Effect of heating of frozen colostrum in two-resonator installation

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Abstract. The study is aimed at the effect substantiation of voluminous heating of the cattle frozen colostrum in the two-resonator installation. The methodology is based on the theory of the electromagnetic field, the laws of thermodynamics and the results of physical modeling. The colostrum dielectric parameters were analyzed in the temperature range from -12 °C to +40 °C. The theoretical studies were carried out for changes finding out in the absorption coefficient of the electromagnetic field and the penetration depth of the electromagnetic waves 12.24 cm long during defrosting/heating of the cow colostrum with the fat content of 6.4%. It is found that the penetration depth of the electromagnetic field into the frozen raw material at negative temperatures range (0.2-1.0 cm) is less than that at the colostrum positive temperatures (1.0-2.17 cm). With such significant difference in the dielectric characteristics of the frozen and thawed colostrum and in their penetration depths of the ultra high frequency electromagnetic field, the rate of their heating is considerably different. The developed continuous-flow ultra high frequency electromagnetic generator contains two voluminous resonators. They provide the colostrum being in different physical states with different doses of the ultra high frequency electromagnetic field exposure.

1. Introduction

The colostrum is the first liquid that is produced in the first few days after delivery [1]. The colostrum is essential for good neonate health [2]. The colostrum is a bioactive rich mammary secretion obtained...

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immediately after parturition and it is endowed with immunity boosting compounds [3]. One of the main problems of the modern animal husbandry is a low survival rate and quality of the offspring obtained [4]. So according to the statistics in the USA, about 10% of newborn calves suffer the diarrhea during the first 7-10 days of their lives. In Canada, these problems’ combating costs up to $8.5 and in Germany $6 to $7.5 for every calf born [5].

According to the estimates of the specialists from the ‘Manager Milk’ company, in our country in the ‘infant’ period, every fifth calf is seriously ill or dies of gastrointestinal diseases of an infectious and non-infectious nature (alimentary-functional diarrhea, colostrum toxicosis, etc.). As a rule, the gastrointestinal diseases are complicated by influence of opportunistic and pathogenic microorganisms [5].

The immunity of a newborn calf is considered to be normal to a sufficient extent when the content of the immunoglobulins in the colostrum is at least 50 g/L, which corresponds to the colostrum density of 1.048 g/cm³ [6].

Usually on a colostrometer, this number is indicated by a green mark. This means that the colostrum from this cow (if it was previously tested for mastitis) can be frozen and saved for a new generation drinking. If colostrum from a cow is recognized as suitable for use, then it is necessary to make an appropriate note in its documents and save as much of this product as possible, Johannes Egbert reminds [5].

It is known that colostrum residues are frozen in plastic bottles (0.1 PET (polyethylene terephthalate)) in order to preserve the immunoglobulin and nutrients contained in the colostrum. When needed for young animals feeding, the colostrum is thawed in defrosters (BMA-50, Primalact, PM2). The defrosting/heating processes are quite long (40-90 minutes), which is why it is not possible to preserve the nutritive value of the colostrum in full [7]. The action principle of the defrosters is based on the water bath use for both bottled colostrum defrosting and its subsequent heating [8,9].

It has become common practice to use the microwave thawing of frozen milk for more rapid accessibility [10].

The frozen colostrum thawed in a microwave oven should be a reasonable source of colostrum for calves feeding, when fresh high quality colostrum is not available [11]. Super-high frequency (SHF) generator is known [12] with its quasi-stationary toroidal resonator. Its disadvantages are as follows: often, raw materials are loaded without packaging; besides, the heating processes are not uniform and last too long. This is due to the fact that the size of the loaded raw material far exceeds the waves penetration depth (which stays within centimeter-based range).

The paper is aimed at development and investigation of SHF generator, which contains two voluminous resonators (ring-shaped one and conical one). Due to those resonators, the colostrum can be in different physical states under exposure of different doses of the super-high frequency electromagnetic field (SHF EMF). The paper is aimed at development of a microwave installation with resonators separating the processes of defrostation and heating of animals’ frozen colostrum, when the aggregate state changes, while maintaining the feed value of the product and ensuring the electromagnetic safety of the equipment.

2. Methods and materials

The cow colostrum (‘AP Knyagininskoe’ LLC, Knyaginino, Nizhegorodsk region, Russia) with the fat content of 6.4% was frozen down to -12 °C in plastic bottles 1.5 liters by volume. The colostrum was defrosted in the microwave oven (ME88SUW, Samsung, Malaysia) at the specific power of 0.5 W/g. The heat flow distribution over the raw material surface was controlled with aid of the thermal imager FLIRi335 (‘FLIR Systems AB’, Sweden). The dielectric parameters analysis was carried out in comparison with the relevant data [13]. Also, there were analyzed the obtained by other scientific schools [14-17] energy-related characteristics of the SHF generators used for thermal treatment in agricultural technological processes. By means of complex experimental studies with the help of the created installation, effective modes of operation of the microwave installation in the Excel 10.0 program have been revealed.
3. Results and discussion

The analysis of the changes in the dielectric parameters of the cow colostrum depending on the temperature shows that the diagrams describing the dielectric loss factor at negative and positive temperatures are opposite (figure 1a). In particular, at the temperature from -10 °C to 0 °C, the dielectric losses factor of the colostrum increases: starting from the value of 4, it reaches the value of 27 [13], i.e. the power absorbed by the raw material during the defrosting process increases several times. In the other temperature range, exactly when heating from 0° to +38 °C, on the contrary, the dielectric loss factor decreases (figure 1b), i.e. the absorbed power decreases with temperature growth. This means that the heating process lasts longer than the defrosting process, so it is necessary to provide the colostrum with the different dose of SHF EMF exposure in the second resonator. Only the separation of these processes by different resonators will reduce dramatically the duration of the entire technological process and preserve the nutritive value of the cow colostrum.

![Figure 1a](image1.png)
![Figure 1b](image2.png)

**Figure 1.** Diagram of dependence of dielectric parameters of cow colostrum with fat content of 6.4% on temperature in two ranges: (a) -10 °C to 0 °C; and (b) 0 °C to +40 °C.

The scientific innovation idea discussed in the article is that as the colostrum can be in different physical states, the installation should contain two resonators so that to provide each colostrum portion with different doses of the SHF EMF exposure [14]. One resonator should be used for defrosting from -15 °C up to 0 °C, while the other resonator for heating from 0°C up to 38-40 °C. The resonators must separate the solid and liquid phases of the raw material at the temperature equal to the phase transition temperature.

The absorption coefficient ($\alpha$) of the electromagnetic radiation by the raw material depends on the wavelength and its dielectric parameters (1):

$$\alpha = \frac{\pi \sqrt{\varepsilon} \tan \delta}{\gamma}$$  \hspace{1cm} (1)

where $\lambda$ is wavelength equal to 12.24 cm; $\varepsilon$ is dielectric permittivity of raw material; and $\tan \delta$ is tangent of angle of dielectric losses of raw material.

With due consideration of the empirical expressions (2)-(4) describing the change in the dielectric parameters of the cow colostrum depending on the temperature, the absorption coefficient of SHF EMF is described by the equations (5)-(7):

- in the temperature range from -20 °C to 0 °C:
  $$\varepsilon = 32.88 \varepsilon_0^{0.122T}$$  \hspace{1cm} (2)
- in the temperature range from 0 °C to 40 °C:

\[ k = 27.87 \chi e^{0.21\Phi} \]  \hspace{1cm} (3)

\[ \tan \delta = 0.85 \chi e^{0.082\Phi} \]  \hspace{1cm} (4)

\[ \varepsilon = 51.05 \chi e^{-0.069\Phi} \]  \hspace{1cm} (5)

\[ k = 27.2 \chi e^{-0.021\Phi} \]  \hspace{1cm} (6)

\[ \tan \delta = 0.54 \chi e^{-0.016\Phi} \]  \hspace{1cm} (7)

The uniformity of the raw material heating occurs if its layer thickness does not exceed the depth \( \gamma \) of SHF EMF penetration. The dependence of the SHF EMF penetration depth into the raw material on temperature is described by the following equations.

The diagrams of the penetration depth of EMF with the frequency of 2450 MHz into the colostrum with the fat content of 6.4% depending on the heating temperature are shown in figure 2.

**Figure 2.** Diagram of dependence of SHF EMF penetration into frozen cow colostrum with fat content 6.4% at temperature a) from -10 °C to 0 °C; b) from 0 °C to +40 °C.

The SHF EMF penetration depth into the frozen raw material increases from 0.14 cm to 0.93 cm with an increase in temperature from -12 °C to 0 °C. When the colostrum is heated from 0 °C up to 40 °C, the penetration depth increases from 1.01 cm to 2.17 cm.

This means that what is thawed gradually is the surface of the frozen raw material contained in the dielectric bottles (figure 3a). If do not remove the thawed liquid fraction, the thickness of which is increased, the protein coagulates (figure 3b). That is why, as far as the raw material is defrosted, the liquid fraction should be drained into another resonator. Based on this feature, the super-high-frequency installation with two resonators has been developed (frequency 2450 MHz, wavelength 12.24 cm). It allows the frozen colostrum defrosting/heating in the dielectric bottles.
Figure 3. Results of studying of raw materials thawing process in laboratory: frozen colostrum in container (a); layer-by-layer coagulation of bottled colostrum in process of its defrosting under SHF EMF (b).

From the technical point of view, the task is to develop a continuous-flow SHF generator with the ring-shaped resonator connected to the base of the conical resonator, which allows separating the processes of defrosting and heating of the cattle colostrum (figure 4). The installation must ensure the electromagnetic safety and the high electric field strength for low-temperature disinfection of the raw material. The ring-shaped resonator 1 with the magnetrons 2 is formed between two coaxially arranged non-ferromagnetic cylinders (outer and inner ones), the upper annular non-ferromagnetic base and the rotating non-ferromagnetic base. N, this rotating base is the base of the conical resonator (3), whose top is pointing downwards and is butted to the ring-shaped resonator. Some magnetrons (2) (with the displacement of 120 degrees between them) are located on the side surface of the ring-shaped resonator, while other magnetrons 6 are located on the surface of the conical resonator, closer to the base, also with the displacement of 120 degrees.

Figure 4. SHF generator for cattle colostrum defrosting: schematic layout (front view) (a); view from above (b); 3D-image (c). This is the ring-shaped resonator having rectangular cross section without bottom base (1), magnetrons on outer side surface of ring-shaped resonator (2), ring-shaped resonator (3), rotating base (4), holes on base 4 (5), magnetrons on surface of conical resonator (6), dielectric partitions forming compartments (7), ball valve (8), open window on outer side surface of ring-shaped resonator (9), non-ferromagnetic cylinder without base (10), open window on the side of the cylinder 10 (11), dielectric guide bar (12), loading duct (13), electric drive (14).
On the rotating base (4), inside of the ring-shaped resonator, the dielectric partitions (7) are installed radially for compartments formation. The average inner perimeter of the ring-shaped resonator is multiple of half the wavelength. In each compartment on the rotating base, there is the hole 5, the diameter of which is no more than a quarter of the wavelength. On the top of the conical resonator, the ball valve (8) is installed. On the side surface of the ring-shaped resonator, there is the open window (9). To this window, the non-ferromagnetic cylinder (10) is butted; it has no base and on its side surface, there is the open window 11. Those windows are butted to each other and form the aperture. Opposite to the aperture, above the dielectric partition, the guiding dielectric bar (12) is attached to the side surface of the inner cylinder of the ring-shaped resonator. On the upper ring-shaped base of the resonator, there is the loading duct (13). It performs the function of an out-of-limit waveguide and its diameter should be not less than the diameter of a plastic bottle contained the raw material. Notably, this duct is located in front of the open window (9) on the side surface of the ring-shaped resonator. Driven by the electric drive 14, the base 4 rotates. Next to the ball valve, there is the thermocouple; it is needed because closer to the top, the conical resonators have a critical cross-section, beyond which the SHF EMF is absent [18].

The technological process of defrosting and heating of the cattle colostrum in the continuous-flow SHF generator with two resonators, one ring-shaped and one conical, is as follows. An operator turns on the electric drive (1) of the rotating base (4) of the conical resonator (3). After closing of the ball valve (8), he loads a container with the raw material into the loading duct (13). Notably, the operator must make sure that the neck of the bottle is butted to the hole (5) on the base (4) of the resonator; he fixes the bottle in this position. Then the operator turns on the magnetrons (2), whose emitters are directed to the ring-shaped resonator 1. As the compartments located on the rotating base 4 move, the operator loads the next dielectric bottles with the frozen raw material, without lids. The migrating wave EMF is excited in the ring-shaped resonator [18]. At a rate, which depends on the EMF penetration depth, the frozen raw material is thawed layer-by-layer and through the open bottle neck, it flows into the hole (5) on the resonator rotating base into the second resonator (3). The operator turns on the magnetrons (6), whose emitters are directed to the conical resonator (3). While the base of the ring-shaped resonator is rotating, the bottles with the raw materials move in the ring space and by the end of the full rotation of the base, they are emptied completely because under the dielectric heating action, the defrosting process occurs. At end of a full turn of the base, the empty bottle rests against the dielectric bar (12) and is pushed into the non-ferromagnetic cylinder (10) without a base. Through the aperture formed by the butted open windows (9) and (11), this bottle falls down into the container, which is empty bottles collector. The liquid colostrum is accumulated in the conical resonator (3) exposed to SHF EMF; here it is heated up to 38-40 °C and dosed into the receiving container through the ball valve 8. The temperature of the colostrum is controlled by the temperature sensor (thermocouple). In both resonators, the electric field is excited of as high intensity as is sufficient for reducing of the product bacterial contamination [19]. The electromagnetic safety is ensured by use of the loading duct (13) as an out-of-limit waveguide and the conical resonator. The empty dielectric bottles should be washed up and sterilized; then they can be used for colostrum freezing again.

4. Conclusions

The research were carried out of changes in the absorption coefficient of the electromagnetic field and in the penetration depth of the wave 12.24 cm long into the cow colostrum with the fat content of 6.4% during its defrosting and heating.

It is found that the depth of the electromagnetic field penetration into the frozen raw materials at the negative temperatures (0.2 to 1.0 cm) is less than that at the positive temperatures (1.0 to 2.17 cm). This can be explained due to an increase in value of the dielectric losses in the negative temperatures range. As the frozen colostrum and the liquid colostrum have such a significant difference in both their dielectric characteristics and the SHF EMF penetration depth into them, their heating rates are considerably different.
The developed continuous-flow SHF generator contains two voluminous resonators (ring-shaped one and conical one). They make possible the colostrum being in different physical states under different doses of the SHF EMF exposure.

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