Agronomy Research **15**(S2), 1295–1303, 2017

Application of ultrasonic waves for the improvement of particle dispersion in drinks

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Abstract. Dispersion is one of the most energy-costly processes in food production. Significant proportions of hard particles remain intact when traditional dispersion methods are used. The intensification of dispersion will lead to the more effective extraction of biologically active components from raw bulk. It will also expedite the ripening of products and will improve their consumer desirability. The goal of this research was to study the dispersing effect of low-frequency ultrasound (US) on drinks which are of vegetable and animal origin (22 ± 0.6 kHz). The subjects of the research were raw cow's milk, reconstituted milk, and cranberry drinks which had been produced with the use of traditional technology and employing ultrasonic power. An ultrasonic technological device with an umbrella-shaped working element was used as an ultrasound generator (Russian Federation patent No 2141386). A Nanotrac Ultra analyser (made by Microtrac Inc, USA) was used to study particle size, using the ISO 13321 standard. An analysis of particle size was based on the method which employs the dynamic dispersion of light, in which the minimal detectable particle size is 0.8 nm. It was found that the particles in raw cow's milk, after ultrasonic processing at 180 W for dive minutes, decrease in size from 2,656 ± 72 nanometres to a prevailing particle size of 294.7 ± 24 nanometres. Following the US processing of reconstituted milk (with power at 180 W and action time at three minutes), the size of the particles decreases from 409.5 ± 62 nanometres to a prevailing particle size in the range of 202.2 ± 41 nanometres. With the cranberry drink, using ultrasound at 180 W for five minutes caused a decrease in particle size from 5,670 ± 62 nm to a prevailing size of 1,960 ± 42 nm. With an increase in ultrasound power and the duration of the application, an aggregation of particles was noted in both plant and animal-derived drinks. Therefore it can be seen that ultrasound can be used to regulate the dispersion processes in food manufacturing.

Key words: milk, cranberry drink, ultrasonic influence, dispersion composition

INTRODUCTION

The dispersion of solid components in a liquid is a difficult process which requires large levels of power consumption in the manufacture of both vegetable and animal-based products. A sizable proportion of solid matter shows resistance to external influence, ie. at traditional levels of mechanical influence, a considerable share of cells cannot be destroyed (Rehbinder, 1978; Shestakov et al., 2013; Kalinina, 2015; Naumenko et al., 2016). The main technological difficulties are a result of the following phenomenon: the low efficiency of the extraction process in the production of drinks from vegetable-based raw materials; the low efficiency levels of drink reconstitution rates from dry raw materials; a deterioration of desirable consumer properties in drinks, etc.

By intensifying the dispersion process, a number of production problems can be efficiently solved. One of the possible approaches in terms of the intensification of dispersion is by ultrasonic cavitational influence. The practicability of applying ultrasonic waves at the dispersion stage can be substantiated by the existence of a few specific intrinsic properties of ultrasonic waves.

According to the data available in current literature, the mechanism behind US acting upon colloid substances consists of the following: when ultrasound waves are sent towards a heterogeneous system, compression and rarefaction areas appear on the phases boundary, which in turn causes a rise in pressure. The overpressure formed by ultrasonic waves is added to the constant hydrostatic pressure, and this synergetic effect can reach several atmospheres. In the rarefaction phase, throughout the entire volume of liquid, in particular on the phase's boundaries in those places in which the smallest solids and gas bubbles are present, cavities are formed (Suslick, 1979; Bunkin et al., 1992; Ashokkumar et al., 2011; Shestakov et al., 2013; Krasulya et al., 2014; Porova et al., 2014; Potoroko et al., 2014).

During recompression, cavitation bubbles are collapsed, and pressure rises to a count of hundreds of atmospheres. The high intensity of the formed shockwave leads to the stress destruction of solid particles. However, it is necessary to consider the fact that, during ultrasound usage in the dispersion process, not only the destruction of particles can occur, but also the coagulation of particles caused by the destruction of the particles' solvation shells during the dispersion phase. The behaviour of cavitation processes in various environments has been actively studied by several authors (Suslick, 1979; Dezhkunov, 2001; Knorr et al., 2004; Ashokkumar et al., 2008; Shestakov et al., 2013; Krasulya et al., 2014; Porova et al., 2014; Potoroko et al., 2014). As a result of their research the applicability of ultrasonic waves for food processing has been fully proven.

The French scientist, Chemat (2011), demonstrated the applicability of ultrasonic wave technology in the manufacture of natural products on the basis of eco-extraction processes. The research focused on innovative methods in terms of nutrient extraction from various vegetable-based raw materials. Dincer et al. (2016), showed the applicability of ultrasonic waves in milk processing technology, focusing on lactose crystallisation. Huang et al. (2007), Ashokkumar et al. (2008), Zuo et al. (2012), and Bai et al. (2016) describe the application of ultrasound for starch modification. Research carried out by Bykov et al. (2011) confirms the suitability of cavitation processing for the production of non-starchy polysaccharides by means of the destruction of plant cell walls. A number of research projects have also been carried out when it comes to the field of modifying the properties of raw whole milk as used for the manufacture of fermented milk products and farmer's cheese (Khmelev, 1997; Potoroko & Tsirulnichenko, 2013; Shestakov et al., 2013; Krasulya et al., 2014; Porova et al., 2014).

The goal for this research project was to study the dispersal effect of low-frequency ultrasound (22 ± 0.6 kHz) on drinks of vegetable and animal origin (raw cow's milk, reconstituted milk, and cranberry drinks), using a laser dynamic light scattering method. An ultrasonic technological device with an umbrella-shaped working element was used as an ultrasound generator (Russian Federation patent No 2141386).

MATERIALS AND METHODS

For the purposes of this research, raw milk, reconstituted milk, and cranberry berry drink were used.

The *raw milk* (produced during the summer lactation period) was delivered from a farm belonging to Agrostimul LLC, Kurgan Region, Russia (the average content of the milk included: dry fat-free substances, 8.57%; protein, 3.17%; and fat, 3.6%).

In order to produce *reconstituted milk*, powdered skimmed milk was used which was produced using a spray-drying method by Chebarkul Lactic Plant JSC, Chelyabinsk Region, Russia (the average content of the powdered milk included: water, 2.85%; protein, 2.69%; and fat, 1.1%).

Reconstituted milk produced using traditional milk reconstitution technology saw powdered milk added to water at a temperature of between 38–45 °C, at a ratio of 1:10, which was then actively mixed and maintained for three hours, with this being used as a reference sample.

Reconstituted milk which was processed using ultrasound was produced by means of applying an ultrasound treatment to a water and powdered milk mix immediately after the mixing process had been completed. In terms of the production of this sample, milk reconstitution was specified without the preliminary heating of the water.

For the *cranberry drink* which was processed using ultrasound production, frozen cultivated cranberries were used, produced by Fresh LLC, Chelyabinsk, Russia.

As a reference sample, thawed and crushed cranberries were added to water at a ratio of 1.5:10, and then the mixture was heated to a temperature of 45 °C, mixed actively (no less than thirty times per minute), and filtered through an eight layer textile filter.

The cranberry drink was processed using ultrasound, with thawed and crushed cranberries being added to water which was at room temperature (20 °C) at a ratio of 1.5:10; the mixture is processed using ultrasound and is filtered through an eight layer textile filter.

All of the samples were treated with ultrasound at the following parameters: a frequency of 22 ± 1.65 kHz; an intensity of 10 W/cm^2; and at a power of 180 W. The exposure time was one, three and five minutes; and the liquid volume was 200ml.

A Volna-M UZTA-0.4/22-OM model submersible ultrasonic device with an umbrella-shaped working element was used as an ultrasound generator for treating the substances in the study. Its technical specifications are shown in Table 1 (Khmelev, 1997).

The ultrasonic vibrating system uses annular piezoelectric elements and is made of BT5 titanium alloy. Its operating principle is based on high-intensity ultrasonic waves propagating in fluid and in fluid-dispersed substances. The engineering solutions used are protected by Russian Federation patent No 2141386 (Khmelev, 1997).

The unique feature of this ultrasonic equipment consists of the applied design behind the ultrasonic oscillatory system, namely the umbrella-shaped tool with a concentrator connector which has a connecting size that is less than the size of the radiating surface. By selecting the optimum ratio for the maximum radiating surface diameter of the umbrella-shaped working tool so that it best matches the diameter of the concentrator end face to which the tool is connected, it is possible to provide a relative reciprocating movement for the working tool's radiating surface, ie. to increase the radiation surface area with an amplitude which corresponds to the increased concentrator amplitude, and thereby to increase energy output in proportion to the square of the diameter; and also to create flexural oscillations in the peripheral area of the working tool's surface. Such an approach allows for the creation of acoustic flows during the course of ultrasound emissions, thereby making it possible to displace the cavitation cloud which interferes with the acoustic energy output from the working tool's end face. This provides for additional agitation of the technological material being processed, and prevents the transition of titanium into the processed liquids.

Table 1. Technical specifications of Volna-M UZTA-0.4/22-OM device

Specification	Value
Ultrasound oscillation frequency, kHz	22 ± 1.65
Power, W	400
Range of power adjustment, %	30–100
Intercity of ultrasound, not less than W/cm^2	10
Power supply voltage, V AC	220 ± 22
Maximum continuous operation time, hours	8
Diameter of emitting surface, mm	25
Overall dimensions:	
electronic generator, mm	300x280x110
oscillating system, mm	Ø70x150
diameter of working element, mm	25

The optimum ratio for the radiating surface diameters in relation to the connecting size increases the device's efficiency by up to 80% (Lebedev et al, 2003; Khmelev et al, 2005).

A Nanotrac Ultra analyser (made by Microtrac Inc, USA) was used for particle size analysis. The measurement procedure carried out with the Nanotrac meets the requirements of ISO 13321. The device's operating principle is based on the passing of a laser beam through liquid, the beam's reflection off moving particles, and its return to the device detector. The particle size is calculated on the basis of the expansion of the reflected ray spectrum. The method for determining particle size distribution is based on an analysis of Doppler spectral shifts. The sample placed into the cell is exposed to laser radiation, and the scattered light caused by Brownian motion of particles is recorded at an angle of 180°. The minimum size of the particles which can be found by the device is 0.8 nanometres; the measurement data are highly precise and can easily be reproduced (Dalgleish, 1995; Alexander & Dalgleish, 2006; Nobbmann et al., 2007).

A typical example of particle distribution curves in terms of dispersal systems for the drinks samples are presented in Fig. 1. All particle distribution curves for dispersal systems for the drinks samples possess a similar overall character, but they differed in terms of the value and location of peaks which correspond to different fractions of particles.

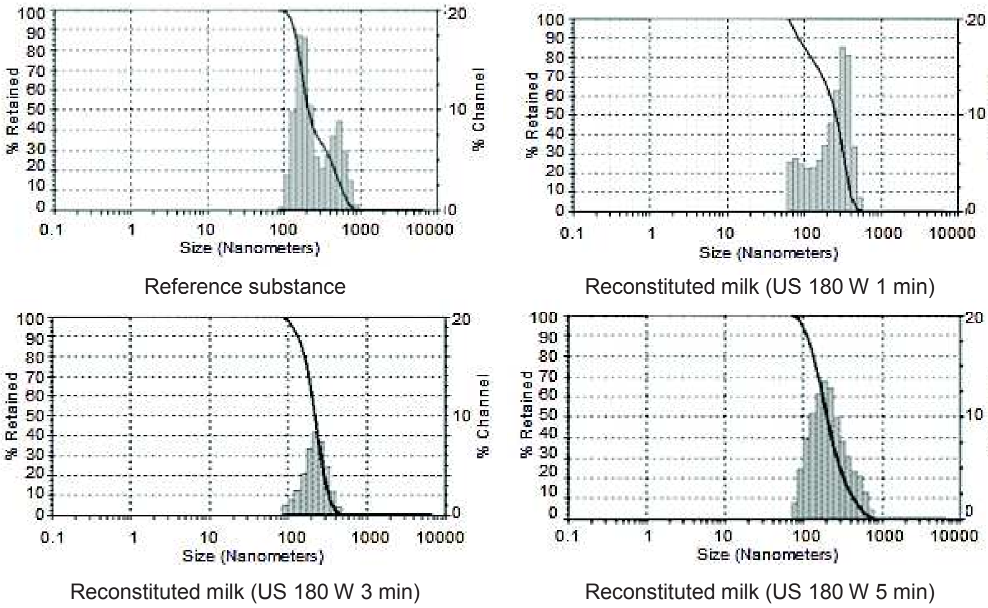

Figure 1. Plots for particle dispersion systems for milk reconstituted with water.

RESULTS AND DISCUSSION

It is well known that milk is a composite polydisperse system in which dispersion phases exist in various states. In particular, protein is present in the form of colloid particles, and the size of these particles can vary from fifteen to 300 nanometres; fat is present in the form of coarse-dispersion particles of various sizes (the diameter of milk fat globules is between 0.1 and 20 microns). Other milk components exist in an ion-molecular state with particle sizes of about one nanometre or less. There is no definite difference between phases, as the aqueous solution of one substance can be a dispersion medium for others (Potoroko & Kalinina, 2010; Hussein et al, 2011; De Kruif & Huppertz, 2012; Tepel et al, 2012). When a close interrelation between phases is reached, a uniformly balanced milk system is formed. Milk dispersion has important technological value for the manufacture of dairy products as it provides the best bioavailability and digestibility of the main components of milk (Potoroko & Kalinina, 2010; Tepel et al, 2012).

The results of dispersion degree analysis for milk systems, for various US processing modes, are given in Fig. 2.

The above results for dispersible analysis show that milk is very sensitive to the ultrasonic cavitation effect, which causes an increase in droplet sizes when the droplet appears in the rarefaction area, and subsequent division into smaller droplets. Ultrasonic cavitation causes changes in the product dispersion state. It can be seen from the results that the distribution of the samples' fractional composition changes; however, different ultrasound modes influence the product system differently. An increase in ultrasonic exposure causes particle sizes to be more equal. In the reference sample for milk (whole milk which was not processed), particles of between 1,000 and 3,000 nanometres were discovered with a particle dominance of 2,656 ± 72 nanometres. For samples exposed to US at the power of 180W for five minutes, the fractional composition changed: particles of two fractions are present: 1,461 ± 30 nanometres at 8.4%; and 294.7 ± 24 nanometres at 91.6%.

The results demonstrate the clear influence of the cavitation process on milk particle size, with the primary focus being on the size of milk fat globules.

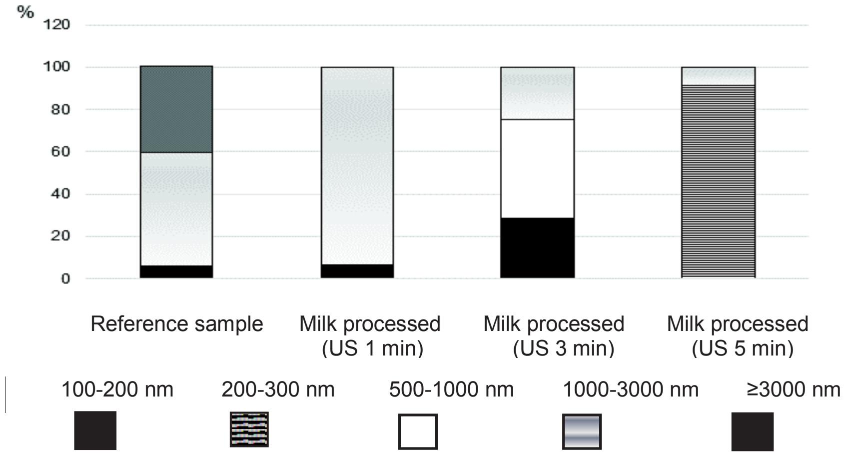

Figure 2. Proportions of size fractions in samples of whole milk, %.

In powdered milk production, it is necessary to strictly control the production technology in order to ensure a balance between separate components in the system, and to ensure the product's digestibility. One way of attaining natural-product properties for reconstituted milk is to achieve the required dispersion state for the system components. Fig. 3 shows the particle size for the reconstituted reference milk sample and the sample with ultrasonic treatment, determined for different time exposures.

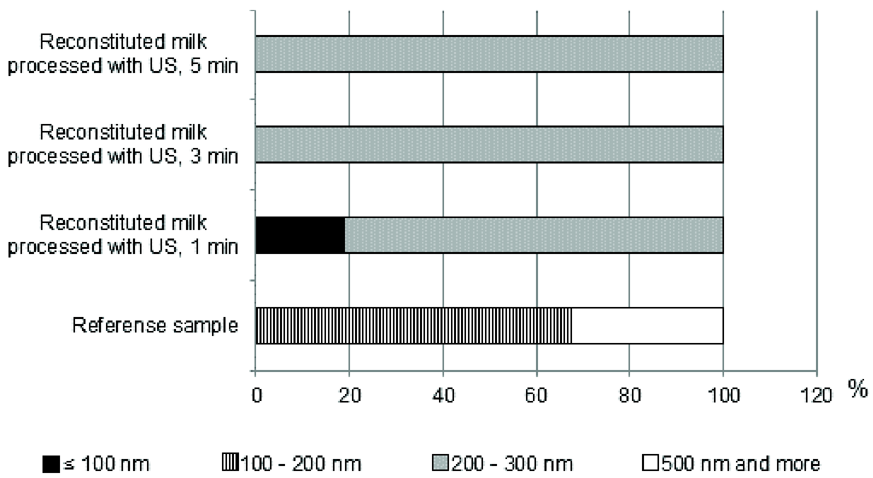

Figure 3. Proportions of size fractions in samples of reconstituted milk, %.

As can be seen from the dispersion analysis data, the structure of reconstituted milk is a composite polydisperse system which is characterised by the presence of various size particles. The reference sample is characterised by the availability of two size fractions: about 41% of the particles have an average size of 409 ± 62 nanometres, and 53% have an average size of 174 ± 18 nanometres; the difference between these values defines the heterogeneity of the system.

Due to the emergence of cavitational processes and additional energy influencing particles of powdered milk, ultrasound exposure facilitates the formation of a uniform milk structure with a particle fraction strictly within 200.2 and 305.6 nanometres, with a prevailing particles size of 202.2 ± 41 nanometres.

It was discovered that ultrasound exposure for one minute reduces the average phase particle sizes by 42.3% and 53.1%, and ultrasound exposure for three and five minutes balances the milk structure to particles of a single size range. At the same time, if the UZV duration is increased (to three and five minutes), the tendency of slight particles to agglomerate in reconstituted milk can be observed, but the 100 nanometres particles fraction had disappeared, even though it had been found in those samples which had been exposed to US for one minute.

Also, it should be noted that the reference sample was reconstituted using a traditional technique, with water preliminarily heated to 38–45 °C. For sample production using ultrasound exposure, the water is not heated, ie. reconstitution occurs only due to mechanical and cavitational effects. Omitting additional heating eliminates the risk of there being any loss of the natural properties (coagulation) in terms of serum proteins, and also the risk of there being a decrease in vitamin content; and besides this, the process makes it possible to intensify technological processes for the manufacture of reconstituted milk products with a decrease in cost, because there is no need to heat the mix.

For the cranberry drink which was produced using ultrasonic treatment, the size range of disperse particles also changes significantly. Particles with a size of 5,670 ± 62 nanometres were detected mainly in reference samples from the extract. For the cranberry drink sample which had been treated with US (for one minute), particles were observed within the range of 743 to 5,200 nanometres, with a dominance of particles of 5,200 ± 41 nanometres (45.6%), and 1,960 ± 42 nanometres (33.1%). An increase in the duration of ultrasonic treatment to five minutes caused the emergence of particles of a size of 236 ± 10 nanometres (11.3%). At the same time, with ultrasonic processing at 180W running for five minutes, agglomeration took place in the cranberry extract and particles were formed of a size of 5,830 ± 30 nanometres.

CONCLUSIONS

The results obtained demonstrate the significant influence of cavitation processes on the dispersion composition of drinks both of vegetable and animal origin.

The dispersion analysis results show that milk, both natural and reconstituted, is very sensitive to ultrasonic cavitation. The fractional composition of cranberries also changed under the influence of ultrasound, enabling a decrease in particle size by 24 times. At the same time, the ability of ultrasound was observed, in some modes, to cause the agglomeration of dispersible particles in the drinks samples. This result shows that ultrasonic cavitation makes possible a reduction in the thermal load of milk's raw materials which will preserve the natural components, providing an alternative to the homogenisation process.

In the production of cranberry drinks, ultrasound is able to intensify the extraction processes via the additional refinement of plant cells, and to improve the consumer appeal of the drinks, which are also positive factors when it comes to manufacturing technology in general.

ACKNOWLEDGEMENTS. The work was supported by Resolution 211 of the Government of the Russian Federation and Agreement № 02.A03.21.0011. Studies were carried out with financial support from the Assistance Fund of the UMNIK Programme. This article was written with support from the Government of the RF (Resolution №211 of 16.03.2013), Agreement № 02.A03.21.0011, and subsidies for the fulfilment of a fundamental part of a state order under Project № 40.8095.2017/BCh.

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