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Energy efficiency of a new distillation process for isopropanol, butanol, and ethanol (IBE)
dehydration

Grisales Díaz Víctor Hugo* and Gerard Olivar Tost

Faculty of Engineering and Architecture. Department of Electrical, Electronics and
Computation Engineering. Universidad Nacional de Colombia Sede Manizales, Cra. 27
No. 64-60, Manizales, Colombia.

*E-mail: vhgrisalesd@unal.edu.co; victor.grisales.d@gmail.com Tel.: (+57) 3008720595

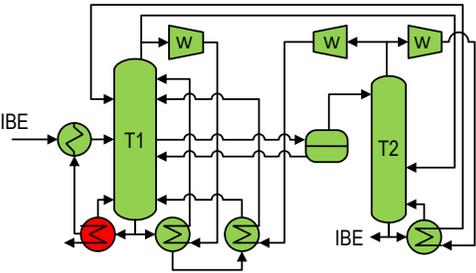
Abstract

Isopropanol, butanol, and ethanol (IBE) is an alternative biofuel. However, dehydration of IBE is complicated by the presence of three binary azeotropes. The new distillation system proposed in this work for IBE dehydration was a combination of azeotropic and extractive distillation. Butanol in a complex reflux system, without an additional entrainer, broke the azeotropic behavior of isopropanol-water and ethanol-water. Decantation dismissed butanol-water azeotrope. The distillation system was evaluated using Aspen Plus® software. The alternative distillation system achieved an energy requirement between 6.5 and 8.2 MJ-fuel/kg-IBE. The fuel requirement using steam compression distillation reduced to 3.4-4.1 MJ-fuel/kg-IBE. The energy efficiency of IBE dehydration was between 0.72 and 0.79. IBE recovery was compared with alternative biofuels. Energy requirement of IBE was 0.92-1.4 and 1.4-2.4 times higher than that of isobutanol and ethanol dehydration, respectively. However, IBE fermentation reached an equivalent energy efficiency by hydrogen production. Biofuels recovery from broth of conventional reactors by heat-integrated distillation achieved the highest energy efficiency.

Keywords: extractive distillation; azeotropic distillation; heat-integrated distillation; intensification; vapor compression; biofuel recovery

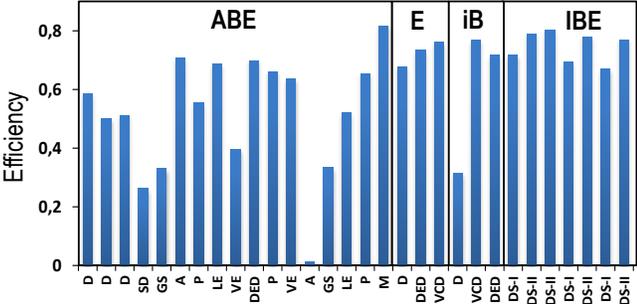
Graphic abstract

New process without an additional entrainer



Distillation system (DS-II)

Energy evaluation of biofuel recovery



Recovery system

Abbreviations

ABE, acetone, butanol, and ethanol

Col1, Column 1

Col2, Column 2

DS-I, Distillation system 1

DS-II, Distillation system 2

IBE, Isopropyl alcohol, butanol and ethanol

IES, ideal energy efficiency

MAVS, membrane assisted vapor stripping

TAC, total annualized cost

1. Introduction

The butanol has a petrochemical production of 10-12 billion pounds per year [1]. Biobutanol is produced mainly by acetone, butanol, and ethanol (ABE) fermentation [2] and it is considered an alternative biofuel. Acetone is sometimes considered an undesired coproduct due to its low properties as biofuel. Reduction of acetone into isopropanol can be achieved using several biocatalysts that belong to the genus *Clostridium* [3,4]. Due to the better properties of isopropanol, an alcohol mixture of isopropanol, butanol, and ethanol (IBE) is a more attractive biofuel than ABE [5].

Alcohol concentration reached with these biocatalysts is lower than 24 g/l, mainly due to butanol inhibition [6]. Integrated reactors with pervaporation [7], gas stripping [3], liquid-liquid extraction [8,9] or adsorption [10] have been proposed to reduce the inhibition and toxicity of butanol in the fermentation [11]. However, the separation units have non-infinite selectivity, and a supplementary purification approach is required. Generally, this approach is distillation.

Distillation is considered as the separation system with the highest energy requirements for ABE recovery (>12.6 MJ/kg-products). However, intensified distillation processes have reported recently lower energy requirements than those for integrated reactors [12,13]. For instance, energy requirements of ABE recovery through heat-integrated distillation with double effect as low as 7.2 MJ/kg-ABE have been reported. This value is 14% and 26% lower than that for integrated processes using pervaporation and vacuum evaporation [12], respectively.

Due to an additional binary azeotrope (isopropanol-water), the recovery of IBE is harder than that for ABE. To our knowledge, IBE dehydration by distillation has not been reported in the literature. Therefore, a paper studying IBE dehydration by distillation is required. Isopropanol or ethanol dehydration are proposed generally through extractive distillation, pervaporation, salting and molecular sieves [14–16]. Although isopropanol and

ethanol separation is difficult due to the proximity of their boiling points (82.6 and 78.4 °C for isopropanol and ethanol, respectively), for biofuel application, it is not necessary to separate ethanol and isopropanol. While, due to the low solubility of butanol, its dehydration does not require a separation agent to break the azeotropic behavior. Consequently, decantation is used conventionally to break the butanol-water azeotrope.

Although butanol does not need an additional separation agent, membrane technologies have been commonly proposed to reduce the energy requirements of distillation [17]. Recently, membrane assisted vapor stripping (MAVS) has been proposed for dehydration of butanol, ethanol, or alcohol mixtures [18,19]. In this process, low energy requirements for ethanol or butanol recovery from fermentation broths are achieved (between 2.3 and 2.5 MJ-fuel/kg-solvent). However, these energy requirements are similar to equivalent dehydration systems with heat-integrated distillation by compression work without membranes [13].

The distillation system proposed in this paper was a combination of extractive and azeotropic distillation. Two columns were required. Butanol is used as entrainer in a complex reflux system and an additional separation agent was not required. Two alternative processes of heat-integrated distillation were proposed for IBE dehydration. In the first distillation system (DS-I), the second column was operated at low-pressure to supply the condensation heat of the first column to its boiler. The second distillation system (DS-II) was integrated with vapor compression. In vapor compression, vapor at the top is compressed and it is used to supply the heat to its boiler [20]. The energy requirements and energy efficiency achieved in this work were compared with those of alternatives biofuels, such as ABE, isobutanol, and ethanol.

2. Process model

The energy requirements were calculated using Aspen Plus V7.3[®]. The base method of simulations was UNIQUAC-RK. The decanter was simulated using the binary UNIQUAC-

LL parameters. The binary butanol-water parameters for vapor-liquid equilibrium were reported by Fischer and Gmehling [21]. Columns were simulated with RadFrac. The distillation system had two columns (Fig. 1). In all simulations, the boiler heat of Col1 and Col2 columns was obtained with design specs toolbox to achieve an IBE recovery and purity of 0.98 and 0.997, respectively.

Feed was preheated with the vinasses. The minimum approach temperature was 10 °C. Recycle of vinasses into the reactor was proposed in this work to reduce the substrate concentration without an additional water stream. Recycle of vinasses is a common practice in ABE production in Chinese industry, in which approximately 40% of vinasses are recycled [22]. Butanol concentration into the “reactor” after recycle was equal to the maximum butanol concentration produced for the biocatalyst. IBE was fed to “reactor”, instead of the substrate, in ratio to yield of the biocatalyst. In all simulations, the “substrate” was fed at 18 w/w %. For instance, the IBE concentration was fed at 5.4 w/w % when IBE yield was assumed as 0.3.

Several alternative biofuels produced by several biocatalysts [23–25] were evaluated. The ideal energy efficiency (IES) of separation systems for biofuel production was calculated using the methodology of our previous work [13]. A theoretical yield was utilized in the calculation of IES. This efficiency of substrate energy conversion is calculated adding the lower value heat (LHV) of all products less the energy requirements of the recovery systems, divided by the LHV of substrate [13].

The IES of the process was considered ideal because only the energy requirements of recovery were calculated. In IBE and ABE fermentations, hydrogen is produced. Therefore, hydrogen was considered as an additional product. The LHV of hydrogen [26], isopropanol [5], acetone [18], ethanol [18], butanol [18] and glucose [27] were 121.5, 30.4, 29.6, 27, 34.4 and 16.45 MJ/kg, respectively. The substrate was glucose. The hydrogen production for ABE and IBE fermentations was calculated from the following stoichiometric reactions:



The efficiency of production of steam is lower than that for electricity production. For this reason, energy evaluation was performed in fuel equivalents [19]. Efficiency for low-pressure steam and electricity was assumed 0.33 and 0.9, respectively. The efficiency of compression was 0.75. The CO₂ production associated at the energy requirements of recovery system is proportional to the fuel requirements. Therefore, a reduction in fuel combustion is equal to CO₂ reduction. The economic evaluation was performed using the methodology proposed in [13].

2.1. Distillation system I (DS-I)

The ideal stages of the Col1 and Col2 columns (Fig. 1) were 40 and 25, respectively. The total number of stages was selected to avoid trays excess. In the Col1 column, vinasses were obtained on the bottoms. Due to butanol-water azeotrope, an intermediate liquid stream from Col1 column was required. This stream was composed mainly of butanol and was fed to the decanter, where binary azeotrope of butanol-water is broken. Organic and aqueous phase from decanter were fed to the Col1 and Col2 columns, respectively. Reflux in the Col1 column and the decantation temperature were selected with the optimization tool of Aspen Plus[®]. The objective function was the minimization of energy requirements in reboilers. Decanter temperature from the optimization was 55 °C.

The feed tray numbers of Col1 column were 26, 23 and 9 for dilute IBE, aqueous phase and the top stream from Col2 column, respectively. The organic phase from decanter was fed at the top of the Col2 column. Isopropanol and ethanol at a concentration close to azeotropic were obtained from the top of the Col1 column (Fig. 1). This stream was fed at stage 15 of Col2 column. Butanol from organic phase was used as entrainer to lose the azeotropic behavior of isopropanol-water and ethanol-water. Therefore, anhydrous IBE was obtained in the bottoms of the extractive Col2 column.

2.2. Distillation system II (DS-II)

In our previous paper [13], due to the high investment of compressors, vapor compression was the less economical option of heat-integrated distillation. However, it was studied in this work because the highest energy efficiency is achieved using this process. The distillation system 2 (DS-II) was proposed with heat integration through vapor compression (Fig. 2). Electricity and steam provide the energy requirements of DS-II. In DS-II, the overhead vapor was compressed and condensed in the reboiler of its respective column. The non-condensate vapor from the top of Col2 was compressed and used in the Col1 column. The number of trays and stage feed were the same as DS-I.

Although vacuum operation increases the diameter of columns, the energy requirement of preheating decreases. Due to the low concentration of alcohol from broth, the preheating was more important than increasing column investment [13]. For this reason, the Col1 and Col2 columns in DS-II were operated at vacuum pressure (0.25 bar). The overhead vapor of Col2 was compressed into two parallel units. The discharge pressure of compressors were 0.63 and 0.75 bar, respectively. The highest and lowest pressure of compressed steam were used in the first and second columns (Fig. 2), respectively. The overhead vapor from the first column was compressed to 0.84 bar.

3. Results and discussion

3.1. DS-I

Fig. 3 shows the isopropanol or ethanol relative volatility behavior increasing in reference at the butanol ratio in an aqueous solution. Ethanol and isopropanol at higher butanol concentrations became into a heavier component than water (Fig. 3). Therefore, anhydrous IBE can be obtained from the bottoms of Col2 (Fig. 4 (a)). The distillation system studied in this work is a combination of extractive and azeotropic distillation. Extractive because butanol is used as an extractant in the Col2 and it is azeotropic because a decanter

is used to break the azeotrope of butanol-water. Water, ethanol, and butanol concentration at the top of the Col1 column were 14, 13 and 0.06 wt%, respectively (Fig. 4).

The energy requirements of IBE dehydration using DS-I and the titer achieved by *C. acetobutylicum* Rh8, *C. acetobutylicum* PJC4BK and *C. acetobutylicum* 824 Δ buk pCLF952 were calculated. *C. acetobutylicum* Rh8 achieved a total alcohol titer of 23.9 g/l (7.6, 15 and 1.3 g/l of butanol, isopropanol, and ethanol, respectively) with a ABE yield of 31.4% [6]. The energy requirements of the first column without vinasses recycle using the ABE yield of *C. acetobutylicum* Rh8 was 7.7 MJ-fuel/kg-IBE.

A recycle of 59.5% with a substrate concentration of 18 w/w% was necessary to obtain a butanol concentration of 15 g/l into the “reactor”. The total energy requirements of the Col1 reduced from 7.7 to 6.5 MJ-fuel/kg-IBE because the recycle of vinasses increased ethanol concentration into the reactor from 1.3 g/l to 1.9 g/l. This ethanol concentration is non-inhibitory for the biocatalyst [28]. Ethanol recovery from broth is more difficult because its relative volatility is 2.3 and 2.8-fold lower than that of butanol or isopropanol, respectively. Additionally, ethanol at concentrations close to azeotropic has a lower volatility than isopropanol at the same ratio of butanol (Fig. 3). Fortunately, the ethanol yield of *Clostridium* strain is between 2.3 and 5.8 times lower than the yield of isopropanol.

A reduction of the pressure of Col2 from 1.0 bar to 0.25 bar decreased the reboiler duty of Col2 from 1.5 to 1.0 MJ-fuel/Kg-IBE. Col2 can work at atmospheric pressure. However, heat integration is more difficult. Therefore, Col2 was operated in this paper at 0.25 atm. The boiler temperature of Col2, the condenser temperature of Col1, and the condenser duty of Col1 were 63 °C, 79 °C and -2.5 MJ/Kg-IBE, respectively. Therefore, the condensation energy of Col1 was adequate to supply the boiler heat of the Col2 column. Due to the dilute concentrations from fermentation, the boiler heat of the Col1 column was 87% of total energy requirement without recovery of the condensation heat of Col1. Energy

requirement of DS-I was equal to that of reboiler of Col1 (6.5 MJ-fuel/kg-IBE) due to the energy integration. Additionally, this integration reduced the requirements of cooling water.

The energy requirement of the distillation system proposed in this work using the yield and concentrations achieved by *C.a. Rh8*, *C.a. PJC4BK* and *C.a 824 Δbuk pCLF952* were of 6.5, 7.3, and 8.2 MJ-fuel/kg-IBE, respectively (Table 1). The total alcohol titer and yield reached by *C. acetobutylicum PJC4BK* strain are 20.4 g/l and 0.33, respectively [3]. *C. acetobutylicum 824 Δbuk pCLF952* achieved a yield of 0.3 and concentrations of ethanol, isopropanol, and butanol of 1, 4.8 and 14.6 g/l, respectively [4]. Vinasses were recycled between 57 and 68%. The energy requirements of Col2 column were 1-1.3 MJ-fuel/kg-solvent (~15% of energy consumption of Col1). Therefore, the alcohol concentration from broth is the main factor in the energy requirement of DS-I.

3.2. DS-II

Total energy requirements of DS-II using the biocatalysts studied in this work were between 3.4 and 4.1 MJ-fuel/kg-ABE (Table 1). The coefficient of performance (COP) of DS-II was 10.1. COP, which is the ratio between the amounts of heat upgraded and power requirements. The TAC of IBE recovery from fermentation broth (*C.a RH8*) of DS-I and DS-II were 0.142 and 0.138 \$/kg-IBE, respectively. Due to vapor compression, DS-II required a capital investment 1.5-fold higher than DS-I. Although total operational annualized cost was 54% lower for IBE recovery by DS-II, TAC of DS-II was 3.1% more expensive than DS-I.

Reduction of TAC using vapor compression distillation regarding non-integrated distillation is strongly tied to steam and electricity costs [13]. For this reason, the recent fluctuations in oil prices is an additional limitation of DS-II. At our knowledge, the energy requirement for dehydration of IBE, as an alternative biofuel, was not reported previously in the literature. Therefore, IBE dehydration requirement was compared to the recovery energy of alternative biofuels (ABE, ethanol or isobutanol).

3.3. Energy requirements of alternative biofuels

The energy consumption with a distillation approach in Jilin Cathy Industrial Biotech, one of leading of ABE producers in China, is 6-7 kg-steam/kg-butanol produced [2] (8.4-9.8 MJ-fuel/kg-ABE assuming an A/B/E ratio of 6/3/1). These energy requirements are between 1.02 and 1.51-fold higher than that of IBE recovery by DS-I (between 6.5 and 8.2 MJ-fuel/kg-IBE). The energy consumptions reported in the literature of another distillation approach by ABE recovery are 12.8 and 15.2 MJ-fuel/kg-ABE using the hyper butanol biocatalysts *C. acetobutylicum* SolRH (ptAAD) and *C. beijerinckii* BA101, respectively [29]. This fuel requirement was between 1.56 and 2.3 times higher than for IBE dehydration by DS-I.

Integrated reactors with liquid-liquid extraction and adsorption for recovery of alcohol titer of *C. beijerinckii* BA101 are the most energy efficient systems reported by Qureshi et al. [30]. Fuel requirement of liquid-liquid extraction and adsorption are 8.9 and 8.2 MJ/kg-butanol or 7.1 and 7.7 MJ-fuel/kg-ABE (calculated assuming a steam efficiency of 0.9), respectively. These energy requirements are between 1.1 and 1.2-fold higher than IBE dehydration from a broth of *C.a. Rh8* by DS-I.

In other paper, pervaporation was the separation system with the lowest energy requirement for integrated reactors reported by Groot et al. [31], with an energy requirement 2.4-fold higher than the achieved in this work using DS-I and *C.a. Rh8* titer. Pervaporation has been reported in our previous work with fuel requirements of 9.6 MJ-fuel/kg-ABE. This fuel requirement was between 1.2 and 1.5-fold higher than IBE dehydration by DS-I. However, integrated reactors increase the fermentation performance. Therefore, an economic analysis for integrated reactors must be performed in future works. In the other hand, the distillation approach proposed in this work can be used with integrated reactors as final IBE purification approach.

A membrane system is the most energy-efficient approach reported in the literature for recovery of butanol from dilute solutions [18,19]. The energy demand in fuel equivalents of membrane assisted vapor stripping (MAVS) for dehydration of ABE from 2 wt% solution

is 3.2 MJ-fuel/kg-ABE. This energy requirement was achieved employing an approach temperature of 5°C in the heat recovery from vinasses. Decreasing the approach temperature to 5°C for recovery of heat in vinasses reduced the total energy consumption from 3.4 to 2.9 MJ-fuel/kg-IBE. The fuel consumption is analogous to the lowest reported in the literature by MAVS under 5°C of minimum approach temperature (3.2 MJ-fuel/kg-ABE). Similar results were found for ethanol and isobutanol dehydration by vapor compression distillation. Therefore, the membrane cost is the most important item for the selection of MAVS for alcohol dehydration instead of vapor compression distillation.

The lowest energy requirement of ethanol and isobutanol dehydration by heat-integrated distillation system has been reported in our previous work [13]. The energy requirement for ethanol and isobutanol dehydration by double effect distillation were between 1.14 and 1.44, and 1.9 and 2.4-fold lower than IBE dehydration by DS-I, respectively. While, the energy requirement for ethanol and isobutanol dehydration by vapor compression distillation were between 0.92 and 1.1, and 1.36 and 1.64-fold lower than IBE dehydration by DS-II, respectively.

In general, IBE recovery has lower energy requirements than ABE dehydration and higher than that of isobutanol and ethanol dehydration. However, a lower production of hydrogen than that for ABE fermentation is achieved, while, ethanol has a lower LHV than IBE. Therefore, the energy efficiency of IBE process studying only the energy requirement of biofuel separation will not be necessarily higher or lower than other biofuels. For this reason, IES was calculated.

3.4. Energy efficiency of alternative biofuels

Hydrogen production was calculated based on the stoichiometric production of acetone (eq. 1) or isopropanol (eq. 2) assuming a substrate conversion of 100%. In isopropanol and acetone reaction, 4.0 and 3.0 molecules of H₂ are produced for each molecule of glucose, respectively. The hydrogen production of *C. beijerinckii* BA101 (A/B/E

of 6/24.6/1) has the lowest hydrogen production for ABE fermentation, due to its low acetone production. For this reason, the hydrogen production of IBE by *C. acetobutylicum* RH8 was 1.2-fold higher than that of *C. beijerinckii* BA101 (Table 2).

The maximum IES, assuming a nil energy recovery, of ethanol, isobutanol, IBE, and ABE fermentation were 0.84, 0.86, 0.87, and 0.88-0.89, respectively. Therefore, ABE fermentation converted glucose in molecules with the highest total LHV (Table 1). The most efficient process reported in the literature for biofuel production was ABE recovery by MAVS (0.82). Although ABE dehydration by MAVS has higher energy requirements than that of IBE recovery for DS-II, the maximum IES of ABE fermentation is higher than that of IBE fermentation.

Only direct separation systems (heat-integrated distillation or MAVS) for biofuels dehydration achieved energy requirements around 90% of the maximum IES. The IES of alternative biofuels using a heat-integrated distillation with vapor compression was similar. Therefore, the viability of biofuel production depended on other factors, such as biofuel properties, separation costs, and biocatalyst capacities (productivity, yield, or hexoses and pentoses conversion). In the second place of IES, integrated reactors by liquid-liquid extraction and adsorption for ABE production (*C. beijerinckii* BA101) achieved an IES between 70 and 80% of maximum IES. Integrated reactor with a polymeric adsorbent was the less efficient separation system for biofuel production, with a nil IES (Table 2). The high-energy requirement of this scheme was due to the low selectivity (10) of selected polymeric adsorbent (XAD8).

3. Conclusions

IBE dehydration by the new distillation systems proposed in this work achieved low energy requirements without an additional entrainer. Vapor compression (DS-II) reduced the fuel consumption of the innovative separation system (DS-I) two times. However, TAC was similar due to compressor investment. The energy consumption of the distillation system

was as high as the most efficient recovery system for ABE dehydration. The highest performance of the distillation system proposed in this work was achieved using the alcohol titer of the biocatalyst *C. acetobutylicum* Rh8. The IES of DS-I and DS-II was between 0.67 and 0.8. IBE dehydration by heat-integrated distillation achieved similar IES than that of ABE, ethanol, or isobutanol dehydration using a similar technology.

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Table 1
 Energy requirements for IBE dehydration from the broth of several biocatalysts

Biocatalyst	Distillation system (DS)	Solvent Yield	Butanol titer (g/l)	Ratio I/B/E	recycle	Energy requirement [MJ-fuel/kg-IBE]		
						Compression work	Boiler of Column I	Total
<i>C.a. RH8</i>	DS-I	0.31	15.0	5.9/	0.60	-	6.54	6.5
	DS-II			11.7/1		1.58	1.78	3.4
<i>C.a. PJC4BK</i>	DS-I	0.33	14.6	4.8/	0.68	-	7.29	7.3
	DS-II			14.6/1		1.65	2.08	3.7
<i>C.a. 824 Δbuk pCLF952</i>	DS-I	0.30	14.1	2.3/	0.57	-	8.25	8.2
	DS-II			7.4/1		2.02	2.04	4.1

Table 2

Energy requirement and energy efficiency of several recovery systems

Biocatalyst	Recovery system	Energy requirement (MJ-fuel/kg-product)	Hydrogen production (MJ/kg-solvents)	LHV of solvents (MJ/kg-solvents)	Theoretical yield of solvents (g/g)	IES
<i>C. acetobutylicum</i> SolRH (A/B/E of 4/8.4/1) [23]	Distillation	12.8 ^a [29]	5.0	32.4	0.39	0.59
<i>C. beijerinckii</i> P260 (A/B/E of 5.6/10/1) [24]	Distillation	16.7 ^a [29]	5.6	32.3	0.39	0.50
<i>C. beijerinckii</i> BA101 (ABE of 6/24.6/1)	Distillation	15.2 ^a [29]	3.2	33.3	0.40	0.51
	Steam distillation	21 ^a [30]	3.2	33.3	0.40	0.37
	Gas stripping	18.9 ^a [30]	3.2	33.3	0.40	0.42
	Adsorption	7.1 ^a [30]	3.2	33.3	0.40	0.71
	Pervaporation	11.9 ^a [30]	3.2	33.3	0.40	0.59
	liquid-liquid extraction	7.7 ^a [30]	3.2	33.3	0.40	0.69
<i>C. saccharoperbutylacetonicum</i> N1-4	Vacuum evaporation	21.8 ^a [30]	3.2	33.3	0.40	0.35
	Double effect distillation	8.0 [12]	4.6	32.6	0.39	0.70
	Pervaporation	9.6 [12]	4.7	32.6	0.39	0.66
	Vacuum evaporation	10.8 [12]	5.1	32.5	0.39	0.64
	Adsorption	36.7 ^a [31]	5.0	32.2	0.39	0.01
<i>C. acetobutylicum</i> (A/B/E of 3/6/1)	Gas stripping	23.3 ^a [31]	5.0	32.2	0.39	0.33
	Liquid-liquid extraction	15.6 ^a [31]	5.0	32.2	0.39	0.52
	Pervaporation	10 ^a [31]	5.0	32.2	0.39	0.65
	MAVS	3.2 [18]	5.0	32.2	0.39	0.82
	Distillation	5.2 [13]	-	27.0	0.51	0.68
<i>Saccharomyces cerevisiae</i> (ethanol only)	Double effect distillation	3.4 [13]	-	27.0	0.51	0.73
	Vapor compression distillation	2.5 [13]	-	27.0	0.51	0.76
	Azeotropic distillation	21.8 ^a	-	34.4	0.41	0.31
<i>E. coli</i> (isobutanol only)[25]	Vapor compression	3.7 [13]	-	34.4	0.41	0.77
	Distillation					
	Double effect distillation	5.7 [13]	-	34.4	0.41	0.72
<i>C. acetobutylicum</i> RH8	DS-I (this work)	6.5	3.9	32.7	0.39	0.72
	DS-II (this work)	3.4	3.9	32.7	0.39	0.79
	DS-II (this work)	2.9	3.9	32.7	0.39	0.80
<i>C. acetobutylicum</i> PJC4BK	DS-I (this work)	7.3	2.9	33.1	0.40	0.69
	DS-II (this work)	3.7	2.9	33.1	0.40	0.78
<i>C. acetobutylicum</i> 824 Δbuk pCLF952	DS-I (this work)	8.2	2.6	32.8	0.40	0.67
	DS-II (this work)	4.1	2.6	32.8	0.40	0.77

^a Efficiency of fuel production was assumed 0.9

Figures

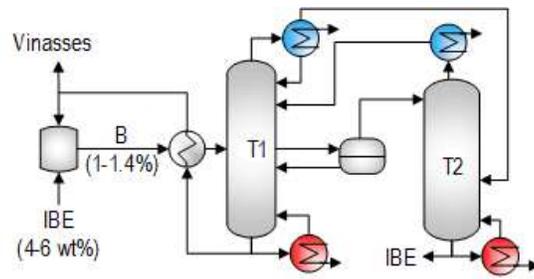


Fig. 1. New azeotropic distillation system by IBE dehydration (DS-I)

One column

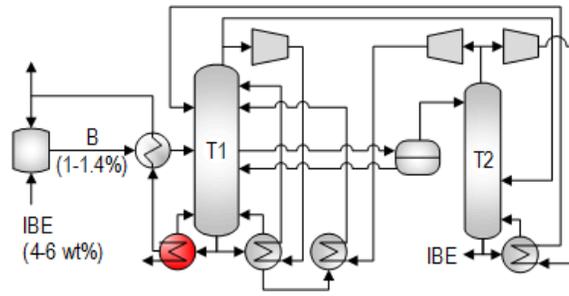


Fig. 2. Azeotropic distillation system with vapor compression by IBE dehydration (DS-II)

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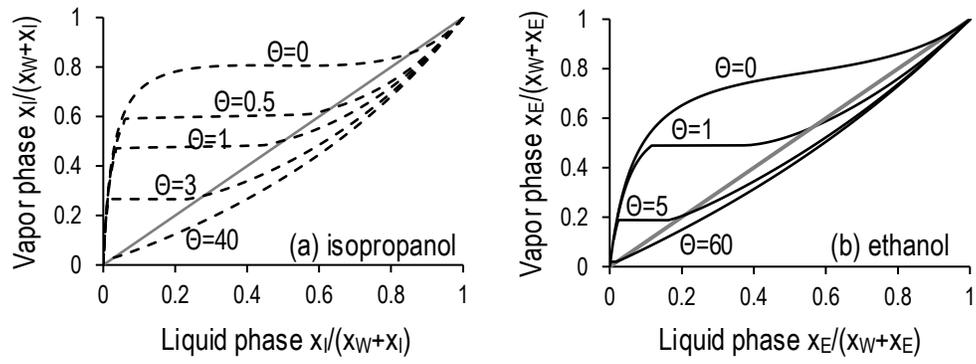


Fig. 3. Water-isopropanol and ethanol-water equilibriums at different butanol/alcohol ratio (θ) in mass basis

Two columns

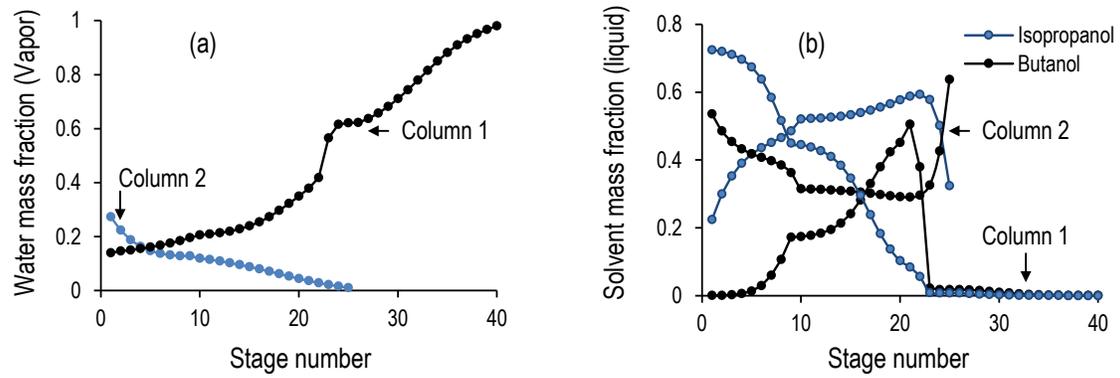


Fig. 4. Profiles of a new distillation system by IBE dehydration from *C. acetobutylicum Rh8* titer. The pressure of Col1 and Col2 were 1.0 and 0.25 bar, respectively

Two columns