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Energetic optimization of Moroccan distillery using simulation and response surface methodology

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A B S T R A C T

Distillation is one of the most widely used separation methods in chemical process industries. In a typical bioethanol distillation process, the high consumption of energy is the major disadvantage of this process. Consequently, the design and optimization of the distillation column have a critical impact on the economics of the entire process. This work aimed to investigate a vacuum distillation process in order to evaluate the operating energy and cost to produce ethanol considering a fermented must with 5 components. The simulation results were compared with industrial data collected from a Moroccan distillery. It was found that the simulation approach was able to correctly reproduce the industrial process. Response surface methodology based on a central composite design was applied to analyze some operating conditions and optimize the process. Two models were proposed to test the required energy for distillation column using simulation results. On the other hand, the reflux ratio has a greater effect on required energy of distillation column compared to the feeding tray position. Working under optimal values of the operating conditions, the results showed that the operating energy and cost of the industrial process were reduced about 7.49% and 5.91%, respectively.

1. Introduction

Molasses is the latest byproduct obtained during the manufacture of sugar from cane and beet, very colorful and viscous. Its composition depends on the variety of the plant, climatic conditions, soil quality and on the process. It contains about 25% of water, sucrose, reducing sugars, vitamins and minerals. It is a high energy food that is generally used in animal nutrition [1]. Its fermentation followed by distillation gives ethanol and a byproduct called vinasse [2]. Ethanol is a very clean energy currently required to replace petroleum energy, because of oil prices rising and depletion of reserves in this resource, on one hand, and the increased emissions of greenhouse gases and their negative impact on the environment, on the other [3].

In the literature, several distillation processes can be distinguished for ethanol production, such as the azeotropic distillation, extractive distillation and vacuum distillation [4]. Azeotropic distillation is a widely practiced distillation process to separate the composition of binary azeotropic mixtures [5,6]. Some disadvantages of this process are use of toxic chemicals and sensitivity to feedstock impurities, its energy consumption can estimate between 2.77 and 4.16 kWh/kg [7]. Extractive distillation is used commercially for the production of anhydrous ethanol. The energy consumption of the extractive distillation with gasoline and ethylene glycol can be varied between 2.50 and 9.46 kWh/kg [3,8]. According to the vacuum distillation process consumes 3.05 kWh/kg of anhydrous ethanol [3]. Among the problems that arise during the distillation step is the significant energy demand. This energy can reach 50% of the total required energy of a distillery and it can be estimated about 3% of the world energy consumption [9–11]. Thus, the high consumption increases both the production costs and greenhouse emissions [12]. The energy efficiency of these processes has been improved continuously due to the strict requirements to produce a high quality and quantity of ethanol. In addition to the energy consumption constraint, it is very important to produce ethanol at high purity by removing impurities. The fermented must contains dozens of minor components, which are responsible for both the difficulty of the modeling of this system and to predict its behavior during the simulation [13,14].

Various researches were made to model and optimize the distillation process, focusing especially on energy consumption, separation methods and control strategies to produce ethanol, without taking into account the presence of minor components in the mixtures that influence the distillation process [14]. Complexity of the industrial distilleries often depends on the desired quality of its products. The lack of quality standards of ethanol at the international level requires industry to set up their own specifications choosing the appropriate operating conditions. The most optimization studies have been used a

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Nomenclature

A	absorbance
D	mass flow rate of distillate (kg/s)
EC	energy consumption (kWh)
F	mass flow rate of feed (kg/s)
f	fugacity
$\mathcal{F}$	pointing factor
H	specific enthalpy (J/kg)
L	mass flow rate of liquid (kg/s)
OF	objective function
P	pressure (Pa)
Q	power (Watt)
R	mass flow rate of residue (kg/s)
T	temperature (K)
V	mass flow rate of vapor (kg/s)
Val	value
x	mass fraction of liquid
X	input factor
Y	output factor
y	mass fraction of vapor
γ	acitivity coefficient
φ	fugacity coefficient

Subscripts

Act	acetaldehyde
C	condenser
cal	calculated
D	distillate
Eth	ethanol
$expe$	xperimental
F	feed
FTP	feeding tray position
i	component i
j	component j
R	residue
Reb	reboiler
RR	reflux ratio
t	tray
V	vapor
vp	vaporization

Superscripts

L	liquid
S	saturated vapor
V	vapor

computer simulation as a tool for investigating and improving bioethanol dehydration processes by extractive and azeotropic distillations, assuming the mixtures to separate as a simple binary mixture of ethanol-water. The extractive distillation for ethanol production was optimized at steady state from residue curve map analysis from a binary mixture of ethanol/water [15]. Simulation study of extractive distillation to produce ethanol from aqueous mixtures of ethanol using ethylene glycol as solvent was performed. The optimal conditions such as the solvent flowrate, distillate flowrate and reflux ratio were obtained using a sensitivity analysis approach [16]. A comparison between the conventional and extractive distillations was carried out for purification of ethanol from the ethanol-water binary system. The extractive distillation process seems to be the best to obtain anhydrous ethanol in term of the energy consumption by optimizing in the operating conditions [17]. The molar ratio of the solvent feed, reflux ratio, feeding tray of mixture, feeding tray of solvent and feed temperature parameters were evaluated to determine the best design that consumes less energy to separate water-ethanol mixture [18]. The effects of number trays of the distillation column, feeding tray and reflux ratio were examined to produce ethanol at high purity by normal distillation from a strongly non ideal binary mixture of ethanol and ethyl acetate [19]. An industrial distillation system for producing azeotropic ethanol was investigated, but the alcoholic wine was also considered as a binary mixture of ethanol and water [20].

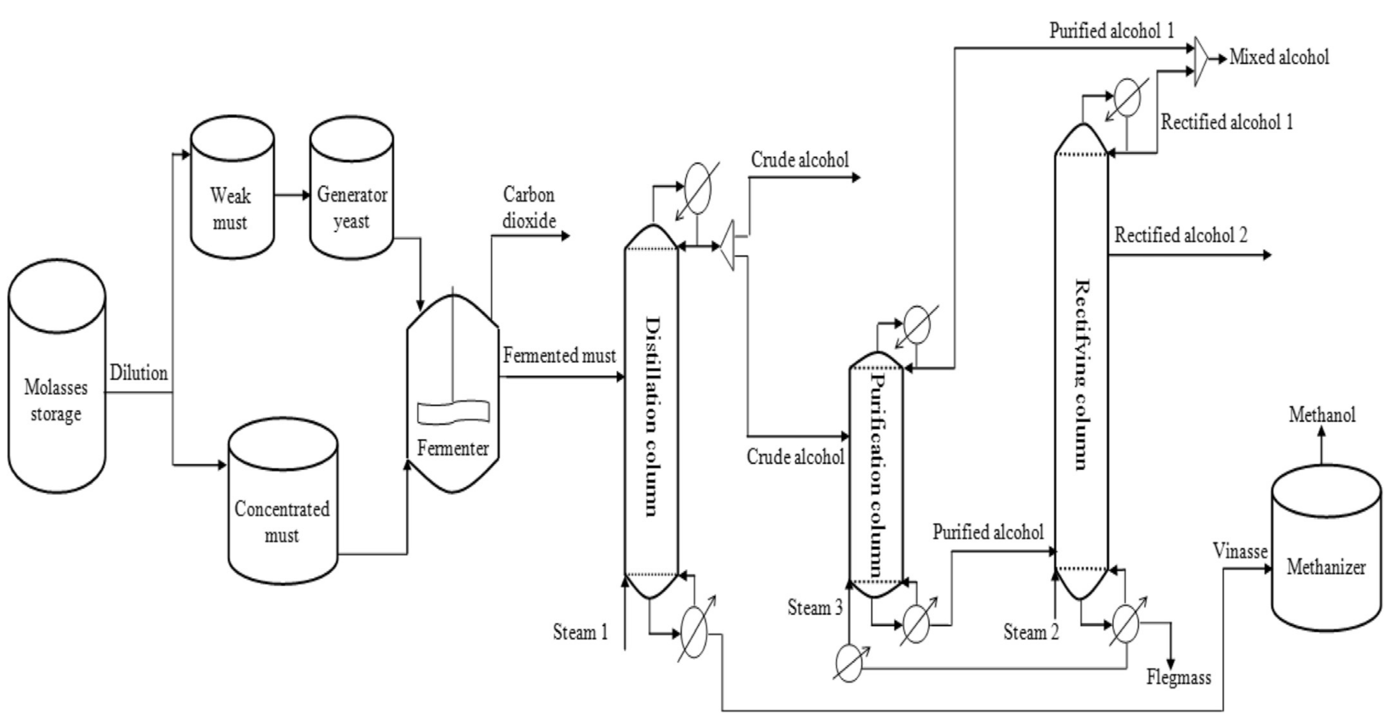

Fig. 1. Simplified schematic of the industrial process.