Justification of the possibility of cooking eggs without water in an ultra-high frequency electromagnetic field

G Novikova¹*, O Orlova², O Mikhailova³, M Prosviryakova⁴ and P Zaitsev⁵

¹Laboratory of energetic and technological equipment, Nizhny Novgorod State Engineering and Economic University, 22 a Oktyabrskaya Street, Knyaginino 606340, Russia
²Chair of physical and mathematical sciences, Nizhny Novgorod State Engineering and Economic University, 22 a Oktyabrskaya Street, Knyaginino 606340, Russia
³Chair of infocommunicational technologies and communication systems, Nizhny Novgorod State Engineering and Economic University, 22 a Oktyabrskaya Street, Knyaginino 606340, Russia
⁴Chair of electrification and automatization, Nizhny Novgorod State Engineering and Economic University, 22 a Oktyabrskaya Street, Knyaginino 606340, Russia
⁵Chair of mechanization, electrification and automatization of agricultural production, Chuvash State Agricultural Academy, 29 Karl Marx Street, Cheboksary 428003, Russia

*E-mail: ngiei-126@mail.ru

Abstract. Rejected hatching eggs after ovoscoping can be used as protein feed for chickens after they have been heat-treated by exposure to an ultra-high frequency electromagnetic field. In this regard, the dielectric and physical-mechanical parameters of the components of a chicken egg are analyzed, the heat treatment modes and structural designs of resonators of ultra-high-frequency continuous-flow installations are justified. Studies show that the yolk is endogenously heated two to three times faster than the protein, which is coagulated mainly by heat transfer from the yolk. This is due to the mass difference and the dielectric loss factor of the egg components. Unconventional resonators have been developed that allow controlling the heating rate of raw material components not only by smoothly regulating the generator power. In a quasi-toroidal resonator, this is done by changing the capacitance in the capacitor part; in mobile hemispherical resonators that provide a downhole technological process of less than 0.5 due to the resonant beam electrodynamic system-by changing the speed of movement of the hemispheres; in a biconic resonator - by changing the downhole process.

1. Introduction
It is known that the volume of rejected hatching eggs after ovoscoping can reach 4 %. This raw material can be used as a boiled protein feed for chickens. Currently, vacuum boilers are used for heat treatment of such raw materials, which have a sufficiently large energy consumption. The use of an ultra-high frequency electromagnetic field could reduce operating and energy costs.

Researchers all over the world are studying the processes of heat treatment of products, including using an ultra-high frequency electromagnetic field [1-3]. During the analysis of these works, it was revealed that the issue of developing a technology and installation for heat treatment of chicken eggs without water remains open. Known works on the study of egg heat treatment processes and the development of ultra-high-frequency installations Yu V Guskov, A A Belov [4, 5], etc. The authors
propose to cook an egg without water in an ultra-high frequency electromagnetic field with a process duty cycle of less than 0.5. This helps to equalize the temperature and pressure in the protein and yolk due to the thermal conductivity from the yolk to the protein. At the same time, all manufactured laboratory samples of ultra-high-frequency installations for egg cooking operate in a periodic mode, since there are no nodes that provide electromagnetic safety. To reduce energy costs for heat treatment of eggs, it is more expedient to develop ultra-high-frequency continuous-flow installations.

The purpose of this work is to analyze the dielectric and physical-mechanical properties of the components of chicken eggs for the development of ultra–high-frequency continuous-flow installations and to justify the design versions taking into account the variety of egg raw materials.

2. Materials and methods
The subject of the study was chicken eggs of category C-2 weighing 45-54 g. For heat treatment of the studied material, magnetrons with forced air cooling with a power of 800 W were used. The duration of egg cooking in an ultra-high frequency electromagnetic field was estimated taking into account changes in the dielectric parameters of the protein and yolk of chicken eggs from the temperature given by I A Rogov [6]. Instant contact temperature measurements in the egg white and yolk were performed using a Testo 925 differential thermometer containing a t-type thermocouple temperature probe. The heat flow distribution over the surface of the raw material was studied using FLIRi3 thermal imager and a FLUKE 62 Mini infrared Thermometer. Preliminary justification of egg processing modes was carried out using a laboratory sample, using active planning of a three-factor experiment in the Statistica 12.

3. Results and discussion
The effect of an ultrahigh frequency electromagnetic field on an egg with a complex structure becomes clearer when analyzing the dielectric parameters of its components and their temperature dependence. According to research by I A Rogov [6], the temperature rise of the raw materials is valid for dipole polarization in two ways: as a result of weakening of intermolecular and intramolecular bonds orientation of dipoles is facilitated and due to the increased thermal motion is attenuated, as the thermal motion disturbs the ordering of the location of the polar particle in an electromagnetic field. In an ultrahigh frequency electromagnetic field, relaxation losses due to dipole losses of free moisture are important. Changes in the dielectric parameters of the protein and egg yolk depending on the heating temperature are shown on figure 1.

Analysis of the graphs shows that the permittivity of the egg components seems to decrease with increasing temperature due to the thermal expansion of the egg components. Empirical expressions describing the dependence of the dielectric parameters of the protein (1) and yolk (2) of a chicken egg on the heating temperature ($T$, °C):

\[
\varepsilon = 79.785 \cdot T^{0.176}, \quad k = 4.774 \cdot T^{0.026}, \quad tg\delta = 0.0597 \cdot T^{0.151} \quad (1)
\]

\[
\varepsilon = 81.508 \cdot T^{0.145}, \quad k = 29.696 \cdot T^{0.373}, \quad tg\delta = 0.3666 \cdot T^{0.229} \quad (2)
\]

where $\varepsilon$ – is the permittivity of the raw material; $k$ – is the temperature-dependent coefficient of dielectric loss components of eggs; $tg\delta$ – tangent of the dielectric loss angle.

The effect of endogenous heating of raw material components in an ultra-high frequency electromagnetic field was estimated taking into account

\[
\Delta = \frac{2 \cdot c}{2 \cdot \pi \cdot f \cdot \sqrt{\varepsilon \cdot tg\delta}}
\]

where $c$ – is the speed of light propagation in a vacuum, $3 \cdot 10^8$ m/s; $f$ – frequency of the electromagnetic field, 2450 MHz.
Figure 1. Changes in the dielectric parameters of the yolk (a) and protein (b) of a chicken egg depending on the heating temperature.

Substituting the empirical expressions (1) and (2) in the formula (3), we calculate the change in the depth of penetration of the electromagnetic field into the components of a chicken egg: protein (4) and yolk (5), depending on the temperature.

\[
\Delta = \frac{2 \cdot c}{2 \cdot \pi \cdot f \cdot \sqrt{79.785 \cdot T^{-0.18} \cdot 0.06 \cdot T^{0.15}}}
\]

(4)

\[
\Delta = \frac{2 \cdot c}{2 \cdot \pi \cdot f \cdot \sqrt{81.51 \cdot T^{0.145} \cdot 0.37 \cdot T^{-0.23}}}
\]

(5)

Taking into account changes in the dielectric parameters, calculations show that the depth of penetration of the electromagnetic field into the egg yolk at a temperature of 20°C is 0.0309 m.

Changes in the depth of penetration of the electromagnetic field into the protein and yolk of a chicken egg depending on the heating temperature are shown in figure 2 the value of the penetration depth indicates a decrease in the power of internal heat sources by \(e\) times.
Figure 2. Changes in the depth of electromagnetic field penetration into the protein and yolk of a chicken egg depending on the heating temperature.

Empirical expressions describing the change in the depth of penetration of the electromagnetic field into the protein and yolk, respectively:

\[
\Delta = 7.2569 \cdot T^{0.061}
\]

\[
\Delta = 2.6131 \cdot e^{0.0071 \cdot T}
\]

When the temperature changes from 20 °C to 80 °C, the depth of penetration of the electromagnetic field into the egg white decreases from 5.93 cm to 5.52 cm, and the yolk increases from 3.09 to 4.57, which should be taken into account when justifying the “heating-cooling” method.

The change in the specific electrical conductivity (\(\sigma\), S/m) of egg yolk and egg white during heat treatment due to conduction currents and dielectric losses can be determined using the dielectric parameters of the raw material components according to the well-known formula [6]:

\[
\sigma = 8.85 \cdot 10^{-12} \cdot 2 \cdot \pi \cdot f \cdot k
\]

We derive a formula for calculating the change in the specific electrical conductivity of the egg components: protein (9) and yolk (10), depending on the temperature change.

\[
\sigma = 8.85 \cdot 10^{-12} \cdot 2 \cdot \pi \cdot f \cdot 2.974 \cdot T^{-0.026}
\]

\[
\sigma = 8.85 \cdot 10^{-12} \cdot 2 \cdot \pi \cdot f \cdot 29.7 \cdot T^{-0.37}
\]

Graphs of changes in the specific electrical conductivity of protein and egg yolk depending on the heating temperature are shown on figure 3.

Empirical expressions describing changes in the specific electrical conductivity of yolk (11) and protein (12), respectively:

\[
\sigma = 1.51 \cdot e^{-0.009 \cdot T}
\]

\[
\sigma = 0.65 \cdot T^{-0.026}
\]

When the temperature changes from 20 °C to 80 °C, the electrical conductivity of the protein remains constant in the range of 0.6 S/m, and the yolk decreases from 1.24 to 0.76 S/m.
Figure 3. Changes in the specific electrical conductivity of protein and egg yolk depending on the heating temperature.

Other electrophysical parameters of egg components are shown in table 1. Based on this information, we calculate the duration of cooking protein and yolk under the influence of an ultra-high frequency electromagnetic field.

Table 1. Analysis of electrophysical parameters of egg components [7-11].

| Name                                           | Yolk          | Protein         |
|------------------------------------------------|---------------|-----------------|
| Changing the dielectric loss factor when the temperature changes from 20°C to 80°C | 9.1–5.6       | 4.5–4.3         |
| Refractiveindex                                 | 1.419         | 1.356           |
| Heat capacity, j/g°C                            | 2677          | 3140            |
| Storage density up to 2 weeks, kg/m³            | 1027–1035     | 1048            |
| The temperature of coagulation, °C              | 65–70         | 57–61           |
| Weight, g                                       | 19–23         | 30–36           |
| The ratio of the egg contents, %                | 36            | 64              |
| Acidity, pH                                     | 4.8–6.2       | 7.2–8.6         |
| Dynamic viscosity at a temperature of 0°C, Pa   | 1.12–1.45     | 1.08–1.14       |

The specific power of the generator is calculated by the formula [6]:

\[ P = \frac{\Delta T}{\Delta \tau} \cdot \rho \cdot C \cdot \frac{1}{\eta}, \]  

(13)

where \( \Delta T \) – temperature change, °C; \( \Delta \tau \) – time increment, s; \( \rho \) – substance density, kg/m³; \( C \) – heat capacity, j/kg°C; \( \eta \) – generator efficiency.

Calculations show that the yolk heating rate is not less than 0.5 °C/s, it is necessary to provide a specific generator power of 1.97 W/cm³:

\[ P = 0.5 \cdot 1029 \cdot 2677 \cdot \frac{1}{0.7} = 1.97 \frac{W}{cm^2}. \]

Taking into account the fact that the yolk is cooked at a temperature of 80 °C, we calculate the duration of processing of raw materials at an increment of 60 °C (the initial temperature of the raw material is 20 °C) with a specific power of 1.97 W/cm³:
\[ \tau = \frac{\Delta T}{P \cdot \rho \cdot C \cdot \frac{1}{\eta}} = \frac{60}{1967595} \cdot \frac{1029 \cdot 2677 \cdot 1}{0.7} = 120. \]

The duration of cooking the yolk at a heating rate of 0.5 °C/s is 120 seconds. Calculate the increment of protein temperature at a specific power of 1.97 W/cm³:

\[ \Delta T = \frac{P \cdot \Delta \tau \cdot \eta}{\rho \cdot C} = \frac{1.97 \cdot 120 \cdot 0.7}{1048 \cdot 3140} = 50. \]

In the developed microwave installation with three magnetrons with a power of 850 W, with equal specific powers (1.97 W/cm³) falling on the egg components, 40 eggs can be loaded into the resonator, while for heat treatment of one egg, the specific power will be 65 W/pcs. In 120 sec, the protein of 40 eggs will be cooked. Due to the fact that the weight of the yolk (21 g) is 1.57 times less than the weight of the protein, the yolk is cooked in 76 seconds. On the other hand, the dielectric loss factor of the yolk at a temperature of 20 °C is 9.1, and the protein is 4.5, therefore, the specific power in the yolk is generated 2.02 times more, and at the end of the process at a temperature of 80 °C – 1.3 times. Then, on average, due to the difference in mass and the factor of dielectric losses of egg components, the yolk at the beginning of the technological process is heated three times faster than the protein, and at the end – 2 times. We can assume that on average, the yolk will cook 2.5 times faster than the protein. In this regard, in the designs of microwave egg cookers developed by previous authors, a “heating-cooling” method with a duty cycle of less than 0.5 is proposed. This will increase the heating temperature of the protein due to heat transfer from the yolk.

Depending on the type of processed raw materials: whole, broken or eggs without shells, we have developed ultra-high-frequency continuous-flow installations (table 2) with quasi-stationary toroidal, spherical and biconic resonators, which implement the “heating-cooling” method.

In these installations, open resonators are used, as well as exorbitant waveguides, as a result of which their own q-factor changes. Taking into account the configuration of resonators and open nodes intended for feeding raw materials and unloading the product, formulas for calculating this parameter are derived. Table 2 shows formulas for determining the intrinsic q-factor of resonators as the ratio of the double volume to the surface area of the resonator, taking into account the thickness of the skin layer \([5]:(14)\):

\[ Q = \frac{2 \cdot V}{\Delta \cdot S}, \]

where \( V \) – is the volume of the resonator, m³; \( S \) – is the surface area of the resonator, m²; \( \Delta \) – is the thickness of the skin layer, m.

These formulas take into account the geometric configuration of the resonators.

Table 3 shows a comparative analysis of energy costs for the technological process of heat treatment of eggs using ultra-high-frequency installations with different design versions of resonators.

The electric field strength in a mobile spherical resonator with low-power magnetrons with three-wave interference will be 0.6 kV/cm, the truncated biconic resonator in the central part has a voltage within 0.8 kV/cm, in the condenser part of a quasi-stationary toroidal resonator, the electric field strength can be increased several times to 1.2–1.5 kV/cm, which maximally meets the microbiological safety requirements of the product.

In the developed installations, the specific energy consumption is less than in the periodic installations (0.185 Wh/g) described in the scientific works of other authors \([4, 5]\). Minimum specific energy costs for the technological process of heat treatment when using an ultra-high-frequency installation with a truncated biconic resonator. Energy costs are reduced due to the use of a single fan for cooling several magnetrons in installations, the continuity of the technological process and the reduction of the power of the mobile mechanism.

Theoretical calculations of the intrinsic q-factor of resonators according to the derived formulas have shown that the maximum value has a truncated biconic resonator (5000) \([12]\), the q-factor of a quasi-stationary toroidal resonator is within 4200. The minimum value for an open spherical resonator is (2400).
Table 2. Formulas for calculating the intrinsic q-factor of resonators with an unconventional configuration.

Quasi-stationary toroidal resonator

\[
V = \pi \left[ \int_0^h \left( \frac{y \cdot (r_1 - r_0) + h_0 \cdot r_0}{h_1} \right)^2 dy + \int_{h_0}^{h_1} \left[ r_1^2 - (y - h_0 + h_1)^2 \right] dy \right] - \int_{h_0}^{h_1} \left[ \frac{(y - h_0 + h_1) \cdot (r_1 - r_0) + h_0 \cdot r_0}{h_1} \right]^2 dy
\]

\[
S = 2 \pi \int_0^h \left[ \frac{y \cdot (r_1 - r_0) + h_0 \cdot r_0}{h_1} \sqrt{1 + \left( \frac{y \cdot (r_1 - r_0) + h_0 \cdot r_0}{h_1} \right)^2} \right] dy + 2 \pi \int_{h_0}^{h_1} \left[ \sqrt{r_1^2 - (y - h_0 + h_1)^2} \sqrt{1 + \left( \sqrt{r_1^2 - (y - h_0 + h_1)^2} \right)^2} \right] dy
\]

Spherical resonator with a mobile hemisphere

\[
Q = \frac{\int_0^h (R^2 - y^2) dy}{\Delta \left( R^2 - y^2 \right) \sqrt{1 + \left( R^2 - y^2 \right)^2} dy}
\]

Truncated conical resonator

\[
Q = \frac{2 \pi \cdot \int_0^h \left( r_2 + \left( \frac{r_1 - r_0}{h_1} \right) \cdot y \right)^2 dy}{4 \Delta \left( \pi \cdot \int_0^h \left( r_2 + \left( \frac{r_1 - r_0}{h_1} \right) \cdot y \right)^2 dy + \frac{d}{dy} \int_0^h \left( r_2 + \left( \frac{r_1 - r_0}{h_1} \right) \cdot y \right)^2 dy + 2 \int_0^h \left( r_1 - r_0 \right)^2 dy + 2 h_1 \left( r_1 + r_2 \right)}
\]

\( r_1 \) – radius of the small base; \( r_2 \) – radius of the large base; \( h_1 \) – height of the truncated cone;
\( \Delta \) – thickness of the surface layer; \( k \) – coefficient that takes into account the efficiency of the technological process.

Table 3. Comparative analysis of microwave units with different structural designs of the resonators.

| The ultra-high frequency unit contains: | Specific energy consumption (kWh/kg) | Voltage (kV/cm) |
|----------------------------------------|-------------------------------------|-----------------|
| quasi-stationary toroidal resonator \(^a\) | 0.154 | 1.2 – 1.5 |
| mobile spherical resonator | 0.163 | 0.6 |
| a truncated conical resonator | 0.103 | 0.8 |

\(^a\) The calculation of specific energy costs is given taking into account the grinding mechanism.

4. Conclusion

The yolk is endogenously heated two to three times faster than the protein, which is coagulated mainly by heat transfer from the yolk. This is due to the mass difference and the dielectric loss factor of the
egg components. The depth of penetration of the electromagnetic field into the yolk when the temperature changes from 20 °C to 80 °C increases by an average of 1.5 cm, and in the protein decreases by 0.4 cm, while the specific electrical conductivity of the protein in this temperature range decreases by 0.5 S/m, and the protein remains constant.

Unconventional resonators have been developed that allow controlling the heating rate of raw material components not only by smoothly regulating the generator power. In a quasi-toroidal resonator, this is done by changing the capacitance in the condenser part; in mobile hemispherical resonators, this is done by changing the specific electrical conductivity of the material components not only by smoothly regulating the generator power. The depth of penetration of the electromagnetic field into the yolk when the temperature changes from 20°C to 80°C increases by an average of 1.5 cm, and in the protein decreases by 0.4 cm, while the specific electrical conductivity of the protein in this temperature range decreases by 0.5 S/m, and the protein remains constant.

Unconventional resonators have been developed that allow controlling the heating rate of raw material components not only by smoothly regulating the generator power. In a quasi-toroidal resonator, this is done by changing the capacitance in the condenser part; in mobile hemispherical resonators, which provide a well life of less than 0.5 due to the resonant beam electrodynamic system, by changing the speed of movement of the hemispheres; in a truncated biconic resonator, by changing the well life of the process.

References
[1] Rombouts I, Wouters G B, Lambrecht M A, Uten L, Van Den Bosch W, Vercruysse S and Delcour J A 2020 Food protein network formation and gelation induced by conductive or microwave heating: a focus on hen egg white. *Innovative Food Science and Emerging Technologies* **66** 102484 DOI: 10.1016/j.ifset.2020.102484
[2] Guo Q, Sun D W, Cheng J H and Han Z 2017 Microwave processing techniques and their recent applications in the food industry. *Trends in Food Science and Technology* **67** 236 DOI: 10.1016/j.tifs.2017.07.007
[3] Muthukumarappan K and Swamy G J 2019 Microwave processing of foods. *Handbook of Farm, Dairy and Food Machinry Engineering* ed M Kutz (New York: Academic Press) chapter 16 pp 417–438 DOI: 10.1016/B978-0-12-814803-7.00016-6
[4] Belov A A 2011 Installations for egg. *Materials of the Int. Scientific and Practical Conf. Topical Issues of Improving the Technology of Production and Processing of Agricultural Products* (Yoshkar-Ola: Mari state University) pp 145–146
[5] Belov A A and Guskov Yu V 2011 Cooking eggs without water. *Materials of the Int. Scientific and Practical Conf. Topical Issues of Improving the Technology of Production and Processing of Agricultural Products* (Yoshkar-Ola: Mari state University) pp 152–153
[6] Rogov I A 1981 *Electrophysical, Optical and Acoustic Characteristics of Food Products* (Moscow: Light and food industry) p 288
[7] Burdo O G, Terziev S G, Yarovoiv I I and Borsch A A 2013 Modeling of food raw material dehydration processes in the electromagnetic field. *Proc. of the Voronezh State University of Engineering Technologies* **3** 62 [in Russian] DOI: 10.20914/2310-1202-2013-3-62-65
[8] Schwägle F C 2011 Egg quality assurance schemes and egg traceability. *Improving the Safety and Quality of Eggs and Egg Products* ed Y Nys, M Bain et al (Amsterdam: Elsevier) chapter 5 62 DOI: 10.1533/9780857093912.1.62
[9] Chambers J R, Khalid Z, Humayoun A and Abdel-Aal El-Sayed M 2017 Chicken eggs. *Egg Innovations and Strategies for Improvements* ed Patricia Y. Hester (New York: Academic Press) chapter 1 10 DOI: 10.1016/B978-0-12-800879-9.00001-9
[10] Xiong L 2011 Simulating analysis and choosing control method on the speed control of egg quality’s detection. *Advanced Materials Research* **268–270** 1179 DOI: 10.4028/www.scientific.net/AMR.268-270.1179
[11] Chukwuka O K, Okoli I C, Okeudo N J, Udendie B I, Ogbuewu I P, Aladi N O, Ilheshiolor O O M and Omede A A 2011 Egg quality defects in poultry management and food safety. *Asian Journal of Agricultural Research* **5** 13 DOI: 10.3923/ajar.2011.1.16
[12] Orlova O I, Belova M V, Zhidanin G V and Obolensky N V 2019 Development and justification of the parameters of the microwave installation for heat treatment of rejected chicken eggs. *Proc. of the Voronezh State University of Engineering Technologies* **1(81)** 47 [in Russian] DOI: 10.20914/2310-1202-2019-1-47-52