ENERGETIC ASSESSMENT OF BIOETHANOL CONGRUENT DEHYDRATION PROCESS

Gunars Bremers, Adolfs Rucins, Kristine Zihmane-Ritina,
Gints Birzietis, Arturs Baltins, Arnolds Skele
Latvia University of Agriculture
arucins@ltk.lv, gints.birzietis@llu.lv

Abstract. The aim of the research was to develop a new energy-saving bioethanol congruent dehydration technology and respective experimental facility. The developed technology is based on the bioethanol semi-dry congruent dehydration principle. As a result of the performed research an experimental facility for congruent dehydration of bioethanol was created and patented (European patent No. EP12160659.4.) by help of which several options of bioethanol dehydration were tested. As a result of the conducted research a scientifically justified new technology and technological equipment for bioethanol dehydration were obtained that allows saving up to 80 % of energy for the production of concentrated bioethanol. When doing the measurements and calculations of energy consumption of the technological cycle, it was discovered that application of the bioethanol congruent dehydration technology in the energy efficient variant ensures approximately 80 % of energy saving, in contrast to the traditional rectification method using the molecular sieve.

Keywords: bioethanol dehydration facility, energy efficiency.

Introduction

The most widely applied technology in the bioethanol production is the alcohol dehydration technology, which means that at first a part of water is separated by means of rectification, and then the remaining water is adsorbed using molecular sieves [1]. Like the other renewable energy resources, bioethanol production requires great investments. In contrast to the traditional bioethanol dehydration technology, the aim of our research was to develop a technology by which it would be possible to reduce sharply the consumption of energy for bioethanol dehydration. As a result, a new bioethanol dehydration technology was developed and patented [2]. The new technology is based on the bioethanol semi-dry congruent dehydration principle where water separation from alcohol takes place simultaneously by means of water adsorption and rectification [3] in this way significantly reducing the energy consumption in bioethanol production. Experimental equipment was developed for the implementation of the new technology for which the European Patent No. EP12160659.4 was granted [4].

The research checked the suitability of the equipment design for the implementation of the new technology by fixing the course of the technological process.

Materials and methods

The design of the experimental equipment is shown in Figure 1. It consists of a column 1 formed from a stainless steel pipe, 100 mm in diameter (~2.5 m long), and a heating unit 2 of an original design. On the top of the column loading of the active water adsorption granules and alcohol to be dehydrated takes place, below there proceeds moistening of the down-flowing granules, bioethanol dehydration and rectification of the alcohol residue within the layer of the down-flowing adsorbent granules. The adsorbent granules may be made on the zeolite basis. The advantage of these adsorbent granules is their thermal durability – about 500 ºC. This provides an opportunity to apply economic heat carriers for regeneration of the granules, such as fume gases [5].

The heating unit is heated by electric heating elements with 2 kW capacity. In the bottom of the unit there takes place emission of the heating water vapour required for alcohol rectification by partly evaporating the water attached to the used adsorbent granules. On the top of the unit the separation process of the residue alcohol starts which is completed at the bottom of the column. After the bioethanol dehydration manipulations are finished, the heating unit is used also for regeneration of the used water adsorption granules.

Measuring methodology of energy consumption. To measure the energy consumption, the experimental equipment was equipped with the following measuring instruments:

in order to determine the mass of granules flowing through the granule dosing unit, the balance CAS DB–1H was used with measuring precision of ±50 g but, to check the moisture degree of the

granules, the laboratory balance KERN 440–35N was used with measuring precision of ±0.01 g. For the energy supply electric heating elements of 2 kW capacity were used.

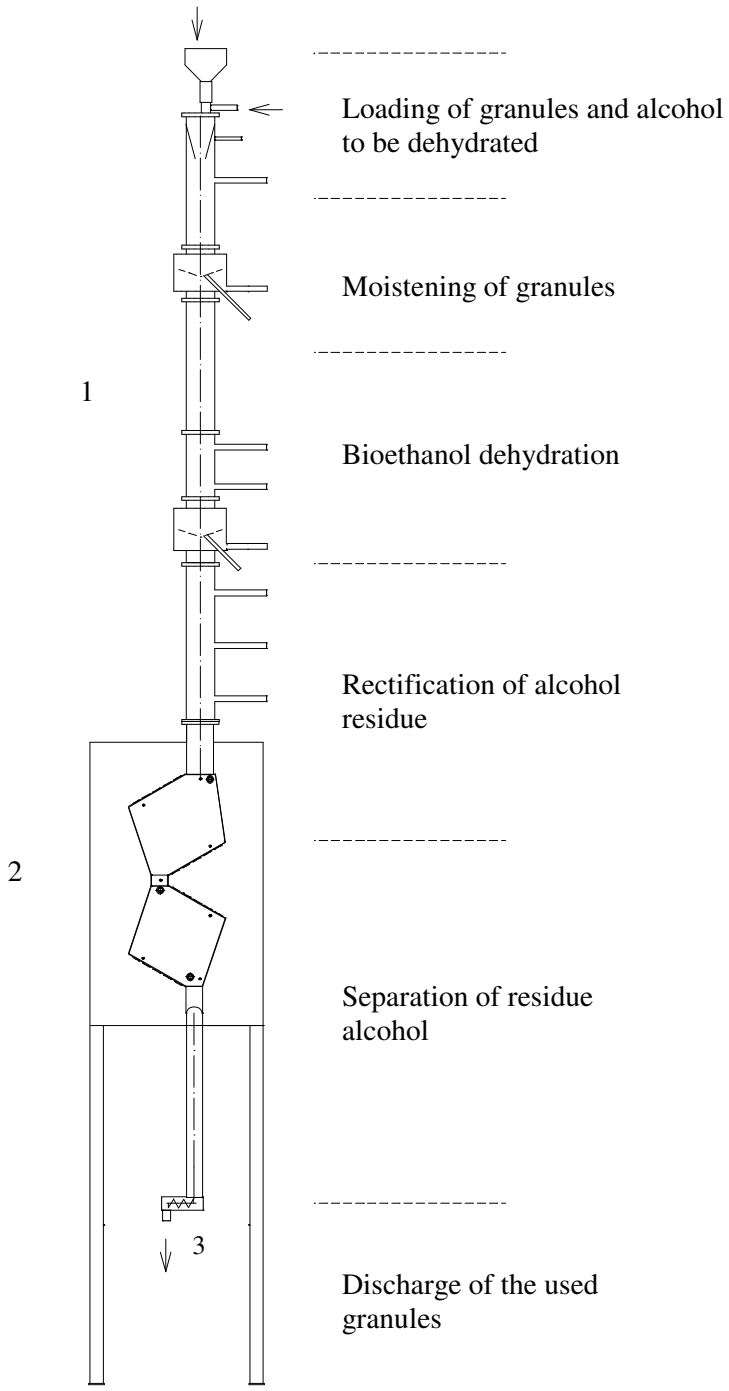

Fig. 1. **A principal scheme of the experimental equipment**

Precise regulated (rated) temperature was maintained by K–series thermoregulators K–31 (technologic) measuring temperature with K–type thermo-couples connected to a data logger TC–08 (Pico Technology Ltd., the Picolog software) for temperature recording where the measuring range is from 270 ºC to +1820 ºC and the measuring precision is within the limits ±0.5 ºC. Accounting of the consumed electric energy is carried out by the energy meter PM–300 with the precision of readings ±0.01 kWh and the accounting precision within the range ±5 % of the sum [6].

The useful consumption of electric energy was calculated by subtracting from the total consumption the losses of energy in the surrounding environment which were determined in previous experiments [4] as shown in Figure 2.

In order to control and evaluate the composition of the products involved in the bioethanol dehydration technological process, a device was worked out for determination of the ethanol concentration as a mixture of two dielectric liquids – bioethanol and water, based on the difference of dielectric constants of the two components of this mixture [8].

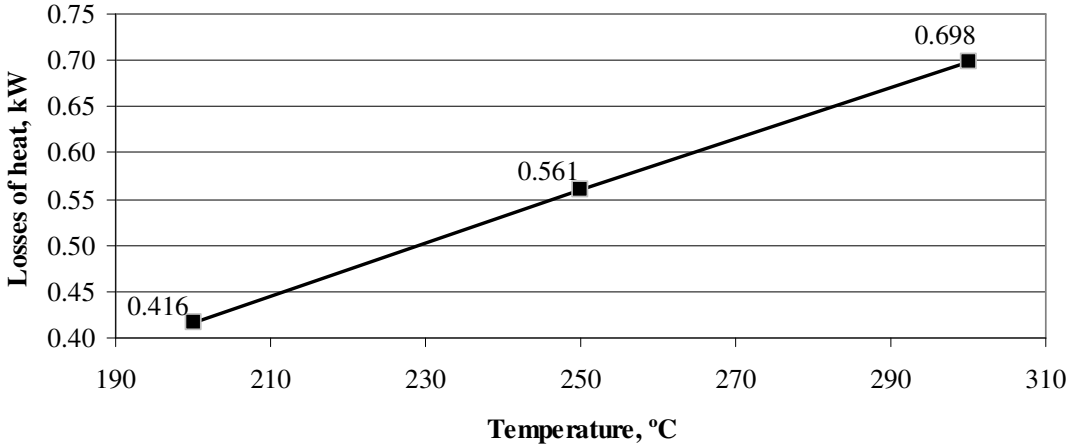

Fig. 2. **Diagram for determination of the losses of heat in the equipment depending on the regulated (rated) temperature inside the heating unit**

Results and discussion

Description of the applied bioethanol dehydration technology. Several variants of bioethanol dehydration technology were used in the experiments. Further the article will analyse the variant of the bioethanol dehydration technology which gave the greatest energy efficiency.

The stages of the entire bioethanol dehydration technological process are shown in Figure 1: granule moistening, bioethanol dehydration, alcohol rectification, separation of the residue alcohol. This does not mean that there are very strict borders between the stages. For instance, bioethanol dehydration starts already in the granule moistening zone but the granule moistening continues also in the bioethanol dehydration zone. Such overlapping of the processes takes place also in other zones.

Before starting the process the equipment is filled with active water adsorption granules [3]. These adsorption granules are active which have a reduced moisture content (0...2...3 %) and which can attract water intensively. The continual flow of granules, which is necessary for the process, is ensured by the granule dosing unit 3 attached at the bottom of the equipment.

It was revealed during the experiments that the moisture content of the water adsorption granules at the end of the process is 12...13 %. It results from the previous that one kilogram of the active adsorbent attaches approximately 100 grams of water. The concentration of the leaven distillate (nutrient liquid) is 85 %, that is, one kilogram contains 150 grams of water. Consequently, 1.5 kilograms of active granules should be filled into the equipment per one kilogram of the leaven distillate. Converted per one litre (density of the liquid is 0.8 $kg \cdot l^{-1}$) this makes 1.2 $kg \cdot l^{-1}$.

The nutrient liquid to be dehydrated is introduced on the upper level of the column 1 using a pump for this purpose. It is difficult to moisten the dry adsorbent granules with the previously mentioned amount of liquid, therefore, inside the lower part of the moistening zone of the column there is a liquid filter arranged by means of which the down-flowing excess liquid is separated and returned by the same feeding pump thus achieving circulation of the liquid and more complete moistening of the granules. With the active granules contacting the liquid, the water attachment process starts alongside with the moistening procedure. In the middle part of the column 1 (the dehydration zone) with the adsorbent granules moving downwards, the water adsorption continues; meanwhile the water molecules from the alcohol solution attached to the surfaces of the granules are selectively and gradually penetrating into the inner deeper pores of the adsorbent granules, but the

alcohol concentration is still increasing. This process takes some time; in the experiments it was approximately two hours.

In the lower part of the bioethanol dehydration zone there is another filter installed by which a part of the liquid – 40...50 % of the total introduced absolute alcohol – freely flowing off is separated. The alcohol concentration in this liquid may already have reached the bioethanol condition (over 99.5 %). Then it is discharged as an end-product. If the concentration of the solution has not yet reached the level required for bioethanol – it is transferred to the pump and included into the granule moistening circulation.

The granules which have arrived under the second filter carry the water adsorbed in the inner pores and the residue alcohol attached to the surface – 50...60 % of the total absolute alcohol introduced together with the nutrient solution.

At first alcohol attached to the granules is separated. This occurs in the lower part of the column where the prevailing process is alcohol rectification. Besides, simultaneous evaporation of the residue alcohol takes place, which starts in the zone below, with the use of the potential of the remaining water adsorption. As a result of this the concentration of the alcohol vapour flowing out of the upper part of the rectification zone does not correspond to the bioethanol condition, and, after being cooled in the condenser, it is discharged as an end-product. However, if the concentration is not yet adequate, the condensate is transferred to the liquid circulation to moisten the granules.

The amount of vapour which is necessary for alcohol rectification and which is produced by maintaining the temperature of approximately 200 ºC in the bottom of the heating unit 2 arises after evaporation of a part of the water adsorbed by the adsorbent granules and the residue alcohol attached to the surface of the adsorbent granules.

An important factor for emission of alcohol vapour is the vacuum–pressure mode in the whole equipment. To prevent the vapour separated in the residue alcohol evaporation zone moving downwards and into the granule outlet, which would cause losses of alcohol, the rectification zone must have greater vacuum. It was found out during the experiments that the vacuum difference between the bioethanol vapour discharge level and the upper level of the evaporation zone of the residue alcohol must be 30...40 mmH_2O. The necessary vacuum can be achieved both by a vacuum pump and by alcohol vapour condensation. To avoid that alcohol vapour remaining in the noncondensable gases sucked out by a vacuum pump may create losses of alcohol when it escapes into the atmosphere, the exhaust gases from the vacuum pump are introduced into the upper part of the equipment – the granule moistening zone.

After the residue alcohol is separated, the granules with the moisture content of 11...12 % are discharged from the equipment by help of a dosing unit attached at the lower part of the equipment [3].

The discharged used water adsorption granules are collected, after that their regeneration is carried out. For this purpose the moisture of the granules with the moisture content of 11…12 % loaded into the heating unit 2, maintaining the temperature of about 300º, decreased to 2...3 %. The duration of the granule regeneration is approximately three hours. The consumption of energy needed for regeneration is determined with the measuring devices attached to the unit [6].

Two design variants of the granule regenerator were tested in the experiments – a variant with a grid of inclined pipes, and a cassette–type variant. Both variants produced a similar efficiency granule regeneration result but the cassette variant is of a simpler design.

The energy consumption in the functional units of the technology was expressed per one kilogram and litre of absolute alcohol (bioethanol).

In order to produce one kilogram of bioethanol, 1.176 kg of nutrient solution with a 85 % alcohol concentration must be loaded into the dehydration equipment and then 0.176 kg of water separated. It was found out in the experiments that the adsorbent granules with 2 % moisture content can also be used for bioethanol dehydration.

If the previously mentioned energy consumption data in individual functional units are used, then the total consumption of energy is $1048+0.176 \cdot 6500 = 2192$ kJ per one kg of absolute alcohol, respectively, bioethanol.

In order to compare the calculated amount of energy with the amount needed for the traditional technology, an account was made using the method of material–energy balance [3] which showed that to produce one litre of bioethanol by the traditional rectification–molecular sieve bioethanol dehydration technology, 6576 kJ of energy or 2.87 kg of the heating water vapour (at the 2293.9 $kJ \cdot kg^{-1}$ water vapour enthalpy) is consumed.

As the density of bioethanol is 0.79 $kg \cdot l^{-1}$, one kilogram corresponds to 1.27 litres. In the technology developed by us the energy consumption per one litre is: 2192/1.27 = 1726 $kJ \cdot l^{-1}$. In comparison with the traditional technology this makes (1726:6576)· 100 = 26.2 %.

This account relates to the direct consumption of energy. But one should take into consideration also the indirect savings of energy consumption. First – the vapour separated in regeneration of the water adsorption granules may be used for distillation of the fermented leaven, which saves 0.176· 2293.9 = 404 kJ per kg of absolute alcohol, or 404/1.27 = 318 $kJ \cdot l^{-1}$. Thus the consumption of energy is reduced to 1726-318 = 1408 $kJ \cdot l^{-1}$.

Second – it is intended to use fume gases instead of the water vapour for heating the new bioethanol dehydration equipment, which means that no boiler is required thus reducing the energy consumption by 10 % (the coefficient of efficiency of a boiler is 90 %).

Therefore, it turns out that the final (indirect) consumption of energy is 0.9· 1408 = 1267 $kJ \cdot l^{-1}$. In comparison with the traditional technology it is (1267:6576)· 100 = 19.3 %, or approximately 80 % saving of energy.

Conclusions

1. Experimental equipment has been developed for congruent bioethanol dehydration by means of which various technological variants were tested.
2. The developed measuring facilities allow the measurement of the energy consumed in different technologies.
3. In contrast to the traditional technology, the consumption of energy in the developed technology constitutes 26.2 %.
4. The research shows that the technological energy is not consumed in the dehydration unit; the technological energy required to separate the residue alcohol attached to the granules has been determined in an experimental way from a series of results 1128; 911; 1170; 982, which makes the average of 1048 $kJ \cdot kg^{-1}$ of absolute alcohol.
5. It was found out in an experimental manner that adsorbent granules of 2 % moisture content can also be used for bioethanol dehydration.
6. It was established in an experimental way that, when the moisture content in the granules is reduced from 11...12 % to 2...3 %, the average consumption of heat is 6500 $kJ \cdot kg^{-1}$ of the separated water.
7. Using fume gases instead of the water vapour for heating the bioethanol dehydration equipment, the consumption of energy can be reduced by 10 %.
8. In contrast to the traditional rectification–molecular sieve bioethanol dehydration method, the variant of the tested more energy-efficient technology gave 80 % saving of energy.

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