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Techno-economic optimization of plant for raw ethanol production based on experimental data

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ABSTRACT

This paper concerns techno-economic optimization of the production process of raw ethanol in a continuous distillation column as a part of the plant for production of rectified alcohol. Optimization was performed in order to determine the optimal ethanol concentration in the residue, which provides the minimum total production costs of existing plant. Total production costs are determined on the basis of experimental data, investment and operating costs and the estimated working life of the plant. It was found that ethanol concentration in the residue is significantly higher than values that can be found in the open literature.

1. Introduction

As well as in past few decades, most of the ethanol is nowadays produced from biomass and most of the ethanol production in Europe and the USA is based on corn [1–3]. The usage of ethanol as a fuel (pure or mixed with gasoline, etc.) provide substantial benefits from economic and CO_2 viewpoints [4], but ethanol is used in many other industrial fields: as a solvent, as industrial feedstock for the synthesis of many compounds in the chemical industry, as an antiseptic in medicine, as the basic raw material for production of alcoholic beverages, etc.

Technology of alcohol production depends on type of raw material and desired quality of final product. Rectified or refined alcohol must meet very stringent requirements of standards i.e. the minimum content of the accompanying components such as esters, aldehydes, fusel alcohols (fusel oils = higher-order alcohols), acids, etc. Water content is also very important. The plant analyzed in this paper is built in Serbia (village Kostojevići) and has a nominal production capacity $\dot{V}_{D_{AA}nom} = 4000$ lAA/d of rectified alcohol (AA denotes absolute or anhydrous alcohol). The distillation process in this plant is divided in two stages:

- in the first stage process takes place in a continuous distillation plant in which the distillate products contains 88%vol of ethanol (or $x_D = 0.6582$ kmol/kmol) – product is called raw (uncertified) ethanol;
- in the second phase batch rectification is used to produce distillate with 96.2%vol of ethanol with low content of accompanied components in accordance with standards for rectified ethanol.

The raw material for ethanol production is corn and the “dry” process [5] is used for preparation of raw material: after milling, cooking, hydrolysis and fermentation the feed for distillation contains 6.6%vol of ethanol ($x_F = 0.02135$ kmol/kmol).

Among other parameters total ethanol production costs depend on the degree of exhaustion of the column residue and this is a fact for raw ethanol production as well as rectified ethanol production.

The analysis presented in this paper concerns the optimization of the continuous distillation plant for production of raw ethanol. One of the main process variables in plant operation is the reflux ratio, which governs the ethanol concentration in residue. A smaller content of ethanol in residue implies lower losses in the ethanol production process, so in that sense, it is desirable that the ethanol concentration in residue is reduced to a minimum. On the other hand, this leads to the greater number of trays in the distillation column and/or greater reflux ratio, accompanied with the increases of the investment and operational costs. Since the distillation energy and exergy efficiency is still the problem of great concern [6–9], the aim of hereby presented analysis was to determine the optimal value of ethanol content in residue (the optimal value of reflux ratio) in order to provide the minimum total production costs of the plant.

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Nomenclature

a	amortization rate, y^{-1}
AA	absolute or anhydrous alcohol
C_{BE}	cost of major process units (basic equipment), EUR
C_{Col}	cost of distillation column, EUR
C_{HE}	cost of heat exchanger, EUR
$C_{HE,B} = f(S_{HE})$	bare module cost, EUR
C_{inv}	investment (capital) cost, EUR
C_{op}	operational cost, EUR/y
C_{op}^{AA}	specific operational cost, EUR/lAA
$C_{SC} = f(D_C, H_C, material, pressure)$	cost of the distillation column shell, EUR
$C_T = f(D_C, material, bubble\ cup\ trays)$	cost of tray, EUR
C_{tot}	overall annual cost, EUR/y
$\left(C_{tot}^{AA}\right)_I$	specific production costs, EUR/lAA
$\dot{D}$	molar flow rate of distillate, kmol/h
D_C	column diameter, m
d	day
E_{MG}	Murphree tray efficiency
$\dot{F}$	molar flow rate of feed, kmol/h
FF	flood factor
$f_i(i = 1 \div 9)$	direct-cost factors (equipment erection, piping, electrical power, instruments, process buildings, storages, utilities, site preparation, etc.)
$f_i(i = 10 \div 13)$	indirect-costs factors (design and engineering, contractor's fees, contingency allowance)
F_M	material factor
F_P	pressure factor
F_T	type factor
$\dot{G}$	molar flow rate of vapor, kmol/s
H_C	column height, m
$\dot{L}$	molar flow rate of liquid, kmol/s
m	slope of the equilibrium line
$\dot{m}_{CW}$	flow rate of water from cooling tower, kg/h
$\dot{m}_F$	mass flow rate of feed, kg/h
$\dot{m}_{HS}$	mass flow rate of steam, kg/h
$\dot{m}_{Well}$	mass flow rate of water from the well, kg/h
N	number of theoretical trays
N_{min}	minimal number of theoretical trays
N_r	number of real theoretical trays
$\dot{Q}_B$	reboiler heat duty, kW
$\dot{Q}_{Cond}$	condenser heat duty, kW
$\dot{Q}_{CT}$	cooling tower heat duty, kW
$\dot{Q}_{HE1}$	heat duty of distillate cooler 1, kW
$\dot{Q}_{HE2}$	heat duty of distillate cooler 2, kW
R	reflux ratio
R_{min}	minimal reflux ratio
R_{opt}	optimal reflux ratio
S_B	heat transfer surface of reboiler, m^2
S_{Cond}	heat transfer surface of condenser, m^2
S_{HE}	heat transfer surface, m^2
S_{HE1}	heat transfer surface of distillate cooler 1, m^2
S_{HE2}	heat transfer surface of distillate cooler 2, m^2
t_F	temperature of the feed, °C
t_{wb}	wet bulb temperature, °C
t_{Well}	temperature of water from the well, °C
$\dot{V}_{DAA}$	distillate volumetric flow rate expressed through the absolute ethanol (alcohol), lAA/h (lAA/d)
$\dot{V}_{DAAnom}$	nominal daily production of distillate expressed through the absolute ethanol (alcohol), lAA/d
V_{DAAy}	annual production of distillate expressed through the absolute ethanol (alcohol), lAA/y
$\dot{W}$	molar flow rate of residue, kmol/h
x_D	mole fraction of component i in distillate, $kmol_i$/kmol
x_F	mole fraction of component i in feed, $kmol_i$/kmol
x_W	mole fraction of component i in residue, $kmol_i$/kmol
y	year
λ	stripping factor
η	normalized efficiency
τ_y	annual working hours, h/y

2. Concentration of ethanol in residue – open literature data

In [10] the residue ethanol concentration was discussed as a function of the feed temperature and number of the column theoretical plates. In specific case of $N = 8.61 \div 11.25$ and temperature of fermented feed of $t_F = 70\,°C$, according to [10] ethanol mole fraction in residue should be $x_W = 62$ ppm.

In [11] the set of equations for determination of the maximum ethanol contain in residue were defined. The set of parameters were found to be of significant importance: x_F, steam flow rate and residue flow rate. It was found that $x_W = 59$ ppm is the upper limit of ethanol content in residue.

Stabnikov in [12] states that, in case of distillation column with 17 trays, the minimal operating costs are achieved in range $x_W = 39 \div 65$ ppm.

The handbook [13] issued by the APV states that the ethanol mole fraction in residue should be $x_W < 78$ ppm, while Rhum Agricole [14] states that the usual range is $x_W = 62 \div 93$ ppm.

In [15], analysis of economic aspects of ethanol production from corn was carried out. It was stated that the exhaustion of residue is usually in range $x_W = 40 \div 50$ ppm.

At the pilot plant described in [16] for ethanol production from lignocelluloses materials, the process is carried out with $x_W < 124$ ppm.

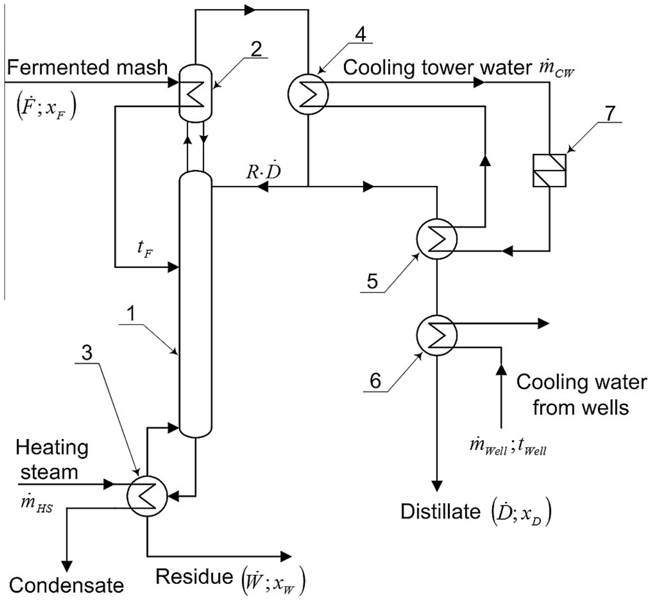

Fig. 1. Flow diagram of continuous distillation plant. 1 – distillation column, 2 – partial condenser, 3 – boiler, 4 – condenser, 5 – distillate cooler A, 6 – distillate cooler B, 7 – cooling tower.