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Development of an Autoclave Thermal Processes Model for the Simulator of Canned Food Sterilization Process

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Abstract

The article describes an autoclave thermal processes model, which is used for the simulator of canned food sterilization process. The simulator is based on a simulation model that adequately describes the reaction of the autoclave to the actions of the control system and the operator of the sterilization unit. The model's parameters were obtained by means of experimental data processing. The computer program "autoclave Model" for simulating sterilization process in the steam and water environment is described. The examples of the canned food's manual control sterilization modeling are shown. The results of numerical mathematical modeling of canned food sterilization processes in the autoclave showed a high degree of the implemented process models quality of approximation. The calculation schemes done as a result of the mathematical models creation were used to develop a hardware-software complex of the sterilization process simulator. The increase of training level on carrying out process of canned goods sterilization will be provided as a result of designing the simulator of sterilization process in educational process. Consequently reducing defects in production and improving the quality of canned products are expected.

Keywords: autoclave, sterilization process, processes model

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1. Introduction

The country food security in current situation should be assured at the highest level while the rules of delivery of foreign fish products have been changed. One of the most important technological processes is the sterilization of canned food. The health of fish products consumers directly depends on the quality of technological processes. The research in the field of food sterilization is one of the leading directions of the scientific group of the Department of Automatic Equipment and Computer Science of the Murmansk State Technical University.

The searching for sterilization processes of canned food models attracted many scientists and researchers of the late twentieth century [1-12]. One of the most famous researchers in this field is Giulio R. Banga, who proposed methods for improving food processing using modern optimization methods [13]. He proposed methods and models used in the food industry. He also considered the features of the introduction of widespread optimization and modeling processes. A more complete consideration of methods for optimizing the processes of heat treatment is shown in the book by F. Erdogdu "Optimization in Food Engineering" (2008) [14].

The work of the autoclave for processes in steam or water environment has been investigated by the research team of the Department of Automation and Computer Engineering in MSTU since 2008. Energy-efficient and step modes of canned fish products sterilization in steam and water environment have been developed. The mathematical description of the autoclave has been constructed and the warming of different types of fish products in popular sizes of canning containers has been investigated [15]. Reducing time and energy costs of the process and preserving maximum amount of nutrients in the product are of great importance. Therefore, a method of F-effect-based sterilization was also worked out.

A hardware-software complex named MIST (Modernization and Innovation in Sterilization) was worked out as a result of these researches. It made possible improvement of the canned food autoclave sterilization process efficient. MIST includes a sterilization process' automatic control system. This system is built using modern national equipment for industrial automation. There are program modules which allow configuring of the control system for a specific type of product. It makes possible reducing the process' resources cost and facilitates the work of the sterilization modes developer. The research of the sterilization process made it possible to start designing a simulator of the sterilization process. The importance of this simulator has recently been perceived quite strongly. It provides high level of training in the fields of "Automation of technological processes and productions", "Technological machines and equipment". Therefore, the purpose of this work was to create preconditions for sustainable development and improving the laboratory facilities of industrial educational institutions, making higher the quality of laboratory classes and training simulators for the sterilization process of canned products.

2. Methods and Equipment

2.1. Methods

The simulator is based on a simulation model. This model describes the reaction of the autoclave to the control system's and operator's actions quite adequately. The models of the autoclave sterilization chamber using the ``Black box'' method were worked out previously. These models are for the stages of blowing, heating and sterilization. They could be used during the adjustment of the autoclave control system. But they are unsuitable for the implementation in the aforementioned simulator.

Taking into account the fact that an inexpensive, reliable and universal microcontroller is supposed to be used as the main computing platform of the simulator, a large amount of calculations is unacceptable. Otherwise it prohibits a hard real-time mode.

Therefore there is a necessity to build a altogether new model of the autoclave. It must answer the reaction to the control system's and operator's actions. Also it should utilize ``Black box'' method and process parameters' dependencies. The model should be optimal in terms of quality-to-operating cost ratio.

The object of mathematical modeling is the autoclave N2-ITA-602. The autoclave control system includes discrete output sensors: upper level of the water; the existence of water supply; the existence of steam supply; the existence of compressed air supply; the condition of the lid (opened or closed). The actuators of the control system are: steam supply valve; cooling water supply valve; drain valves (upper and lower); air supply valve.

A mathematical description of the autoclave is suggested to be a system consisting of the following objects: apparatus body, canned product, water, steam and air. The water is implied to be a mix of condensate, sterilization water (for the sterilization in water environment) and water for the cooling stage. Steam and air form a steam-air mixture. The body of the apparatus always takes part in the calculations. The presence of the other elements depends on the condition of the apparatus and also on the actions of the operator and the control system.

Each part of the calculations is represented as the object with concentrated parameters for simplicity. An exception is the sterilization chamber because it naturally has geometric dimensions. Each object is also represented by temperature, mass and heat capacity. The parameters of the model are calculated using time sampling with a heat exchange between the objects (Figure 2).

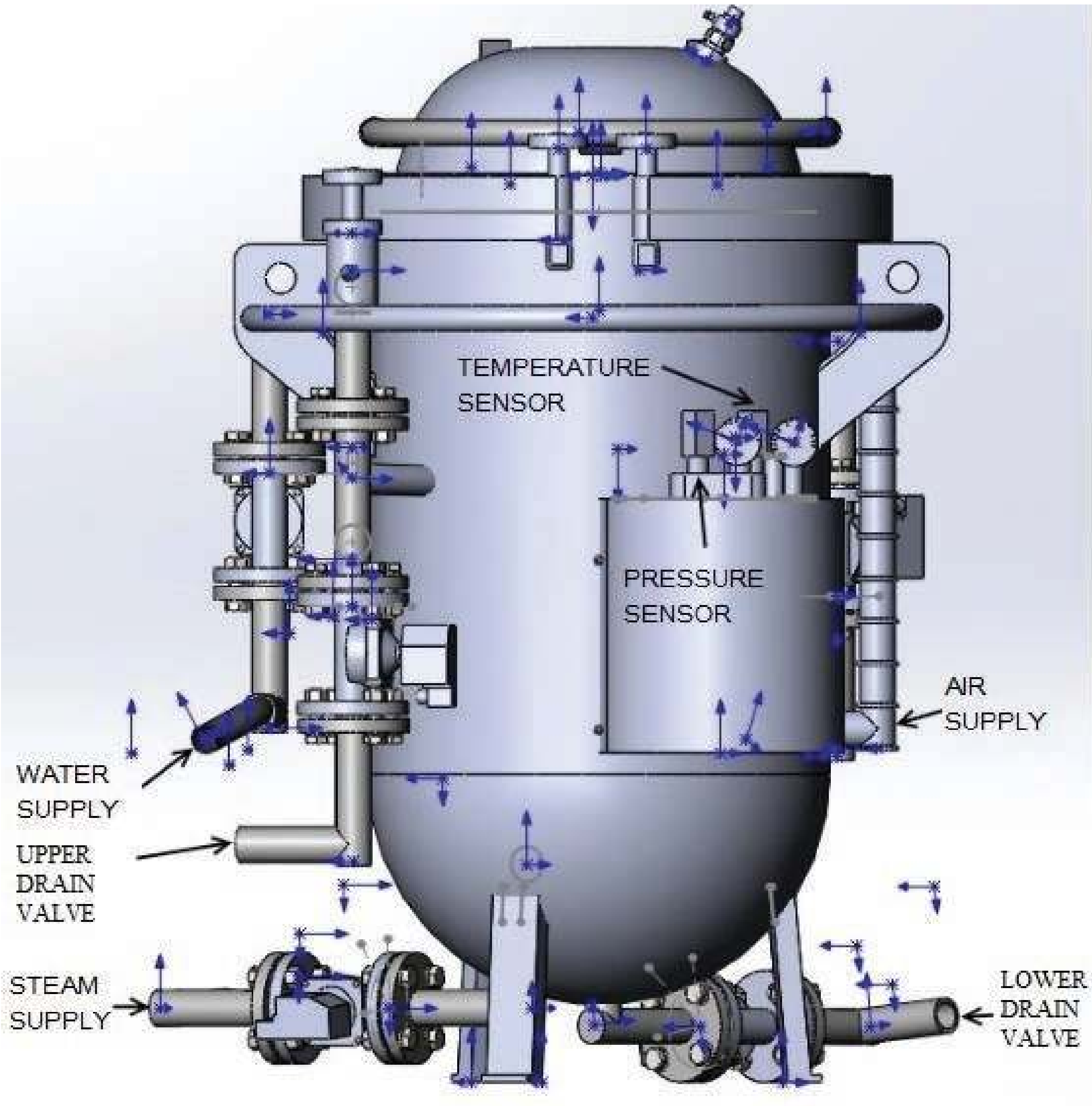

Figure 1: 3D model of N2-ITA-602 autoclave.

A freely distributed integrated development environment Lazarus and programming language Free Pascal were used with the purpose of studying and optimizing calculation scheme. Thus the program "autoclave Model" was produced. It allows simulating the interaction of the operator with the sterilization unit. In order to control the sterilization process, the autoclave model provides the actuators described above. There are window controls which allow putting the product in the sterilization chamber and closing or opening the apparatus' lid. The model also produces data of the temperature sensor model ``installed'' at a certain height in the sterilization chamber and a pressure sensor.

Results based on the numerical modeling the following calculation scheme were considered as having the highest quality-to-operating cost ratio. There are separate program modules for calculating parameters of each media (steam, air and water) that may be present in the sterilization chamber of the autoclave.

The calculation procedure of the steam environment module is described below. The module begins with a description of the medium inflow Δm. If the corresponding supply valve is open the steam mass increment is calculated according to the formula:

$$\Delta m = S \cdot \sqrt{\frac{\Delta P}{\rho(t)}} \cdot h \quad (1)$$

where S is the minimum cross-section of the steam transmission path; ΔP is the pressure difference between the main and the autoclave; ρ(t) is the density of saturated steam at temperature t; h is the quantization step size.

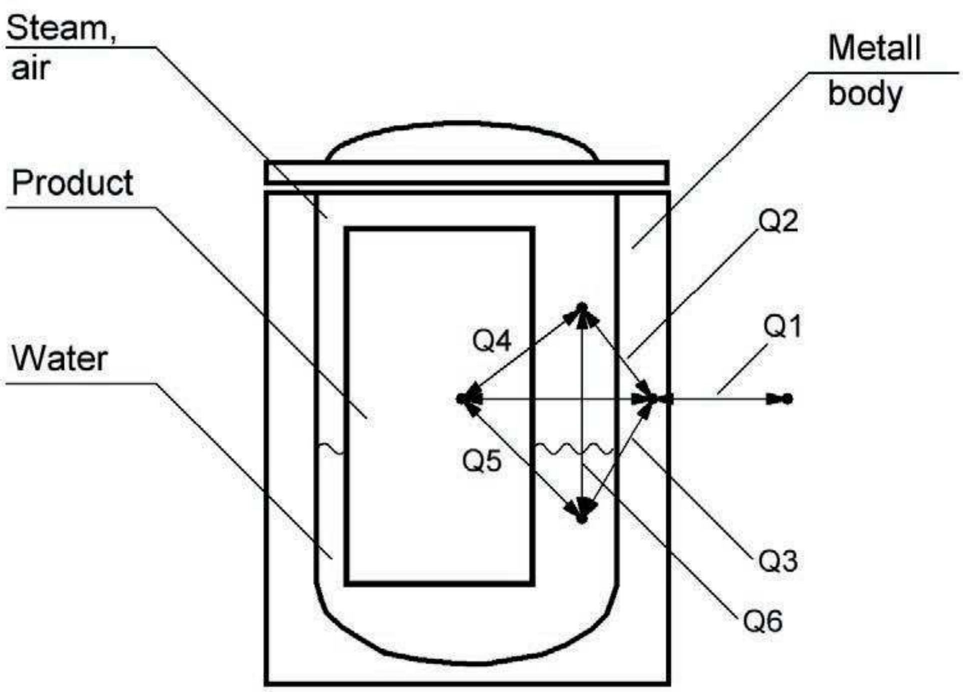

Figure 2: heat transfer diagram for the autoclave model (Q1 -- heat transferred from the apparatus to the environment; Q2 and Q3-heat transferred from the steam-air mixture and water to the body, respectively; Q4 and Q5-heat transferred from the steam-air mixture and water to the product, respectively; Q6-heat exchanged between the steam-air mixture and water.).

Change of the steam mass due to the inflow Δm influences on the steam temperature t_{st} which is calculated according to the simple formula:

$$t_{st} = \frac{m_{st} \cdot t_{st} + \Delta m \cdot t}{m_{st} + \Delta m} \quad (2)$$

where t is the temperature of the steam in the supply line; m_{st} is the mass of the steam in the autoclave.

The partial pressure of the steam is calculated in the appropriate module. The traditional approach to calculating the steam pressure in the apparatus is quite resource-intensive. Therefore the following method is proposed for the purpose of reducing the number of calculations. The fraction of the available mass of steam from the maximum possible steam mass in the apparatus at a given temperature (so called k coefficient) is calculated according to the formula:

$$k = \frac{m_{st} + \Delta m}{\rho(t) \cdot V_{free}} \tag{3}$$

where *Vfree* is the free volume in the apparatus. The free volume means capacity of the apparatus which the steam-and-air mixture can occupy. The steam pressure is calculated as

$$P_{st}(t) = P_{s.st}(t) \cdot k \tag{4}$$

where *Ps.st* is the saturated steam pressure at temperature *t*.

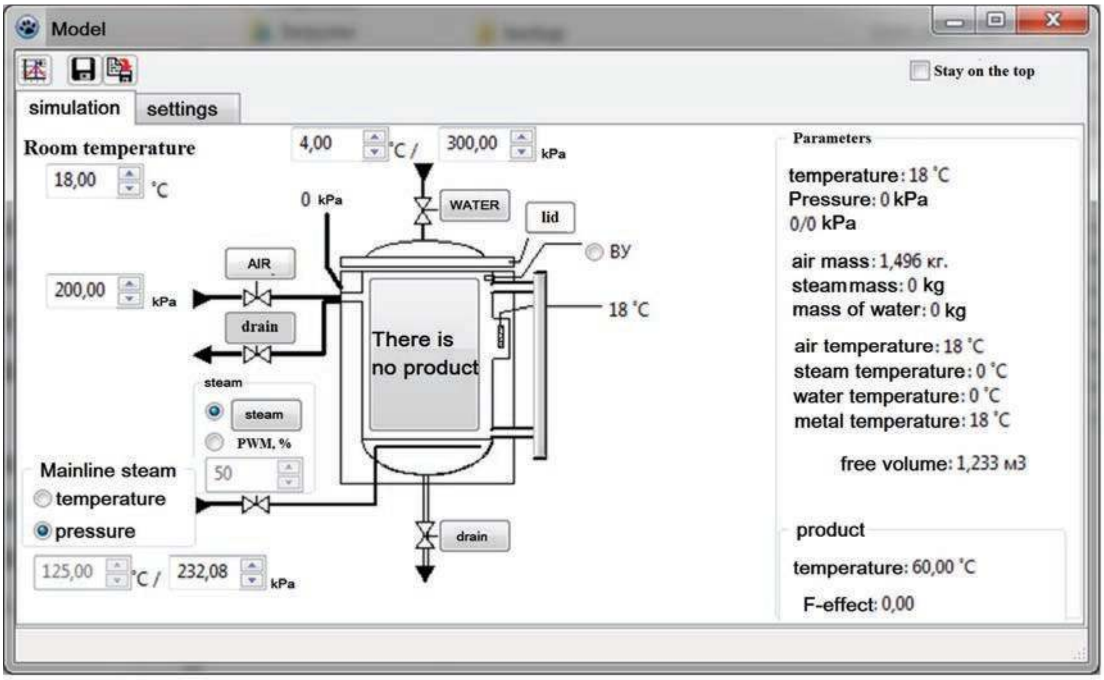

Figure 3: Main window of the "autoclave Model".

The steam inside the apparatus takes part in the heat exchange according to the following scheme (Figure 2). The amount of heat Q transferred from the steam to other objects in the scheme (water, air, metal and product) could be calculating using the formula (5):

$$Q = F \cdot \alpha \cdot \Delta T \tag{5}$$

where F is the surface area between the steam and the object; α is coefficient of proportionality of the heat exchange; ΔT is temperature difference between the steam and the object.

The value of the incoming or outgoing heat is determined by the temperature change Δt of each object:

$$\Delta t = \frac{Q}{C_{ob} \cdot m_{ob}} \tag{6}$$

where C_{ob} is the specific heat of the object material; m_{ob} -- the mass of an object.

The resulting calculations of the values of heat are then summarized. The sum value is used for the condensed steam mass m_{cond} calculation (formula (7)). Then condensed steam mass is added to the mass of water in the apparatus.

$$m_{cond} = \frac{\Sigma Q}{R_n \cdot C} \tag{7}$$

where $\sum Q$ is the total heat obtained by steam from air, product, water and metal of the autoclave;

R_n - specific heat of vaporization; C is a correction factor determined by the analysis of experimental data (assuming that not all amount of the heat is spent on condensation).

When there is a gauge pressure in the autoclave, the program checks the condition of the blowing valve, both drain valves, state of the lid. In the case when any of these elements is connected to the atmosphere, the mass of the steam is reduced by the amount of flow per unit of time calculated by the formula (1). The only exception is the case when there is a certain amount of water in the apparatus and lower drain valve is opened, the steam is not transported through this transmission path.

If the temperature and mass of the steam have been changed due to the heat and mass transfer, its partial pressure is recalculated according to the formulas (3) and (4). Also its temperature is recalculated according to the known dependencies (function of pressure for saturated steam) based on the value of the pressure.

The module for calculating parameters of the water is similar. The only difference occurs when there is a steam in the apparatus. When the water is transferred into the sterilization chamber, the heat exchange between cold water and hot steam is calculated (producing condensed steam). This ensures adequacy of the calculation scheme at the cooling stage during sterilization of canned food in the steam environment. Also the water level in the sterilization chamber and the areas of heat exchange for the water--body, water--product, air-steam mixture--body, air-steam mixture--product, air-steam mixture --water are calculated using values of the water level and geometric dimensions of the autoclave body and tin cans.

The module for determining parameters of the air corresponds to the scheme above. The air pressure is calculated by the formula:

$$P_{air} = \frac{m_{air}}{V_{free} \cdot M} \cdot R \cdot t_{air} \tag{8}$$

where P_{air} is the partial air pressure; m_{air} is the air mass; M is the molar mass of the air; R is the universal gas constant.

When the lid is open, air mass in the apparatus could be modified according to the formula (1) depending on the sign of overpressure. In case of pressure below atmospheric the inflow of ambient air with room parameters is taken into account. Then the temperature of the autoclave body is calculated according to the formula (5) due to heat exchange with the environment of the room.

Steam and air in the apparatus form the steam-air mixture (SAM). Its temperature t_{sam} is calculated in accordance to the masses and temperatures of the respective substances:

$$t_{sam} = \frac{m_{st} \cdot t_{st} + m_{air} \cdot t_{air}}{m_{st} + m_{air}} \tag{9}$$

The simulator model of the autoclave is ``equipped'' with the temperature sensor. Its metal body produces certain thermal inertia. The temperature that the sensor produces therefore is calculated using Euler method for a linear differential equation of the 1st order with a time constant of 10 seconds and a transmission coefficient of 1 (close to experimental results). The choice of the Euler method is due to its relative computational simplicity. When the the water level in the apparatus exceeds the height of the temperature sensor installation (sensor body is in water), the water temperature is taken as the input value for calculations. Otherwise sensor readings are calculated based on the temperature of the steam-air mixture.

The pressure in the apparatus is the sum of the partial pressures of air and steam (if there is any). The autoclave may be filled with water considered as an incompressible liquid completely. In this case the pressure there is determined by the condition of the water supply, discharge and drain valves.

The aforementioned calculation scheme is based on a number of assumptions. The heat transfer and peculiarities of steam, water and air transportation as are considered in a simplified manner. The processes of heat and mass transfer in the sterilization chamber are considered as being not simultaneous and time-discrete. The peculiarities of heat transfer through the condensate film to the apparatus body and the product are not taken into account. The influence of the temperature on the heat capacity of the objects in the sterilization chamber is ignored. The dependency between the parameters of saturated steam and the heat of vaporization is also not used. Steam is always is considered as dry saturated with a degree of dryness of 1. The product is considered to be homogeneous. There are no phase transformations of the cans contents, etc.

3. Results

The parameters of the model were achieved using computer simulation and comparing its results with the experimental data. An example of simulating of the sterilization process of canned products in the steam environment in the designed program "autoclave Model" is shown in Figure 4. The process of controlling the model of the sterilization plant in manual mode could be described as follows.

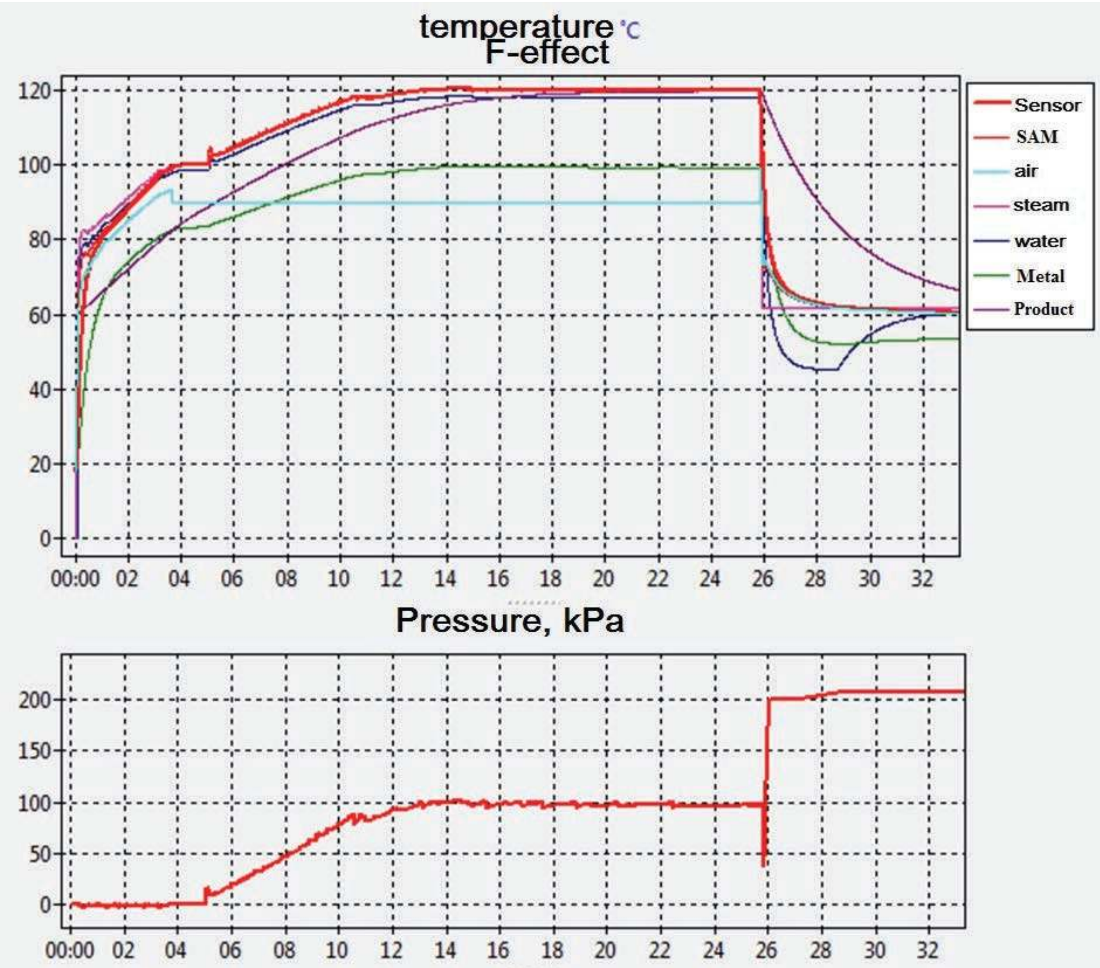

Figure 4: Example of simulation of the canned food steam environment sterilization in the program ``autoclave Model''.

The shown process starts with loading canned food into the machine. Then the lid is closed and steam supply and both drain valves are all opened. The stage of blowing the device by steam begins. In five minutes from the beginning of the blowing stage the sterilization chamber is thoroughly heated to 100 C. The air from the apparatus is vented intensifying the heat exchange processes. Then the operator closes both drain valves. It implies beginning of the heating stage. During this stage the temperature in the sterilization chamber reaches the sterilization level (120 C in Figure 4). After that the stage of sterilization begins. During this stage the temperature in the autoclave is kept at the level determined by the sterilization formulae for a certain time. After the sterilization stage begins the cooling stage. In this stage cooling water is supplied into the apparatus. Cold water removes excess heat from the product and the autoclave. This reduces the temperature to the values at which the product can be removed from the sterilization chamber (approximately 60 C). In addition, compressed air is also supplied into the sterilization chamber during the cooling phase. It prevents a sudden drop in pressure due to steam condensation.

The example of simulating the sterilization process of canned food in water environment is shown in Figure 5. Before starting the sterilization process, water is poured into the autoclave to the level of two-thirds of the total volume of the autoclave (Figure 5) and heated to the sterilization temperature of 60 C.

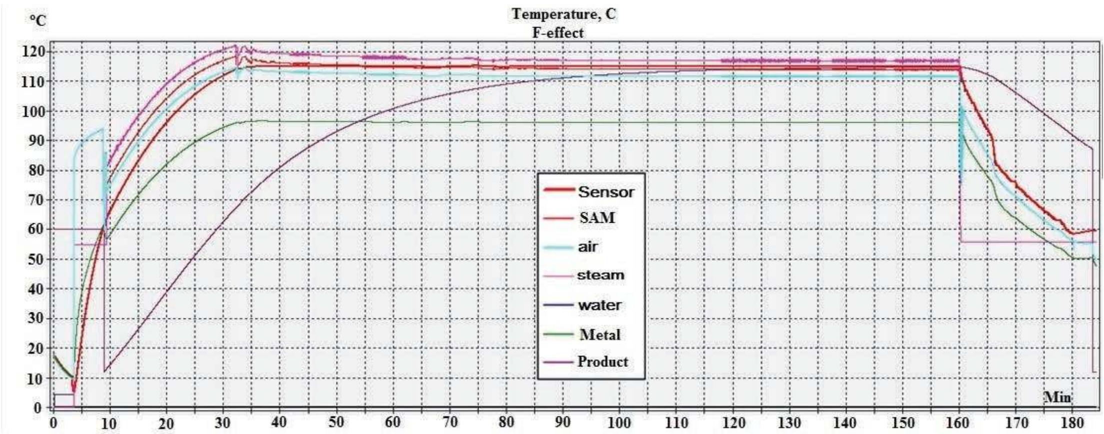

Figure 5: Example of simulation of the canned food water environment sterilization in the program ``autoclave Model''.

The process begins with loading the canned food into the machine. After that the lid is being closed and the steam valve being opened. Then, the heating of the water environment with the product starts. In twenty-five minutes from the start of the heating stage, the temperature in the apparatus reaches the preset level (115 C in the shown sterilization mode). Then a stage of sterilization during which the temperature in the autoclave is kept at a predetermined level for a certain time takes place.

After the sterilization stage goes a cooling stage. The water is supplied into the apparatus, reducing the temperature to the safe level so the product could be removed from the autoclave. In addition to water, compressed air is also supplied to the unit during the cooling phase to prevent a sudden drop in pressure in the unit.

4. Discussion

The results of numerical mathematical modeling of canned food sterilization processes in the autoclave showed a high degree of the implemented process models quality of approximation. The calculation schemes done as a result of the mathematical models creation were used as a base for the software of the sterilization process simulator. Hardware part of the simulator is based on the Microchip PIC18F2520 microcontroller. This device carries out many functions for the simulator. It provides input of the control signals from the control system: switching valves of the autoclave. It also calculates the process parameters in accordance with the above model in real-time mode. Microcontroller also generates output signals: temperature and pressure in the sterilization chamber, water level and the safety valve state. The program code is written on the MPASM macroassembler language. This language is often used for developing time critical program code for the microcontrollers manufactured by Microchip.

The simulator model with the control system is shown in Figure 6. The body of the model is made using 3D printing technologies FDM / FFF. The simulator allows simulating abnormal situations such as failure of actuators by disconnecting from the model of the valve connector that provides link to the control system.

Figure 6: Sterilization process simulator model with control system.

The simulator provides the ability to change the type of product using the parameter *C* in the formula (6) for different educational task variants. This is done by specifying the appropriate code with a switch.

The sterilization process control system is an original development of the Department of Automatic Equipment and Computer Science in MSTU. It is built on the basis of a programmable logic controller SPK-207, carrying out the exchange of information with the operator via the touch screen. Sterilization process is controlled by means of HMI. Development of control system algorithms was carried out in 3S CoDeSys.

5. Conclusion

During the development of the simulator the comprehensive model of the autoclave has been produced. It shows high level of similarity of the reactions to the actions of the operator and control system. Nowadays sterilization process simulator with control system is used in the educational process of the Murmansk State Technical University. It helps to increase the training level by means of studying stages of the canned food sterilization process. Reducing defects in production and improving the quality of canned products are expected. The aforementioned simulator could also be used instead of the ``real'' autoclave on the stages of developing control system for the sterilization process and coefficients tuning.

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