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AUTOMATION OF A LABORATORY ELECTRIC AUTOCLAVE USING A PROGRAMMABLE LOGIC CONTROLLER

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Abstract

The article analyzes the use of an electric autoclave with the proposed automated control system for implementation in the educational process. An analysis of the implementation of the technological process of sterilization of canned food in an electric autoclave was carried out on the automated stand for controlling the electric autoclave called. Options for operating modes of the Programmable Logic Controller (PLC) OWEN PR200 with an electric autoclave are considered. The principle of debugging an automated stand for sterilizing canned food by students is given. It has been experimentally proven that the heating of an electric autoclave is started either by a directly programmable logic controller or by a computer with a Supervisory Control and Data Acquisition (SCADA) program. For distance learning students, there is the possibility of using remote access to monitor parameters and control the operation of the autoclave using a cloud web server. This allows students to access and control this object anywhere in the world with an Internet connection. Modeling was conducted in the MATLAB environment to determine the PLC settings, and the control system was modeled using MATLAB/Simulink. It has been studied that the electric autoclave is heated within the time specified by the technological process to the specified parameters. An example of using the stand for option №8 is given. The need to improve the quality of autoclave control has been identified. Using a Proportional-Integral-Differential (PID) regulator instead of a PLC two-position relay regulator is proposed. The advantages of using the Proportional-Integral (PI)-law regulation are presented. PID regulation through the PLC's analog output effectively produces canned food from vegetable ingredients. A further research direction may be using a controller based on fuzzy logic and its discretization.

Keywords: technological parameters; electrical equipment; operating modes for sterilization of canned meat; technological process; PLC automation; food product; SCADA.

АВТОМАТИЗАЦІЯ ЛАБОРАТОРНОГО ЕЛЕКТРИЧНОГО АВТОКЛАВА ЗА ДОПОМОГОЮ ПРОГРАМОВАНОГО ЛОГІЧНОГО КОНТРОЛЕРА

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Анотація

У статті проаналізовано використання електричного автоклава із запропонованою автоматизованою системою керування для впровадження в навчальний процес. Аналіз реалізації технологічного процесу стерилізації консервів у електроавтоклаві проводили на автоматизованому стенді керування електроавтоклавом. Розглянуто варіанти режимів роботи програмованого логічного контролера (ПЛК) OWEN PR200 з електроавтоклавом. Наведений принцип налагодження студентами автоматизованого стенду для стерилізації консервів. Експериментально доведено, що розігрів електричного автоклава запускається або безпосередньо програмованим логічним контролером, або комп'ютером з програмою Наглядового Контролю і Збору Даних (SCADA). Для студентів дистанційної форми навчання є можливість використання віддаленого доступу для моніторингу параметрів та керування роботою автоклава за допомогою хмарного веб-сервера. Моделювання проводилося в середовищі MATLAB для визначення налаштувань ПЛК, а система керування моделювалася за допомогою MATLAB/Simulink. Досліджено, що електричний автоклав нагрівається протягом заданого технологічним процесом часу до заданих параметрів. Наведено приклад використання стенду за варіантом №8. Визначена необхідність підвищення якості автоклавного контролю. Запропоновано використання пропорційно-інтегрально-диференціального (ПІД) регулятора замість двопозиційного релейного регулятора ПЛК. Представлено переваги використання Пропорційно-Інтегрального (PI) регулювання. ПІД-регулювання через аналоговий вихід ПЛК ефективно виробляє консерви з рослинних інгредієнтів. Подальшим напрямком досліджень може стати використання контролера на основі нечіткої логіки та його дискретизація.

Ключові слова: технологічні параметри; електрообладнання; режими роботи стерилізації м'ясних консервів; технологічний процес; автоматизація програмованого логічного контролера; продукт харчування; SCADA.

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Introduction

Currently, the use of non-automated equipment and manual labor in the food industry significantly limits the ability to achieve high efficiency, reduces the competitiveness of enterprises, and can cause additional costs for production and quality control [1; 2]. Without automation, enterprises are often limited in their ability to quickly adapt to changes in demand or scale production. In processes that require high accuracy and control (for example, in processing research results or quality control), manual data entry and measurement can lead to loss of information or errors, affecting the accuracy of results [3]. The introduction of automated systems allows for increased speed, accuracy, and safety of processes, reduced costs, and improved product quality [4; 5]. Using non-automated equipment in various branches of mechanical engineering [6], especially in the food industry, can significantly negatively impact the environment, as it is usually associated with less efficient use of resources and higher emissions. Non-automated equipment is generally less energy efficient compared to modern automated systems. It can operate at higher energy costs and perform the same or even less efficiently. This leads to increased carbon dioxide (CO_2) emissions and other greenhouse gases due to the consumption of additional electrical energy, especially if the sources of this energy are not renewable. Therefore, using non-automated equipment contributes to increased environmental pollution due to higher energy costs, more inefficient use of resources, and increased emissions. To reduce the negative environmental impact, it is necessary to introduce automation and modern technologies that reduce emissions, save resources, and preserve the natural environment [7; 8].

Today, advances in automation technology have led to the development of competitive, intelligent systems that can learn and adapt to different situations, increasing the efficiency and effectiveness of production processes [9]. The competitive success and security of the food industry and manufacturing companies primarily drive automated systems [10]. The most valuable benefits of automated systems are increased labor productivity, product quality, and profitability [11; 12]. This has been proven to provide better flexibility, increased efficiency, and a higher cost-to-industry ratio over a limited period [13; 14].

All industries are shifting towards the Industry 4.0 concept of automation [15; 16]. Industry 4.0 (4th industrial revolution) embodies rising technological advances in improving clever manufacturing strategies. Industry 4.0 has excellent potential for many manufacturing companies to allow customization of products, provide flexibility to meet new needs in real-time and produce highly efficient jobs. The 4th Industrial Revolution and rising technologies– which include the Internet of Things, artificial intelligence, robots, and more excellent productions-affect the emergence of the latest manufacturing techniques and commercial enterprise fashions that transform fundamental manufacturing [17; 18]. Foreign researchers have conducted several studies in automated technologies using PLC and SCADA [19; 20]. Some scientists have suggested using PLC and SCADA instead of controlling through DCS, WIA-PA [21], or IoT [22; 23]. Compared to implementing and replacing hardwired controls such as relays and timers, PLCs are widely used in the automated chemical process control industry because they are easily programmable, reliable, less time-consuming, more accessible to troubleshoot, and less prone to hardware failure [24; 25]. Other scientists are creating similar stands for chemical industry workshops or other industries [26; 27]. S. Kannan [28] highlighted challenges and future directions in innovative process measurement and automation. He also discussed the issue of multiple inputs and outputs, the limited nature of industrial processes, and sensor nonlinearity compensation [29].

The main focus is the challenges faced during parameter measurement and data acquisition of intelligent processes in the automation industry, such as nonlinearity, uncertainty, and noise, and possible solutions and directions to address these challenges [30]. A. Christler et al. [31] demonstrate the importance for reducing operator-specific effects of semi-automated process analysis on test results of typical analytical methods. In this work, they present semi-automated methods using liquid handling stations for various biochemical tests such as binding affinity and endotoxin. These robust and reproducible analytical methods are also helpful in establishing process analytical techniques and preparing downstream processes for Quality by Design methods.

They are also helpful in preparing downstream processes. For Cleaning-in-Place (CIP), many process industries use an automated bench to clean industrial equipment such as tanks in the food and pharmaceutical industries such as 3-stage, 5-stage, and 7-stage CIP [32]. The focus is on automating the food production process by

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designing an automated system based on programmable logic controller (PLC) technology for accurately dosing dough quantities and filling a product mold on a conveyor belt that rotates at a specific speed [33]. Now, the number of probable errors has reduced to a great extent in many industries.

As for using PLCs and SCADA in conjunction with thermal equipment, such research has been practically unexplored. One of the most well-known solutions is methods for improving food processing using modern optimization technologies [34].

A study of optimization of heat treatment processes is presented in the book "Optimization in Food Engineering" by F. Erdoğdu, as well as in the works of other researchers, where, as an example, energy-efficient and stepwise modes of sterilization of canned fish in a steam and water environment are described [35].

Despite several studies in the field of canning and sterilization, several issues remain pressing – reducing the time and energy costs of the process, preserving the maximum amount of valuable substances in the canned product, and maintaining the canning process in the given technological level modes [36].

A way to solve these issues can be creating an automated stand for the technological process of sterilizing canned food, including an autoclave and a control device.

The article aims to introduce an automated process for controlling an electric autoclave using a programmable logic controller to sterilize canned food in the Sumy National Agrarian University laboratory at the Faculty of Food Technology.

Results and their discussion

In the laboratory "Automation of production processes" of the Sumy National Agrarian University, an experimental stand called "Stand for automatic monitoring and control of technological parameters of thermal equipment" was created, as shown in Figure 1.

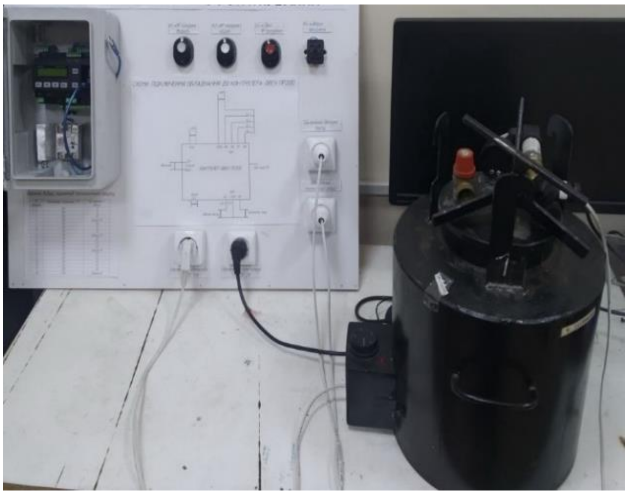

Fig.1. General appearance of the stand

The stand makes it easier for students to work with the autoclave and monitor the technological process on the digital display of the programmable logic controller OWEN PR200 (PLC). The electric autoclave works directly with the help of PLC, which controls the technological process of cooking canned food with feedback using a pressure sensor and a resistance thermometer. During the technological process, all parameters of the technological mode are synchronously displayed on a personal computer via Supervisory Control and Data Acquisition (SCADA).

The structural diagram of the experimental stand is shown in Figure 2.

To conduct experimental research using the stand, students perform the following actions:

1) Prepare the contents of the canned food that needs to be heat treated; place it in a 0.5-liter glass jar with twist-off screw lids, seal the jar tightly with a lid, and load it into the autoclave;

2) Pour water into the autoclave so that the canned food is covered with water at a level of 2-3 cm from above.

3) Hermetically close the lid of the autoclave;

4) Connect the autoclave pressure sensor and resistance thermometer to the PLC (contacts AI3, COM3, AI1, according to Fig. 2);

5) Connect the power wires of the electric heating elements of the autoclave to an alternating current network with a voltage of 220 Volts, 50 Hz through the switch of the PLC (contacts DO1 and DO2 as shown in figure 2);

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6) Turn on the PLC power;

7) Turn on the personal computer and configure the SCADA program to which the PLC is connected via the USB port;

8) The PLC screen displays the autoclave's current temperature, the current pressure inside the autoclave, and the number of program options. The program number is selected using the buttons K1, K2, and K3, according to the table in Figure 3;

9) The selected program is executed using switch K4,.

10) After compling the selected program is, the autoclave is disconnected from the power supply and allowed to cool to a temperature not higher than 30 °C at room temperature, naturally. The cooling stage is important when performing sterilization in an autoclave. At this stage, it is necessary to equalize the pressure that has formed inside the can with the canned food, the pressure inside the autoclave, and the pressure outside the autoclave body. If the pressure is not equalized, the cans with the canned food will become depressurized. In laboratory conditions, the simplest way to equalize the pressure is to cool the autoclave at room temperature for a certain period of time. The finished canned food is unloaded when the pressure inside the autoclave decreases to atmospheric. This technological process of autoclave cooling is used in industrial enterprises, making it impossible to depressurize the cans due to the difference in pressure inside and outside.

An automated stand for studying the technological process of sterilization of canned food allows for heat treatment of canned food from various raw materials. These can be meat, vegetables, and vegetable canned food. Specific time and temperature intervals for the sterilization process have been developed to carry out heat treatment of the above-canned foods. These parameters are presented in the program options used by the PLC. The table in Figure 3 shows the main parameters of the technological process for sterilizing canned food by the program option.

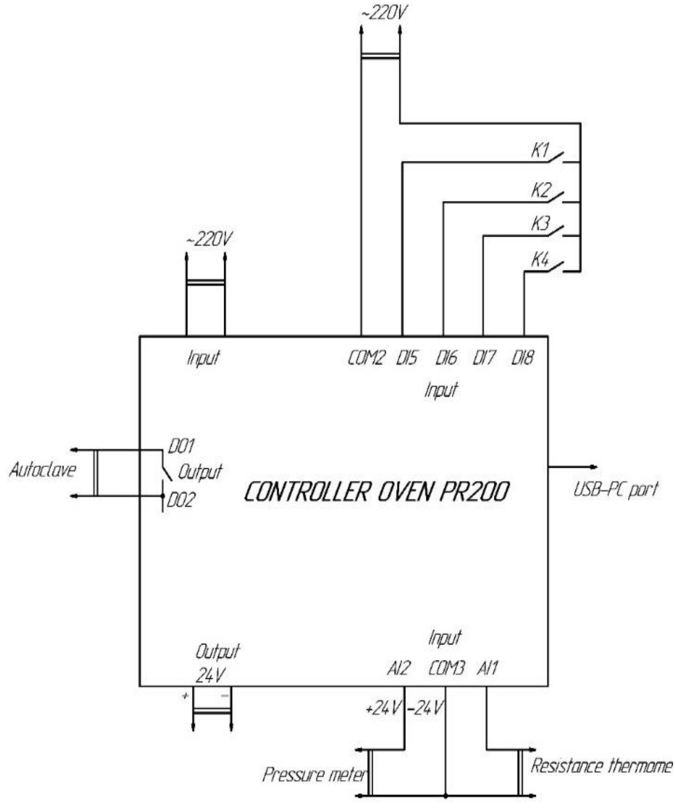


Fig. 2. The structural diagram of the experimental stand

The process of sterilizing canned food is heating the canned food at a temperature of over 100 °C and holding it for a period of time to heat it throughout the can. This achieves the complete destruction of microorganisms. After the heating is finished and the autoclave is disconnected from the electrical network, the sterilization process of canned food continues for some time due to the high temperature inside the can with the product. The sterilization effect of such high-temperature exposure can reach up to 20 %. Correctly performed sterilization allows you to obtain products that can be stored for several years.

Students select a program based on the technological process provided by the laboratory assignment of the discipline. The power supply to the electric heating elements of the autoclave is connected, and the water inside the autoclave is heated to the temperature indicated by the selected program. When this temperature is reached, the power to the electric heating elements is turned off. When the temperature drops by 1 degree Celsius, the heating elements are turned on again by the PLC. Thus, the sterilization process is maintained throughout the entire technological process. After the end of the technological process, the heating elements automatically turn off.

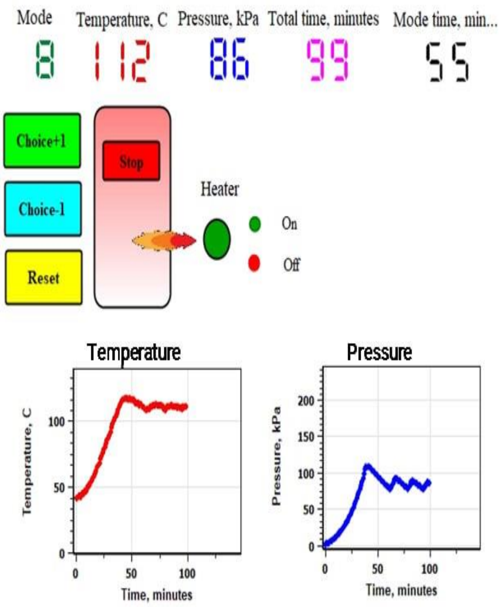
SCADA is set up for the visibility of technological process parameters monitoring and the convenience of autoclave management, the view of which is shown in Figure 3. In SCADA, students can set the mode number using the "Choice+1" and "Choice-1" buttons. Students can start or stop the operation autoclave using the Start/Stop toggle switch. Students can reset all readings using the Reset button. Digital indicators of mode, temperature, pressure, heating, and holding time are provided to control technological parameters. The "Heater" indicator is used to monitor the condition of the heating element. Temperature and pressure readings are also expected to be presented as graphs. To make it easier to select a sterilization mode, SCADA displays the technological characteristics of each mode in the form of a table. In addition to the graph on SCADA, the dependencies of temperature and pressure on time are transferred to the MS Excel editor.

Remote access for monitoring parameters and controlling the autoclave's operation through a cloud Web Server is organized for students who study in a distance format. This allows students to access and control this facility anywhere worldwide as long as they have an Internet connection.

To determine the PLC settings parameters, simulation is carried out in the MATLAB environment, and to simulate the control system - MATLAB/Simulink.

Experimental part

Analysis and calculation of control system settings is carried out by students of the Faculty of Food Technology based on experimentally obtained results. For this, operating mode No. 8 with a sterilization temperature 110°C is selected (as shown in Figure 3). Since, when sterilizing canned food, failure to maintain the set temperature can destroy bacteria and, taking into account the inertia of thermal processes in the autoclave, the set temperature for the PLC increases by 2°C to 112°C. The holding time of mode eight is selected with a duration of 55 minutes (as shown in Figure 3) to thoroughly study the nature of changes in the controlled parameter (temperature).



№mode	Sterilization temperature T, °C	Holding time t, minutes
1	100	10
2	100	15
3	100	20
4	100	>20
5	110	20
6	110	30
7	110	40
8	110	>40
9	115	20
10	115	25
11	115	30
12	115	>30
13	120	20
14	120	30
15	120	40
16	120	50
17	120	60
18	120	>60

Fig. 3. SCADA for controlling the autoclave

The experimentally obtained graph of temperature (red) and pressure (blue) dependencies on time, as shown in Figure 4.

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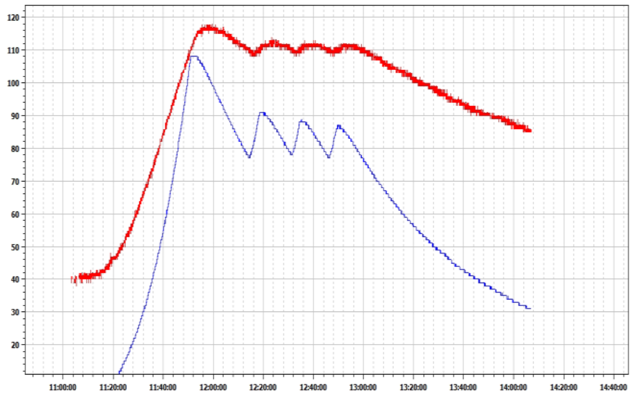

Fig. 4. Graphs of dependences of temperature (red) and pressure (blue) at the time of the technological process of sterilization

The approximate graphs of the results of the experimental data and switching of the PLC relay that controls turning the autoclave heating element on and off are shown in Figure 5.

The temperature graph (as shown in Figure 5) shows that when choosing mode No. 8, the temperature change process is close to an oscillatory one. The heating time of the autoclave until the temperature reaches 110 °C is 44 minutes. When the set temperature reaches 112 °C, the PLC turns off the power to the heating element, but despite this, the temperature continues to increase to 117 °C. Moreover, the increase in temperature after turning off the heating element lasts another 7 minutes. This is due to the high inertia of the autoclave itself and its thermal processes.

In the experiment, controlling the steam pressure in the autoclave was not set, but only its measurement was carried out (as shown in Figure 5). It can be seen from the pressure graph that steam formation occurs during heating, which leads to an increase in pressure to a value of 108 kPa.

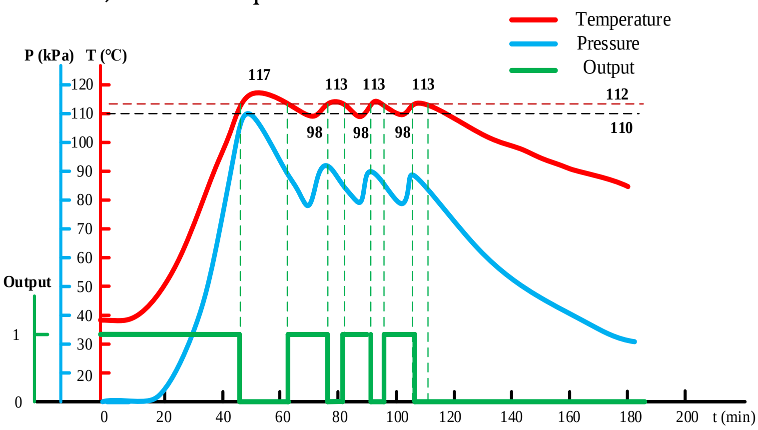

Fig. 5. Approximate graphs of dependences of temperature (red), pressure (blue), and switching of the controller relay (green) at the time of the technological process of sterilization

After the temperature decreases from 117 °C to 112 °C in 15 minutes, the PLC relay is turned on, and the heating process resumes. Still, due to the inertia of the system, the temperature shown by the sensor decreases to 98 °C. The experimentally obtained temperature graph shows that during 10 minutes, the temperature maintained in the autoclave is lower than 112 °C. But considering that the regulation temperature has been increased by 2 °C compared to the sterilization temperature, the duration of exposure with a temperature lower than the set temperature (110 °C) is 4 minutes. After reaching a temperature of 112 °C, the heater is turned off, but the temperature in the autoclave continues to increase to 113 °C and for 2 minutes is higher (113 °C) than the set temperature. Further, the graph shows an oscillating process with an amplitude of +1 (up to 113 °C) –2 °C (up to 98 °C). This process continues until the end of the waiting time, displayed in the SCADA on the computer display.

The total time when the temperature was lower than 112 °C was 32 minutes out of 55 minutes of the total sterilization mode. Still, the temperature below 110°C was kept for only

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4 minutes, which is 7.2 % of the entire duration of the technological process.

Analyzing the experiment results, it is worth noting that the maximum relative error of temperature control is 4.5 % for a temperature of 112 °C and as much as 6.4 % for a temperature of 110 °C set by student technologists. Instrumental measurement error, which is at least 1 %, and measurement inertia (dynamic error) must be added to it. Such deviations can satisfy the technological process of manufacturing canned meat or fish (for example, stews) but are unacceptable when sterilizing vegetable preserves. In the latter case, there is a need to improve the quality of autoclave controls. For this purpose, instead of a PLC two-position relay regulator, it is suggested that a proportional-integral-differentiating regulator (PID regulator) be used, which is currently one of the most standard regulators.

Modelling results

A simulation of the control system was created in the MATLAB / PID Tuneup environment to determine the tuning parameters of the PID regulator. The mathematical model (Figure 6) contained the transfer function of the autoclave (the heating object) and the PID regulator. The transfer of the heating function to the autoclave was determined by the experimentally obtained temperature graph, as shown in Figure 5. As a result of using the System Identification package of the MATLAB medium, it can be written in this form:

$$f = \frac{-0.01568*s^3+0.0001044*s^2-2.449e^{-07}*s+6.609e^{-10}}{s^4+0.003002*s^3+9.215e^{-06}*s^2+1.246e^{-08}*s+9.263e^{-12}} \quad (1)$$

Which indicates an aperiodic phase of the 4th order.

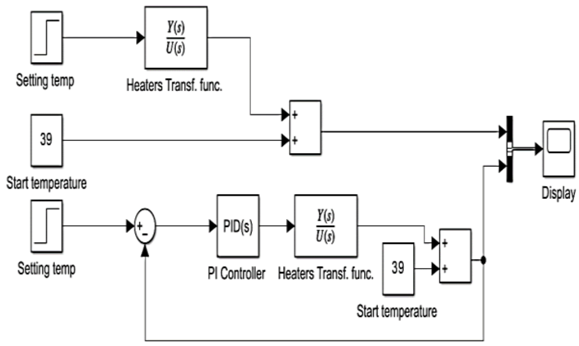

Fig. 6. Modeling of the heating system in MATLAB /Simulink

The coefficients of the PID regulator were determined by the single-circuit adjustment method during the modeling process. The following values are small: $Kp=3.64\cdot10^{-3}$, $KI=5.69\cdot10^{-6}$. The differential storage did not affect the modeling; due to the thermometer's inertia, the fragments did not receive data about the temperature change. Based on this, the PI-law regulation was chosen to control the heating of the autoclave heater.

The comparison of the graphs of transient processes for the PID regulator obtained during the modeling process (as shown in Figure 7) with the experimental results (as shown in Figure 6) showed that the loss of the model did not exceed 10 %.

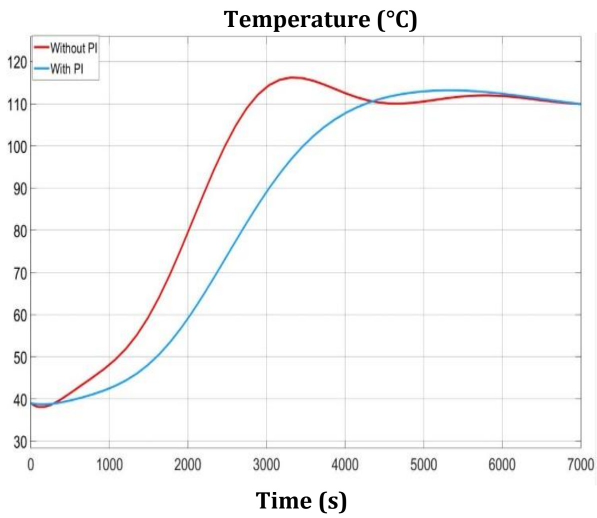

Fig. 7. Graphs of transition processes

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The duration of reaching the set temperature of 110 °C in PID regulation mode is 25 minutes longer than in the PLC two-position relay regulator. But after reaching 110 °C, the temperature gradually increases to 113 °C, which decreases to the set 110 °C and remains almost constant. This graph shows that the overshoot coefficient does not exceed 3 %, and the process changes from oscillatory (with the PLC two-position relay regulator) to aperiodic (with PID regulation). The advantage of using the PID regulation is that the temperature in the autoclave is as close as possible to the set value without reducing it below 110 °C.

It should be noted that more accurate control of the set technological parameters at the output of the PID regulation makes it possible to sterilize canned food from many plant ingredients.

The research results indicate a satisfactory quality of temperature control of autoclave sterilization. In addition, almost every autoclave has a built-in thermostat and a timer that can be set manually. However, they can only work with a two-position relay PLC controller. The advantage of using the control system proposed in the work is the possibility of remote control and monitoring of autoclave sterilization modes, which is carried out using sensors, PLC, and SCADA. These results can be recorded digitally, processed, and transmitted to any point in the world.

The two-position relay heating controller of the PLC autoclave has a satisfactory control quality, but it can only be used to prepare canned meat and fish. For such canned food, increasing the upper limit of the sterilization temperature leads to a decrease in the time of complete destruction of microorganisms. It has almost no effect on changing the structure of dietary fiber of meat raw materials. For vegetable canned food, increasing the upper limit of the sterilization temperature leads to a significant change in the dietary fiber of vegetable raw materials, significantly affecting the quality of the finished product.

PID control is effective via the controller's analog output for producing canned food from plant ingredients. The PID regulator provides better control since it has a differentiating component, i.e., it reacts not only to the temperature but also to the rate of its increase, which makes it possible to stop heating the canned food in the autoclave in advance, after which the temperature will increase by inertia. The PID regulator will also react to the tendency to decrease the temperature, which will lead to the inertia of the response, which is inherent in a two-position controller. A further research direction may be using a controller based on fuzzy logic (FUZZY controller) and its discretization. It will be interesting to compare the quality of control by the FUZZY controller in analog and discrete PLC output signals.

The advantage of using the PID regulator is the most accurate approximation of the temperature in the autoclave to the set temperature value.

Precise adherence to the set parameters allows you to sterilize canned food from plant ingredients.

Conclusions

At the Sumy National Agrarian University, at the Faculty of Food Technology, for the educational process, an automated experimental stand called "Stand for automatic monitoring and control of technological parameters of thermal equipment" was created for the first time to study the technological process of sterilization of canned food. Technology students research the production of canned meat products using modern information technologies. An automated stand for exploring the technological process of sterilization of canned food allows for heat treatment of canned food from various raw materials. The PLC two-position relay regulator of autoclave heating has a satisfactory control quality, but it can only be used to prepare canned meat and fish. In this case, you can use the discrete output of the PLC. PID regulation through the PLC's analog output effectively produces canned food from vegetable ingredients. Thanks to the precise maintenance of specified technological parameters when using a PID regulator, it becomes possible to sterilize canned food with herbal ingredients and maintain the technological parameters of the equipment without significant fluctuations. The graphs of transient processes show that when using a PID regulator, the overshoot coefficient does not exceed 3 %, and the process changes from oscillatory (with a PLC two-position relay regulator) to aperiodic (with a PID regulator). The great advantage of using a PID regulator is that the temperature in the autoclave gets as close as possible to the set value and remains at the same level. A further research direction may be using a controller based on fuzzy logic (FUZZY controller) and its discretization. It will be interesting to compare the FUZZY controller's control quality in analog and discrete PLC output signals.

The created automated stand will allow for heat treatment of canned food in an electric autoclave using meat, vegetable, and meat-vegetable raw materials to repeat the experiment several times with specified indicators of the sterilization technological process to clearly demonstrate and record on electronic media the change in temperature and pressure over time during the technological process.

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