PATTERNS OF CHANGING SETTINGS OF THE TEMPERATURE FIELD AT VAPOUR-CONTACTING HEATING BY STERILIZING PRODUCTS IN CYLINDRICAL CONTAINERS

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ЗАКОНОМІРНОСТІ ЗМІНИ ПАРАМЕТРІВ ТЕМПЕРАТУРНОГО ПОЛЯ ПРИ ПАРОКОНТАКТНІЙ СТЕРИЛІЗАЦІЇ ПРОДУКЦІЇ У ЦИЛІНДРИЧНІЙ ТАРІ

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ABSTRACT

In the article, we sustained the heat exchange process and regime parameters and defined the changing patterns of temperature characteristics of the pressure in the working area in terms of vapour-contacting heating in container.

РЕЗЮМЕ

У статті обґрунтовано теплообмінні режимні параметри процесу та визначені закономірності зміни температурних характеристик тиску в робочій зоні в умовах пароконтактного нагріву в тарі.

INTRODUCTION

The kinetics of biochemical reactions under varying degrees depends on the thermal, chemical and mechanical sensitivity of the processed product, on pressure, temperature and chemical potential. Pressure is distributed in a liquid by Pascal principle in all directions, accompanied by a large adiabatic pressure changes with the speed of sound. For this reason, we can assume that there is pressure almost instantaneously throughout the chamber. From this assumption it follows that the effect of pressure comparing with the thermal process has the advantage that can influence rapidly and in homogenous way to all the processed stuff regardless of shape, size and composition. However, it was left unattended possibility of physical and thermal heterogeneity *(Alekseev E. and Pakhomov E., 1982; Belyaeva M., 2003; Nechepurenko I., 1991; Tugolukov E. 2004; Voronenko B. et al, 2008).*

Creating high-productive heat exchange equipment that meets modern level of industry and technology development requires significant intensification of heat exchange processes that are sufficiently widely implemented in known scientific schools *(Palamarchuk I. et al, 2013; Terzyev S. et al, 2014; Terzyev S. and Kurakov A., 2012; Tsurkan O. et al, 2010; Tsurkan O. et al, 2015).*

Among the intensification means factors were used devices of mechanical and technological vibration action (*Palamarchuk I., Bandura V., Palamarchuk V., 2013; Palamarchuk I., 2008),* the use of infrared radiation *(Terziev S., Malashevych S., Ruzhytska S., 2011; Terziev S., 2016),* baro-thermal effect and others *(Terziev S. ,2016).*

One effective way, both in terms of the intensification of the process of heat and energy savings is the product contact heating with steam use, which makes technology's impact on processed products.

Heat at products vapour-contacting heating is a complex phenomenon associated with the simultaneous transfer of heat and mass substance. The number of transferred mass is determined by the condensed steam and transferred to the heat (if vapour) - heat of vaporization *(Voronenko B. et al, 2008).*

In vapour-contacting heating it is taken into account a significant number of determining factors, the most important are the thermal properties of the heating steam, and the physical and chemical properties of the product. Taking into account all the factors that affect the process of heat transfer at vapour-contacting heating and analysis are very difficult, not only in theory but in the experimental aspects as well.

The main parameter during heat sterilization of food, including using vapour-contacting heating temperature is a product, which is the major factor for the establishment of canned food sterilization regimes. Therefore, one of the main objectives of the study sterilization process at the appointed method of heating is to determine the product temperature field or identify the dynamics of temperature change at different points in the product, depending on the parameters of steam that heats the conditions of supply to the product and the physical properties of the treated material *(TU 10.1-22769675-001, 2013).*

Therefore, for foundation of heat exchange operational parameters it is necessary to determine the patterns of temperature change characteristics of pressure in the working area in terms of vapour-contacting heating in container.

MATERIAL AND METHOD

Instability of temperature field can be explained by the fact that the pressure rises in the phase of volume increase due to changes in the temperature of the treated environment. The adiabatic change of state in a clean, inert and homogeneous medium changes the temperature according to changes in pressure, which is determined by (1):

$$dT = \frac{T \cdot \beta}{\rho \cdot c_p} dp \tag{1}$$

where:

T – the temperature, (K);

– coefficient of thermal expansion, (K^{-1});

º – liquid density, (kg / m^3);

c_p – specific heat, (J / (kg·K));

p – pressure, (Pa).

Depending on the product being processed at the pressure of 1 GPa temperature rises to several tens of Celsius degrees. Filled chamber pressure is a system consisting of product packaging materials, medium transmitting the pressure (intermediate fluid) and the steel wall of the chamber. These materials have different thermal properties. Consequently, despite the initial parameters of homogeneous temperature distribution, while increasing the pressure in the chamber, it can form a homogeneous temperature field *(Nechepurenko I., 1991).*

For the formal definition of the temperature increase caused by increased pressure, we took the first equation of conservation, which brought the equation (2) of total heat capacity *H*:

$$\frac{d(\rho \cdot H)}{d\tau} + \nabla \cdot (\rho \cdot \vec{v} \cdot H) = \frac{dp}{d\tau} + \nabla \cdot (\lambda \nabla T) + \nabla \cdot (\xi \cdot \vec{v}) + \rho \cdot \vec{q} \cdot \vec{v} \tag{2}$$

where:

¬⃗ – velocity vector fluid;

q – vector of gravity;

2 – time, (sec).;

a – thermal conductivity of material, (W / (m·K));

¶ – tensor of stresses in the material.

For specific heat capacity *h*:

$$\rho \frac{dh}{d\tau} - \frac{dp}{d\tau} = \nabla \cdot (\lambda \nabla T) + \eta \cdot \Phi + \rho \cdot \vec{q} \cdot \vec{v} \tag{3}$$

where:

Φ – dissipation function;

r – container radius, (m);

R_1 – autoclave radius, (m);

¦ = $ln\ (r / R_1)$ – independent argument of desired temperature.

Then, using thermodynamic ratio:

$$\frac{dh}{d\tau} = \left.\frac{dh}{dp}\right|_T \frac{dp}{d\tau} + \left.\frac{dh}{dT}\right|_p \frac{dT}{d\tau} = \frac{1}{\rho}(1 - \alpha \cdot T)\frac{dp}{d\tau} + c_p \frac{dT}{d\tau} \tag{4}$$

where:

~ – coefficient of heat on the outer surface of the cylinder.

We got the heat equation:

$$\rho \cdot c_p \frac{dT}{d\tau} = \alpha \cdot T \frac{Dp}{D\tau} + \nabla \cdot (\lambda \nabla T) + \eta \cdot \Phi + \rho \cdot \vec{q} \cdot \vec{v} \tag{5}$$

The last equation shows that the material derivative of temperature *T* as to time ^{2} carries material derivative of pressure on *P* as to time ^{2} , until dissipation function Φ and the potential energy and flow that carries high temperature, are low. Taking into consideration this fact, we came to approximate heat transfer equation:

$$\frac{dT}{d\tau} \approx \frac{dT}{\rho \cdot c_p} \frac{dp}{d\tau} \tag{6}$$

It is considered that the fluid motion is obvious in the processing of liquid substance pressure. To show this mathematically, we assumed that the density increases with pressure and decreases with increasing temperature grounded for much of the food and similar substances in the environment *(Palamarchuk I., Tsurkan O., Hurych A., 2015).* The appearance of the flow in the liquid, which initially is at rest was shown using mass balance equation:

$$\frac{d\rho}{d\tau} + \nabla \cdot (\rho \cdot \vec{v}) = 0 \tag{7}$$

During the compression phase density increases with pressure. So, the first member of the equation (7) is different from zero. Since the left side must be zero fluid velocity $\vec{\neg}$ must accept non-zero value. Therefore, increasing the pressure increases the fluid flow. Temperature gradients are important in handling a deviation from hydrostatic flow conditions. We have traced this conclusion using the basic equations of hydrostatics:

$$\frac{dp}{dx} = 0 \tag{8}$$

$$\frac{dp}{dy} = 0 \tag{9}$$

$$\frac{dp}{dz} = -\rho \cdot \vec{q} \tag{10}$$

The equations (8-10) *x, y* and *z* are Cartesian coordinates. Without loosing *z* overview we accepted that the vector of gravity points in the negative *z* direction. Further conversion of (9) and in respect of (10) in relation it gave the following result:

$$\frac{d^2p}{dydz} = \frac{d^2p}{dzdy} = -\frac{d\rho}{dy}\vec{q} \tag{11}$$

Thus, the right side of equation (11) and original density must be constant and equal to zero:

$$\frac{d\rho}{dy} = 0 \tag{12}$$

However, this condition, as the hydrostatics cannot be kept. While density is a function of temperature, and the latter is exposed to a direction different from the direction of gravity vector, equation (12) is broken. As a consequence, there must necessarily appear vapour stream at a rate different from zero, which leads to convective heat transfer and suspended solids.

For the developed scheme of autoclave where heat is carried by vapour placed outside cup, the problem reduces to the calculation of non-stationary temperature field in a container that is heated from the outer surface of the heat source given by the intensity of the light convection in the radial direction.

It is assumed that the thermal resistance of the outer wall is relatively small, and the thermal properties of the material do not depend on temperature. This heat equation considering the convective component has the form *(Tugolukov E., 2004):*

$$\frac{dt}{d\tau} + u\frac{dt}{dr} = \frac{\lambda}{c_p \cdot \rho \cdot r} \frac{d}{dr}(r\frac{dt}{dr}) \tag{13}$$

where:

u – velocity of the fluid m / s.

Terms of uniqueness:

- Initial conditions for $^{2} = 0$

$$t(r,0) = t(r) = t_н \tag{14}$$

- Extreme conditions

$$(\frac{dt}{dr})_{r=R_1} = -q / \lambda \tag{15}$$

$$(\frac{dt}{dr})_{r=R_2} = -a \cdot (t - t_в) / \lambda - \frac{q_2}{\lambda} \tag{16}$$

where:

$t_в$ – ambient temperature, (K);

$t_н$ – the initial temperature of the material processed, (K);

q – specific heat flux on the inner surface of the autoclave, (W/m^2);

R_2 – radius packaging, (m).

RESULTS

As we consider the problem of calculating the temperature field depending on the radius of the autoclave, it is assumed that the specific heat flow and the velocity of steam through the surface of the container does not depend on its length and thus is not considered a limiting effect, manifested through the finite size of the packaging.

Accordingly, we define the relationship between speed and specific heat flow. In vapour-contacting heating steam is fed evenly and specific heat flow is equal to:

$$q_1 = G_n \cdot i_x / 2 \cdot \pi \cdot R_1 \cdot l \tag{17}$$

where: G_n – steam consumption, (kg/s);

i_x – enthalpy of steam (J/kg);

l – the length of container, (m).

The actual amount of steam, creating a convective flow can be determined from the heat balance equation:

$$G_n \cdot i_x = G_ж \cdot t_н \cdot c_{p.ж} \tag{18}$$

where:

$G_{ж}$ – number of newly condensate, (kg/s);

$c_{p.ж}$ – specific heat capacity mass of condensate, (J/(kg K)).

The velocity of steam in an autoclave with *r* radius defined by:

$$u = G_ж / 2 \cdot \pi \cdot r \cdot l \cdot \rho_ж \tag{19}$$

where: $^{\circ}{}_{ж}$ – density of vapor.

Substituting (17) in (18) and (18) to (13), we get:

$$\frac{dt}{d\tau} = (\frac{\lambda}{c_p \cdot \rho} - \frac{G_n}{2 \cdot \pi \cdot l \cdot \rho}) \frac{1}{r} \frac{dt}{dr} + \frac{\lambda}{c_p \cdot \rho} \cdot \frac{d^2 t}{dr^2} \tag{20}$$

$$\left(\frac{dt}{dr}\right)_{r=R_1} = \frac{G_n \cdot c_p \cdot t_н}{2 \cdot \pi \cdot R_1 \cdot \lambda \cdot l} \tag{21}$$

$$\left(\frac{dt}{dr}\right)_{r=R_2} = -\frac{a}{\lambda}(t - t_в) + \frac{G_n \cdot c_p \cdot t}{4 \cdot \pi \cdot R_2 \cdot \lambda \cdot l} \tag{22}$$

$$t(r,0) = t_н \tag{23}$$

Equation (17-22) can be written in parametric form. As characteristic parameters we introduce the following dimensionless quantities:

$\bar{} = t / t_н$ – the required dimensionless grand;

$\bar{}_g = t_в / t_н$ – dimensionless magnificent environment;

$F_0 = {}^2 \cdot {}^a / c_p \cdot {}^\circ \cdot R_1^2$ – the number of Fourier;

$B_i = a \cdot R_1 / {}^a$ – the number of Biot.

$$Q_1 = G_ж \cdot c_p \,/\, 2 \cdot \pi \cdot l \cdot \lambda \quad \ln(R_2 / R_1) \tag{24}$$

With regard introduced dimensionless equations (20-23) will be:

$$\frac{d\theta}{dF_0} = exp(-2 \cdot \eta)\left[(1-Q_1)\frac{d\theta}{d\eta} + \frac{d^2\theta}{d\eta^2}\right] \tag{25}$$

$$\left(\frac{d\theta}{d\eta}\right)_{\eta_1=0} = Q_1 \tag{26}$$

$$\left(\frac{d^{-}}{d¦}\right)_{¦_2=0} = \left| B_i({}^{-}_g - {}^{-}) - Q_1 \cdot R_1 \cdot \frac{-}{R_2} \right| \exp ¦_2 \tag{27}$$

$$t(\eta_1, 0) = 1 \tag{28}$$

The mathematical model, taking into account boundary conditions of a system of differential equations (25)÷(28), which solution has the form *(Alekseev E. and Pakhomov E., 1982)*:

$$^{-} = {}^{-}(F_0, B_i, ¦, Q_1, \frac{R_1}{R_2}) \tag{29}$$

Thus, the mathematical model determining the dynamics of the temperature field in the container is found dependence (29), satisfying the conditions of the field $D\{(F_0, ¦); o \le F_0 \le \phi;\ O \le ¦ \le ¦_2)\}$ of (25) and limit (26, 27) and the initial conditions (28), respectively.

To solve this problem we apply numerical method *(Belyaeva M., 2003)*. That is why we build a uniform space-time increments chart:

$$\Delta ¦ = ¦_2 / N \tag{30}$$

where:

N – number of quantization step of given area $\Delta F_0 = \Phi_1 / M$;

M – the number of partitions of a given region, pc.;

Φ_1 – Fourier pre-specified number (time).

Using conventional implicit difference scheme approximation of (25-27) it will be:

$$\theta_{i,j} - \theta_{i,j-1} = \Delta F_0\, exp(-2\eta_i)\left[(1-\theta_1)(\theta_{i+1,j} - \theta_{i-1,j}) / 2\Delta\eta + (\theta_{i+1,j} - 2\theta_{i,j} + \theta_{i-1,j})\right]\Delta\eta^2 \tag{31}$$

where:

$(i = 1,2,3...N-1;\ j = 1,2,3...M)$

$$\theta_{1,j} - \theta_{o,j} = \theta_1 \Delta\eta \tag{32}$$

$$\theta_{N,j} - \theta_{N-1,j} = \Delta\eta \cdot exp\,\eta_2\left[B_i(\theta_g - \theta_{N,j}) - Q_1\theta_{N,j} \cdot R_1 / R_2\right] \tag{33}$$

We rewrite equation (29, 31, 32) in the form:

$$-A_i{}^{-}_{i-1,j} + C_i{}^{-}_{i,j} - B_i{}^{-}_{i+1,j} = f_i(i = 0,1,2,3...N) \tag{34}$$

where:

$C_o, B_o, f_o, A_N, C_N, f_N$ – coefficient describing boundary conditions;

${}^{-}_{i,j}$ – dependent function;

A_i, B_i, C_i, f_i – energy equation coefficient.

Accordingly, (25-28), the expression for the coefficients of the system (33) takes the form:

$$A_o = 0;\ C_o = 1;\ B = -1;\ f_o = -Q_1\Delta\eta$$

$$A_i = \Delta F_o\, exp(-2 \cdot \eta i)\left[(\Delta\eta^{-2} + 0{,}5 \cdot Q_1 \cdot \Delta\eta^{-1})\right]$$

$$B_i = \Delta F_o\, exp(-2 \cdot \eta i)\left[(\Delta\eta^{-2} + 0{,}5 \cdot Q_1 \cdot \Delta\eta^{-1})\right] \tag{35}$$

$$C_i = 1 + 2\Delta F_o \Delta ¦^{-2} \exp(-2 \cdot ¦\, i)$$

$$f_i = \overline{}_{i,j-1}$$

$$A_N = 1; C_N = 1 + \Delta\eta \, exp\, \eta_2 (B_i + Q_1 \cdot \frac{R_1}{R_2})$$

$$B_N = 0;\ f_N = B_i \overline{}_x \Delta ¦ \exp ¦_2$$

Thus, using linear approximation of unknown function boundary problem is reduced to a system of algebraic equations.

To solve this system we apply three-diagonal matrix algorithm. The solution of the boundary problem for the j^{th} time layer is defined by:

$$\overline{}_{1,j} = a_{i+1,j} \overline{}_{i+1,j} + _{i+1,j} \tag{36}$$

where: $a_{i+1,j}$, $_{i+1,j}$ – selective coefficients are determined by recurrent formulas.

$$a_o = B_o / C_o;\quad {}_o = f_o / C_o; a_{i+1,j} = \frac{B_i}{(C_i - A_i a_i)};\quad {}_{i+1} = \frac{f_i + A_i\ {}_i}{(C_i - A_i a_i)} \tag{37}$$

Note that the expression for $\overline{}$ the point (N, j), respectively (34) taking into account (36) takes the form:

$$\overline{}_{N,j} = _N \tag{38}$$

The results of numerical experiment to calculate the temperature field along the radius of the cylindrical container, depending on the parameters of steam that heats and the product, are shown in Fig.1,2.

Fig.1 shows the curve of temperature field at vapour-contacting heating of product from initial temperature $t_н$ = 50°C to a final temperature $t_{н\,к}$ = 100°C condensing steam with temperature $t_п$ = 100°C at the rate of steam equal to 0.001 kg/s, where r – distance distribution of temperature field. Ambient temperature accepted $t_в$ = 20°C and the heat transfer coefficient on the outer surface of the cylinder is a=10. As shown in Fig.1 at the initial time (1.5-3 sec), the temperature in the central layer almost instantaneously increases to a temperature steam condensation. In the peripheral layers of the product temperature does not change.

With further heating, mainly due to the resulting radial convective flows and thermal conductivity, heat flow gradually reaches the peripheral layers over time ^{2} = 260 s. As a result, throughout the range is set the uniform temperature field. To determine the influence of parameters of the heating steam at the temperature field distribution of the product, we performed calculations at different temperatures vapour.

Fig.2 shows the curve of the temperature field at the heating vapour $t_п$ = 110°C. Apparently, fever helps intensify the process of heat transfer. However, this leads to pronounced temperature difference between central and peripheral fields.

Comparison of computer results with experimental data leads to the conclusion that the solution of the problem of computer calculation the temperature field of product gives very satisfactory results between the calculated and experimental data.

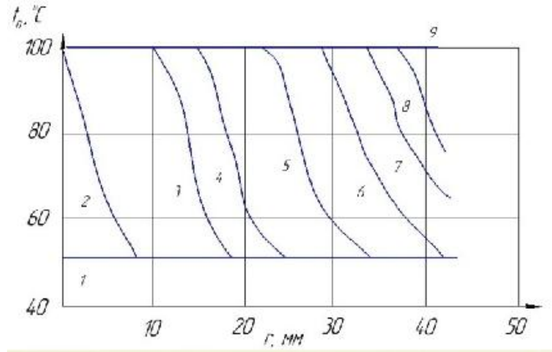

Fig. 1 – Curve of temperature field in the heat vapour-contacting product in a cylindrical container with an external supply of heat at the heating vapor:

$t_п$ = 100°C :1 – t = 0; 2 – t = 1; 3 – t = 20; 4 – t = 40; 5 – t = 80; 6 – t = 120; 7 – t = 160; 8 – t = 180; 9 – t = 200

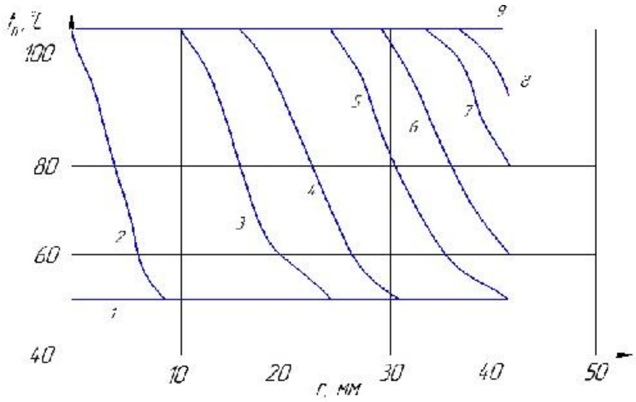

Fig. 2 – Curve of temperature field in the heat vapour-contacting product in a cylindrical container with an external supply of heat at the heating vapor:

t_n = 110°C : 1 – t = 0; 2 – t = 1; 3 – t = 20; 4 – t = 40; 5 – t = 80; 6 – t = 120; 7 – t = 160; 8 – t = 180; 9 – t = 200

CONCLUSIONS

- The presence of thermal heterogeneity in food and its further growth needs forecasting and research measures to counter effectively implemented in the vapor-contacting sterilization.
- In mathematical modeling vapour-contacting heating products during sterilization had composed the heat equation, taking into account factors such as changes in temperature, pressure, fluid flow rate and the basic physical and mechanical properties of interacting environments.
- By using the methods of numerical analysis have been built depending graphic variables of temperature fields that have identified the necessary conditions for intensification of heat exchange in the vapour-contacting sterilization, which allows identifying effective operating modes of treatment.

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