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BALANCE AND OPERATIONAL ANALYSIS OF TECHNOLOGICAL NODES OF BIOETHANOL PRODUCTION PLANT

The paper presents monthly material and energy balances and operational analysis of the technological nodes of a bioethanol production plant. The plant was divided into five technological subsystems: raw material preparation, mashing, fermentation, rectification and utilization of the spent wash. Basic production indexes are also analyzed.

1. INTRODUCTION

Regulations concerning the limits of emission of toxic compounds from exhaust gases to the atmosphere are more and more restrictive. This causes a still growing interest in liquid fuels which are ecologically pure. Such fuels are welcomed in urbanized areas, especially in city centers, where particular consideration is given to health protection, and in historical centers, where additionally the conservation of historical objects is of primary importance.

Using an additive of ethanol for petrol becomes more and more common. Modern car engines are in most cases adapted to combustion of ethanol mixtures of concentrations up to 10%. The production of ethanol, so-called bioethanol, from agricultural materials is profitable for reasons of both economy and environmental protection.

Bioethanol production plants additionally generate animal feed from spent wash which is a by-product of the rectification process.

The operational analysis and balances of the technological stages in one of the Polish industrial plants producing bioethanol and animal fodder are presented. The throughput of the plant is 1000 t/month of maize. The consumption indexes of materials, energy and other media have been calculated and the efficiency of the process has also been evaluated.

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2. BIOETHANOL PRODUCTION STAGES

The main stages of bioethanol production from maize are specified below.

- Raw material preparation, i.e., the cleaning and grinding of the grain. In the product, 97% of particles is below 1 mm in size and 70% of particles is above 0.3 mm in size.
- Mashing – a stage of starch decomposition at an elevated temperature, by means of liquefying and saccharifying enzymes, resulting in the formation of fermenting sugars. It includes the following substages: mixing of the ground product with water, addition of liquefying enzyme, heating the mash, break, cooling, addition of saccharifying enzyme, cooling, addition of yeast and pitching.
- Fermentation – sugar conversion into bioethanol.
- Rectification – release of high wines.
- Spent wash utilization – fodder production.
- Dehydration of the ethanol.

The last of these stages is performed outside the plant, so its analysis is not taken into account in the calculations.

3. AVERAGE MONTHLY BALANCE OF TECHNOLOGICAL NODES

Material and energy balances of the technological nodes are presented in the tables. In energy balance, the consumption of electric energy and of heating steam, saturated at 155 °C (heat of condensation equal to 2100 kJ/kg) and generated in a fuel-oil fired boiler house, has been taken into account.

- *Raw material preparation*. After cleaning, the initial mass of the maize reduces by 4%. Maize itself contains about 60% of starch, which is the main raw material for bioethanol production. In order to establish the correct process parameters it is important to determine the proportion of the starch which can be converted to alcohol. The results of material and energy balances for this stage are presented in tables 1 and 2.

Table 1

Material balance for raw material preparation

Maize [Mg]	Contaminations [Mg]	Cleaned maize [Mg]	Starch [Mg]
1045.1	41.8	1003.3	602.0

Table 2

Energy balance for raw material preparation

Stage of process	Time of operation of devices	Power requirement	Energy consumption	
	[h]	[kW]	[kWh]	[MJ]
Cleaning	100	59.9	5990.0	
Grinding	348	130.8	45518.4	
Total			51508.4	185430.24

• *Mashing*. Material and energy balances for this stage are presented in tables 3 and 4.

Table 3

Material balance for mashing stage

Component	Amount [Mg]
Grinding product	1003.3
Yeast nutrient ($CaCl_2$ and $(NH_4)_3PO_4$)	1.67
Enzyme solutions	2.17
Yeast solution	332.33
Water	2645.28
Steam (direct heating)	1222.44
NaOH	trace amount
H_2SO_4	trace amount
Total	5207.19

Table 4

Energy balance for mashing stage

Medium	Amount	Energy amount [MJ]
Electric energy	81360.0 kWh	292896
Steam	122.44 Mg	257124
Cooling water	ca. 200 m^3	
Total		550020

• *Fermentation*. The material balance for the fermentation stage over one month is presented in tables 5 and 6. The total content of mash tubs, after removing 332.33 tons of starter yeast, is pumped over to the fermentation tubs, which must be prepared by careful sterilization with steam for 15–20 minutes. The amount of CO_2 produced was not measured, but estimated according to the theoretical conversion ratio for fermentation (theoretically 100 kg of starch can be converted into 56.8 kg of ethanol and 54.3

kg of CO_2, with water taking part in the reaction).

Table 5

Material balance for fermentation stage
(after seed yeast taking out)

Semi-product/product	Amount [Mg]
Sweet mash	4875
Fermented mash	4548
CO_2	327

Table 6

Energy balance for fermentation stage

Medium	Amount	Energy [MJ]
Electric energy	11520 kWh	41472
Steam	No measuring system	
Cooling water	No measuring system	

• *Rectification*. The fermented mash is fed to the rectifying column through a condenser. In the condenser, the mash is heated by the heat from the condensing alcohol vapours. Material and energy balances for the rectification stage are presented in tables 7 and 8. The product of rectification is 322.246 dm^3 (equivalent to 296.466 dm^3 of 100% ethanol).

Table 7

Material balance for rectification stage

Semi-product/product	Amount [Mg]	Total amount [Mg]
Fermentated mash	4548	4866
Steam (direct heating)	318	
Distillate	253	4866
Spent wash	4613	

Table 8

Energy balance for rectification stage

Medium	Amount	Energy amount [MJ]
Electric energy	6192 kWh	22291.2
Steam	318 Mg	667800.0
Cooling water	No measuring system	
Total		690091.2

• *Spent wash utilization*. The second product of maize processing, in addition to ethanol, is a granulated material, which can be used as animal fodder. It is obtained from the spent wash. Its production is based on passing the spent wash through a centrifuge, concentration of the separated material by evaporators, then drying and granulating. Material and energy balances for this stage are presented in tables 9 and 10.

Table 9

Material balance for spent wash utilization stage

Semi-product/product	Amount [Mg]
Spent wash	4613
Water	4245
Granulated fodder	368

Table 10

Energy balance for spent wash utilization stage

Medium	Amount	Energy amount [MJ]
Electric energy	230868 kWh	831124.8
Steam	1915.55 Mg	4022655000.0
Total		4023486125.0

4. OPERATIONAL ANALYSIS OF THE RECTIFYING COLUMN

In order to evaluate the operation of rectifying column, its overall efficiency was tested. The overall efficiency is equal to the ratio of the number of theoretical plates to the number of real plates fitted in the column. On the basis of processing the data, the following equations have been arrived at (where x and y are the mole fractions in the liquid and gas phases, respectively):

• upper operating linear equation

$$y = 0.71\ x + 0.2, \tag{1}$$

- lower operating linear equation

$$y = 3.5\ x - 0.005, \tag{2}$$

- feed linear equation

$$x = 0.075. \tag{3}$$

The number of theoretical plates was determined by the McCabe–Thiele method, assuming equilibrium data for the ethanol–water system according to [4] and was found to be 7. The number of real plates fitted in the column was 40. The overall efficiency of this column was only 17.5%. From the analysis it is clear that if only the efficiency of the present processing method were increased, a smaller number of real plates would be required. This also implies that the column described has considerable processing reserves.

5. CONCLUSIONS

Based on the balance data the operational effectiveness of the production plant discussed could be evaluated. The most important efficiency index is the actual alcohol productivity referred to 100 kg of starch. This index mainly depends on the equipment used and the state of the technology employed in the production system. The index is evaluated by an experts' committee, according to criteria imposed by the Ministry of Agriculture. For this particular production plant the index should be 60.64 dm^3 of alcohol/100kg of starch. The actual efficiency index for alcohol obtained from 100 kg of starch, calculated according to the real balance data, is 49.25 dm^3 (which makes it less by 11.39 dm^3). This demonstrates deficiency in the processing economy of this plant, because the effectiveness of starch processing reaches only 81%. There could be many reasons for this economic inefficiency. The main ones are given below.

- Operating conditions – the state of technology employed in the production as well as the choice of process parameters, especially for the fermentation stage.
- Accuracy of laboratory analysis of the materials processed (starch content in the raw material, degree of mash saccharification).
- Choice of the proper yeast strain.
- Ensuring the presence of oxygen traces, necessary in the fermentation process to assure long life of the yeast.
- Microbiological purity of the equipment (sufficient degree of sterilization).
- Efficiency of the rectification process.

Better instrumentation and measurements performed on the existing production system could lead to better control and operational analysis at each technological node. In this plant, some better monitoring system is needed for the following elements of the production system:

- steam delivery,
- cooling water supply,
- rectifying column, feeding and outlet.

The total amount of steam generated per month is 3456 Mg. This was used in calculating the energy indexes.

The actual efficiency of alcohol production per 100 kg of raw material amounted to 29.55 dm^3. Additionally, in relation to 1 dm^3 of 100% ethanol, 1.24 kg of granulated fodder was produced. The production of granulated fodder improves the plant profitability.

Global material and media consumption indexes in terms of 1 dm^3 of 100% ethanol are presented in table 11. Energy consumption indexes, excluding spent wash utilization stage, are presented in table 12. These can be used for the economic assessment of this stage. On comparing the results, it is clear that the stage of spent wash utilization is energy consuming.

Table 11

Material and media consumption indexes in terms of 1 dm^3 of 100 % alcohol

Material/medium	Consumption index	Energy consumption index [MJ]
Maize	3.4 kg	
$CaCl_2$	0.003 kg	
$(NH_4)_3PO_4$	0.003 kg	
Enzymes	0.0013 kg	
Yeast	0.001 kg	
NaOH	0.1 kg	
H_2SO_4	0.003 kg	
Electric energy	1.1 kWh	3.96
Steam	11.7 kg	24.57
Mazout (for steam production)	0.45 kg	
Water	9.7 kg	
Total energy index [MJ]		28.53

Table 12

Indexes of energy consumption in terms of 1 dm^3 of 100 % alcohol
(excluding spent wash utilization)

Medium	Consumption index	Energy consumption index [MJ]
Electric energy	0.79 kWh	2.844
Steam	5 kg	10.500
Mazout (for steam production)	0.2 kg	
Total energy index [MJ]		13.344

The total energy index given in table 12 describes the energy input required for the production of 1 dm^3 of ethanol from maize, excluding the energy required for the ethanol dehydration. It is high in comparison with the net calorific value of pure alcohol, which is 26.8 MJ/dm^3.

The plant considered emits to the atmosphere the following amounts of impurities (per month): SO_2 – 1.56 Mg, NO_2 – 0.695 Mg, CO – 0.07 Mg, CO_2 – 232 Mg (from the mazout burnt, CO_2 from the fermentation process is utilized), dust – 0.382 Mg. The total level of atmospheric pollution due to such plants should be taken into account when general assessment is made of the effects of the implementation of liquid fuels with bioethanol addition.

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BILANS I ANALIZA PRACY WĘZŁÓW TECHNOLOGICZNYCH ZAKŁADU PRODUKCJI BIOETANOLU

Przedstawiono bilans i analizę pracy poszczególnych węzłów technologicznych w zakładzie produkcji bioetanolu. Zakład podzielono na 5 następujących węzłów produkcyjnych: przygotowanie surowca, zacieranie, fermentacja, rektyfikacja, utylizacja wywaru. Dla każdego węzła przeprowadzono miesięczny bilans materiałowy i energetyczny. Przeanalizowano również kluczowe wskaźniki produkcyjne.