Mathematical model of colostrum defrosting in super-high-frequency generator equipped

I Ershova1,*, M Prosviryakova2, O Mikhailova3, G Novikova3, G Samarin1, D Poruchikov1 and V Storchevoy2

1Laboratory of Electrophysical Impact on Agricultural Objects and Materials, Federal Scientific Agroengineering Center VIM, 5 First Institutskiy proezd, 109428, Moscow, Russian Federation
2Department “Automation and Robotization of Technological Processes named after Academician I. F. Borodin”, Russian State Agrarian University - Moscow Timiryazev Agricultural Academy, 6/24 Listvennichnaya Alleya, 127550, Moscow, Russian Federation
3Department of Infocommunication Technologies and Communication Systems, Nizhny Novgorod State University of Engineering and Economics, 22A Oktyabrskaya street, 606340, Knyaginino, Russian Federation

*E-mail: vim@vim.ru https://orcid.org/0000-0003-1126-3837

Abstract. The paper is devoted to development and parameters studying of two-resonator super-high-frequency (SHF) generator based on continuous flow principle of action. It is equipped with two quasi-stationary toroidal resonators; so it allows to separate such processes of cattle colostral milk treatment as defrosting and heating and thus to ensure both the electromagnetic safety and the high electric field strength. In order to improve efficiency of the cattle colostrum defrosting/heating performed by its exposure to the super-high frequency electromagnetic field, the methodology was developed for the SHF generator designing. It includes, firstly, development & studying of mathematical models based on due consideration of the phase transitions and, secondly, the structural designing of the SHF generator working chamber with examination of its effective operating modes. The mathematical model is proposed of the electromagnetic waves interaction with the raw material (colostral milk) being in different physical states. With aid of the electric field strength control (by the generators power changing) and the gap adjustment in the capacitor part of the resonators (by smooth movement of the common perforated base), it is possible to achieve the equipment capacity up to 170…200 L/h. The energy expenses are 0.025 (kWꞏh)/kg.

1. Introduction

In Germany, Japan, and the USA, the bovine colostrum and its fractions are produced in a wide range and in various forms [1]. Colostrum is one of the most important sources of essential nutrients to improve the neonatal survival likelihood [2, 3]. Timely feeding of newborn calves with the colostrum helps to maintain the health of the gastrointestinal tract of young calves at an optimal level and to prepare animals for the consumption of the vegetable feed in an early age [4]. Newborn calves’ drinking of a large volume of high-quality colostrum in the first hour after birth can reduce the incidence among young calves by 70%. In particular, this way, the incidence of the gastrointestinal disorders of both infectious and non-infectious nature can be reduced by 50%. Delaying of the colostrum first drinking by 4 h not
only increases the risk of intestinal problems but also delays the calves’ growth rate up to 21 days of age [5].

On farms, where ruminants and other animals are growing up, for newborns feeding, the colostral milk is used. The excessive stock of the colostrum is stored in its frozen form as it contains a lot of broad-spectrum immunostimulants and other substances necessary for the young animals’ growth and normal development. Before young animals’ feeding, the colostrum in containers (located into the defroster) is firstly defrosted by the steam-water method (from $-10^\circ$C to $0^\circ$C) and then heated up to $+37$...$+38^\circ$C. As both defrosting and heating are quite long-lasted processes (1.5...2 h), the nutritive value of the colostrum decreases [6].

Cold colostrum should not be given to calves. It must be heated with great care in warm water, as even at the slightest overheating, it coagulates. The temperature, at which colostrum defrosting/heating occurs, should not exceed 42 $^\circ$C, because only under these conditions, immunoglobulins and useful substances are preserved. Only after fulfillment of all these conditions, the colostrum can be given to calves. It is impossible to do it correctly without special equipment (Salutem, Belarus).

The need of having of a proper technology/device at disposal for the colostrum defrosting is determined, first of all, by the need to feed a large number of newborn calves with high-quality colostrum, while ensuring high retention of calves and reducing the purchasing cost of imported heifers for herd repair (Holm & Laue, Denmark).

That is why the development of both the technology and the equipment allowing to speed up the process of the cattle colostrum defrosting/heating is timely and important. In order to deal with this problem, the innovative technology is proposed for the cattle colostrum thawing under super-high frequency (SHF) electromagnetic field (EMF) exposure. The method allows to speed up the technological process several times and this is what our research work is aimed at.

The paper is aimed at development of a continuous-flow SHF generator and investigation of its parameters. The generator must be with two quasi-stationary toroidal resonators as this design allows to separate the cattle colostrum defrosting and heating and to provide the system with the electromagnetic safety and high electric field strength needed for reduction of the total microbial number at a low raw material temperature.

The methodology of the SHF generator development foresees includes mathematical models construction of the cattle colostrum defrosting/heating by SHF EMF exposure with due consideration of the phase transitions; their examination, and the structural design development of the SHF generator working chamber taking into account the effective operating modes.

For this, the following scientific problems should be solved:

- to develop and investigate the mathematical model of cattle colostrum defrosting/heating under the SHF EMF action in the SHF generator equipped with two quasi-stationary toroidal resonators on a common base and, upon that, to take the phase transition into account (defrosting up to $0$...$+1^\circ$C);
- to conduct the EMF intensity distribution optimization in the quasi-stationary toroidal resonators located on a common perforated base;
- to develop the structural design of the installation with the quasi-stationary resonators as this design allows to separate the processes of cattle colostrum defrosting and heating under SHF EMF exposure in different doses.

In our scientific team, various SHF-generators have been developed for defrosting/heating of the cattle colostrum, where different design versions of the resonators were used [7, 8]. But not each of the developed working chambers of the SHF generators was able to meet each one of the following five main criteria: 1) continuity of the combined technological processes (grinding, thawing and heating of the cattle colostrum) at high intrinsic quality of resonators and high electric field strength (EF) applied to the raw material (which allows to achieve the bactericidal effect); 2) electromagnetic safety of the SHF generator and universal suitability of the working chamber for thermal treatment of raw materials of various composition; 3) uniform distribution of both the electric field and the raw materials in resonators actuated by several magnetrons; 4) possibility of performance varying and; 5) easy dismantling of the assembly units.
We need to collect and study more information about the colostrum defrosting; that is why the development of a mathematical model for colostrum processing is considered to be important problem [9, 10].

The aim of the paper was to develop a mathematical model of cattle colostrum defrosting in super-high-frequency generator equipped with quasi-stationary toroidal resonators.

2. Methods and materials

Used as the studied raw material, the cow colostrum was taken from clinically healthy animals. Its fat content was 6.4%, it had the density of 1.06...1.05 g/cm³ and acidity of 50 °Т. The colostrum was frozen down to −10 °C in special plastic bags in the form of 2×4×2 cm briquettes. There were applied the following temperature conditions: defrosting of raw materials up to 0...+1 °C and heating up to +35...+38 °C. The temperature of the raw material under the action of SHF EMF was controlled by the pyrometer Testo 925 (Testo AG, Germany), while the heat flow distribution over the raw material surface was controlled by the thermal imager FLIRi335 (Flir Systems, USA, Sweden). The dose control of the SHF EMF exposure to the raw material was carried out by measurement of the electric field strength at a frequency of 2450 MHz, for which the electromagnetic radiation meter PZ-31 (NTM Zashita, Russia) was used.

The recommendations were developed for improvement of the SHF generator resonant chambers used for the raw material thermal treatment causing the change in its physical state. Upon that, the developed mathematical models were taken into account.

The design of the resonant chamber should ensure a uniform internal heating throughout the entire volume of the raw material. The linear dimensions of the resonator should be 5-6 times more than the wavelength of the generator. In our resonators, more than ten different types of vibrations are excited, and everyone has its own individual EMF distribution, i.e. this is a multimode resonator. Due to the fields’ interference of various types of the vibrations in the resonator volume, an uneven distribution of EMF occurs.

2.1. Uniform distribution of EMF in the resonant chamber

Uniform distribution of EMF in the resonant chamber can be achieved in various ways. The first way needs to choose a resonator of such dimensions that allow to excite a certain type of vibrations, while the interference ensures their uniform distribution in the volume.

The second way uses several generators working on similar frequencies; besides, the emitters located on the magnetrons should be directed into a single resonator. Upon that, the dimensions of the resonators should be comparable and yet not equal. By several inputs applying, it is possible to increase the number of types of vibrations excited in a given range and to improve the heating uniformity of the raw material.

Inside of the resonator representing the standing wave system, it is possible to ensure the EMF uniform distribution. This enables to heat the raw material uniformly regardless of its physical state and at the same time to intensify the processes of defrosting/heating of the cattle colostrum and to preserve its nutritive value. In order to do this, it is necessary to make correct calculations for optimal locations of several low-power air-cooled magnetrons and for optimal design of the resonator, which allows adjustment of the electric field strength. The resonators based on the standing wave principle allow to expand the capabilities of the SHF generator and, in particular, to take into account the sizes of the frozen raw material briquettes having different fat content and density.

If to choose the SHF generator design based on the migrating wave system, it is rather difficult to ensure the raw material uniform heating. In order to do this, it is necessary to create a uniform specific density of the power flow in the volume of the re-treated raw material and to prevent a heat transfer to the environment. It is possible and as an example of such a system, the SHF installation with a ring resonator can serve.
2.2. Loading rate of the resonator

Loading rate of the resonator (with raw materials) affects the transfer of the SHF energy to the raw material. If the resonator is filled completely with the raw material having the high permittivity value and the high dielectric losses factor, then it loaded Q-factor drops sharply; in such cases, it is easier to coordinate the energy input. But when the resonator loading with the raw material is incomplete and the raw material has the high permittivity value, or while there is a lot of raw material in the resonator but its permittivity value is low, the loaded Q-factor decreases just slightly [11].

For the cattle colostrum defrosting process, the changes in the raw material physical state should be taken into account. That is why it is necessary to solve the thermal conductivity equation in the area of the mobile interface separating the frozen colostrum from the liquid phase and, upon that, to take the temperature of the phase transition into account.

In the development of mathematical models of the SHF EMF impact on the raw materials, many scientists are engaged [11-14]. The solving method of the boundary value problem for the migrating wave-based working chamber on waveguides of complex shape was presented by V A Kolomeitsev [13]. In his review, he showed that in literature, there were no studies of the cattle colostrum defrosting/heating processes in the SHF generators with working chambers containing two-resonators.

That is why the development of mathematical models taking into account the mutual impact of electromagnetic and thermal processes and allowing to find out really effective design versions of the resonators ensuring the uniform EMF distribution in raw materials is an urgent task.

In real conditions, depending on the moisture content of the raw materials and chemical processes in them, during the raw materials SHF-heating, there is formed an unevenness of both the raw materials dielectric losses factor and the electric field strength distribution. This results in overheating of some parts of the raw material and insufficient heating of others. In order to obtain the dependence associated with the heat transfer phenomena, it is necessary to take into account the changes in the electric field in both the resonator and the raw material, the changes in the raw material temperature, humidity and density, as well as the complex mutual relations between them. In the direct manner, the electric field strength affects the heating temperature and the moisture distribution in the raw material. The temperature range of the raw material changes its physical state.

The correct configuration of the resonant chamber should ensure the concentration and uniformity of the electric field in the area, where the raw material is located. This is possible in resonators having a clearly expressed gap made in the form of a separate capacitor part, where a uniform electric field is excited. For example, a specific feature of the quasi-stationary toroidal resonators is a quite clear spatial separation of the electric and magnetic fields at the oscillation with the lowest resonant frequency; it is meant here that mainly, the energy of the electric and magnetic fields is concentrated in different parts of the resonator volume: the toroidal and capacitor parts. In the area of engineering, in as small range as the centimeter-based one, the electrodynamic and thermal properties in quasi-stationary resonators located on a common perforated base are studied not in full, especially if the resonators are filled with raw materials just partially (incompletely) and their physical state varies. The insufficient studying does not allow to use them effectively for uniform defrosting/heating of the cattle colostrum.

3. Results and discussion

Based on this feature, the super-high-frequency generator was developed as follows. Its frequency makes 2450 MHz and wavelength 12.24 cm; it is equipped with two quasi-stationary toroidal resonators for colostrum thawing/heating under SHF EMF exposure in different doses and at either negative or positive temperature range. The reason, why it is needed, is like this: the nature of the change in the dielectric losses factor is opposite for colostrum in its frozen and liquid states with an increase in the heating temperature (figure 1).

As it is known, the specific dielectric loss per volume unit of a dielectric material depends on the square of the electric field strength, on the factor of dielectric loss of the material, and on its heat capacity and density [15]. Upon this, for the colostrum, at a temperature from –10 °C to 0 °C, the value of dielectric losses factor increases from 4 to 27 (figure 1a), i.e. the power absorbed by the raw material
increases and so does the rate of its warming-up during thawing. When the colostrum is heated from 0 °C up to +40 °C (figure 1b), the dielectric loss factor decreases, i.e. with increasing temperature, the absorbed power decreases and so does the heating rate of the liquid raw material (figure 1c).

![Diagram](image1.png)

Figure 1. Changes of cow milk dielectric parameters at transition from solid frozen state to liquid state: (a) frozen colostrum; (b) mixture of frozen colostrum with liquid fraction; (c) unfrozen colostrum; fat content 4.5%-6.4%.
Let us give consideration to the cattle colostrum defrosting/heating processes in the SHF generator with two quasi-stationary toroidal resonators (figure 2) – general view (figure 2a), layout of technological process (figure 2b). The continuous flow SHF generator for the cattle colostrum defrosting/heating includes two vertically mounted quasi-stationary toroidal resonators (upper and lower), that are butted to a common perforated base. Above the perforated base, a dielectric mixing mechanism with a dielectric shaft is installed; it is butted to the screw shaft. In the central part of the upper resonator, the discharge screw of the grinding mechanism is inserted. In the capacitor part of the lower quasi-stationary toroidal resonator, there is a dielectric plate without a bottom (perforated one). Air-cooled magnetrons with a 120 degree displacement are mounted on the surfaces of the resonators in the area of their condenser parts.

The technological process of defrosting/heating of the cattle colostrum in the continuous-flow SHF generator with the quasi-stationary toroidal resonators can be described as follows. After closing the ball valve 6, an operator loads the frozen raw material into the receiving container 10. Now he turns on the electric drive of the grinding mechanism (1, 2, 3) and the dielectric mixing mechanism 13. The frozen raw material is grinded and enters the condenser part 12 of the upper quasi-stationary toroidal resonator 4. On the next step, the operator turns on the generators 10, after which the SHF EMF is excited in the resonator 4. Under its action, the frozen raw material is thawed, and the liquid fraction flows through the perforated base 11 into the capacitor part 7 of the lower resonator 5 and is accumulated passing through the perforated dielectric plate 8.

Figure 2. SHF-generator of continuous flow type for cattle colostrum defrosting/heating: (a) general view; (b) layout of technological process: 1. grinding mechanism; 2. pressure auger; 3. knife and grill; 4. upper quasi-stationary toroidal resonator; 5. lower resonator; 6. ball valve; 7. condenser part of lower resonator; 8. dielectric plate without bottom (perforated); 9. magnetrons on lower resonator surface; 10. magnetrons on upper resonator surface; 11. common perforated base of two resonators; 12. condenser part of upper resonator; 13. dielectric mixing mechanism.
Then, the operator turns on the generators. Under the SHF EMF action, the liquid raw material is heated up and drains through the perforated base of the lower resonator. In the capacitor parts of both resonators, a high-voltage electric field is excited with strength sufficient for reducing of the product bacterial contamination.

We examined the processes of cattle colostrum defrosting/heating at various specific capacities of the SHF generators. Under the SHF EMF action, in the first quasi-stationary toroidal resonator, the frozen raw material passes from its solid state to the liquid state. The calculation of the quasi-stationary toroidal resonators performance was carried out approximately using the program CST Studio Suite 2018. The capacitance of the capacitor part of the resonators was determined by the formula (1):

\[ C_1 = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{\pi \cdot (D)^2}{h_1}, \quad C_2 = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{(D)^2}{h_2}. \] (1)

and the inductance formed by the resonator walls on the equation (2):

\[ L_1 = \frac{\mu_0 \cdot l}{2 \cdot \pi} \cdot \ln \frac{D}{d}, \quad L_2 = \frac{\mu_0 \cdot l}{2 \cdot \pi} \cdot \ln \frac{D}{d}, \] (2)

where \( D \) is diameter of resonator base; \( d \) – short capacitor base; \( l \) – height of resonator toroidal part; \( h \) – gap between bases; \( r \) – active resistance of resonator; and \( \mu \) – magnetic permeability.

The natural Q-factor of the resonator is determined by the equation (3):

\[ Q_1 = \frac{\sqrt{L_1 / C_1}}{r_1}, \quad Q_2 = \frac{\sqrt{L_2 / C_2}}{r_{12}}. \] (3)

Along with this, we investigated the temperature distribution in the frozen raw materials and the duration of complete thawing of the cattle colostrum. In the second resonator, the liquid raw material is heated. For a theoretical substantiation of the installation parameters, it is necessary to solve the interrelated problems in frames of the electrodynamics and the thermal conductivity for the quasi-stationary toroidal resonators placed on the common perforated base as they are filled with raw materials being in different physical states and the phase transition temperature should be taken into account.

When developing the mathematical model of the electromagnetic waves interaction with the raw material, we gave the due consideration to the fact that the electrophysical and thermal parameters were functions of temperature.

The study was carried out in two resonators (table 1):

1) dielectric heating of the frozen raw material and its transition to the liquid state;
2) dielectric heating of the cattle colostrum in its liquid state from 0°C to +40°C.

**Table 1.** Sequence of processes study steps in two resonators taking into account changes in dielectric and thermophysical parameters of raw materials.

| Parameters | Parameter identifiers |
|------------|-----------------------|
| Dielectric parameters of air and layer thickness | \( \varepsilon_0, \tan \delta_0, h_0 \) |
| Dielectric parameters of frozen cattle colostrum and layer thickness | \( \varepsilon_1, \tan \delta_1, h_1 \) |
| Dielectric parameters of mixture of frozen colostrum and partially thawed raw material and layer thickness | \( \varepsilon_2, \tan \delta_2, h_2 \) |
| Dielectric parameters of thawed colostrum and layer thickness | \( \varepsilon_3, \tan \delta_3, h_3 \) |
| Second quasi-stationary toroidal resonator | |
| Dielectric parameters of liquid colostrum at temperature 0°...+1°C and layer thickness | \( \varepsilon_3, \tan \delta_3, h_4 \) |
| Dielectric parameters of liquid colostrum at temperature 40°C and layer thickness | \( \varepsilon_4, \tan \delta_4, h_5 \) |
Let’s represent the amplitudes of the electric and magnetic fields in \( i \)-th layer of the raw material along the y-axis:

\[
E_i(y) = b_i \cdot \exp\left(-i \cdot \omega \cdot \sqrt{\varepsilon_i \cdot \mu_i} \cdot y\right) + r_i \cdot \exp\left(i \cdot \omega \cdot \sqrt{\varepsilon_i \cdot \mu_i} \cdot y\right),
\]

\[
H_i(y) = \left[b_i \cdot \exp\left(-i \cdot \omega \cdot \sqrt{\varepsilon_i \cdot \mu_i} \cdot y\right) - r_i \cdot \exp\left(i \cdot \omega \cdot \sqrt{\varepsilon_i \cdot \mu_i} \cdot y\right)\right] / Z_i,
\]

where \( b_i = 1 \) is maximum amplitude of electromagnetic field; \( \omega \cdot \sqrt{\varepsilon_i \cdot \mu_i} \) is complex wave number in \( i \)-th layer, which characterizes electromagnetic energy attenuation in raw material layer; \( b_i \) and \( r_i \) are coefficients taking into account the waves passage (\( b_i \)) and the reflection (\( r_i \)) in \( i \)-th layer; and \( Z_i \) is wave resistance in \( i \)-th layer.

The temperature distribution in the raw material takes place in accordance with the function of the power density of heat losses (\( p_i(y) \)) on the y-axis:

\[
p_i(y) = \omega \cdot \varepsilon_i \cdot \varepsilon_r \cdot \tan \delta_i \cdot |\vec{E}_i|^2,
\]

where \( \omega = 2 \pi f \) is cyclic frequency, 1/s; the frequency of the electromagnetic field is \( f = 2450 \text{ MHz} \) and the dielectric permittivity \( \varepsilon_0 = 8.85 \times 10^{-12} \text{ F/m} \).

The depth of penetration of the electromagnetic wave into the raw materials being in different physical state \( \Delta \) depends on the dielectric permittivity (\( \varepsilon_i \)), the tangent of the dielectric loss angle (\( \tan \delta_i \)) and the wave length \( \Lambda = 12.24 \text{ cm} \) [14]:

\[
\Delta_i(y) = \frac{\Lambda}{\sqrt{2 \cdot \varepsilon_i \left(1 + \tan^2 \delta_i - 1\right)}}.
\]

The empirical dependences of the permittivity, the tangent of the dielectric loss angle, and the dielectric loss factor of the colostrum with the fat content 4.5...6.4% are given below:

1) in range \((h_0 < y_1 < h_1)\) of negative temperature values (-12...0 °C)
   \( \varepsilon_1 = 53.78 \cdot e^{0.25 \cdot T}, \tan \delta_1 = 0.48 \cdot e^{0.055 \cdot T}, k_1 = 25.54 \cdot e^{0.19 \cdot T} \);

2) in range \((h_1 < y_2 < h_3)\) of phase transition (-1.5...+2.5 °C)
   \( \varepsilon_2 = 51.75 \cdot e^{0.025 \cdot T}, \tan \delta_2 = 0.47 \cdot e^{-0.0097 \cdot T}, k_2 = 24.28 \cdot e^{-0.036 \cdot T} \);

3) in range \((h_2 < y_3 < h_3)\) of positive temperature values (0...40 °C)
   \( \varepsilon_3 = 50.74 \cdot e^{0.0550 \cdot T}, \tan \delta_3 = 0.54 \cdot e^{0.016 \cdot T}, k_3 = 27.31 \cdot e^{-0.021 \cdot T} \).

The product of the permittivity (\( \varepsilon_i \)) by the tangent of the dielectric loss angle (\( \tan \delta_i \)) characterizes the factor of dielectric losses of raw materials (\( k_i = \varepsilon_i \tan \delta_i \)) being in different physical states during the exposure of EMF with the frequency 2450 MHz, i.e. the dielectric losses factor of the frozen colostrum \((\varepsilon_1)\), the mixture of the frozen colostrum and partially unfrozen raw material \((\varepsilon_2)\), and the colostrum in its liquid state \((\varepsilon_3)\) (figure 2).

The change in the depth of electromagnetic waves penetration into the colostrum, while it changes its physical state, is described as follows:

\[
\Delta_1(y) = \frac{\Lambda}{\sqrt{2 \cdot 53.78 \cdot e^{0.25 \cdot T} \left(1 + \left(0.48 \cdot e^{-0.055 \cdot T}\right)^2 - 1\right)}},
\]

\[
\Delta_2(y) = \frac{\Lambda}{\sqrt{2 \cdot 51.75 \cdot e^{0.025 \cdot T} \left(1 + \left(0.47 \cdot e^{-0.0097 \cdot T}\right)^2 - 1\right)}},
\]

\[
\Delta_3(y) = \frac{\Lambda}{\sqrt{2 \cdot 50.74 \cdot e^{0.0550 \cdot T} \left(1 + \left(0.54 \cdot e^{0.016 \cdot T}\right)^2 - 1\right)}}.
\]
For example, while the colostrum phase transition from the solid state to the liquid phase takes place, the penetration depth of EMF with the wavelength equal to 12.24 cm makes 32.89 mm.

Similarly, using the formulas 8, it is possible to calculate the electromagnetic waves penetration depth into the colostrum being at any physical state.

In order to find out the temperature values distribution, it is necessary to create a system of heat conduction equations with initial and boundary conditions so that the phase transition temperature and the movement speed of the phase transition boundary were taken into account. Also, it is needed to define a function determining the change in the thickness of each layer. Then the system of equations is solved with aid of the variable time step algorithm. Below presented is the system of the thermal conductivity equations describing the processes running in the first quasi-stationary toroidal resonator:

\[
\Delta_t(y) = \frac{\Lambda}{\sqrt{2 \cdot 50.74 \cdot e^{-0.0050 \cdot \tau} \left( \sqrt{1 + \left(0.54 \cdot e^{-0.016 \cdot \tau}\right)^2} - 1 \right)}.
\]

For example, while the colostrum phase transition from the solid state to the liquid phase takes place, the penetration depth of EMF with the wavelength equal to 12.24 cm makes 32.89 mm.

\[
\Delta_t(y) = \frac{122.4}{\sqrt{2 \cdot 50.74 \left( \sqrt{1 + (0.54)^2} - 1 \right)}} = 32.89 \text{ mm}.
\]

Similarly, using the formulas 8, it is possible to calculate the electromagnetic waves penetration depth into the colostrum being at any physical state.

In order to find out the temperature values distribution, it is necessary to create a system of heat conduction equations with initial and boundary conditions so that the phase transition temperature and the movement speed of the phase transition boundary were taken into account. Also, it is needed to define a function determining the change in the thickness of each layer. Then the system of equations is solved with aid of the variable time step algorithm. Below presented is the system of the thermal conductivity equations describing the processes running in the first quasi-stationary toroidal resonator:

\[
\frac{c_1 \cdot \rho_1 \cdot \partial T^{(1)}}{\partial t} = \frac{\lambda_1 \cdot \partial^2 T^{(1)}}{\partial y_1^2} + q_1(y_1), \quad t > 0, \quad 0 < y_1 < h_1,
\]

\[
\frac{c_2 \cdot \rho_2 \cdot \partial T^{(2)}}{\partial t} = \frac{\lambda_2 \cdot \partial^2 T^{(2)}}{\partial y_2^2} + q_2(y_2), \quad t > 0, \quad h_1 < y_2 < h_2,
\]

\[
\frac{c_3 \cdot \rho_3 \cdot \partial T^{(3)}}{\partial t} = \frac{\lambda_3 \cdot \partial^2 T^{(3)}}{\partial y_3^2} + q_3(y_3), \quad t > 0, \quad h_2 < y_3 < h_3,
\]

where \(h_i\) is thickness of each layer; \(c_1, c_2, c_3\) are heat capacity of frozen raw material, a mixture of frozen & liquid raw material and colostrum in its liquid state, respectively; empirical dependence of colostrum heat capacity on positive temperature is \(c_3 = 4053T^{-0.012}, \text{ J/kg}^0\text{C}\); \(\rho_1, \rho_2, \rho_3\) are densities of frozen raw material, a mixture of frozen & liquid raw material and colostrum in its liquid state, respectively; empirical dependence of density of colostrum in its liquid state on positive temperature is \(\rho_3 = 1049.1 \cdot e^{3\cdot10^{-4}T}, \text{ kg/m}^3\) and that of milk \(\rho_3 = 1039.2 \cdot e^{5\cdot10^{-4}T}, \text{ kg/m}^3\); \(\lambda_1, \lambda_2, \lambda_3\) are thermal conductivity of frozen raw material, a mixture of frozen & liquid raw material and colostrum in its liquid state, respectively; empirical dependence of thermal conductivity of colostrum in its liquid state on positive temperature is \(\lambda_3 = 0.52 \cdot e^{0.0019T}, \text{ W/(m}^0\text{C)}\).

Upon that, the initial conditions must be taken into account: \(T(0, y) = T_1, \quad 0 < y < h_1,\)

\[
T(y_1, y_2) = T_2, \quad h_1 < y_2 < h_2,
\]

\[
T(y_2, y_3) = T_3, \quad h_2 < y_3 < h_3.
\]

Next, the boundary conditions should be accepted:

\[
-\lambda_1 \cdot \frac{\partial T^{(1)}}{\partial y_1}(0, t) = \alpha_1 \cdot (T_1 - T_\circ),
\]

\[
\lambda_2 \cdot \frac{\partial T^{(2)}}{\partial y_2}(h_2, t) = \alpha_2 \cdot (T_2 - T_1),
\]

\[
\lambda_3 \cdot \frac{\partial T^{(3)}}{\partial y_3}(h_3, t) = \alpha_3 \cdot (T_3 - T_2).
\]

where \(\alpha_1, \alpha_2, \alpha_3\) are empirical constants.
where $\alpha_1$, $\alpha_2$, $\alpha_3$ are heat transfer coefficients of the frozen raw material, the mixture of frozen & liquid raw material and the colostrum in its liquid state, respectively, W/(m²·°C).

The formula for determining of the colostrum heat transfer coefficient ($\alpha$) taking into account the phase transitions looks like as follows:

$$\alpha_i = 2.04 \cdot \sqrt{\frac{\chi^3 \cdot \rho_i \cdot g \cdot r}{\nu_1 \cdot h_1 \cdot \Delta T}},$$

(12)

where $g$ is acceleration of free fall, m/s²; $r$ is specific heat of water vaporization (2.258·10⁶ J/kg); $\nu_i$ is kinematic viscosity coefficient, m²/s ($\nu = 2.5817e^{-0.02\cdot T}$); and $\Delta T$ is temperature difference, °C.

The heat transfer coefficient of colostrum in the positive temperature range:

$$\alpha_3 = 2.04 \cdot \sqrt{\frac{0.52 \cdot e^{-0.0019 T} T}{2.58 \cdot e^{-0.02 T} \cdot h_3 \cdot 40}} = 152.66 \cdot \sqrt{\frac{e^{0.026 - T}}{h_3}}.$$

Based on this formula, it is possible to determine the heat transfer coefficient at changes of the temperature and thickness of the raw material. For example, the heat transfer coefficient of colostrum during the phase transition from the frozen state to the liquid state is 482.75 W/(m²·°C).

For practical calculations, the most important formula is one of the specific power (13), which takes into account the changes in the electro-physical parameters of the colostrum being in different physical states:

$$p_1(y) = \omega \cdot \xi_0 \cdot \xi_1 \cdot g \cdot \delta_1 \cdot |\vec{E}|^2$$

$$p_1(y) = 0.555 \cdot f \cdot k_1 \cdot E_1^2 = 0.555 \cdot 2450 \cdot 10^6 \cdot 25.54 \cdot e^{0.19 T} \cdot E_1^2 = 3.47 \cdot 10^{10} \cdot e^{0.19 T} \cdot E_1^2$$

$$p_2(y) = 0.555 \cdot 2450 \cdot 10^6 \cdot 24.28 \cdot e^{0.036 T} \cdot E_2^2 = 3.30 \cdot 10^{10} \cdot e^{0.036 T} \cdot E_2^2$$

$$p_3(y) = 0.555 \cdot 2450 \cdot 10^6 \cdot 27.31 \cdot e^{-0.021 T} \cdot E_3^2 = 3.71 \cdot 10^{10} \cdot e^{-0.021 T} \cdot E_3^2$$

where $f$ is frequency, Hz; and $E$ is electric field strength, kV/cm.

For example, in the area of the boundary separating the solid and liquid phases, where the temperature is equal to the temperature of the phase transition at the electric field strength of 0.6 kV/cm [2], the specific power generated per a volume unit of the raw material makes:

$$p_3(y) = 0.555 \cdot 2450 \cdot 10^6 \cdot 27.31 \cdot e^{-0.021 T} \cdot 0.6^2 = 3.71 \cdot 10^{10} \cdot 0.36 = 1.34 \cdot 10^{10}$$

Thus the heating rate of the raw material is equal to

$$\frac{\Delta T_3}{\Delta t_3} = \frac{p_3 \cdot \eta}{\rho_3 \cdot c_3} = \frac{13400 \cdot 0.57}{1049.1 \cdot 4053} = 0.0018 \text{ C / c.}$$

If 25 L of colostrum are defrosted colostrum in the upper toroidal resonator and another 25 L are in the lower resonator already in the liquid state, then the duration of heating to +38…+40°C makes as little as 8-9 minutes.

As the dielectric loss factor of frozen raw materials increases from 4 to 27 with the temperature increase from -10 to 0°C and at positive temperatures, it decreases, the colostrum defrosting process sees the increase of the generated specific power. So, by way of controlling of the electric field strength (changing the generators power) and adjusting the gap of the capacitor part of the resonators (smooth moving of the common perforated base), it is possible to achieve the installation performance of 170…200 L/h. Upon that, the energy expenses will amount to 0.025 (kW·h)/kg.

The basic colostrum defroster Econom BMA-50 (Alfapanel, Belarus) with the power consumption of 6kW works with an energy expenditure of 0.3 (kW·h)/kg. The duration of the colostrum defrosting/heating process in the proposed design version is reduced by 4 times, which makes it possible to assume that the colostrum nutritive value is preserved.
A mathematical model of the process of interaction of electromagnetic waves with raw materials of various aggregate states is proposed, which describes the electromagnetic and thermal processes in quasi-stationary toroidal resonators with a common perforated base.

Due to the opposite dynamics of changes in the dielectric parameters of animals’ colostrum from the temperature of the working range (−10...+40 °C), subject to heat treatment using microwave technology, problems related to heat transfer should be solved with aid of the equations of thermal conductivity in the area of the boundary dividing solid and liquid phases, and having the temperature equal to the phase transition.

4. Conclusion

The main ways are proposed of meeting the established design criteria for microwave installations of continuous flow operation, including a method for uniform heating achieving of frozen colostrum during defrosting and heating.

The methodology for the development of a microwave installation is provided for the mathematical models construction of defrosting and heating of animal colostrum by the action of an electromagnetic field of ultra-high frequency; the methodology takes into account the phase transitions, their studying and the development of the structural design of the working chamber of the installation with the effective operating modes.

The mathematical model is proposed able to describe the electromagnetic and thermal processes of the electromagnetic waves interaction with the raw materials of different physical states in the quasi-stationary toroidal resonators with the common perforated base.

At the heat treatment of the cattle colostrum using SHF technology, due to the opposite dynamics of the changes in the colostrum dielectric parameters depending on the temperature of the operating range (from −10 °C to +40 °C), the problems related to the heat transfer should be solved through the equations of the thermal conductivity in the area of the boundary separating the solid and liquid phases and having the temperature equal to the temperature of the phase transition.

The main ways are proposed for meeting the established design criteria for continuous-flow SHF generators including the method of the heating uniformity achievement of the frozen colostrum during its defrosting/heating.

By control of the electric field strength (changing the generators power) and by adjusting the gap of the resonators capacitor part (moving the common perforated base smoothly), it is possible to ensure the installation performance of 170...200 L/h. Upon that, the energy costs will be 0.025 (kW·h)/kg.

The work that has been done in the field of colostrum processing as well as in the field of heat treatment and the use of additives is important and beneficial for dairy farms. The search for new developments in the field of optimal nutrition for dairy calves and new promising research will be, of paramount importance for the operation of ecologically efficient dairy farms and so will be their management.

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