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Impact of acoustic cavitation on food emulsions

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ABSTRACT

The work explores the experimental and theoretical aspects of emulsification capability of ultrasound to deliver stable emulsions of sunflower oil in water and meat sausages. In order to determine optimal parameters for direct ultrasonic emulsification of food emulsions, a model was developed based on the stability of emulsion droplets in acoustic cavitation field. The study is further extended to investigate the ultrasound induced changes to the inherent properties of raw materials under the experimental conditions of sono-emulsification.

1. Introduction

Emulsions are obtained by mixing of two or more immiscible liquids, in which one is dispersed (the dispersed phase) into another (the continuous phase) in the form of very small droplets. Examples of emulsified products include margarine and low-fat spreads, salad cream and mayonnaise, meat sausages, ice-cream and cakes. Two types of relatively simple liquid–liquid emulsions are oil-in-water (O/W) (for example, milk) and water-in-oil (W/O) (for example, margarine) in comparison to cake and mayonnaise which are multiple emulsions. Meat emulsions are ground meat containing a mixture of water, protein, fat, salt and small amounts of other ingredients [1–3] which are important human diet. The role of food industry is to provide improved bioactives/nutraceuticals in complex food matrices by choosing suitable delivery vehicles including simple solutions, association colloids, emulsions, suspensions, gels, solid matrices etc [4]. Most bioactive/nutraceuticals have poor water solubility and hence new approaches of delivering them in the form of emulsions are growing [5,6]. Researchers have identified the use of ultrasound (US) for creating emulsions in food. Much of the existing research work in the area of ultrasonic emulsification has focused mainly on simple matrix such as an emulsion of sun flower oil in water [7–10]. Delivery of nutraceuticals in milk and juice has recently been reported [11]. The application of US in food processing is discussed in several review articles [12–18]. They have discussed its usage in a range of processes such as extraction, food analysis and quality control, microbial cell reduction, meat tenderization, filtration, viscosity reduction, enzyme inhibition, drying, osmo-dehydration and crystallization. US emulsification is used in liquid food processing and only limited number of reviews exclusively focus on the "emulsification capability" of US in broader areas involving pharma, food and chemical systems [19,20].

The purpose of this work is to provide theoretical and experimental approach to deliver stable emulsions of bioactives in simple and complex food matrices, viz., sunflower oil in water and meat sausages by using US. In addition, the possibility of the physical effects of US affecting the inherent properties of the food system during the emulsification process is also discussed.

2. Experimental section

Meat samples were prepared from ground meat (50% beef, 50% pork) of regular as well as PSE (pale soft exudative) and DFD (dark

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firm and dry) quality. The amount of brine (NaCl) in meat samples was adjusted to the value of 3.85 g per 100 g. Brine treatment was carried at ambient temperature for 30 min. Water holding capacity was evaluated as described below: weighed test tubes with meat samples were placed in water a bath and kept for 20 min at 98 °C, upon cooling to ambient temperature released moisture drops were collected with filter paper and test tubes were re-weighed. All chemicals for brine preparation were purchased from fosfate-ABASTOL and were the purest grade available. Bottled drinking water was used in all experiments. Ultrasound treatment of water was carried at operating frequency of 20 kHz. pH measurements were performed on pH-213 (Hanna Instruments, Germany). Standard viscometer (A&G, Japan) was used to measure absolute viscosity.

All parameters for brine processing reactor such as ultrasound intensity, frequency, and flow rate based on dissolving ability of US treated water were previously optimized and reported elsewhere [21,22]. It is also important to note that experimental conditions were set up in such a way that final meat product would not contain more than 10% of brine by volume. The brine was treated in brine processing reactor with a piezoceramic converter, with the capacity of 5 l/min, and subject to the recipe the brine was added at the first chopping stage. The received minced sausage was formed in a nylon cover, compressed within 2 h and then exposed to thermal treatment in the modes provided by the regulatory documentation (GOST R 52196-2011).

"Milk" complex supplement consisting of phosphates, sodium glutamate, sodium erythorbate, natural colorant and extracts of spices was also added at the first chopping stage. The brine prepared in the ratio of 1:12 (culinary salt:water) was used in the test sample.

A thermostated SV-100 vibroviscosimeter (manufactured by A&G Co., Japan, measurement range from 1 to 100 Pa s, the temperature in the cell comprised 85 °C) was used to measure the viscosity at various temperatures. The data were recorded on a PC and processed by Excel software. SV-100 vibroviscosimeter was selected because viscosity measurement by this device does not lead to the destruction of the forming structure as opposed to coaxial-cylinder viscosimeters.

3. Results and discussion

The preparation of food emulsions using acoustic cavitation is widespread as a basic technique to upgrade the quality of finished products, improve their organoleptic characteristics and boost economy of the production process. Two approaches to the ultrasonic preparation of food emulsions were considered:

(1) direct sonication of the system by immersion of the operating tool of the ultrasonic oscillatory system (radiator) into a medium containing disperse and continuous phases, and generation of emulsion by acoustic cavitation;
(2) cavitation activation of the continuos medium (for example, brines, syrups, etc.) in the cavitation reactor, as a result of which water acquires unique properties related to its structural changes.

In order to determine optimal conditions for ultrasonic emulsification of food emulsions (approach 1: sunflower oil in water), an emulsion drop decay model in an acoustic cavitation field was developed. The model is based on the droplet deformation Eq. (1), a mathematical model developed by Taylor [23]. The surface of a droplet is presented as a load with weight m on a spring (equivalent to surface forces) with a damping device (equivalent to viscosity of the disperse phase):

$$m\ddot{x} = F - kx - d\dot{x}, \tag{1}$$

where m – drop weight in kg; F – external force acting on the drop from the side of the fluid flow, N; k – elastic coefficient of the drop, n/m; d – damping coefficient of the drop, kg/s; x – deformation value, m.

The elastic coefficient of the drop is calculated by the following formula:

$$\frac{k}{m} = C_k \frac{\sigma}{\rho_d R^3}, \tag{2}$$

where C_k – proportionality coefficient depending on the drop deformation mode; σ – surface tension on the border of the carrier and the disperse phase interface, N/m; ρ_d – density of the disperse phase, kg/m^3; R – drop radius, m.

The damping coefficient of the drop is calculated by the following formula:

$$\frac{d}{m} = C_d \frac{\mu_d}{\rho_d R^2}, \tag{3}$$

where C_d – proportionality coefficient depending on the drop deformation mode; μ_d – viscosity of the disperse phase, Pa s.

At ultrasonic cavitation external force F is proportional to the pressure amplitude of the shock waves generated on cavitation bubble collapse.

The solution to differential Eq. (1) allows to find the maximum drop deformation value and to determine its potential decay. Subject to the earlier published work [23], if maximum drop deformation exceeds one fourth of its diameter d, the drop is decayed into 2 equal drops with the diameter of $\frac{d}{\sqrt[3]{2}}$.

Therefore, the dependence of the drop diameter on time is described by the following differential equation:

$$\frac{\partial d}{\partial t} = dt_{bu}(d) \ln \frac{1}{\sqrt[3]{2}} \tag{4}$$

where $t_{bu}(d)$ – dependence of the individual drop decay time on its diameter.

The dependence of the individual drop decay time on its diameter is determined as follows. Subject to Eq. (1), the maximum drop deformation value is proportional to the external force acting on the drop from the side of the fluid flow. This force is proportionate to the shock wave pressure amplitude [24], when it reaches the drop's surface. Whereas the drop is decayed only when its maximum deformation exceeds a half of its radius, the decay will accordingly pass when the shock wave pressure amplitude near the drop's surface exceeds some threshold value.

It means that the drop will decay on the impact of cavitation bubbles formed around it due to diffusion of the shock wave as shown in Fig. 1.

Based on the above mentioned layout, the drop decay time is determined by the interval, during which at least one cavitation bubble is formed in area V_b.

The time interval of bubble formation resulting in the drop decay is calculated on the basis of the probabilistic approach using the formula mentioned below:

$$t \approx \frac{T}{nV_b}, \tag{5}$$

where n – number of cavitation bubbles determined as reported earlier [25], m^{-3}; T – bubble collapse period, s; V_b – volume of the area of bubble collapse leading to the drop decay, m^3.

The drop decay time calculated by Eq. (5) allows to find the dependence of the drop diameter on time (Fig. 2) at emulsification of exemplary food emulsion "sunflower oil in water". The physical