Theoretical and experimental substantiation of the amplitude and source of oscillations on a container of an acoustic butter churn

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Abstract. A method has been developed for butter production and a unit for its practical implementation which makes it possible to use oscillations efficiently at the macro level for the vibration of a container with cream, and at the micro level for the effect of oscillations on milk fat globules until the desired butter granules are obtained. The experimental studies of the proposed butter churn in laboratory conditions have shown that the optimal frequency for churning butter should be 5 Hz. In order to reliably estimate the number of oscillating actuators and their lay-out on the container surface of a butter churn it is necessary to take into account the motion trajectory of the fat globules which can be simple and complex. To ensure the complex motion trajectory of fat globules, a method has been developed for butter production and a unit to implement this method which gives a possibility to use oscillations in the most efficient way at the macro level for the cream container vibration, and at the micro level for the effect of such oscillations on fat globules in order to obtain butter granules. Analysis of the research results showed that butter corresponding to GOST was obtained at a frequency of 5 Hz and an amplitude of oscillations of the cream container in 5 mm.

1. Introduction
It is known that fat globules in milk are distributed more or less evenly. However, their concentration, to a greater extent, occurs on the surface of milk due to their lower density, and this process only leads to the formation of cream. In addition, the natural process of concentrating fat globules on the surface of milk requires a significant amount of time and energy costs [1].

Cream, by its consistency, contains milk in which the concentration of fat is at least 30%. The most common method for isolating cream is the separation of milk which allows one to increase the concentration of fat globules by isolating them from the initial product. The process of milk separation with subsequent cream processing operations is the required operation of any technology for butter production.

Ready-to-eat butter represents a continuous fat phase, which is in a plastic state at an ambient temperature of 18 °C ... 25 °C, which is caused by the content of olein in the butter. In this state of butter, milk fat globules and drops of buttermilk are concentrated in it.

Fat is contained in the form of globules. Each globule of fat contains fusible glycerides. The outer membrane of the fat globule contains hard-melting glycerides in the solid phase at a temperature of 18 °C ... 25 °C. In addition, the outer membrane also contains proteins, vitamins, phospholipids and
cholesterol.

Having analyzed the existing technologies for butter production, we can conclude that all of them are aimed at reversing the phases during which they realize the convergence of globules of fat with their subsequent formation into butter granules.

From the flotation theory it follows that in the process of processing the feedstock, in particular, cream into butter, 3 stages can be distinguished: the formation of air bubbles, the destruction of the dispersion of air bubbles and the formation of butter granules.

At stage 1, the process of intensive cream stirring forms a significant number of air bubbles, which subsequently collapse in the cream layer bordering the air. Air bubbles also collapse at the moment when their duration in the cream layer is sufficient to stretch the bubble membrane. However, at the first stage, the process of the air bubble formation prevails over the process of their destruction, and foam forms in the total amount of processed cream, which, in addition to plasma, contains air and fat.

At stage 2, the amount of “non-foamed” cream is quite intensively reduced. This significantly reduces the time of the air bubble formation in the processed cream. At this stage, the amount of air which is removed from the cream is slightly more than it comes into it, and this helps to reduce dispersion. In addition, the foam represents a mesh structure which is formed in the cream. The amount of this foam increases due to the inclusion of cream plasma in it. This plasma is also spent on the formation of surfaces formed during the destruction of large air bubbles into smaller ones. A part of the plasma from the cream is held by a foam consisting of small bubbles and separated by immobile layers of liquid. The immobility of these layers is due to the appearance of additional crystalline bonds between the triglycerides. In the process of mechanical stirring of the churned mass, the resulting bonds of the crystalline type are destroyed, followed by splitting the aggregate foam and the formation of fat lumps of an insignificant size, consisting of fat globules that are stuck to each other.

At the 3rd stage, due to the ongoing process of whipping cream, butter granules are formed from separately located lumps of fat.

It is necessary to take into account that the use of well-known technologies for mechanical cream churning by the working bodies of butter churns is often applied in the industry. However, their drawback is the mechanical deformation of fat globules during removal of the protein coat, as well as the wear of the working bodies of butter churns that are in direct contact with churned cream, which significantly affects the quality of butter obtained.

When churning cream, it is necessary to eliminate the protein coat from fat globules. However, this process is implemented by a combination of strokes, shear of fat globules under pressure and cavitation. However, a stroke is undesirable, as it contributes not only to the destruction of the membrane, but also to the fat globules themselves, reducing the butter quality.

Analyzing the works of leading scientists and inventors in the Russian Federation, we can conclude that all scientists note the appearance of foam when churning cream. Foam promotes the aggregation of fat globules due to the transition of protein coats to the surface of bubbles. Globules of fat, in most cases, become firm, being drawn into the foam. Due to the surface pressure on the bubbles of the foam and the direct contact of these bubbles to each other - the globules of fat get compressed.

Scientists have also found that foam has a significant effect on the formation of butter granules only at slow motion when cream is stirred. An increase in the speed of stirring the cream helps to reduce the diameter of fat globules, and, consequently, to increase the time of butter production [1, 2].

2. Materials and research methods

Scientists have also found that a promising area in butter production is the use of butter churns with an oscillating actuator [3, 4].

In order to reliably estimate the number of oscillating actuators and their lay-out on the container surface of a butter churn, it is necessary to take into account the motion trajectory of fat globules, which can be simple and complex.

To ensure easy movement of fat globules, one source of oscillation is required, which will be installed, for example, in the lower part of a butter churn. In addition, such a movement of fat globules
can also be converted into a complex one by exposing it to a modulated signal from an oscillation source. In this case, fat globules will perform both reciprocating low-frequency movement and oscillatory high-frequency movement.

To implement a complex trajectory of the movement of fat globules, a method for the production of butter and a device for its implementation have been designed. This contributes to use oscillations in most efficient way at the macro level for vibration of the container with cream, and at the micro level for the effect of vibrations on fat globules with the purpose of obtaining the required butter granules.

The proposed method consists in the mechanical activation of cream churning, combined with the influence of oscillations. Oscillations in the initial product are generated by acoustic signals. Such signals contribute to the performance of oscillations in the container with the product (due to low frequencies) and lead to oscillations of fat globules of the mass being churned at high frequencies.

For the practical implementation of the developed method, a unit was made for non-contact cream churning (Fig. 1).

Preliminarily, the container (1) is filled with the initial raw material (cream) (2). A periodic signal is supplied to the acoustic wave source (3) from the generator (5), and the required parameters are changed by the RA and RF regulators — the amplitude and frequency of the oscillations. When the container (1) oscillates, acoustic waves (6) propagate along a parabolic trajectory in cream (2), acting on the fat globules and contributing to the intensification of the butter churning process.

The oscillating actuator (3) in the form of a source of acoustic waves allows one to directly control the process of cream processing by varying the amplitude and frequency of oscillations of the source of acoustic waves (3), as well as improve the quality of the resulting product by eliminating the contact of butter with the stirring components of butter churns.

![Figure 1. A unit for non-contact cream churning: 1-container; 2- cream; 3-electromagnet actuator (source of acoustic waves); 4-connecting wires; 5-generator of acoustic waves (RA –regulator of amplitude; RF- regulator of frequency); 6- areas of propagating acoustic waves in the product.](image1)

The location of the oscillation source of the acoustic range on the outer side of a butter churn depends on the form of a trajectory set for fat globules (Fig. 2).

![Figure 2. Location of the oscillation source on the outer surface of the container (dashed lines show the possible trajectories of the movement of fat globules when stirring the cream): 1-container; 2- a source of acoustic range oscillations.](image2)
Taking into account the fact that the container is filled with cream not more than 70%, it is considered expedient to place the source of oscillations on the outer surface at the bottom of the container.

The preliminary creation of a complex trajectory of movement of fat globules increases the efficiency of churning cream and, accordingly, obtaining high-quality butter. Based on the assumption previously put forward, it can be concluded that the motion of fat globules along a complex path can be achieved by using at least two sources of oscillatory vibrations of the acoustic range.

A complex motion trajectory of fat globules in churned cream can be achieved by two methods: adding up unidirectional oscillations of close frequencies and adding mutually perpendicular oscillations.

In view of the sinusoidal dependence of the motion of fat globules in cream on the oscillation frequency \( x = A \sin \omega t \), we determine the force, \( F \), of forced oscillations of fat globules:

\[
2 \omega _{\omega} \sin \omega \omega = - m \omega^2 A \sin \omega t ,
\]

where \( m = (4 \pi r^3 \rho_{\text{fat}}) / 3 \) – weight of fat globules, kg; \( r \) – radius of fat globules, m; \( \rho_{\text{fat}} \) – density of fat globules, kg/m³; \( \omega \) – cyclic frequency of forced oscillations, rad/s; \( A \) – amplitude of forced oscillations, m; \( t \) – time of fat globule travel, s.

It is known that force, \( H \), contributing to vertical oscillations of fat globules:

\[
F = F_{\text{head}} + F_a - F_t ,
\]

where \( F_{\text{head}} \) – the force of head resistance that arises when fat globules oscillate, \( H \); \( F_a \) – thrust force, \( H \); \( F_t \) – the force of gravity of fat globules, \( H \).

The force, \( H \), of head resistance of fat globules can be defined by

\[
F_{\text{head}} = S \pi r^2 \rho_v \omega \omega'^2 ,
\]

where \( S = \pi r^2 \) – the cross section area of one fat globule, m²; \( \rho_v \) – travel speed of a fat globule in oscillations, m/s.

Thrust force, \( H \),

\[
F_a = 4 \pi r^3 \rho_{\text{fat}} .
\]

The speed of travel \( \omega \), m/s, of a fat globule is a derivative value of movement \( x \) in time \( t \):

\[
\omega = \frac{dx}{dt} = A \cos \omega t .
\]

Having differentiated the expression (6) we obtain:

\[
-S \omega \omega'^2 + 4 \pi r^3 \rho_{\text{fat}} x \omega + 4 \pi r^3 g (\rho_{\text{fat}} - \rho_{\text{water}}) = 0 .
\]

Having substituted the variables: \( a = -S \); \( b = 4 \pi r^3 \rho_{\text{fat}} \); \( c = F_a = 4 \pi r^3 g (\rho_{\text{fat}} - \rho_{\text{water}}) \), the expression (8) will be written:

\[
a \left( x' \right)^2 + bx + c = 0 .
\]

Making some transformations of the equation (9) we obtain:
\[
\sqrt{a} \int \frac{dx}{\sqrt{-(bx+c)}} = \int dt.
\]  

(11)

Having substituted \(\sqrt{-(bx+c)} = y\), we get:

\[
x = -\frac{y^2 + c}{b},
\]

(12)

\[
dx = -\frac{2ydy}{b}.
\]

(13)

Having put the expressions (12) and (13) in the expression (11) we define:

\[
x = -\frac{b}{4a} t^2 - \frac{c}{b},
\]

(14)

\[
y = -\frac{b}{2\sqrt{a}} t.
\]

(15)

Having performed the inverse substitution of variables we define the motion of fat globules, \(m\):

\[
x = \frac{r \omega^2}{3} t^2 - \frac{g(\rho_{ca} - \rho_{am})}{\rho_{am} \omega^2}.
\]

(16)

Taking into account that

\[
x = A \sin \omega t,
\]

(17)

then, having equated the expressions (16) and (17) we determine the required amplitude of oscillations of fat globules:

\[
A = \frac{\frac{r \omega^2}{3} t^2 - \frac{g(\rho_{ca} - \rho_{am})}{\rho_{am} \omega^2}}{\sin \omega t}.
\]

(18)

Thus, the required amplitude of oscillations depends on the frequency \(\omega\), the cream churning time \(t\), the initial cream density \(\rho_{ca}\), radius of the fat globules \(r\) and their density \(\rho_{am}\).

The expression (18) makes it possible to determine the amplitude of oscillations of fat globules, as well as the amplitude-frequency characteristic of a non-contact cream churning device and to identify optimal modes of its operation.

Preliminary theoretical calculations showed that the optimal frequency for churning butter should be in the range of 2 ... 5 Hz and 115 ... 118 Hz.

To confirm the theoretical positions in the experiments, we studied the lay-out of one source of the acoustic range of an oscillating actuator which was installed on the lower outer side of the container. This arrangement of an oscillating motor made it possible to ensure the complex motion of fat globules.

The studies of the proposed method in laboratory conditions were implemented with the application of a device for non-contact cream churning (Figure 3). The waveform was monitored by a C1-68 oscilloscope.

![Figure 3](image_url)

Figure 3. A unit for non-contact cream churning: 1 - generator G3-36; 2- signal amplifier 35U-102; 3 -oscilloscope; 4 - speaker 25 GDI-3-4 (the source of acoustic waves); 5 - a cream container.

To choose optimum modes among the design and operation parameters of the method the following controlled factors were used: \(x_1\) – diameter of the container; \(x_2\) – weight of the raw material; \(x_3\) –
signal frequency of the generator; \( x_4 \) – oscillation amplitude (Table 1).

| Varied factors | Levels of factor variation |
|----------------|----------------------------|
|                | upper (+1) | lower (-1) | main (0) |
| \( x_1, \text{sm} \) | 20         | 10          | 15       |
| \( x_2, \text{g} \)  | 100        | 50          | 75       |
| \( x_3, \text{Hz} \)  | 117        | 5           | 56       |
| \( x_4, \text{mm} \)  | 5          | 0.5         | 2.75     |

In experimental studies, before the start of the process of churning the feedstock, its temperature was 10 ± 0.3 °C.

3. Analysis and discussion of the results
The results obtained during the experiment were processed according to the technique for planning a multifactor experiment [5, 6, 7].

At the end of the butter formation process, the research results were processed with the use of the program “Statistica” and mathematical models were obtained such as regression equations adequately describing fat content, moisture content, milk solids, churning time and butter temperature.

**Fat content**

\[
Y_i = 65,10027 - 3,328044x_1 - 0,1500118x_2 - 2,527981x_3 + \\
+ 3,1947x_4 - 6,558711x_1 - 3,758723x_2 - 1,258723x_3 - \\
- 0,9587044x_4 - 0,8187497x_2 + 2,96875x_3 - 3,03125x_4 + \\
+ 1,043751x_3 - 0,2562501x_4 - 3,043751x_4 \tag{19}
\]

**Moisture content**

\[
Y_i = 54,74532 + 3,311376x_1 + 0,1333436x_2 + 2,477976x_3 - \\
-3,244704x_4 + 0,4478135x_1 - 2,352205x_2 - 4,852205x_3 - \\
- 5,152193x_4 + 0,8375x_2 - 2,9125x_3 + 3,0875x_4 - \\
- 0,9875003x_3 + 0,3125001x_4 + 3,0625 . \tag{20}
\]

**Milk solids**

\[
Y_i = 3,079374 + 0,016668x_1 + 0,016668x_2 + 0,050004x_3 + \\
+ 0,050004x_4 - 0,1630964x_1 - 0,630964x_2 - 0,1630964x_3 - \\
- 0,1630964x_4 - 0,01875x_2 - 0,05625x_3 - 0,05625x_4 - \\
- 0,05625x_3 - 0,05625x_4 - 0,01875x_4 \tag{21}
\]

**Time**

\[
Y_i = 70,71301 + 1,1112x_1 + 1,16676x_1 + 1,16676x_1 - \\
- 3,22248x_2 - 4,055088x_1 - 2,555088x_2 - 4,555088x_3 - \\
- 5,055088x_4 + 1,4375x_2 - 3,3125x_3 + 2,1875x_4 - \\
- 2,5625x_3 - 0,0625x_4 + 2,4375x_4 . \tag{22}
\]

**Temperature**

\[
Y_i = 29,29355 + 0,16668x_1 - 0,77784x_1 + 0,38892x_2 + \\
+ 0,2778x_4 - 2,797013x_1 - 1,297013x_2 - 1,797013x_3 - \\
- 1,797013x_4 + 0,375x_4 + 0,375x_2 + 0,25x_3 - 0,5x_4 . \tag{23}
\]

Having checking the equations (19 … 23) with the use of F-test, Student’s t-test and the Cochran’s C test, we confirmed the adequacy of the obtained mathematical models, the significance of the coefficients of the regression equations, and the reproducibility of measurement results, respectively.

The butter obtained during the experiment was evaluated in relation to moisture content, fat content, and milk solids. The above indicators were determined according to the requirements of [8, 9].
Butter according to GOST was obtained at a frequency of 5 Hz and an oscillation amplitude of a container with cream in 5 mm. The diameter of the container was 10 cm, and the weight of the product ranged from 50 to 100 g.

4. Conclusions

The results of experimental studies of the developed method and technical equipment confirmed the basic theoretical principles, as a result of which the proposed method for butter production can be used in the industry with the application of oscillating actuators of the acoustic range.

Butter, with a fat content of more than 70%, was obtained at a frequency of 5 Hz and an oscillation amplitude of 5 mm. In this case, it is necessary to select a container with a lid and install two oscillating actuators at the lower outer side of the container. A change in the remaining conditions of the experiment made it possible to obtain only sandwich butter, since the fat content in the butter was below 70%.

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