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EFFICIENT AUTOMATIC CONTROL OF THE ENERGY-SAVING PROCESS OF DEALCOHOLIZATION OF WINE IN THE FLOW IN A THERMOELECTRIC HEAT PUMP INSTALLATION

Author: Serhiy Pashkov

Advisor: Aleksandr Mazur

Odesa National University of Technology (Ukraine)

Abstract. *The work is devoted to development systems of efficient automatic control of the energy-saving process of dealcoholization of wine in the flow in a plant with a thermoelectric heat pump. For this, the technological process (TP) was studied, an effective regulation of the TP management was found, a structural diagram of the process was drawn up as an OK, dynamic and quasi-static characteristics were studied and obtained from a simulation model in the Matlab environment Simul and nk, development and parametric optimization of control algorithms were carried out.*

Key words: *Dealcoholization, azeotrope point, thermoelectric converter, evaporation, condensation, heat and mass transfer, automatic control, parametric optimization.*

I. INTRODUCTION

Dealcoholization is one of the technological processes of wine production. The separation of alcohol from the wine material requires heating the product to the boiling point of alcohol and further heating to evaporate the alcohol. When the pressure is reduced to 80 mbar, the boiling point of alcohol is 27 °C. This temperature is called the "azeotrope point", below which no water evaporates from the wine, but only alcohols and ethers evaporate. When working in this mode, the energy consumption for heating raw materials, due to the low boiling point, and for the liquid-vapor phase transition, due to the evaporation of only alcohols and ethers, is significantly reduced.

Another way to reduce energy costs and reduce the level of thermal "energy waste" in the technological processes of the food industry is the use of thermoelectric heat pumps, which in this case heat the wine material and evaporate alcohols and cool and condense alcohol vapors. But their introduction increases the number of interconnections in the OC, which definitely complicates the management of the TP.

The work is dedicated to solving this problem. In the course of which, a process simulation model was implemented in the Matlab simulation environment In Simulink , the static and dynamic properties of the main conversion channels were studied on the process simulation model, the process control algorithms were developed and the behavior of the control system was simulated.

II. LITERATURE ANALYSIS

There are various methods of automatic control of the dealcoholization process, which differ in technological schemes, the number of adjustable parameters and control methods.

A method of automatic process control is known the removal of alcohol from the drinking liquid by means of vacuum extraction , which includes measuring and regulating the flow of wine in contact with the distribution surface, measuring and regulating the internal pressure of the vessel at the level of 16 to 29 inches of mercury. and measuring and adjusting the temperature of the wine in contact with the distribution surface between 30° C and 60° C [see application for invention, USA No.: 20130243922 A1. Removal of alcohol from potable liquid using 50 vacuum extraction / Judd B. Lynn, Kelli Lynn Fuller. Publ. 19.09.2013. fig. 3] [1] .

The disadvantage of this method of automatic control is high energy consumption for heating raw materials, due to high boiling point, and for liquid-vapor phase transition, due to evaporation of not only alcohols and ethers, but also water.

III. OBJECT, SUBJECT, AND METHODS OF RESEARCH

The process of dealcoholization of wine is a complex heat-mass exchange process of evaporation of alcohols from the wine material. To reduce the boiling temperature, with the aim of significantly reducing energy consumption, as well as reducing the degradation of the taste and useful properties of wine, the evaporation of alcohols is carried out at low pressure. This process is called vacuum dealcoholization. When the pressure is reduced to 80 mbar, the boiling point of alcohol is 27 °C. This boiling point of the water-alcohol solution is called the "azeotrope point", below which no water evaporates from the wine, but only alcohols and ethers evaporate.

The hardware and technological scheme of the process of dealcoholization of wine in the flow in the installation with a thermoelectric heat pump is shown in Fig. 1 .

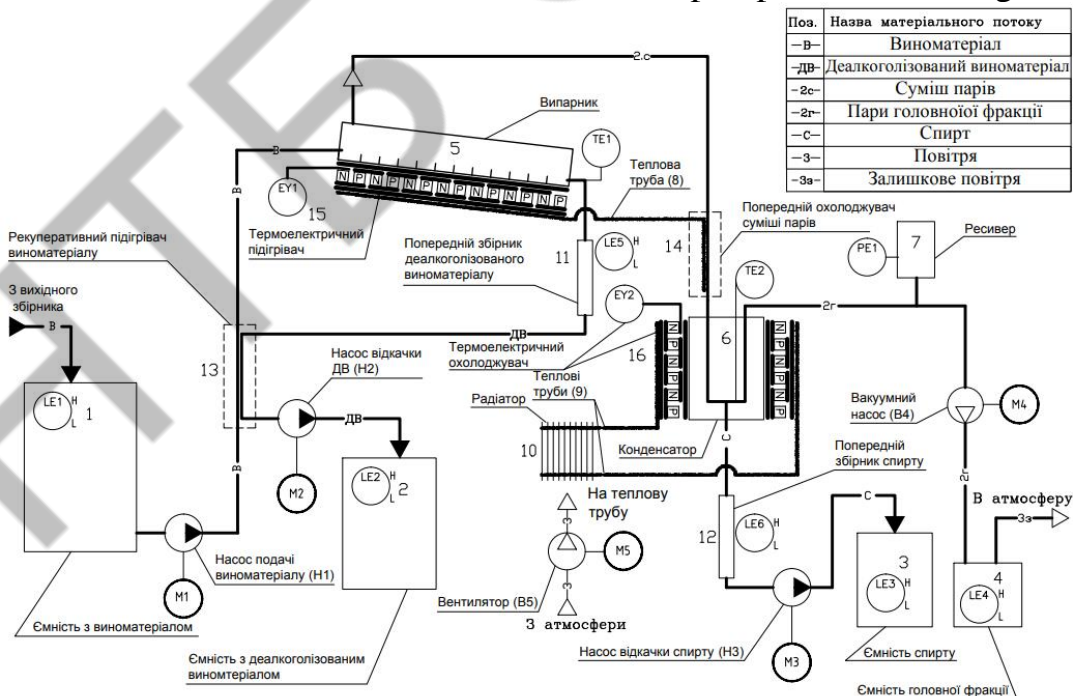


Fig. 1 – Equipment and technological scheme of the process of dealcoholization of wine in the flow in the installation with a thermoelectric heat pump

Air is pumped out of the system by a H4 vacuum peristaltic pump to a pressure of 68mBar (Measured by the PE1 sensor). From the receiving container 1, the peristaltic wine material supply pump H1 through the recuperative wine material heater 13 supplies the wine material to the evaporator 5. In it, the heat flow from the "hot side" of the thermoelectric heater 15 heats the wine to a temperature of 28 °C (Measured by the TE1 sensor) and the alcohols evaporate. The dealcoholized wine material (DV) enters the preliminary collection of DV 11, from where, upon reaching the upper level (Measured by the sensor L E5), the DV pump H2 is pumped through the recuperative wine material heater 13 into the DV container 2. The mixture of vapors from the evaporator 5 under the influence of the pressure drop in the steam pipeline cooler, the vapor mixture enters the condenser. In it, they are cooled by the cold from the "cold side" of the thermoelectric cooler 16 to a temperature of + 19°C (Measured by the TE2 sensor). The alcohol is condensed, collected in the preliminary alcohol collector 12, and when the upper level is reached (Measured by the sensor L E6), it is pumped by the alcohol pumping pump H3 into the alcohol tank 3. The vapors of the main fraction are pumped out by the vacuum peristaltic pump H4 into the tank of the main fraction 4, where they are condensed under atmospheric pressure. Residual air is removed to the atmosphere.

To carry out the process of vacuum dealcoholization of wine, it is necessary to maintain the specified pressure level in the vacuum system and to supply heat to the evaporator 5 and remove excess heat from the condenser 6, maintaining the specified pressure in them. Several thermoelectric modules on Peltier elements are used as thermoelectric heater 15 and thermoelectric cooler 16 . The "hot side" of the thermoelectric heater heats the evaporator 5, the "cold side" connected to the heat pipe 8 cools the pre-cooler of the vapor mixture 14. The "cold side" of the thermoelectric cooler cools the condenser 6, and the heat flow from the "hot side" is removed with the help of heat pipes 9 to the radiator 10, from which the heat is blown by the B5 fan.

An intermediate receiver 7 is installed between the condenser and the vacuum pump, the purpose of which is to stabilize sharp pressure fluctuations in the vacuum system.

Level measurements in the wine, DV, alcohol, and main fraction containers are measured respectively by level sensors LE 1, LE 2, LE 3, and LE 4. Peltier elements are controlled by current amplifiers EY 1 and EY 2.

The regulations for conducting the technological process of vacuum dealcoholization of wine are given in Table 1.

Table 1 - Table of regulations

Name of parameters	Marking	Unit of measurement	Nominal value of the parameter	Permissible deviations from face value		
				Long (t→∞)	Short-term (0<t<<∞)	
				size	size	time, sec
1	2	3	4	5	6	7
The temperature of the DW at the outlet of the evaporator	T _{dv}	°C	28	± 0.5	± 1	60
The temperature in the condenser	T _k	°C	19	± 0.5	± 1	60
Pressure in the receiver	P _p	mBar	68	± 2	± 5	60

IV. RESULTS

4.1. Specification of the task of complying with the regulations for managing the technological process of dealcoholization of wine in the flow in a plant with a thermoelectric heat pump, development and implementation of a complex of its models as an object of regulation

Analysis of the technological process of vacuum dealcoholization of wine in the stream as OK allows us to identify three main regulation tasks:

1. Stabilization of pressure in the receiver;
2. Stabilization of the DV temperature at the outlet of the evaporator;
3. Temperature stabilization in the condenser.

The structural diagram of the technological process of dealcoholization of wine in the flow in the installation with a thermoelectric heat pump as the OK of the object is shown on Figure 2.

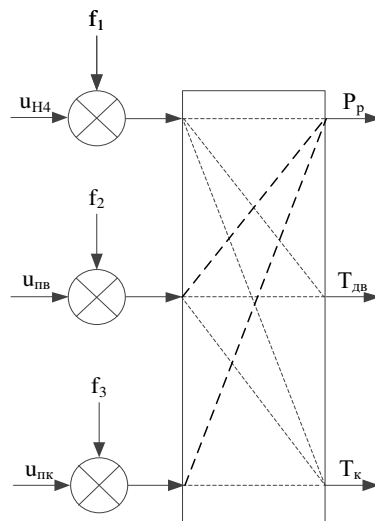


Fig. 2 – Structural diagram of the object of regulation

In fig. 2 the following designations are given:

Regulated variables:

P_p – pressure in the receiver;

T_{dv} – the temperature of DW at the outlet of the evaporator ;

T_k - the temperature in the condenser;

Controlling influences:

U_{n4} – change in the rotation frequency of the vacuum pump motor;

U_{pv} – change in the current of the thermoelectric heater;

U_{pk} - the change in the current of the thermoelectric cooler.

All input actions, except for control actions, are classified as uncontrollable disturbances f_1, f_2, f_3 . The deterministic component of these disturbances is additively applied to the control actions, and the stochastic component to the regulated coordinate.

Having performed the decomposition of the technological process on separate structural elements, it can be said that the general mathematical model of the process as OK should have models of heat and mass transfer processes in the evaporator and condenser, thermoelectric converters (TEC) of the evaporator and condenser, the steam pipe from the evaporator to the condenser, heat transfer through a flat wall, pumping out gases from the apparatus and fan with radiator. The figure shows the general structure of the mathematical model of the process of dealcoholization of wine in a stream in a thermoelectric heat pump installation with the main relationships between models of individual elements of the process.

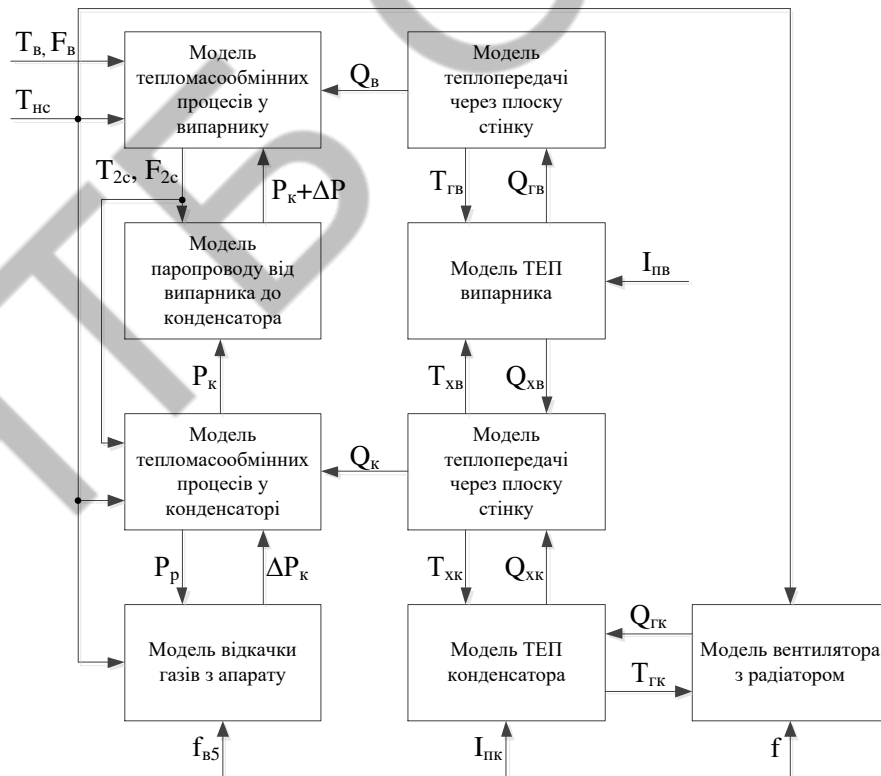


Fig. 3 – Structural diagram of the mathematical model of the process in-flow dealcoholization of wine in a thermoelectric heat pump installation

Where: ΔP - the pressure difference between the evaporator and the condenser;
 F_B – consumption of wine material after the recuperative wine material heater;
 T_B – the temperature of the wine material after the recuperative heater of the wine material;
 T_{2c} – the temperature of the vapor mixture;
 F_{2c} – steam mixture consumption;
 P_p - pressure in the receiver;
 P_k - pressure in the condenser;
 $I_{пв}$ – the power supply current of the Peltier thermoelectric elements of the evaporator;
 $I_{пк}$ – the supply current of the thermoelectric elements of the Peltier capacitor;
 T_{hc} – ambient temperature;
 $T_{гв}$ – the temperature of the hot side of the TEC evaporator;
 $Q_{гв}$ – heat flow from the hot side of the TEC evaporator;
 T_{xb} – the temperature of the cold side of the TEC evaporator;
 Q_{xb} – heat flow from the cold side of the TEC evaporator;
 $T_{гк}$ – the temperature of the hot side of the TEC condenser;
 $Q_{гк}$ – heat flow from the hot side of the TEC condenser;
 $T_{xк}$ – the temperature of the cold side of the TEC condenser;
 $Q_{xк}$ – heat flow from the cold side of the TEC condenser;
 Q_B – heat flow to the evaporator;
 Q_k – heat flow to the condenser;
 f – pump rotation frequency;
 $f_{в5}$ – fan rotation frequency.

This model was developed analytically - based on the description of heat and material balance equations, and implemented in the Matlab simulation environment Simulink during the performance of the student research paper "Автоматизація керування процесом вакуумної dealcoholization вина в потоці" [2].

4.2. Study of the process of dealcoholization of wine in a flow in a plant with a thermoelectric heat pump on its simulation model.

For research of the process of vacuum dealcoholization of wine in the flow as an OK in order to obtain its static and dynamic properties in the main and cross channels of transformations, we will use the simplest structure SAR, the structural diagram of which is presented in Figure 4.

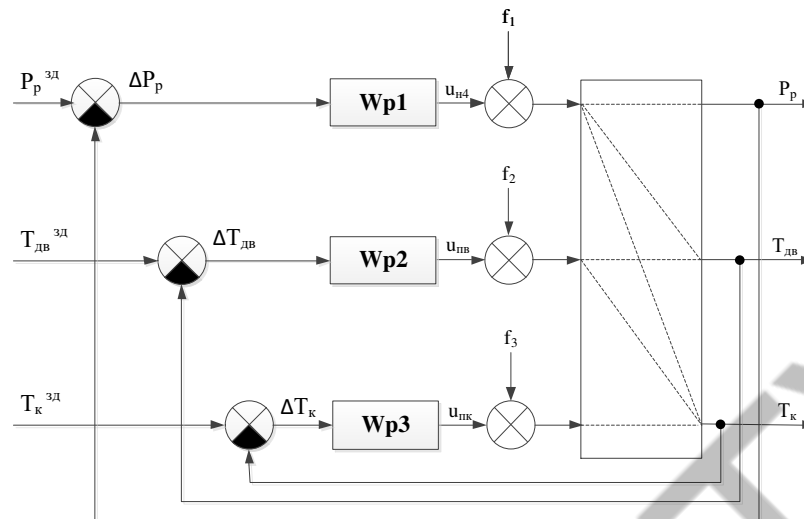


Fig. 4 – Structural diagram of the simplest structure for the study of a simulation model of the process of dealcoholization of wine in a stream in a plant with a thermoelectric heat pump like ok

Experimental obtaining of quasi-static modes of any OC by classical methods assumes an admissible number of variable levels for such modes, the transition between which is carried out in dynamic modes. This leads to the loss of information between the selected levels for the vacuum evaporator and condenser, the operation of which includes phase transitions of matter and gas, the discretization of static characteristics may not allow detecting the points of changing fundamentally important regimes. In addition, the organization of a classic experiment to obtain static characteristics is quite difficult, requires considerable time spent on transient processes and confirmation of the start of a new static process. Taking into account the above, experiments were organized to study the static properties of the vacuum evaporator and condenser model, which can be considered as obtaining quasi-static characteristics. Their essence consists in an alternate change with a constant, preselected, speed of the current value to the thermoelectric heater and cooler from 0-12A, and the frequency of rotation of the vacuum pump from 0-50Hz and registration of variable temperatures at the control points of the object ($T_{дв}$ - temperature of the DV at the outlet of the evaporator, T_k - temperature in the condenser, P_p - pressure in the receiver).

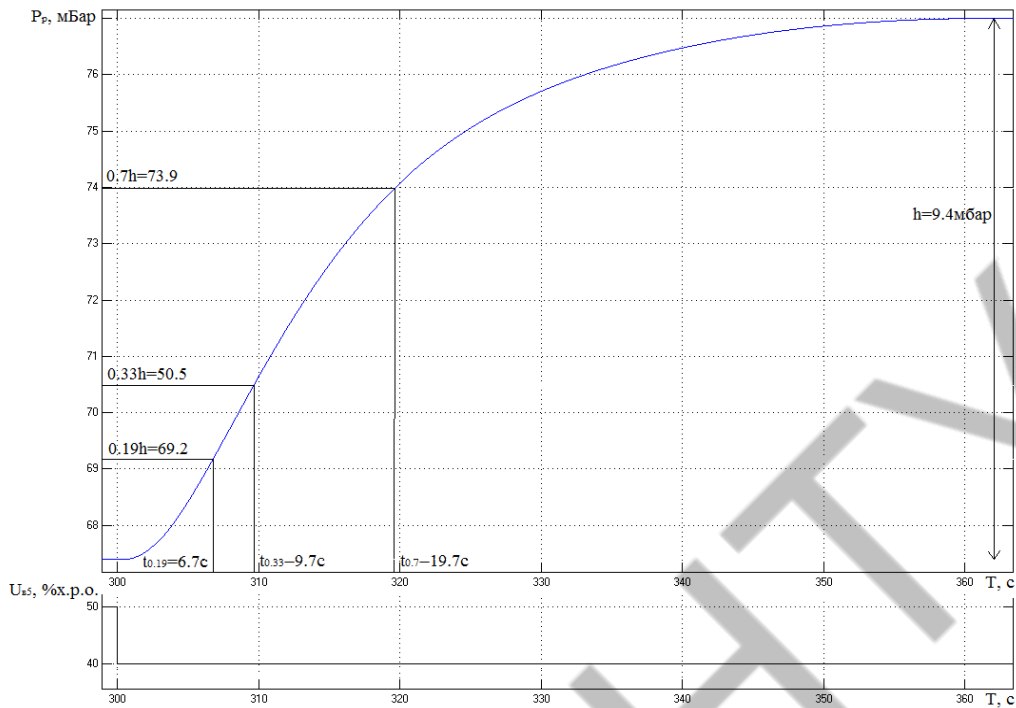


Fig. 5 – Response of the pressure in the receiver to a step change in the rotation frequency of the vacuum pump

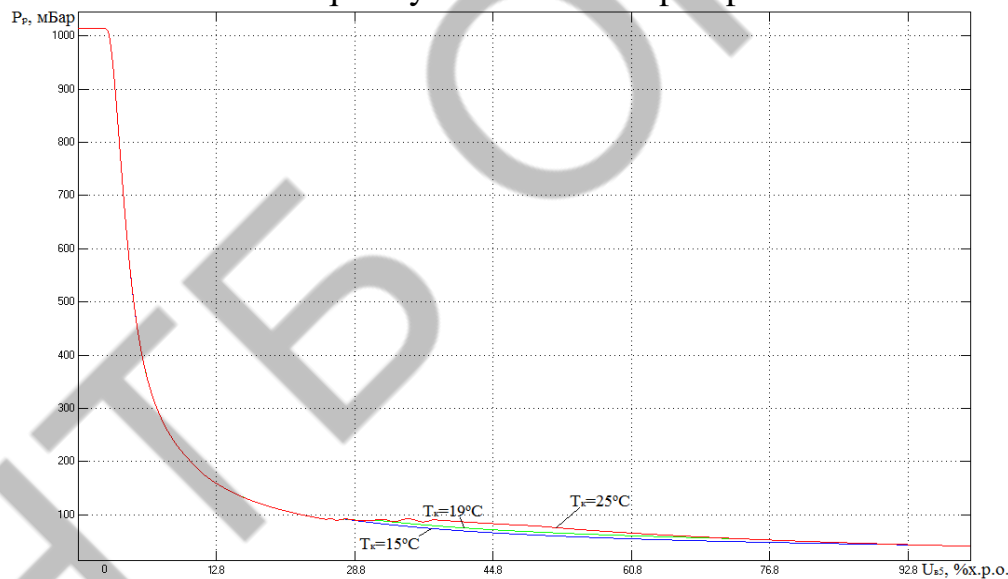


Fig. 6 – Quasi-static dependences of the pressure in the receiver on the frequency of rotation of the vacuum pump at different temperatures in the condenser

Figure 6 shows the quasi-static dependence of the pressure in the receiver on the frequency of rotation of the vacuum pump at different temperatures in the condenser. Such a static characteristic can be explained by the fact that at small rarefactions, the penetration (suction) of air is small, and the system appears to be astatic, but when the rarefaction increases, the suction increases and the system becomes static, that is, the flow rate of air penetrated into the device depends linearly on the pressure difference (atmospheric and rarefaction in the device). This explains the decrease in the pump transmission ratio.

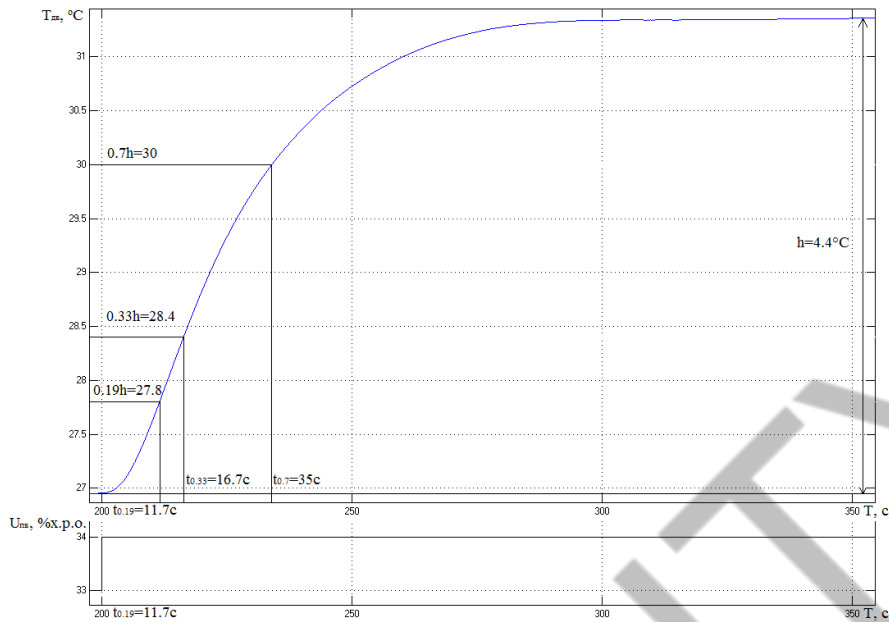


Fig. 7 – Reaction of the temperature of the DW at the outlet of the evaporator to a step change in the power supply current of the TEC of the evaporator

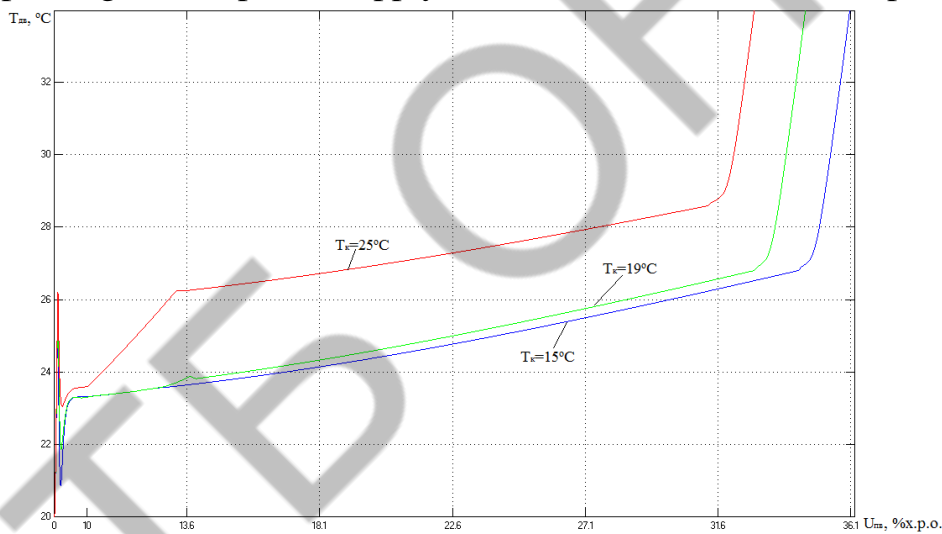


Fig. 8 – Quasi-static dependences of the temperature of the DW at the outlet of the evaporator on the supply current of the TEC of the evaporator at different temperatures in the condenser

Figure 8 shows quasi-static dependences of the temperature of the DW at the outlet of the evaporator on the TEC current of the evaporator at different temperatures in the condenser torus. The nature of these dependencies indicates that the temperature of the DW at the evaporator outlet is determined mostly by the pressure in the evaporator, which in turn depends on the pressure in the condenser and the pressure drop in the steam pipe connecting the evaporator to the condenser. This differential pressure depends on its hydraulic resistance and steam consumption from the evaporator. Also, a decrease in the temperature in the condenser causes a decrease in the energy efficiency of the thermoelectric heater. In the zone up to 33% and at $T_k = 19^\circ\text{C}$, evaporation of alcohols is observed.

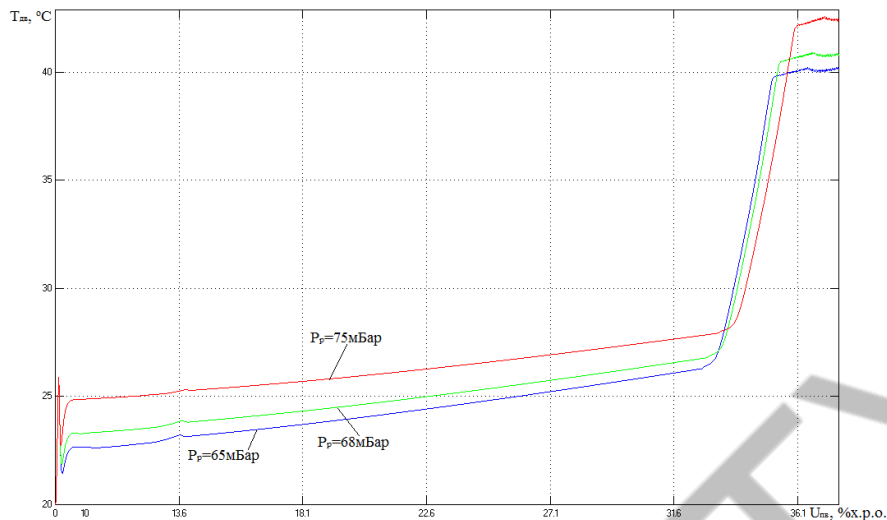


Fig. 9 – Quasi-static dependences of the temperature of the DW at the outlet of the evaporator on the power supply current of the TEC of the evaporator at different pressures in the receiver

Figure 9 presents quasi-static dependences of the temperature of the DW at the outlet of the evaporator on the power supply current of the TEC of the evaporator at different pressures in the receiver. The nature of these dependencies indicates that the temperature of the wine in the evaporator is determined mostly by the rarefaction in the evaporator, which in turn depends on the rarefaction in the condenser and the pressure drop in the steam line connecting the evaporator to the condenser. This differential pressure depends on its hydraulic resistance and steam consumption from the evaporator. In turn, the rarefaction in the capacitor depends on the pressure in the receiver. In the zone up to 33% and at $P_p = 68$ mBar, the evaporation of alcohols is observed.

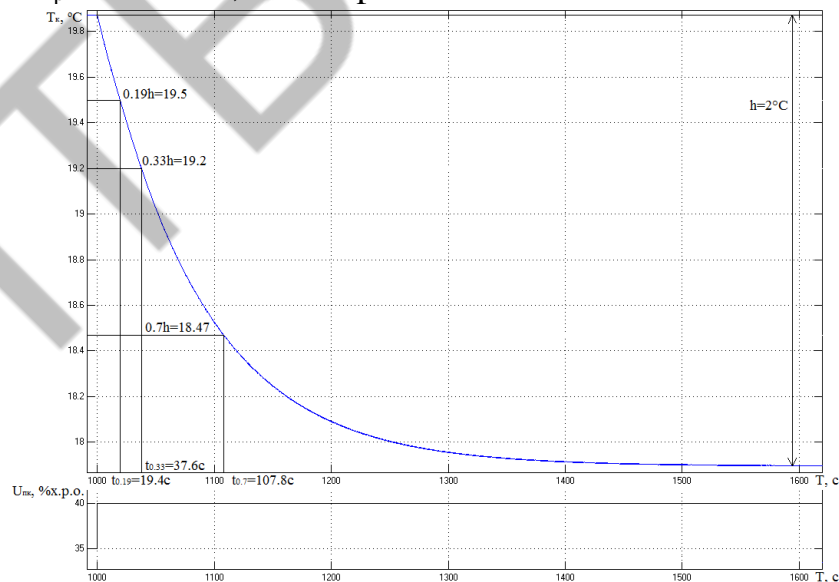


Fig. 10 – The reaction of the temperature in the capacitor to a step change in the power supply current of the TEC capacitor

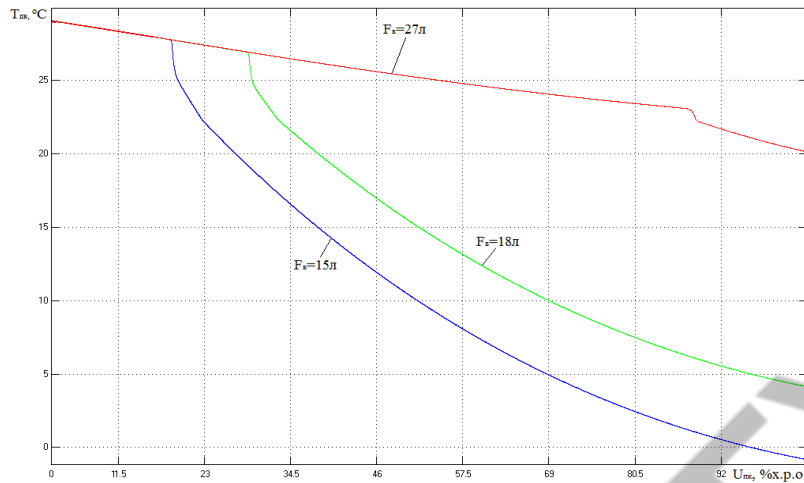


Fig. 11 – Quasi-static dependences of the temperature in the condenser on the power supply current of the TEC condenser at different consumption of wine material

Figure 11 presents quasi-static dependences of the temperature in the condenser on the power supply current of the TEC condenser at different consumption of wine material. The nature of these dependencies indicates that the temperature in the condenser is determined mostly by the amount of steam, which in turn depends on the consumption of wine material. Also, a decrease in the temperature in the condenser causes a decrease in the energy efficiency of the thermoelectric cooler.

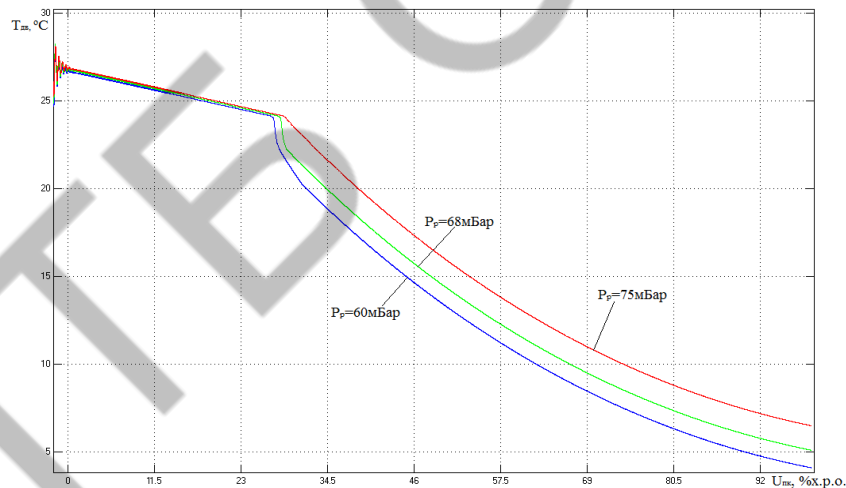


Fig. 12 – Quasi-static dependences of the temperature in the condenser on the supply current of the TEC condenser at different pressures in the receiver

Figure 12 presents quasi-static dependences of the temperature in the condenser on the power supply current of the TEC condenser at different pressures in the receiver. The nature of these dependencies indicates that the temperature in the condenser is determined by the vapor condensation temperature, which in turn depends on the pressure in the receiver. Also, a decrease in the temperature in the condenser causes a decrease in the energy efficiency of the thermoelectric cooler.

The results of parametric identification of the first-order model on the $U_{pv} - T_{dv}$ channel.

$$K_0 = \frac{\Delta T_{ДВ}}{\Delta u} = \frac{31,3 - 26,9}{34 - 33} = 4,4 \text{ } ^\circ\text{C} / \%x.p.o.$$

For the 1st order model

$$\tau_0 = 0,5 \cdot (3 \cdot t_{0,33} - t_{0,7}) = 0,5 \cdot (3 \cdot 16,7 - 35) = 7,4c$$

$$T_0 = (t_{0,7} - \tau_0) / 1,2 = (35 - 7,4) / 1,2 = 23c$$

The transfer function of the 1st-order OK model will look like this:

$$W_0(p) = \frac{4,4 \cdot e^{-7,4p}}{23p + 1}$$

The results of the parametric identification of the first-order model by the channel $U_{pk} - T_k$.

$$K_0 = \frac{\Delta T_k}{\Delta u} = \frac{19,9 - 17,9}{35 - 40} = -0,4 \text{ } ^\circ\text{C} / \%x.p.o.$$

For the 1st order model

$$\tau_0 = 0,5 \cdot (3 \cdot t_{0,33} - t_{0,7}) = 0,5 \cdot (3 \cdot 37,6 - 107,8) = 2,5c$$

$$T_0 = (t_{0,7} - \tau_0) / 1,2 = (107,8 - 2,5) / 1,2 = 87,8c$$

The transfer function of the 1st-order OK model will look like this:

$$W_0(p) = \frac{-0,4 \cdot e^{-2,5p}}{87,8p + 1}$$

The results of the parametric identification of the first-order model on the $U_{n4} - P_p$ channel.

$$K_0 = \frac{\Delta P_p}{\Delta u} = \frac{67,4 - 76,8}{50 - 40} = -0,94 \text{ } \text{мБар} / \%x.p.o.$$

For the 1st order model

$$\tau_0 = 0,5 \cdot (3 \cdot t_{0,33} - t_{0,7}) = 0,5 \cdot (3 \cdot 9,7 - 19,7) = 4,7c$$

$$T_0 = (t_{0,7} - \tau_0) / 1,2 = (19,7 - 4,7) / 1,2 = 12,5c$$

The transfer function of the 1st-order OK model will look like this:

$$W_0(p) = \frac{-0,94 \cdot e^{-4,7p}}{12,5p + 1}$$

4.3. Development and parametric optimization of regulation algorithms

Coordinate scheme of in-flow dealcoholization of wine using a thermoelectric heat pump shown in Fig. 2. According to it and to the structural diagram corresponding to the closed-loop control principle, the structural diagram of the ACS will have the form shown in Fig. 13.

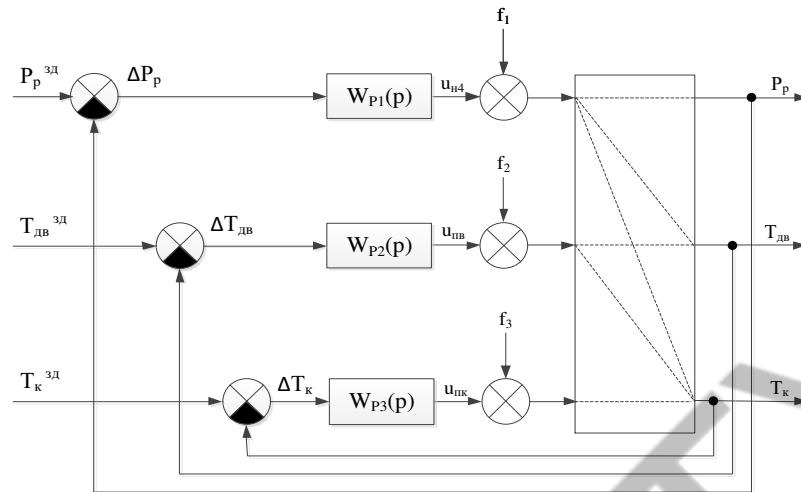


Fig. 13 – Structural diagram of the control system corresponding to the closed-loop control principle

In the picture in :

$u_{н4}$ – rotation frequency of the vacuum pump ;

P_p – pressure in the receiver ;

P_p^{3d} – a given value pressure in the receiver ;

ΔP_p – adjustment error _ pressure in the receiver;

f_1 – a vector of uncontrolled disturbances;

$W_{P1}(p)$ – the transfer function of the pressure regulator in the receiver ;

$u_{нв}$ – current of the thermoelectric heater ;

$T_{дв}$ – the temperature of the DW at the outlet of the evaporator;

$T_{дв}^{3d}$ – the set temperature value of the DW at the outlet of the evaporator;

$\Delta T_{дв}$ – temperature regulation error and _ wine in the evaporator;

f_2 – a vector of uncontrolled disturbances;

$W_{P2}(p)$ – the transfer function of the wine temperature regulator in the evaporator ;

$u_{нк}$ – the current of the thermoelectric cooler ;

$T_к$ – alcohol condensation temperature ;

$T_к^{3d}$ – the set temperature value __ condensation of alcohol ;

$\Delta T_к$ – temperature regulation error and _ alcohol condensation;

f_3 – a vector of uncontrolled disturbances;

$W_{P3}(p)$ – the transfer function of the alcohol condensation temperature regulator .

As a regulation algorithm, we choose proportional-integral-differential (PID) regulation algorithms.

The transfer function of the PID controller

$$W^P(p) = K_p \cdot \left(1 + \frac{1}{T_B p} + \frac{T_{yII} p}{0,2 \cdot T_{yII} p + 1} \right)$$

The structural diagram of modeling a three-dimensional ACS with a PID controller is shown in Fig. 14. The results of optimization of the PID controller settings are shown in Fig. 15. The results of checking the ACS for roughness are shown in Fig. 16.

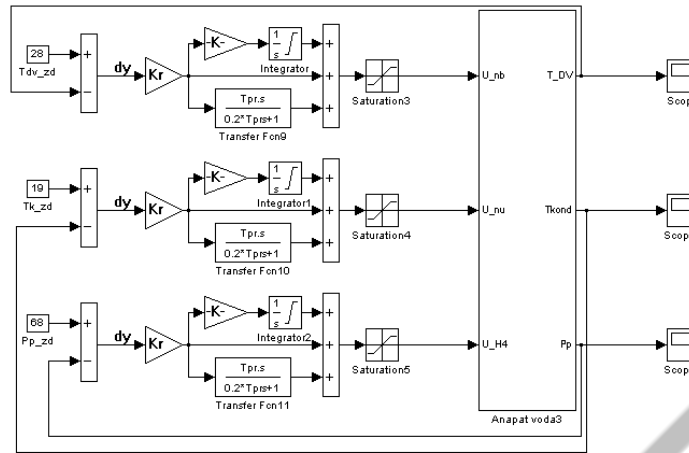


Fig. 14 – Structural diagram of the model of the ACS with PID controller

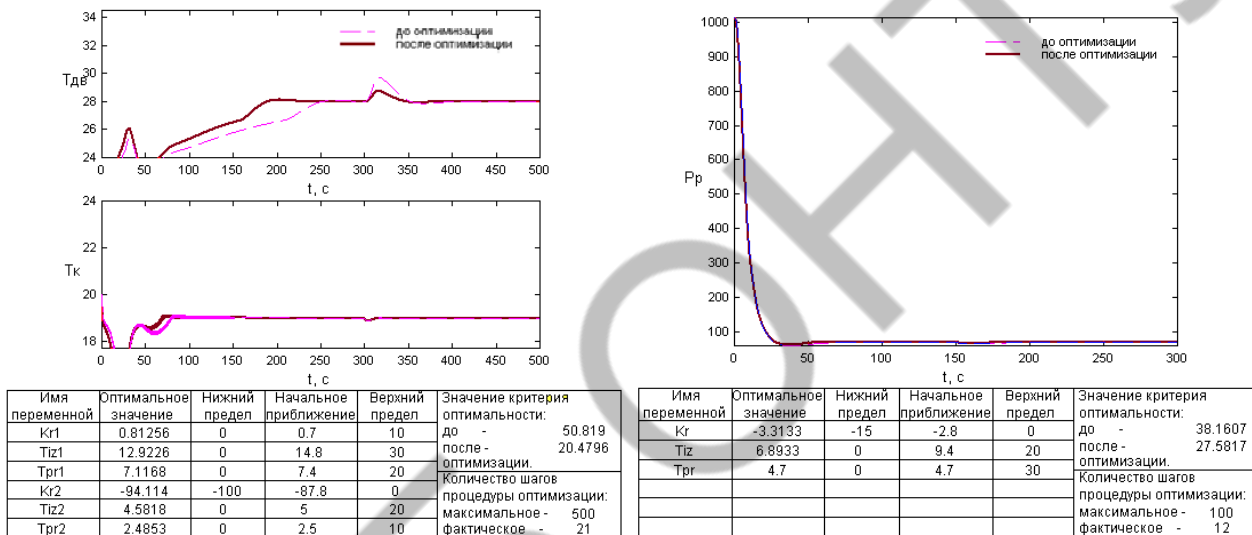


Fig. 15 – The results of optimizing the settings of the PID controller of the temperature of the DW at the outlet of the evaporator, the temperature in the condenser and the pressure in the receiver

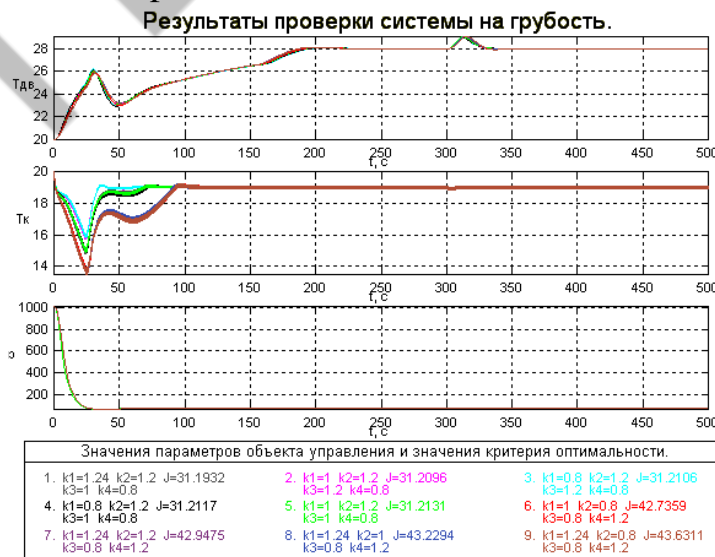


Fig. 16 – The results of the test ACS with PID-regulator for roughness

V. CONCLUSIONS

The scientific work was carried out in order to investigate the possibilities of increasing the efficiency of the automatic control of the energy-saving process of dealcoholization of wine in the stream in the installation with a thermoelectric heat pump by developing appropriate control algorithms.

The analysis, synthesis and parametric optimization of the ACS of the basic structure were performed. The developed ACS is implemented in the MATLAB Simulink environment.

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