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Proposition of alternative configurations of the distillation columns for bioethanol production using vacuum extractive fermentation process

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In this work, alternative configurations to fermentation and distillation process for hydrous ethanol production were proposed and evaluated. Three configurations were analyzed: conventional fermentation and distillation (CFCD), vacuum extractive fermentation coupled with double effect distillation (VFDD) and vacuum extractive fermentation coupled with conventional distillation (VFCD). The VFDD configuration provided a significant reduction on energy consumption; however, ethanol losses were considerably high. Regarding ethanol recovery on the distillation process, VFCD configuration achieved the highest value (95.5%) among the studied processes.

1. Introduction

Bioethanol is produced through fermentation of sugars from sugarcane in Brazil and other tropical countries, like India. Two configurations of the fermentation process are commonly employed in Brazilian biorefineries: feed-batch and continuous, both with cells recycle. These processes use low concentration of substrate, resulting in a low ethanol concentration in the wine. These conditions are necessary since conventional alcoholic fermentation is a typical inhibitory process, with cells growth rate affected by cellular, substrate and product concentration (Rivera et al., 2006). Since ethanol content of the wine is relatively low (7 – 10 wt%), large volumes of vinasse are generated in the further purification step, in which distillation columns are employed.

Because of the inhibitory effects of ethanol over the yeast cells, the extraction of this product from the fermentation medium is desirable (Costa et al., 2001), and it can be achieved through a fermentation process coupled to a vacuum flash chamber, studied by Silva et al. (1999). In this process, ethanol is produced and removed simultaneously, so ethanol concentration in the fermentor remains at low levels during all the time.

Wine produced on the vacuum extractive fermentative process contains higher ethanol concentration than that of the conventional fermentation processes, thus decreasing energy consumption in the further distillation stage. Besides, flows and other process

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parameters, such as pressure and temperature, are quite different for each process. Thus, the separation process based on distillation columns used for product purification must be reformulated.

In this work, simulations of the vacuum extractive fermentative process were carried out using software Aspen Plus, considering formation of fermentation by-products, such as glycerol and acetic acid. These components affect the general distillation column behaviour, increasing system complexity and energy consumption on column reboilers. A configuration of the double effect distillation system, which allows the thermal integration between reboilers and condensers, was considered and evaluated. The proposed configuration was compared to the conventional fermentation and distillation employed in the industry.

2. Simulation of the fermentation processes

In industrial fermentation, sugarcane juice is used as a source of sugars for the production of ethanol. Sucrose, the most abundant sugar, is hydrolyzed into glucose and fructose (reaction 1), which are converted into ethanol and carbon dioxide (reaction 2), in reactions catalyzed by the yeast *Saccharomyces cerevisiae*.

$$C_{12}H_{22}O_{11} + H_2O \rightarrow 2\ C_6H_{12}O_6 \quad (1)$$

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \quad (2)$$

Besides ethanol and carbon dioxide, several fermentation by-products are produced as well, as a result of parallel fermentation reactions, cells growth and impurities in the sugarcane juice, among other factors. In this work, the production of glycerol and acetic acid from glucose was considered, as shown in reaction 3.

$$2C_6H_{12}O_6 + H_2O \rightarrow C_2H_4O_2 + 2C_3H_8O_3 + C_2H_5OH + 2CO_2 \quad (3)$$

The reactors of both conventional and vacuum extractive fermentation processes were modelled assuming the same reactions and fixed conversion values adopted by Franceschin et al. (2008), which are given in Table 1.

Table 1. Conversion values for the fermentation reactions based on sugar consumption

Reaction number	Conversion (%)
1	99.0
2	99.5
3	0.5

2.1 Conventional fermentation process

In the conventional fermentation process, sugarcane juice is fed to the reactor along with yeast. Since both ethanol and substrate have inhibitory effects over the yeast cells, concentration of sugars in the feed stream must be relatively low (around 200 g/L), consequently producing wine of low ethanol concentration (between 7 and 10 ºGL).

2.2 Vacuum extractive fermentation process

The vacuum extractive fermentative process consists on a continuous fermentation reactor coupled to a vacuum flash evaporator, which allows ethanol produced to be simultaneously removed from the reactor, thus providing a relatively low concentration of ethanol in the fermentor, what reduces its inhibitory effect on yeast cells. For this reason, substrate may have a larger concentration of sugars than that of conventional fermentation (around 450 g/L). Wine obtained in the vacuum flash chamber has an ethanol concentration as high as 36 ºGL, which allows a reduction of wine volumes, consequently decreasing energy consumption and residue generation on the distillation stage. The proposed vacuum extractive fermentative configuration is shown in Figure 1.

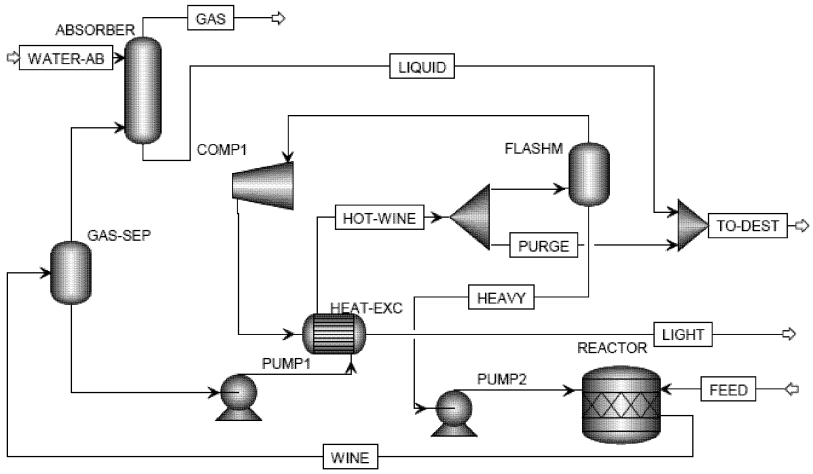

Figure 1 .Configuration of the vacuum extractive fermentation process.

3. Simulation of the distillation

Concentration of the wine is achieved using a series of distillation (columns A, A1 and D) and rectification columns (B and B1) in order to produce hydrous bioethanol (around 93 wt% ethanol). Two configurations of the distillation system were studied, namely: conventional (Figure 2) and the double effect (Figure 3). In the conventional configuration, both distillation and rectification columns operate under atmospheric pressure (101-125 and 101-135 kPa), while in the double effect configuration different pressure levels (19-25 and 101-135 kPa) are employed in these columns. The temperature levels created allow the integration of the distillation column reboiler to the rectification column condenser.

Differently from the conventional fermentation process, two ethanol-rich streams are obtained in the vacuum extractive fermentation process: “light” (around 36 wt% ethanol), which is comprised by the vapour phase obtained in the flash chamber, and “to-dest” (around 8 wt% ethanol), which is comprised by a purge from the liquid phase of the reactor and the liquid phase obtained in the absorber, as depicted in Figure 1. Since the flash chamber operates under vacuum (5 kPa), it is necessary to raise the pressure of the “light” stream using a series of compressors, before feeding it to the conventional distillation column (around 101 kPa). The double effect system does not require a large pressure change, and only one compressor may be used to provide the necessary pressure. Thus, according to the arrangement of the different configurations of fermentation and distillation processes, different process parameters and operations are required, and the need to carry out a detailed simulation study is justified. The combined simulation of the fermentation and distillation steps allows a better understanding of the bioethanol production process.

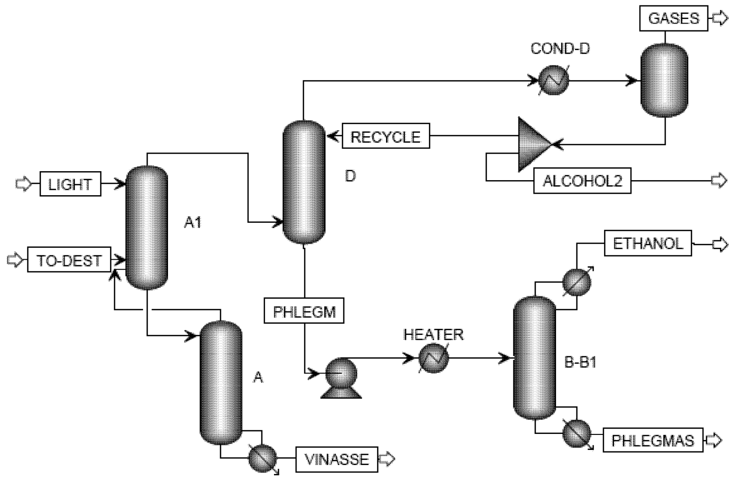

Figure 2.Configuration of the conventional distillation process.

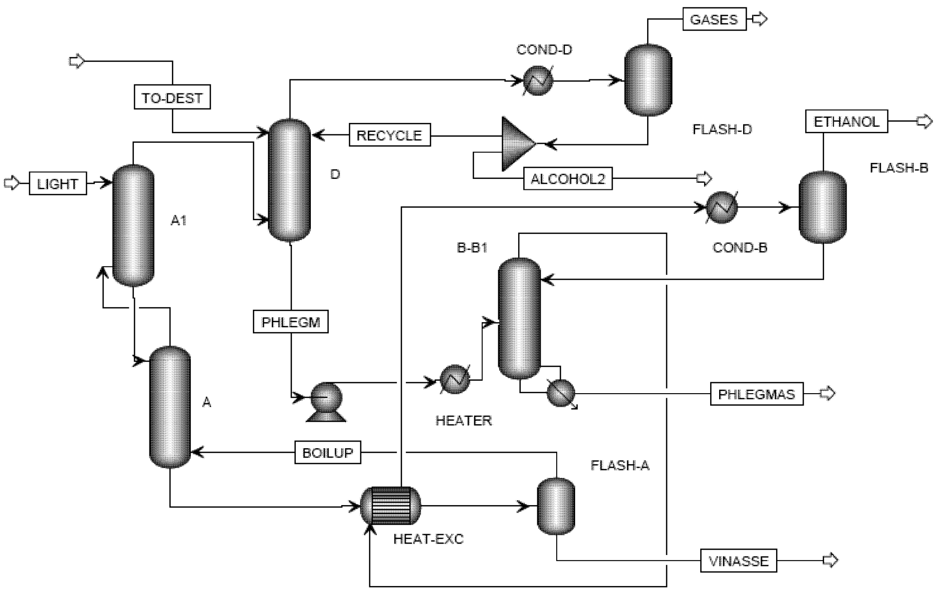

Figure 3.Configuration of the double effect distillation process.

4. Results and discussion

Process simulations were carried out using software Aspen Plus and NRTL was the model used to calculate the activity coefficient on the liquid phase, since it suitably represents the system behaviour.
Three different process configurations for the production of hydrous bioethanol were evaluated: conventional fermentation and distillation (CFCD), vacuum extractive fermentation and double effect distillation (VFDD) and vacuum extractive fermentation coupled with conventional distillation (VFCD). Stream flows and hydrous bioethanol production on each process are shown in Table 2.

Table 2.Streams flows and bioethanol production for each process.

	Mass flow (kg/h)		
Stream	CFCD	VFDD	VFCD
FEED	460.7	169.0	169.0
TO-DEST	460.7	69.6	69.6
LIGHT	-	84.9	84.9
LIQUID	-	10.6	10.6
VINASSE	312.7	22.7	78.1
GASES	37.1	17.0	12.4
ALCOHOL2	1.2	0.3	0.6
PHLEGM	109.8	114.5	63.4
PHLEGMAS	74.8	81.1	26.5
ETHANOL	35.0	33.4	37.0

Energy consumption on each of these processes was evaluated and compared. Heat duty in terms of amount of hydrous ethanol (93 wt%) produced are presented in Table 3. The values provided consider thermal integration between process streams, so that heat exchange between process streams has a heat duty equal to zero.

Table 3. Energy consumption of the studied processes.

	Heat duty (kJ/kg hydrous ethanol)		
Unit operation	CFCD	VFDD	VFCD
Reactor cooling	-1132	0	0
Wine heating	3014	0	0
Column A reboiler	6704	0	1475
Column D condenser	-6016	-2125	-2651
Column B reboiler	4790	3488	3339
Column B condenser	-3670	-1304	-2346
Total heating energy	14507	3488	4814
Total cooling energy	-10818	-3429	-4997

CFCD: conventional fermentation and conventional distillation; VFDD: vacuum extractive fermentation and double effect distillation; VFCD: vacuum extractive fermentation coupled with conventional distillation.

Since wine produced in the vacuum extractive fermentation process is more concentrated than that produced in the conventional process, the amount of vinasse produced in the conventional process is significantly larger. Therefore, in order to concentrate this vinasse and reduce its volume, a further vaporization step would be necessary and, consequently, energy consumption on conventional fermentation and distillation would increase considerably.

The configurations based on the vacuum extractive process contain compressors, so electricity is required in these configurations. Electricity requirements were 5.5 kW and 12.6 kW in VFDD and VFCD configurations, respectively.

Ethanol recovery on the distillation step was also evaluated on each case and results are summarized on Table 4.

Table 4. Ethanol recovery in the studied processes.

Configuration	Ethanol Recovery (%)
CFCD	90.0
VFDD	86.2
VFCD	95.5

In spite of providing energy savings, VFDD presented larger ethanol losses due to the low pressure in the gas separator, so ethanol losses on the stream “gases” are quite significant. VFCD presented the best results regarding ethanol recovery.

5. Conclusions

Vacuum extractive fermentation process has been considered as a suitable alternative to conventional fermentation, since it provides a highly concentrated wine and, as a result, reduces the amount of vinasse and energy consumption on the subsequent distillation step. Also, double effect distillation allows thermal integration between columns reboiler and condenser, reducing even more energy consumption on column reboilers, making bioethanol production more economically attractive.

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