Investigation of the process of structure formation during ultrasonic homogenization of milk

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Abstract. The article studies the processes of structure formation of milk during homogenization carried out on various equipment. A comparative analysis of the distribution of the sizes of fat globules before and after homogenization is given. The formulation of the probability mathematical model of milk and milk mixture homogenization give the opportunity to identify the real variabilities of the textural composition of milk and milk mixture in optimum performance with the use of statistics facts about dynamics of the fat globules size. The foundation for developing such model was used for experimental results of fat globules within the ultrasound process. The dependences of the density distribution of the sizes of fat globules after ultrasonic treatment are given. Obtained dependences allow conducting statistics analysis of the homogenization of food mass for the evaluation of its total effectiveness and determination of defects.

1. Introduction
The possibility of application of ultrasound in processing industry is widely spread that gave the opportunity to get information about food media and effects on it. The main factor in the ultrasound process is cavitation. The use of ultrasound technologies makes diffusion and dissipation fast and activates chemical reactions in food media.

The influence of ultrasound reactions responds is explained by the fact that within the cavitation process free ions form. Until recent times, there has been no information about physical processes occurring in particles which compose a structure product. That’s why the model of such effects is so contradictory. There are a lot of information about caving, for example a high pressure and temperatures in caving, deep discharging and cryotemperatures promote destroying of microparticles, for instance fat globules of milk [1, 2, 3]. Such dissentions are required because of the difficulties arising in the cavitation process. Practical research of the cavitation process generated by ultrasound created optimal terms, allowed using it in food and processing industries and getting high sustainability.

Nowadays, there is a break in the ultrasound use in different technological processes in AIC: it happens only for emulsification and suspension, removing the oxide layer and sonification surfaces of equipment, liquids sterilization, crushing starch kernels, crushing fat globules.

2. Materials and methods
In order to find out the ultrasound application in AIC the analytical research method was used. The formulation of the probability mathematical model of milk and milk mixture homogenization gives the
opportunity to identify the real variabilities of textural composition of milk and milk mixture in optimum performance with the use of statistics facts about dynamics of the fat globules size [4, 5]. The foundation for developing such model was used for obtaining experimental results about fat globules within the ultrasound process [6, 7]. The comparation of fat globules with its size was conducted on the laser diffractional granulometer Malvern 2000 within the automatic fixation of the particles quantity with different diameters in a sample.

The experiment on the homogenization process was similar to a comparative experiment on a special rotatory dispergator of the type Turreks and an ultrasound device with solid magnetostriiction replicating arrangement.

3. Results and their discussion

Then, the experiment on the homogenization process with milk and milk mixture was made using different equipment; the results are shown in Figure 1.

On the axis, there are fat globules in the sample, on the abscissa – the diameter of fat globules. The effect of dispersing force of ultrasound on fat globules is apparently from 0.01 μm to 40.01 μm with the empiric distribution frequency of fat globules after ultrasound homogenization (curve 2) and after lab dispergation (curve 3).

The distribution curves of fat globules suggest the inclination to Maksvel distribution:

\[ f(r) = 2A^2 \cdot r \cdot e^{-(Ar)^2}, \]  

(1)

where \( A \) – constant dimension, m\(^{0.5}\); \( r \) – fat globules diameter, m.

Let’s consider the variant of frequency friction of fat globules with the formula (1). We can guess the reduction factor of fat globules which is proportional to the square of separation, i.e. diameter square \( r \) for its separation. According to [7] the probability at the point in radius \( R \) is:

\[ P = \int_0^R f(r) \, dr, \]  

(2)

where \( f(r) \) – density function of fat globules dimension in processed milk.

Relating to the homogenization process of fat globules, the expression is interpreted like the probability of collision for the destructive factor of fat globules.

Let us accept that the probability function, i.e. function internal (2) from 0 to \( \infty \) is equal to one:

\[ P = f(r) = \int_0^\infty f(r) \, dr = 1, \]  

(3)

Figure 1. The dependence of quantity of fat globules from the diameter: No. 1 – milk; No. 2 – ultrasonicated; No. 3 – after homogenization on the rotatory dispergator device type Turreks

The distribution curves of fat globules suggest the inclination to Maksvel distribution:

\[ f(r) = 2A^2 \cdot r \cdot e^{-(Ar)^2}, \]  

(1)
where \( P \) – probability of the size of fat globules in the interval from 0 - \( \infty \).

In Figure 2, there is a density plot for empirical and theoretical distribution \( r \); in Figure 3 – integral curves for these functions. Curve 1 in Figure 2, according to the results of discrete areas of experimental curve 1 in Figure 1 multiplied by the normalizing factor, is equal to 0.00685. Thus, \( r \to \infty \) is an integral function from this curve \( f(r) = 1 \) (Figure 3).

It is obvious that a one-parameter arrangement when \( A = 0.0615 \) with a high degree of adequacy describes actual distribution of fat globules in raw milk.

![Figure 2](image1.png)

**Figure 2.** The dependence of the density of fat globules in milk on its size: curve 1 – distribution of diameters of fat globules throughout the experiment data on curve No. 1, multiplied by the coefficient, which is equal to 0.00685; curve 2 – theoretical distribution with \( A = 0.0615 \)

![Figure 3](image2.png)

**Figure 3.** The dependence of integral curves on empirical and theoretical curves of fat globules density on sizes \( r \)

The attempt to describe the distribution curves of fat globules after homogenization with the use of one-parameter distribution doesn’t give the adequate accuracy. For the creating the function of distribution density of fat globules after homogenization of the acceptable dispersion, let’s note a
variety of fat globules contained in two subsets: 1 – a subset of fat globules with breaking up and 2 – a subset of fat globules, aggregated in large formations.

This gives the opportunity to obtain the density function of fat globules like a sum of the density function of the first and second subsets:

$$f(r) = 2 \cdot \left[ a \cdot A^2 \cdot r \cdot e^{-(A^2 r)^2} + b \cdot B^2 \cdot r \cdot e^{-(B^2 r)^2} \right],$$

(4)

where $f(r)$ – density function of fat globules, $r$ – diameter of fat globules; $A$ – empirical parameter for intensity of fat globules crush; $B$ – empirical parameter for intensity of the clustering process of fat globules; $a$ – empirical parameter for percent of the first subset in the whole subset of fat globules; $b$ – empirical coefficient for the second subset in the whole subset of fat globules, and therefore, $a+b=1$.

In Figure 4, there is dependence of the density of empirical and theoretical diffusion on the sizes of fat globules in milk, ultrasonicated on one occasion throughout the cavitation location. This increases the percent of fat globules of the minor diameter and reduces the diapason of diffusion. Curve 1 – empirical distribution; curve 2 – theoretical distribution for the formula (4) in the following value: $a = 0.35; b = 0.65; A = 0.35; B = 0.095$.

![Figure 4](image-url)

**Figure 4.** The dependence of fat globules distribution sizes after the first stage of ultrasonic processing: curve 1 – empirical distribution; curve 2 – theoretical distribution from the formula (4) with the defined value: $a = 0.35; b = 0.65; A = 0.35; B = 0.095$

Figure 6 shows the integral curves of the functions shown in Figure 5. The definitions were equal (4) and obtained by the selection of fluctuations of summation curves in Figure 4. In the capacity of the reasonable test of graphics, we used the max relative deviation of the theoretical integral curve from empirical (Figure 5) in 5.7% percent for minor size of fat globules. For sizes definitions of fat globules from 4 $\mu$m, the deviation is no less than 2.8% that represents a high degree for the theoretical module of the granulometric milk composition which is ultrasonicated.
Figure 5. Probabilistic distribution function of fat globules after ultrasound processing: curve 1 - graph of the integral function of the empirical distribution function; curve 2 - graph of the cumulative function of the theoretical distribution function

Essentially the smallest dissipation is obtained for fat globules definition in milk after the stage of ultrasonic processing, Figure 6.

Figure 6. Graphs of the densities of the empirical distribution of fat globules after a 3-fold passage through the focus of ultrasound (solid line) and a theoretical one according to formula (5)

In this case, the approximate function should contain not a sum of two, but a sum of four forms:

$$f(r) = 2\left[ a \cdot A^2 \cdot r \cdot e^{-(A^2)r^2} + b \cdot B^2 \cdot r \cdot e^{-(B^2)r^2} + c \cdot C^2 \cdot r \cdot e^{-(C^2)r^2} + d \cdot D^2 \cdot r \cdot e^{-(D^2)r^2}\right],$$  (5)
no more than 4.5%. Here with \(a+b+c+d = 1\).

In table 1 there are meanings of the mean square deviation in the following coefficients \(A\), \(B\), \(C\) and \(D\) from the formula \((A_i)^t = \sigma_i\).

|   |   |   |   |
|---|---|---|---|
| \(A\) | \(B\) | \(C\) | \(D\) |
| \(\sigma_1 = 0.139\) | \(\sigma_2 = 0.357\) | \(\sigma_3 = 1\) | \(\sigma_4 = 4\) |

The responsibility of the theoretical structure module of milk after three-step processing is rather high, the maximum deviation is no more than 1%.

4. Conclusions

Now, therefore, fat globules distribution in milk that was exposed homogenization process, was described like a one-parameter function of density distribution:

\[
f(r) = 2 \cdot \sum a_i \cdot A_i \cdot r \cdot e^{-\left(\frac{r}{A_i}\right)^2},
\]

where \(f(r)\) – density function of probability of fat globules distribution; \(a_i\) – coefficient for the subset of fat globules corresponding to the homogenization cycle; \(A_i\) – parameter which corresponds to the total of fat globules.

The fat globules distribution in homogenized milk was accounted like regularities which describe the function density of fat globules distribution, like a sum of density functions of distribution (6) and weight coefficients:

\[
f(r) = \frac{2r}{\sigma^2} e^{-\left(\frac{r}{\sigma}\right)^2}.
\]

Obtained dependences allow conducting statistics analysis of the homogenization process of the food mass for the evaluation of its total effectiveness and determination of defects. A scheme of the model for the homogenization process may be inform (6) by the function character (7), like a mean square deviation (\(\sigma\)) in a given type and its mode. That is, it corresponded to the most reasonable size of fat globules in a subset. For example, using value \(\sigma\) in the table it is possible to point to the distribution graphics of fat globules sizes (Figure 6), in such range of sizes with the corresponding center of the distribution of this or that subset. That, in turn, is an instrument of performance evaluation of the detergent ultrasound homogenizer.

References

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