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Batch pervaporative fermentation with coupled membrane and its influence on energy consumption in permeate recovery and distillation stage

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ABSTRACT

In the ethanol production process from sugarcane molasses, the distillation process is a high-energy demand stage. The distillation energy efficiency is strongly associated with the alcoholic fermentation performance in the process. The final ethanol concentration in the alcoholic wines has a direct impact on consumption of thermal energy in ethanol separation. In this paper, ethanol production with a H-SBMF (Hybrid-Simple Batch Membrane Fermenter) using PDMS (polydimethylsiloxane) pervaporation membrane was modelled and simulated, in order to determine its influence on energy consumption in distillation. Steam in distillation and electrical energy needs in permeate recovery were mainly influenced by membrane adaptation. The H-SBMF achieved a higher ethanol production in the range of 10 −13% compared to the conventional batch fermenter, and an increase in productivity of 150%. The distillation system consisted of two sets of columns: the ethanol recovery column and the rectification column. The permeate recovery system (i.e. vacuum and compression) was regarded in order to evaluate the electrical energy requirement, and the thermal energy demand was evaluated. A decrease in steam consumption was evidenced by the adaptation of the membrane to the fermenter. Higher energy efficiencies were achieved in distillation with larger membrane areas, achieving almost 17% steam reduction.

1. Introduction

It is clear that in Brazil and the United States, fuel alcohol has been adopted as an alternative energy source. Energy policies and technology trends have been developed regarding alcohol fuel; consequently there have been a many studies on ethanol production. However, most current research is aimed at second-generation ethanol production rather than improving actual ethanolic fermentation technology [1]. After all, according to [2,3] in the Brazilian case, the technology of fermentation and distillation equipment used in ethanol production from cane molasses has not changed in the last 30 years.

Low performance in ethanolic fermentation occurs due to ethanol inhibition factors associated with the *saccharomyces cerevisiae* microorganism (i.e. yeast cells that are widely used in ethanol fermentation), thus ethanol concentration in wines hardly exceeds 90 kg/m^3 [4,5] under normal conditions used in the industry. Different workers [6,7] have concluded that ethanol accumulation in fermentation broth is the main reason why lower fermentation performances are reached in industry. According to Aiba [8], ethanol inhibits the active site of *S. cerevisiae* in a non-competitive way. Then, a progressive increase of ethanol concentration in fermentation broth produces a reduction of ethanol production rates, to the point of terminating the ethanol formation. Others [5,9] have indicated that temperature rise has negative effects on *S. cerevisiae* ethanol tolerance, decreasing the limits of inhibition by ethanol concentration.

This generated drawback by ethanol inhibition factors on *S. cerevisiae microorganism* necessitates the use of low-relative substrate concentrations for better substrate utilisation. For ethanol concentrations of around 90 kg/m^3 in a free-yeast cell wine, the mass fraction of ethanol is about 8%. High energy consumption in distillation is due to the low ethanol concentration of wine in the distillation feed, thus a slight increase in final ethanol

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Nomenclature

A	membrane area [m^2]
C	concentration [kg/m^3]
c	molar concentration [$kmol/m^3$]
D^{eff}	Maxwell–Stefan effective coefficient of diffusion [m^2/h]
E	activation energy [kJ/kmol]
F	mass flow [kg/h]
H	adsorption (Henry) coefficient [$kmol/m^3bar$]
J	permeate flux in membrane [kg/m^2h]
L	membrane thickness [m]
M	Mass [kg]
m	molecular weight [kg/kmol]
N	permeate molar flux in membrane [$kmol/m^2h$]
P	total pressure [bar]
p	partial pressure [bar]
p_{sat}	vapour pressure [bar]
Q	heat of adsorption [kJ/kmol]
R	gas constant [kJ/kmol K]
r	kinetic rate reaction [kg/m^3 h]
T	temperature [K]
T	time [h]
u	velocity [m/h]
V	fermenter volume [m^3]
v_M	volumetric flow of permeate [m^3/h]
X	molar fraction
$\tilde{x}$	average molar fraction
W	weight fraction
Z	position in membrane wall [m]

Greek symbols

γ	activity coefficient
Θ	membrane area/fermenter volume relation [m^2/m^3]
μ	chemical potential [kJ/kmol]
ρ_{mix}	density of mixture (water-ethanol) at fermentation conditions [kg/m^3]

Subscripts

i	component i
M	membrane
mix	mixture
0	initial
P	ethanol
S	substrate
T	total
W	water
X	yeast cells

Superscripts

C	conventional fermentation
D	diffusion
F	membrane feed
O	standard state
P	permeate
PV	pervaporation

Abbreviations

ANP	National Agency of Petroleum, Natural Gas and Biofuels
H-SBMF	Hybrid-Simple batch membrane fermenter
PDMS	Polydimethylsiloxane
SBF	Simple Batch Fermenter

concentration of wine can considerably reduce the steam requirements in distillation. According to [3,10,11], the amount of steam[1] used in distillation per litre of dehydrated ethanol is in the range of 1.8–3 kg/l. This consumption is equivalent to 50–60% of thermal energy in the overall ethanol process without energy integration [10,12]. The fact that distillation consumes the most energy in the process creates an interesting opportunity to improve the energy efficiency in ethanol recovery.

Maximising ethanol production in fermentation through a simultaneous inhibitor separation and reaction, a lower amount of energy is required to separate the ethanol in the distillation stage. Thus, a modification in the fermenter to intensify the ethanol production in this stage of the process promotes improvements in subsequent operation to the fermentation step.

For instance, Junqueira et al. [13] propose a vacuum extractive system coupled with a fermenter and double effect distillation, achieving an energy saving of 66% of total energy in a partial integrated process. In Ref. [14], a comparative energy consumption analysis was made for three fermentation configurations: SBF (simple batch fermentation), CF (cooling fermentation) and VEF (vacuum extractive fermentation). The lowest thermal energy consumption was presented in VEF, but there was an increase in electrical energy demand. In the above cases, the reduction in thermal energy consumption is promoted by the increase of ethanol concentration in alcoholic wine.

[1] Saturated steam at 2.5 bar.

Pervaporative fermentation is similar to VEF, the difference lying in the fact that the membrane governs the mass transfer according to its selectivity and solubility properties [15], while the VEF is controlled by the thermodynamic equilibrium. Pervaporation is a separation process in which a liquid mixture is placed in contact with one side of a membrane, while the other side is kept under vacuum pressure. The membrane works as a filter, allowing the passage of specific species in liquid mixture. According to [15,16], the solution-diffusion model has been accepted in the last 30 years as an approach to describe the permeation phenomena in a polymeric membrane. The transport of components in the solution-diffusion model is driven by a chemical potential gradient across the membrane. Separation of components occurs due to diffusion of the components with higher solubility in the membrane, and a subsequent evaporation of the transferred components from the liquid feed through the membrane [17]. For this solution-diffusion model approach, the diffusion from the bulk of membrane feed to the membrane interface is faster than mass transfer by diffusion across the membrane. Then, mass transfer by permeation is the limiting step in the overall mass transfer of pervaporation.

Basically, a membrane hybrid fermentation (hereafter referred to as “hybrid fermenter”) is a fermenter coupled with a membrane, whether inside or outside the fermenter. The membrane removes key components from the fermentation broth according to the fermentation type. For ethanolic fermentation, the PDMS (polydimethylsiloxane) membrane removes a water-ethanol mixture.

A comparison of scientific works about hybrid fermentation is complex, due to the variety of considered variables in the results of