

ADAPTIVE CONTROL ALGORITHM OF THE FIELD ESTERIFICATION PLANT

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Abstract

Biofuel production to power compression ignition engines on a small scale, using alkaline catalysts is not a difficult process. The problem could be the collection of excess alcohol, which is used during production in this conduct of process of biofuel. The authors attempted to develop the control algorithm of alcohol evaporation process, in the "field esterification plant" which is used to produce biofuels on demands for Department of Mechatronics and Information Technology Education Chair of University of Warmia and Mazury. The article describes the mobile installation used for the production of biofuels and requirements, which this installation should conform, working in a variety of conditions. The installation should work properly with different mixtures of components with different proportions of vegetable and animal fats mixed with methyl or ethyl alcohol. The algorithm controls the process in a way that it was possible to use of not only methyl alcohol, but also other alcohols, at variable temperature of refrigerant cooling excess alcohol vapours. The adaptive control algorithm of alcohol evaporation process improves the efficiency of system operation by reducing production time and decrease of electricity power and water (needed to cool the heat exchanger) consumption. Software upgrade also affects the quality of the obtained final product, as well as on the whole process.

Keywords: *biodiesel production, control algorithm, methyl esters, ethyl esters, air pollution*

1. Introduction

A mobile esterification plant is an experimental device in which the methodology to produce alcohol esters from vegetable and animal fats as well as their mixtures is developed with the usage of alkaline catalysts. The system presented in Fig. 1 is mounted on Star 266 vehicle shown in Fig. 2.

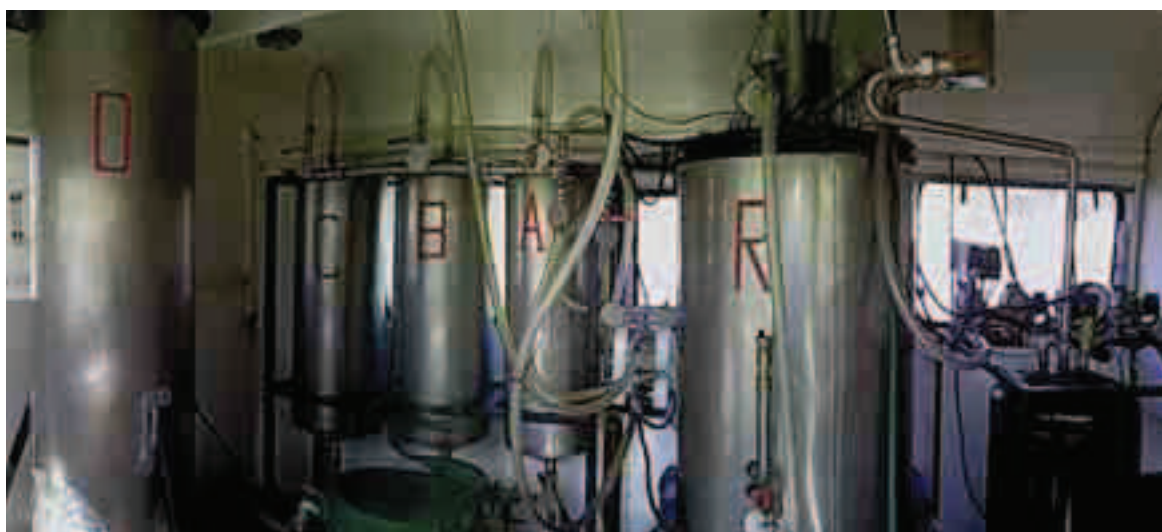


Fig. 1. A panoramic photograph of a mobile biodiesel production plant constructed inside the body of a Star 266



Fig. 2. Star 266 on which the system is constructed

Such construction makes it possible to transport the installation of the plant on hardened roads and in the off-road area, thus esters can be produced virtually anywhere. All elements required to assure proper functioning of the plant are installed on the vehicle, the only component needed on the premises being running water used to cool heat exchangers, which in turn cool alcohol vapours generated in the esterification process. The system is able to produce up to 300kg of esters in 24h.

The installation comprises the following elements:

- A transesterification reactor equipped with a water jacket, a heating system and a stirrer. The water jacket heats the inside of the reactor, passing the heat into the reaction mixture and enables excess alcohol stripping.
- A, B, C, and D separator where ester and glycerine phases are separated.
- Containers for the process reactants.
- A compressed air system, with the air delivered from a compressor equipped with a pressure reducer. Compressed air is used to the power pumps of the feed system and actuators of the control system. To minimize the explosion threat, during operation process the compressor is kept outside the vehicle.
- A pump taking off glycerine and esters phases from the reactor and separators.
- A power aggregate, which is mounted on a one-axis trailer.
- An electrical system and control panel (Fig. 3) with electrical protection elements, a power supply and a PLC-HMI controller with a control panel.
- A hydraulic pipeline, which facilitates pumping the substrates and products of the process.



Fig. 3. A control cabinet with electrical protection elements and a PLC-HMI controller installed on the cabinet door

The measuring elements and actuators comprise:

- A cold-water valve – a regulation valve with a positioner and pneumatic drive controlled by a 4-20mA signal, presented in Fig. 4.

- Dual-position pneumatic valves controlled with 0-24V signal (Fig. 5), which regulate airing the system, stopping vacuum and filling the pump.
- A temperature sensor checking the temperature of the mixture, alcohol condensate (Fig. 6) and the water jacket – the sensors have temperature range of 0-100°C and are equipped with 4-20mA converters.
- A pressure sensor to check the pressure inside the reactor – a negative pressure and overpressure converter of $\pm 100\text{kPa}$ range.
- The heating system of the jacket – 6 heaters, 1500W each, in two 3-heater sections.
- A stirrer inside the reactor, powered by specially protected engines for areas threatened with explosions.
- A vacuum pump providing negative pressure in the reactor during the esterification process. It enables a faster excess alcohol off take from the reactor when the process comes to the end.



Fig. 4. A cold-water valve with a positioner



Fig. 5. Dual-position pneumatic valves, which regulate air inlet of the system, stopping vacuum and filling the pump



Fig. 6. A temperature sensor of the mixture temperature, alcohol condensate with a heat exchanger

2. The transesterification process characteristics

Transesterification is a reaction as a result of which glycerol from a fat molecule (triacylglycerol) is replaced by low molecular aliphatic alcohols (methanol, ethanol, propanol, or butanol). The course of the reaction is presented in Fig. 7. The stoichiometric description of the reaction shows that ethanolysis of 1 mol of triacylglycerol uses 3 moles of ethyl alcohol, which gives 3 moles of fatty acids ethyl esters and 1 mol of glycerol. Since alcoholysis is an equilibrium reaction, in order to increase the amount of esters in the final product it is necessary to apply an excess of one of the substrates (usually alcohol) or perform the reaction in phases, after every phase receiving the side product (glycerol). Alcoholysis continues until equilibrium is reached, which depends on the quantity ratio of the compounds, which take part in the reaction. In fact, intermediary compounds such as diacylglycerols and monoglycerols are produced in the reaction.

The yield the reaction of triacylglycerol (fat) in the process of transesterification depends on:

- chemical composition of plant oil and the level of its purity (water content, free fatty acids content),
- a kind of alcohol used,
- mol proportions of oil to ethanol,
- how long the process lasts,
- temperature in which the process is performed,
- a kind of catalyst used.

Depending on the conditions in which the reaction is performed, its general yield can reach 99%, yet in the final product, one can trace products of intermediary phases, which is unfavourable since the produced ester reveals worse properties.

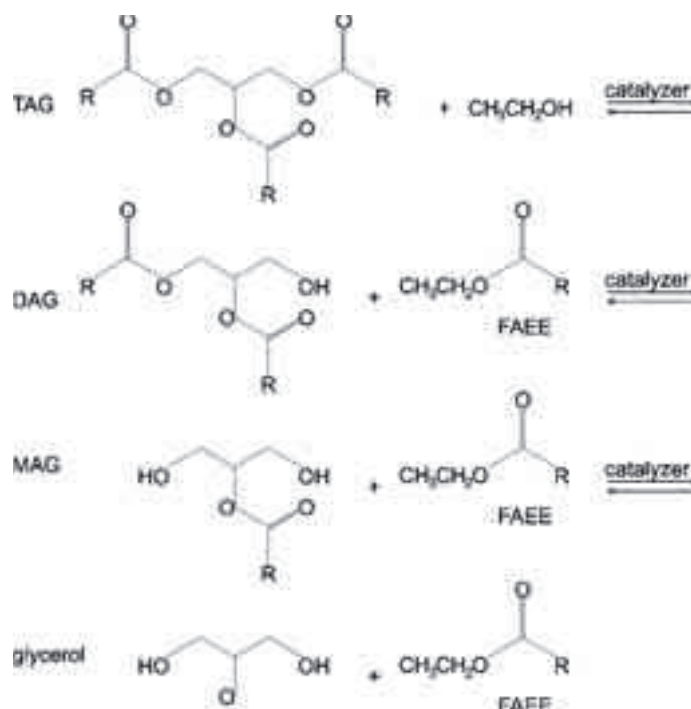


Fig. 7. The course of transesterification reaction

3. A description of the technological process of the installation's performance

A measured amount of fat (III), which is heated to a set temperature, is added to the preheated reactor. Then, alcohol (II) is added and the mixture in the reactor is heated, which precedes adding a catalyst mixture (I) comprising potassium hydroxide solved in alcohol. Everything is then heated until it reaches the esterification temperature. When esterification is over, the excess of alcohol

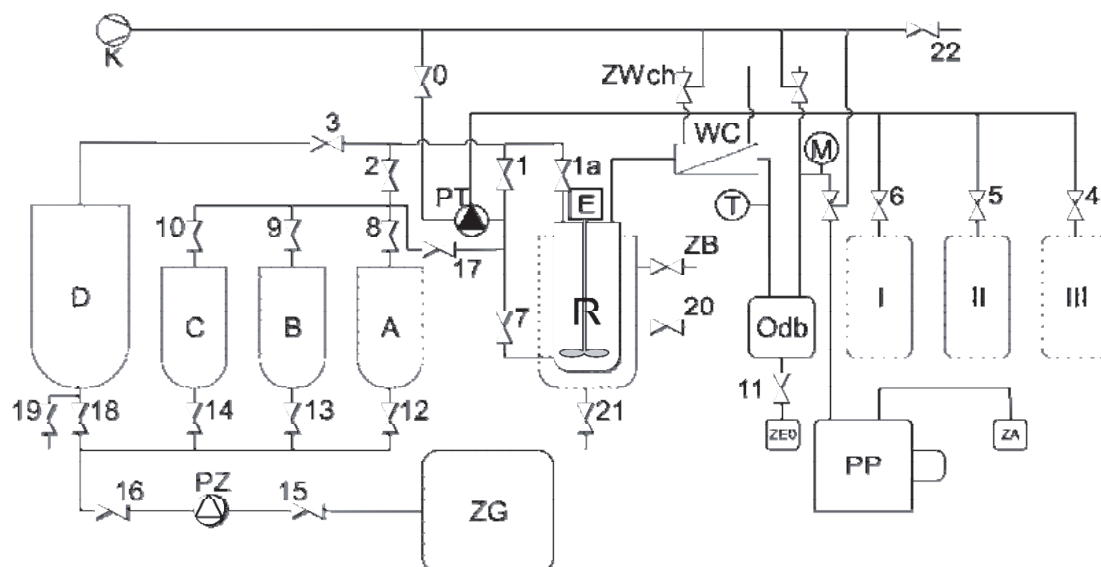


Fig. 8. System diagram. R – reactor, I – catalytic mixture tank, II – ethanol tank, III – oil tank, A, B, C – post-reaction mixture separators, D – 24-hour tank, K – compressor, E – electric engine, Odb – ethanol receiver, PP – vacuum pump, PT – tapflo pump, PZ – gear pump, T – thermometer, P – pressure gauge, WC – heat exchanger, ZA – alcohol tank, ZB – safety valve, ZE0 – ethanol tank, ZWch – cooling water valve, 0 – air supply valve to tapflo pump, 1, 2, 3 – four-terminal network valves, 1a – reactor valve, 4, 5, 6 – reactor tank valves, 7 – reactor valve, 8, 9, 10 – separator inlet valves, 11 – ethanol receiver valve, 12, 13, 14 – glycerol separator outlet valve, 15, 16 – glycerol gear pump valve, 17 – tank filling valve, 18 – glycerol draining from the D tank valve, 19 – D tank draining valve, 20 – reactor coat filling valve, 21 – coat draining valve, 22 – compressed air valve, 23 – atmospheric pressure valve

which was present in the process is vaporized. Vaporizing consists in gradually decreasing the pressure in the reactor in order to make the alcohol boil. Alcohol vapours are then cooled in plate heat exchangers and stored in a special container (Odb), from which the alcohol is retrieved after the end of the whole process. Such alcohol can be used again during esterification if it has not been too diluted. The mixture of the ester and glycerol phases is pumped from the reactor to one of the three separators (A, B, C), where the phases are separated. After the preliminary separation, the ester phase is pumped to a '24h' container (D), where phases are again separated.

4. Conditions of the vaporization process

The very process of esterification is relatively simple to control by algorithms and modify, because it requires introducing all the substrates into the reactor in an appropriate order, heating them to set temperatures and mixing for a set period of time.

Yet, automating the process of retrieving the excess alcohol from the reactor as fast as possible meets certain difficulties resulting from the necessity of the control algorithm to control a lot of changing factors, such as:

- the need to save energy in the process,
- the amount and composition of the mixture in the reactor,
- the temperature of the surroundings and of the cooling agent in the condenser,
- the amount of water used for cooling,
- the amount of retrieved alcohol.

The need to save electric energy in the process influences the cost of the final product. Both cooling water consumption and alcohol loss in the vaporization process also generate costs.

The quantitative content of the substrates, which undergo transesterification, is different each time and depends on the kind of substrates used and the manner in which the process is conducted.

The quantitative content of substrates is limited not only by the rated volume of the reactor but also by the kind of fat used in the process. During the experiments, it was found that if there are

more animal fats the mixture gets foamier when heated. As a result, the quantity of such mixture has to be decreased in comparison with a vegetable fats mixture, since during alcohol vaporization the condenser can unnecessarily retrieve not only alcohol vapour but also the products of the transesterification process.

Because of the need to save energy and time, the excess alcohol is vaporized as a result of boiling at lowered pressures. The diagram of the boiling temperature of ethyl alcohol depending on its pressure is shown in Fig. 9.

It shows that there are two methods of bringing the mixture of esters and alcohol to the boiling point. It can be done by heating the mixture to the boiling temperature and maintaining it during vaporizing, but it can also be done by lowering the pressure in the reactor. The effect is best when in the beginning stages of the vaporizing process the mixture is heated to a given temperature, which provides as much heat as it is necessary to vaporize all the alcohol which it contains. Then, the pressure is gradually lowered, which makes it possible to maintain the boiling temperature at the expense of the heat accumulated in the mixture and in the water jacket of the reactor.

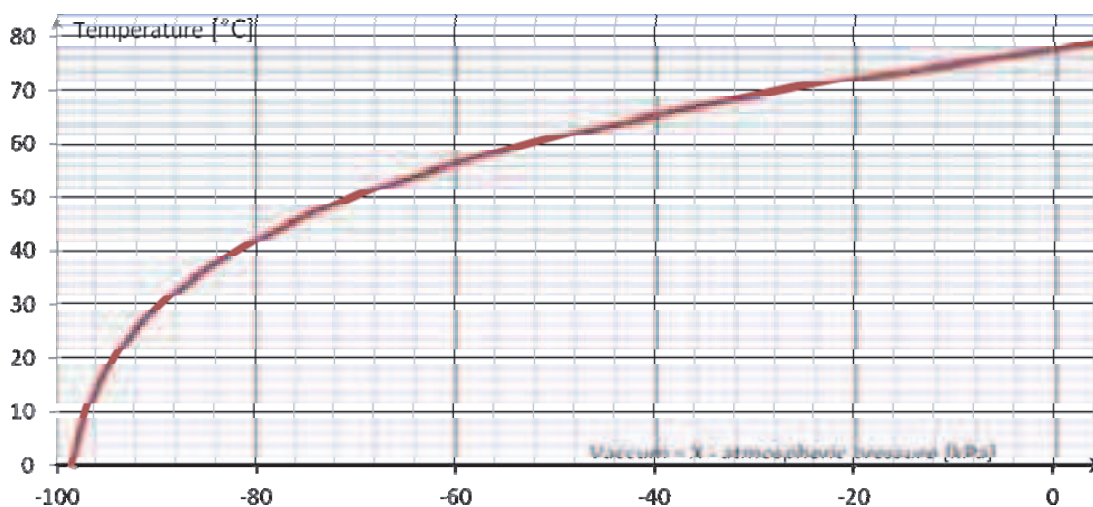


Fig. 9. The diagram of the correlation of the boiling temperature of ethyl alcohol and negative pressure

Difficulties in designing an algorithm to control the alcohol vaporization process result from the fact that the quantity and composition of the mixture vary and the device is supposed to function properly vaporizing both methyl as well as ethyl alcohol. For different proportions of substrates, the course of the boiling curve will be different, and the quantity of the mixture and percentage of alcohol will influence the overall time of vaporization. This time should be as long as not to cause rapid boiling whenever the pressure is lowered, which means not producing excess foam in the reactor. The pressure should be lowered further only when the process of alcohol vaporization at a given pressure in the reactor is going to cease. The pressure should not be lowered any further when the intensity of vaporization is as high as to ensure high efficiency of the process, yet not too high, so that efficient cooling is also possible (at a full capacity of the applied condenser). At the same time, the boiling mixture cannot foam too much.

The efficiency of the condenser, i.e. its capacity for absorbing the stream of heat from the alcohol vapours is a function of its construction, size and temperature of cooling liquid. The same efficiency can be achieved by expanding its dimensions or by lowering the temperature of the cooling agent. In a given installation, the type of the applied condenser is already chosen and its capacity for absorbing heat results only from the cooling agent's temperature and its amount flowing through the exchanger. In the case of a mobile installation, the cooling water's temperature and its flow rate happen to vary and fluctuate within a wide range. Thus the time of every stage of vaporizing varies and is influenced by many factors, such as thermal inertia of the reactor and properties of the cooling agent.

Experimental determination of vaporizing curves for methyl and ethyl alcohols for mixtures with the highest content of excess alcohol would enable conducting vaporization in a way safe also for the mixtures containing less alcohol. It would yet take more time than necessary, require more energy and unnecessarily use an excessive amount of water-cooling the condenser. It would not be an optimal solution, and could even be unreliable in the case of cooling water temperatures other than the set one.

5. An adaptive algorithm in controlling alcohol vaporization

Due to the above reasons, an attempt was made to design a control algorithm for the mobile esterification plant which would take into account all the described conditions, minimize the time of the process, as well as saving energy and water and increasing the efficiency of the installation.

An adaptive algorithm of controlling alcohol vaporization, controlling the temperature of the condensate, controls the process of lowering the pressure in the reactor so that the mixture does not boil too intensively. At the same time, the vaporizing alcohol is being retrieved equally intensively, independently of the kind and proportion of the substrates used in the mixture. The algorithm is insensitive when the cooling water temperature does not considerably exceed the room temperature, since it appropriately lengthens the time of every phase of pressure lowering in the reactor. It thus means that more water has to be used because the cooling agent has to absorb the stream of heat of alcohol vapours in a higher temperature.

The control system designed on the basis of a PLC driver (Horner, HE500CS053) controls all the performing systems, reads the sensors, shows data necessary for the controller to monitor the production process and enables introducing data which modify the transesterification process and subsequent vaporization of the excess alcohol.

When transesterification comes to an end, the reactor contains a mixture of esters, glycerine and alcohol (which needs to be retrieved to obtain the final product) which are heated to a certain temperature and continuously mechanically stirred.

In order to vaporize the alcohol, the control system employs indications of the thermometers, which are placed inside the reactor and show temperatures of the mixture and the alcohol condensate, which leaves the heat exchanger. In the initial stage of vaporization, the heaters in the reactor's jacket are controlled, while in the next stage the process is controlled by a hopping setting of a required negative pressure in the chamber of the reactor. Additionally, the algorithm controls the valve, which regulates the flow velocity of the cooling water, which goes through the condenser, in order to limit the use of water.

The time of heating the mixture to the temperature set on the control panel depends on the esterification temperature, the weight of the substrates and the final temperature. It should not be too low because the amount of heat delivered to the water jacket of the reactor and thus the mixture must be sufficient to vaporize all the excess alcohol. The heat in this process is absorbed from these two liquids and lowers the temperature of the charge of the reactor. Vaporization without pre-heating the mixture might have led to freezing the installation in the final stage. In the mobile esterification, the temperature is set within the 75-82°C range. The temperature can be set at a lower level for a lower amount of alcohol in the input mixture.

The next stage consists in lowering the pressure in the reactor. Thus the vacuum pump is set the final negative pressure in kPa. The automated system of the pump makes it work until the moment the set pressure is achieved in the reactor and then switches it off. The pump works with a hysteresis loop and starts again when the negative pressure (due to leaks in the system) increases by 4 kPa.

The control algorithm lowers the set pressure by 1 kPa in some intervals and checks the temperature of the condensate. These intervals depend on the thermal inertia of the filled installation and cannot be too short, because it is easy to make the mixture boil rapidly. In the mobile esterification plant, the intervals are set at 10 to 60 seconds.

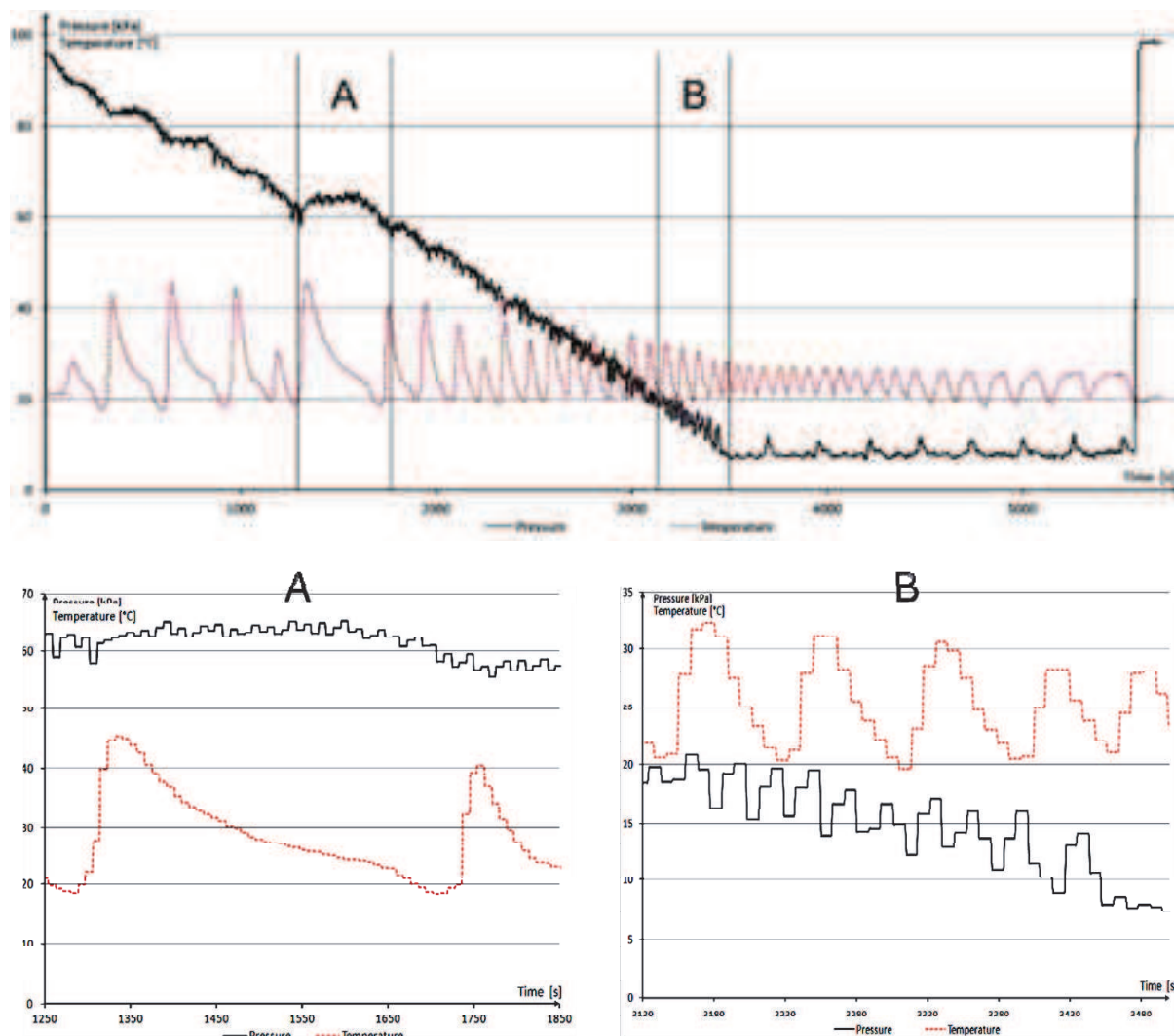


Fig.10. Condensate temperature and negative pressure in the reactor during alcohol vaporization

When the temperature of the alcohol condensate starts to come to the boiling point, the process of introducing vacuum in the reactor is halted and the valve of the condenser is opened. The alcohol vapours which leave the reactor are condensed and retrieved to a special container.

If the control system 'notices' that the condensate's temperature has reached a temperature higher than one of the thresholds, it slows down the boiling process of the mixture by decreasing the negative pressure in the reactor by 1 kPa or 5kPa respectively. In the mobile esterification plant the temperature of the first threshold is set within the 32-37°C range, and of the second threshold – 37-45°C.

After vaporization at a set pressure and with a given amount of alcohol, the temperature of the mixture decreases and vaporization stops. The temperature of the heat exchanger reaches the room temperature and the valve regulating the cooling water flow cuts it off.

The process of increasing vacuum in the reactor continues until the temperature of the alcohol condensate rises, which leads to reactivation of the boiling process of the mixture in the reactor.

There are a few dozen periods when the mixture boils in the reactor. Their length and vaporization intensity decreases in line with the amount of vaporized alcohol, decreasing pressure and temperature of the mixture.

The process of lowering the pressure finishes when it reaches 0 kPa, yet despite the constant performance of the vacuum pump, it is not able to reach such a state. The pressure depends on the technical condition of the pump, tightness of the installation and alcohol residues in the mixture. In the mobile esterification plant, it was assumed that this stage of alcohol vaporization lasts half an hour and concludes the process of retrieving alcohol from the mixture of transesterification products.

6. Conclusion

The designed adaptive control algorithm of alcohol vaporization in the mobile esterification plant was tested in various proportions of substrates and different degree of filling the reactor. Fig. 10 shows changes in condensate temperatures and negative pressure in the reactor as the function of time.

The figure shows clear breaks in the process of lowering the pressure in the reactor during a few dozen vaporizations. In the first few, which are relatively long and intensive, it can be seen that the process of gradual pressure lowering even reverses.

This method had been tested in practice and the alcohol content in the received condensate exceeded 98%*m/m*.

The algorithm worked equally well at the rated as well as partial reactor filling. During the tests, it was found that if there were more animal fats the mixture – when heated – got foamier than that with plant fats. It enforced diminishing the amount of substrates introduced into the reactor, thus the amount of the ready ester produced in one cycle. Yet, at the same time such a cycle lasted shorter.

Moreover, it was found that when the cooling agent was introduced at a lower temperature, less water was needed, since the proportion valve, which regulates its flow, doses it to the condenser more effectively.

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