Complex for modeling and optimization the sterilization process

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Abstract. Stages of developing new or improving the existing heat treatment regimes of canned food are considered. In the paper, the method of using numerical process models as a part of the software to optimize preliminary stage costs is offered. Two software products with best functionality are described. The advantages of transfer functions in the software complex TPM & PRSC (created by the authors of the article) at the preliminary selection stage of the canned food heat treatment regime are shown using the example of the development of the sterilization regime of canned food «Murmansk cod liver» in the tin can 38K.

1. Introduction
In the market economy conditions, position of the company in the marketplace is determined by the level of competitiveness. This is associated with two criteria - price and manufacturing quality level. The second factor gradually becomes more prominent. Attention to this factor is a necessary condition for the company’s survival and sustained development.

The typical customer anticipates systematic update of the product range and improvement its consumer properties. One of the popular products is canned food. Heat treatment is the key process that determines its safety and quality. Despite the long history, heat treatment of raw materials continues to grow rapidly, and will remain popular due to its convenience and long shelf life in the future [1, 2].

Heat treatment of products is traditionally carried out in the following way [2]. Hermetically sealed cans with the product are placed in the sterilization chamber of the autoclave. Afterwards the heating medium temperature is raised to the specific sterilization temperature level. Water vapor or water may be used as a heating medium. The sterilization temperature is maintained for a definite period of time, after which it is lowered, and upon reaching a certain level, cans are unloaded from the sterilization chamber. The ratio of temperature and sterilization time determines the microbiological efficiency of the process, which is characterized by lethality. Consequently, sterilization regime of canned food is a set of factors such as duration of the heat treatment stages, temperature of the heating medium, pressure in the autoclave during sterilization and cooling stages and the normative lethality.

2. Rationale
Analysis of the current sterilization regimes for various types of canned food indicates that in some cases the established temperature-time sterilization regimes lead to significant excess of the normative lethality.

Process of canned food sterilization requires finding a compromise between the beneficial and harmful effects of high temperatures on the product. On the one hand, heat treatment inactivates spores,
microorganisms and enzymes that are present in food and have a negative impact on the consumer’s health and products safety. At the same time, the concentration of nutrients which are unstable to high temperatures (like proteins and vitamins – retinol, thiamine, folic acid, ascorbic acid, calciferol and others) decreases [3]. For this reason, it is an important task for researchers to find the optimal temperature-time regimes of heat sterilization, which would simultaneously ensure the achievement of the required degree of microbial inactivation - in terms of «normative sterilization effect (microbiological lethality)», preservation of product biologically active labile substances, energy consumption and sterilization process duration reduction [4-6].

The development of new and improvement of existing heat treatment regimes of canned food is an important task of the fishing industry in Russia. Currently, manufacturers of canned products use modern sterilization equipment and pack units, which require the creation of appropriate sterilization regimes. However, the process of development and justification of new regimes is time consuming, requires significant energy, time and, as a consequence, material costs. Therefore, development of the information technology for this process optimization is highly relevant.

3. Development stages of heat treatment regime

Generally, the development process of canned food sterilization regimes is time consuming and consists of some stages: preliminary selection, laboratory test with subsequent production inspection, registration, agreement and approval.

At the stage of laboratory test, an approximate sterilization regime of the product selected at the previous stage is checked by inoculation culture of heat-resistant microorganisms into the product followed by testing for:
- absence of test-microorganism in canned food;
- achievement of actual lethality (F$_f$) is higher than normative (F$_n$);
- compliance of canned food with the requirements of industrial sterility;
- preservation of product’s physical-chemical and organoleptic qualities provided by the regulatory documentation.

When these conditions are met, the current canned food sterilization regime is recommended for production inspection.

At the production inspection stage, an experimental batch, not less than one thousand «physical» cans, is produced. After that, this batch is subjected to complete control, removing canned foods that have defects, draw up an act of developing an experimental batch and deposit it for storage for not less than 90 days in accordance with the conditions of regulatory documentation. At the end of storage process, the experimental batch is tested in the same way as in the laboratory test.

When the necessary conditions of industrial sterility and lethality are met, the procedures for registration, agreement and approval of the sterilization regime take place. Only after this the developed regime is transferred for further utilization in the production process.

4. Theoretical process model

The longest and most expensive stage in development of the sterilization regime is its preliminary selection. The duration of further stages in the development of the sterilization regime depends on the choice of approximate sterilization regime of canned food from hydrobions. Reducing costs at the preliminary selection allows to save sufficient amount of time and tools of developer of canned food sterilization regimes on food production. Obviously, this is possible only by means of obtaining a process model that represents set of autoclave (sterilization chamber) and product temperature models. Usage of adequate models allows to reduce number of trial autoclaving, as well as time, material and energy costs for their realization, and to create the optimal temperature-time regime of heat treatment, ensuring the achievement of required lethality [5].

Mathematical models of thermal processes in the sterilization chamber of autoclave and can with product usually consist of differential equations that depend on many factors that are difficult to take into account (initial product temperature, coolant temperature, dependence of objects heat capacity...
involved in heat exchange on process parameters, coolant’s phase transformations, size and shape of cans, the shape of sterilization chamber, etc.). Each factor’s value is selected depending on the experimental data, therefore it is difficult to develop the object comprehensive mathematical model. For instance, the problem of calculating the heating in autoclave of the circular cylindrical tin can, filled with a product conducting heat conductively, could be summarized as the solution of the following equation [7]:

$$\frac{\partial T(r,z;\tau)}{\partial \tau} = a \left[ \frac{1}{r} \frac{\partial T(r,z;\tau)}{\partial r} + \frac{\partial^2 T(r,z;\tau)}{\partial r^2} + \frac{\partial^2 T(r,z;\tau)}{\partial z^2} \right],$$  

(1)

with further boundary and initial conditions: $0 < r \leq R; -h \leq z \leq h; T(r; z; \tau) = T(r; \pm h; \tau) = T_{av}(\tau) = \text{const}; T(r; z; 0) = T_0$, where $T$ is the temperature, K; $r, z$ - coordinates; $\tau$ - time, sec; $a$ - coefficient of thermal diffusivity, $m^2/s$; $R$ – can radius, m; $h$ - half of can height, m; $T_{av}(\tau)$ is the temperature of can surface, °C; $T_0$ - initial product’s temperature, °C.

Simplification of this procedure is possible by obtaining numerical mathematical model of canned food sterilization process in the form of transfer functions constructed from experimental data for the input $X(p)$ and output $Y(p)$ process parameters:

$$W(p) = \frac{Y(p)}{X(p)} = K \frac{\prod_{m=0}^{m=m-1} p^{m-1} + \cdots + p^1}{\prod_{n=0}^{n=1} p^n + \cdots + p^1},$$  

(2)

where $T_n ... T_1, \tau_m ... \tau_1$ are time constants; $p$ - Laplace transform operator; $K$ - transfer coefficient; $m$ - order of numerator; $n$ - denominator order.

This approach allows creation of the correct and adequate model reflecting main characteristics of process dynamics [8].

Construction of the time dependences described by the transfer functions of the model’s blocks was carried out using fourth-order Runge-Kutta numerical method for solving differential equations.

5. Software for optimizing heat treatment conditions
A modern solution to the problem of optimal parameters selection for heat treatment is the utilization of modern mathematical methods and models of the sterilization process as part of software with graphical user interface (GUI). Today the most functional of them are: the OPT-PROx software and the software complex for the selection of canned food sterilization regime, created by the Department of Automation and Computer Engineering of the Murmansk State Technical University, consisting of two programs: TPM (Thermal processing modeller) and PRSC (Selection of canned food regime sterilization).

5.1. OPT-PROx software
Software product OPT-PROx was created by the group of Abakarov in the integrated development environment Borland C++ Builder [9]. This program uses global optimization methods and variable regimes of heat treatment to optimize the process of products heat treatment.

OPT-PROx consists of two working tabs. The first tab «Thermal diffusivity estimation» is used to calculate the thermal conductivity of the product using the experimental temperature curves of the autoclave and the critical point of the can (Figure 1). The second tab «Thermal processing optimization» is focused on solving problems of optimizing the canned food sterilization process with various objectives and limitations (Figure 2). To solve formulated problems, an adaptive random search algorithm is used in conjunction with correction functions and a finite difference method together with a third-order spline approximation [10].

OPT-PROx allows selection of the following objective functions: total process time minimization; processing costs minimization; surface product preservation quality maximization; average product preservation quality maximization. It is also possible to use the following optimization constraints: surface product quality; medium product quality; processing costs; lethality value; total process time. All features of OPT-PROx are described in the included help file.
Figure 1. Window of «Thermal diffusivity estimation» tab.

Figure 2. Window of «Thermal processing optimization» tab.

Using the OPT-PROx software for solving real problems allows for significant decrease in the total processing time and an increase in the quality of the final product compared to the traditional heat treatment process at a constant temperature [9]. However, specially designed regulator, able to work out
these temperature profiles, is needed to perform the sterilization process according to the characteristics
selected in the program, also requirements for sterilization equipment characteristics are increased. This
is one of the major challenges to the implementation of specified regimes in real industrial autoclave.

5.2. Software complex TPM & PRSC

Particular attention is paid to the search for the optimal temperature-time regime of raw materials heat
treatment not only abroad, but also in Russia.

The software complex for obtaining sterilization regime of canned food from hydrobionts at the
preliminary selection stage, created by the Department of Automation and Computer Engineering of the
Murmansk State Technical University, consists of two programs: TPM and PRSC. Complex allows
optimization of developer’s working time when creating a new or correcting the existing sterilization
regime of canned food from hydrobionts.

Software TPM makes possible:
- automatic numerical models’ identification (transfer function coefficients) of the temperature
  process, occurring in the can with product, up to the third order inclusively for the heating and
  sterilization stages, and for the cooling stage;
- display of temperature profiles of the autoclave, real (according to experimental data from
  temperature sensors) and simulated thermal process in can with the product and their difference \( E = T_{\text{real}} - T_{\text{model}} \);
- output of actual sterilizing effect (F-effect) value of the real and simulated thermal processes in the
  can with product (in terms of given base temperature in Celsius degrees and value of particular
  microorganism’s heat resistance) and their difference for the whole and individual stages of sterilization
  process;
- calculation of integral criterion equal to the integral of the sum of absolute magnitude of difference
  between real and simulated temperatures of thermal process in the can with product and absolute
  magnitude of difference between derivative of the same values \( J = \int (|E| + |E'|) \text{ dt} \);
- calculation of thiamine average volume preservation (in percent) for can number 3.

To start working with TPM software user need to open file with registered data from temperature
loggers. Next, select the desired product temperature profile, type («Heating» and/or «Cooling») and
order (first, second or third) of product thermal model. Then user need to click «Model Identification»
button and save selected product model and sterilization regime to files for PRSC software.

Further mathematical simulation at the stage of sterilization regimes’ preliminary selection is
performed in PRSC software.

First, parameters of product model, autoclave or sterilization regime (traditional or stepwise), initial
and final conditions and type of sterilization process (steam or aqueous medium) are introduced in the
program. Next, the program calculates temperature curves in the sterilization chamber of autoclave and
cans placed in three areas of the autoclave (by heating: the most, the least and average).

For given sterilization regime and the indicated areas of the autoclave, values of actual lethality are
calculated using the data obtained. After that, PRSC software allows user to select the optimal (by
sterilizing effect, sterilization temperature and sterilization stages’ duration) parameters of the canned
food sterilization regime in automatic (using the adaptive simplex method) or manual mode (user
changes required parameters).

Moreover, PRSC software makes possible performing the following functions:
- output in graphical or tabular form the process with chosen product model;
- display formula of traditional sterilization regime;
- simulation any kind of sterilization regime using experimental data with autoclave temperature
  profile;
- report file creation (Microsoft Word document) with thermal data for regime approval at the
  preliminary selection stage by setting necessary parameters on «Saving thermal data» tab.

6. Research of software complex
Employees of the departments of automation and computing technology and food production of MSTU conducted research to obtain the optimal parameters of canned food sterilization regime based on numerical mathematical models of temperature processes at the preliminary selection stage.

6.1. Objects and materials

The following objects and materials were used for research: sterilized product - cod liver (Gadus morhua - the most common object of fishing in the Arctic region) and new type of package - conical tin can 38K, universal laboratory autoclave AVK-30M with microprocessor control system that completely simulates sterilization process in modern imported and domestic industrial autoclaves (ASCAMAT (Germany), Panniny (Italy), AGK, etc.), industrial autoclave ASCAMAT-230 and temperature loggers Ellab TrackSense PRO (Denmark).

Laboratory autoclave AVK-30M was designed and manufactured by upgrading VK-30 sterilizer (Figure 3).

For research and development of sterilization regimes AVK-30M was equipped with hardware and software of the domestic production association OWEN, on the basis of which the autoclave control system was developed (position 29 in Figure 3). It consists of programmable logic controller PLC-154, analog input module MVA-8 and discrete input-output module MDVV. During sterilization process, control system receives information from temperature and pressure sensors and controls autoclave using electromagnetic valves and tubular electric heaters [11].

Autoclave ASCAMAT-230 manufactured by ASCA GmbH (Germany) (Figure 4) was chosen as an industrial sample for research. It is a vertical autoclave with a capacity of 230 liters which heats with three tubular electric heaters located in the bottom and side parts [12].
Figure 3. Laboratory autoclave AVK-30M: 1 - compressor; 2 - air receiver; 3, 10, 14 - overpressure sensors; 4, 9, 27 - manometers; 5 - temperature sensor in the sterilization chamber; 6 – sterilization chamber cap; 7 - baskets with cans; 8 - autoclave outer jacket; 11 - air supply valve; 12 - sterilization chamber; 13 - temperature sensor in the steam generator; 15 - valve for supplying cooling water to the sterilization chamber; 16 – water-vapor chamber (steam generator); 17 - tubular electric heaters; 18 - valve for supplying water to the steam generator; 19 – valve for draining from the sterilization chamber; 20 - valve for draining from the sterilization chamber to the economizer; 21 - valve for draining from economizer; 22 - steam supply valve; 23 - valve for draining from the steam generator to the economizer; 24 - drain valve; 25 - temperature sensor in the economizer; 26 - economizer; 28 - valve for draining from economizer to steam generator; 29 - control system.
Collection of information about the temperature in the sterilization chamber of autoclave and can with product was performed using the Ellab TrackSense PRO loggers. This set of loggers allows exploration of the temperature in the least heated area of the can and directly in the autoclave sterilization chamber. After autoclaving (one full cycle of canned food sterilization), the actual sterilizing effect ($F_a$) can be calculated using values of the temperature dependence inside the can on the sterilization time, taking into account conversion coefficients, and the degree of canned food suitability can be assessed for use and long-term storage.

6.2. Research plan

As a part of research, a series of experiments were carried out for preliminary selection of the sterilization regime for canned food «Murmansk cod liver» in the can 38K for the industrial autoclave ASCAMAT-230.

The plan of experiment consists of the following items:

1. carry out a preliminary trial process of sterilization and cooling in water with back pressure in the laboratory autoclave AVK-30M of canned food «Murmansk cod liver» in a can 38K at regime of 25–70–20 and sterilization temperature of 115 $^\circ$C, using an economic method of development sterilization regimes for large volume industrial autoclaves [11];
2. obtain three transfer functions for the product model in TPM software: in the least heated region of the autoclave $W_{\text{min}}(p)$, average for heating $W_{\text{aver}}(p)$ and most heated $W_{\text{max}}(p)$, using the data from the Ellab TrackSense PRO loggers (temperatures in the sterilization chamber and canned product);
3. carry out a preliminary selection of sterilization regime parameters of the canned food «Murmansk cod liver» using PRSC software;
4. carry out an experimental sterilization process in the industrial autoclave ASCAMAT-230, confirming the correctness of canned food sterilization regime parameters, obtained in PRSC software.

6.3. Results

In TPM software, three transfer functions for the product model were obtained using automatic mode for the test autoclaving for canned food «Murmansk cod liver» in the can 38K. The results are presented in Figure 5.
Figure 5. Transfer functions coefficients of the product model.

The obtained transfer functions coefficients for the product model, parameters of the autoclave model, the type of sterilization process (water medium), and the initial and final temperatures of the autoclave were entered into the PRSC software.

To start working in the program, the traditional sterilization regime was chosen and the duration of the heating, sterilization and cooling stages and the sterilization temperature were set. Based on these data PRSC software has built time-temperature dependence in the sterilization chamber, and product temperature values in the least heated, average for heating and the most heated areas of the autoclave in graphical or tabular variants.

The normative sterilizing effect value for this type of product sterilized in can 38K corresponds to 4.7 cond. minutes [8]. Next, in PRSC software, sterilization regime of canned food «Murmansk cod liver» was selected according to the actual lethality (6.5 cond. minutes) close to the normative sterilizing effect with the required margin of at least 20 percent (Figure 6). At the last stage, document in Microsoft Word with thermal data was created automatically on the tab «Saving thermal data» for regime approval (Figure 7).
| Time, min | Tautoclave, °C | Tcan1, °C | L1, cond. min | Tcan2, °C | L2, cond. min | Tcan3, °C | L3, cond. min |
|----------|----------------|-----------|---------------|-----------|---------------|-----------|---------------|
| 0        | 80,00          | 5,00      | 5,00          | 5,00      | 5,00          | 5,00      |
| 5,00     | 86,98          | 10,90     | 10,75         | 12,39     |               |           |
| 10,00    | 93,86          | 23,05     | 22,69         | 26,19     |               |           |
| 15,00    | 99,98          | 36,82     | 36,31         | 40,64     |               |           |
| 20,00    | 107,98         | 50,29     | 49,71         | 54,11     |               |           |
| 25,00    | 114,98         | 62,60     | 62,21         | 66,29     |               |           |
| 30,00    | 114,98         | 74,05     | 73,46         | 77,07     |               |           |
| 35,00    | 114,98         | 83,50     | 82,97         | 85,91     |               |           |
| 40,00    | 114,98         | 91,05     | 90,59         | 92,84     | 0,00          |           |
| 45,00    | 114,98         | 96,93     | 96,54         | 98,17     | 0,02          |           |
| 50,00    | 114,98         | 101,42    | 101,11        | 102,24    | 0,06          |           |
| 55,00    | 114,98         | 104,03    | 104,56        | 105,33    | 0,16          |           |
| 60,00    | 114,98         | 107,40    | 107,20        | 107,67    | 0,34          |           |
| 65,00    | 114,98         | 109,32    | 109,17        | 109,44    | 0,62          |           |
| 70,00    | 114,98         | 110,76    | 110,64        | 110,79    | 1,02          |           |
| 75,00    | 114,98         | 111,84    | 111,74        | 111,81    | 1,55          |           |
| 80,00    | 114,98         | 112,64    | 112,57        | 112,58    | 2,20          |           |
| 85,00    | 114,98         | 113,24    | 113,18        | 113,16    | 2,95          |           |
| 90,00    | 114,98         | 113,68    | 113,64        | 113,60    | 3,80          |           |
| 95,00    | 114,98         | 114,01    | 113,98        | 113,93    | 4,72          |           |
| 100,00   | 114,98         | 113,63    | 113,63        | 113,39    | 5,67          |           |
| 105,00   | 114,98         | 110,48    | 110,55        | 110,55    | 6,27          |           |
| 110,00   | 114,98         | 103,79    | 103,99        | 101,95    | 6,45          |           |
| 115,00   | 114,98         | 93,75     | 94,09         | 90,97     | 6,47          |           |

**Figure 6.** Sterilization regime for achievement of normative sterilizing effect.
Figure 7. Document with thermal data for regime approval.

So, a preliminary parameters selection for the canned food sterilization regime, based on the obtained numerical mathematical product models, combined with an economical method of using AVK-30M to develop a sterilization regime for an industrial autoclave ASCAMAT 230, significantly reduced the time to develop an optimal sterilization regime of canned food «Murmansk cod liver» in can 38K. The study of this preliminary selection method for the sterilization regime showed that the selection of the real canned food sterilization regime can be carried out using no more than three test autoclaving in AVK-30M. This is, on average, twice less than it is necessary according to the instruction for the development of sterilization regimes for canned fish and seafood.

Finally, this preliminary selection method for the sterilization regime reduced the energy costs by 85 percent and the consumption of raw materials - by 90 percent for one test autoclaving (Table 1), because the volume of autoclave AVK-30M sterilization chamber and energy consumption are about 7 times less, than the similar parameters of the industrial autoclave ASCAMAT-230 performing an identical sterilization process [11].

Table 1. Energy costs for autoclaves AVK-30M and ASCAMAT-230.

| Autoclave name   | Volume, ltr | Heating stage energy costs, kJ | Sterilization stage energy costs, kJ | Total energy costs, kJ | Total unit energy costs (in terms of 1 liter of volume), kJ | Total energy costs, percent of costs for ASCAMAT-230 |
|------------------|-------------|--------------------------------|-------------------------------------|-----------------------|-----------------------------------------------------------|---------------------------------------------------|
| AVK-30M          | 30          | 2420                           | 1210                                | 3630                  | 120                                                        | 14                                                |
| ASCAMAT-230      | 230         | 17785                          | 8180                                | 25965                 | 113                                                        | 100                                               |
7. Conclusion
As a result of the research, it can be concluded that, due to the simulation and optimization processes using computing technology, it is possible to significantly reduce time for the development of new optimal product sterilization regimes and accelerate the commissioning of new sterilization units with greater energy efficiency, which improve the quality of the final product and its safety. Thus, software based on mathematical process models is an effective and convenient tool for predicting and optimizing thermal sterilization regimes.

Improvement of software complex functionality will allow creating a computer-aided design system for sterilization regimes of canned food from hydrobionts at the preliminary stage of the regime selection, which, in the future, will significantly shorten the development time for a new or correction an existing sterilization regime of canned food from hydrobionts.

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