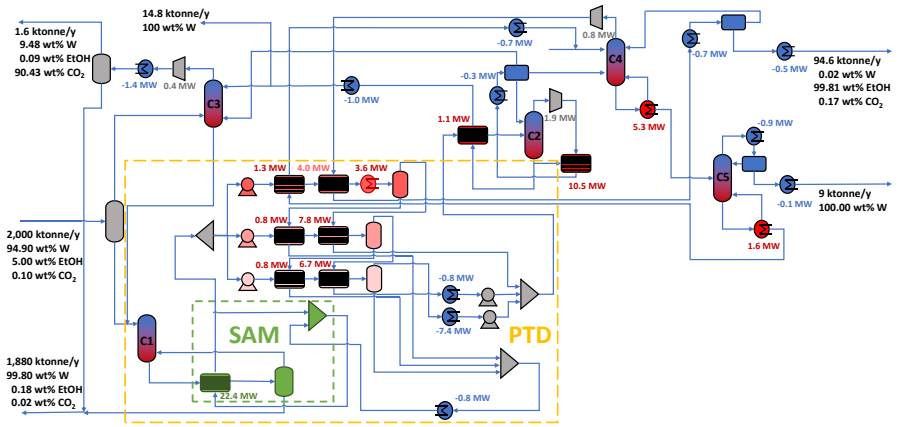

Figure 3. Flowsheet of bioethanol recovery process, PTD-MED configuration

The top product from column C2 is preconcentrated ethanol solution, while the bottom product is pure water that is used to preheat the feed stream for this column. Additionally, since temperatures at top and bottom of the distillation column are relatively close, mechanical vapor recompression (MVR) was applied to reduce energy requirements (Kiss and Infante Ferreira, 2016).

Furthermore, to obtain high-purity ethanol product, more CO_2 needs to be removed in the partial condenser of the column C2. Separated ethanol is captured from two CO_2-rich streams (from the degasser unit and from the partial condenser of column C2) using part of the bottom water from column C2 in an additional stripping column C3. Returning captured ethanol to the recovery process reduces the amount of lost ethanol from 14% to less than 0.002%.

The preconcentrated ethanol-water mixture is further dehydrated, in column C4, using extractive distillation with ethylene glycol since this method was proven to be the best one for large-scale ethanol preconcentration in terms of both investment and operating costs (Kiss et al., 2014). The top product from this column is high-purity (99.8 wt%) ethanol, while the bottom product is ethylene glycol-water mixture that is sent to solvent recovery column C5. Pure water, obtained at the top of column C5, can be cooled and recycled to the upstream process to reduce need for fresh water. Ethylene glycol is obtained as the bottom product and can be reused in extractive distillation column C4.

Additional heat integration opportunities were considered to maximize process performance. Since recovered ethylene glycol requires cooling before being recycled to column C4, it was used in PTD-HP to evaporate part of the bottom liquid from column C4. A side reboiler was added to column C4, whereby compressed top vapor from this column was used to evaporate part of the liquid side stream. These two heat integrations reduced external heating requirements for the extractive distillation part by about 57%. Lastly, water product from column C2 and recovered ethylene glycol were used for heating diluted LiBr in the PTD part, which reduced compressor duty in the heat pump system. In PTD-MED, compressed top vapor from column C2 and recovered ethylene glycol were used to heat HP stream in the MED part. Consequently, external heating requirements for the PTD part decreased by about 60%.

3.4. Analysis of economic and environmental impact

To evaluate the performance of the designed recovery processes, a complete analysis of economic indicators and sustainability metrics was conducted following published recommendations (Humbird et al., 2011; Schwarz et al., 2002). A comparison between the two processes is given in Table 1. Generally, both processes are highly cost- and energy-efficient, and the choice of the optimal downstream process should depend on the exact location site and availability of utilities. In case of lower electricity cost, enhancing PTD with heat pumps (PTD-HP) is preferable solution. Alternatively, if steam is more readily accessible, multi-effect distillation is more favourable choice for desorption and condensation parts of PTD (PTD-MED).

Table 1. Key performance indicators

	PTD-HP	PTD-MED
Economic indicators		
CAPEX (k$)	33,595	28,378
OPEX ($/$kg_{EtOH}$)	0.088	0.101
Total annual costs ($/$kg_{EtOH}$), 10 years payback period	0.122	0.131
Sustainability metrics		
Thermal energy requirements ($kW_{th}h/kg_{EtOH}$)	0.320	0.889
Electrical energy requirements (kW_eh/kg_{EtOH})	0.561	0.378
Primary energy requirements ($kW_{th}h/kg_{EtOH}$)	1.723	1.834
Water consumption (m^3_w/kg_{EtOH})	0.158	0.234
CO_2 emissions, grey / green electricity (kg_{CO2}/kg_{EtOH})	0.292 / 0.035	0.309 / 0.136

4. Conclusion

This original paper is the first one to develop a complex property model for the ternary system LiBr-ethanol-water and include it in unique process design. The main contribution of this research is the design of recovery process for large-scale bioethanol production using a novel pass-through distillation method (PTD). High-purity bioethanol (99.8 wt%) is obtained by combining PTD with further preconcentration and dehydration steps. Enhancing PTD with heat pumps (PTD-HP) and multi-effect distillation (PTD-MED) resulted in cost- and energy-effective downstream processes (total recovery cost of 0.122 and 0.131 $/$kg_{EtOH}$, and energy requirements of 1.723 and 1.834 $kW_{th}h/kg_{EtOH}$ for PTD-HP and PTD-MED, respectively).

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