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Novel hydrothermodynamic food processing technology

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ABSTRACT

A novel hydrothermodynamic (HTD) technology for simultaneous crushing, homogenizing and pasteurization of whole food in a turbulent flow as a single-unit operation was developed. The HTD technology is based on the phenomena of high turbulence and cavitation in viscous liquids. HTD differs from hydrodynamic (HD) cavitation because it fully utilizes heat generated in the turbulent flow for product pasteurization. Pilot-scale HTD processing of whole blueberry resulted in homogeneous suspension with 13% solids, 1.45–2.76 Pa s viscosity, stable texture and low sedimentation. HTD processing minimized effect of thermal degradation of bioactive phenolics and increased shelf-life of pasteurized blueberry food. Pasteurization at 95 °C provided <10 CFU/g microbial load, which was satisfactory for long-term storage. This research proved the potential of HTD technology for manufacturing of innovative natural whole foods with high nutritional and nutraceutical values.

1. Introduction

Global demand for health promoting foods with high nutritional and nutraceutical values is increasing (Bagchi, 2008). It is estimated that by 2020, the global market for whole and functional foods will reach US $800 billion (Drouin and Gosselin, 2002). This trend requires the development of novel minimal processing technologies. Most of conventional food processing technologies are based on contact heating and involve multiple processing steps that introduce fruit to the atmosphere and therefore accelerate oxidation. Although high temperature short time (HTST) pasteurization and ultra-high temperature (UHT) sterilization could reduce effect of oxidation due to decreasing time of exposure (Lozano, 2006), they are successfully used only for low-viscosity foods, like milk and fruit juice, but not very efficient for processing of viscous foods, like thick juice, sauce or puree.

“No additives and preservatives “and “pure natural” food concepts led to the development of novel technologies that are able to keep food safe and fresh with minimal thermal processing. Several non-thermal processing techniques were recently introduced; in particular, high pressure processing (HPP), pulsed electric field (PEF), ultrasonic and irradiation (Knorr et al., 2011). HPP is the fastest developing option that emerged in food processing in the last 5–10 years. In HPP, food in sealed container is subjected to a high hydrostatic pressure over time, which inactivates most of microorganisms and prevents oxidation (Briones-Labarca et al., 2011; Vázquez-Gutiérrez et al., 2011; Oey et al., 2008). More than 100 food companies around the world have already implemented HPP to produce premium juices and other products with unique functional and nutritional properties. Another alternative is PEF technology with short high energy electric pulses, resulting in electric shock waves in the liquid that damage cell membranes (Martín-Belloso and Soliva-Fortuny, 2011). However, it was acknowledged that PEF could not provide food sterilization that is often required for industrial applications (Lelieveld et al., 2001). The same conclusion was made about ultrasonic, which could provide partial microbial inactivation only in combination with thermal treatment (Chandrapala et al., 2012). Food irradiation partially destroys harmful pathogens by damaging proteins and DNA; however, there is concern on the food safety after exposure to radiation (Junqueira-Goncalves et al., 2011). All these novel techniques share common characteristics, in particular very high energy inputs that damage foodborne pathogens, which will also increase the cost of processing.

Yet another underexplored food processing technology is hydrodynamic (HD) cavitation (Gogate, 2011). Cavitation is defined as the phenomenon of the formation, growth and collapse

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Abbreviations: FBDG, Food Based Dietary Guidelines; C3G, cyaniding-3-glucoside; GAE, gallic acid equivalent; HD, hydrodynamic; HPP, high pressure processing; HTD, hydrothermodynamic; HTST, high temperature short time; ORAC, oxygen radical absorbance capacity; PEF, pulse electric field; UHT, ultra high temperature; US, ultrasonic.

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of cavities occurring over an extremely small interval of time (milliseconds), releasing large magnitudes of energy at the location of transformation (Rayleigh, 1878). It was assumed that cavitation on the microscopic level is accompanied by high pressure and temperature gradients in the range of 100–5000 bar and temperature gradients in the range of 1000–10,000 K (Suslick, 1990). However, this assumption was not experimentally proven with direct measurements. On the macroscopic level cavitation is characterized by a dimensionless cavitation number *Ca*. This number expresses the relationship between the pressure gradient and kinetic energy per volume, indicating the potential of the flow to cavitate (Batchelor, 1967):

$$Ca = \frac{p - p_v}{0.5\rho V^2} \tag{1}$$

where p is pressure of the liquid, p_v is a vapor pressure, ρ and V are density and characteristic velocity of the moving liquid.

According to Eq. (1), cavitation number is mostly determined by the flow velocity and pressure gradients. Usually, cavitation occurs at $Ca \leqslant 1$ with the best operational conditions in the range of 0.1–1 (Gogate, 2011). Cavitation requires the low pressure and high velocity of the moving liquid. Minimum flow velocity, causing cavitation, is calculated as:

$$V = \sqrt{\frac{p - p_v}{0.5\rho}} \tag{2}$$

Energy, dissipated in the process of cavitation, is calculated from the pressure drop Δp (Winter, 1987):

$$E = Q \cdot \Delta p \tag{3}$$

Due to the effect of high energy inputs on microbial cells disruption, HD cavitation could be used for food pasteurization (Arrojo et al., 2008; Milly et al., 2007). However, mechanical erosion of contact surfaces is the challenge for HD applications in industrial settings. For example, cavitation in high-shear blenders leads to quick wearing of moving parts (Chatterjee and Arakeri, 1997). Vortex cavitation addresses the problem of mechanical erosion by focusing turbulence/cavitation in the center of the stream. Shear forces are due to liquid–liquid friction, which minimizes friction on the interface. Due to the viscous dissipation, cavitation energy is directly converted into heat. The average temperature increase for adiabatic pipe flow is calculated from equation (Winter, 1987):

$$\Delta T = \frac{\Delta p}{\rho c_p} \tag{4}$$

Heat, generated on the microscopic level, provides volumetric heating due to the mechanism of diffusion. High velocity and turbulence of the flow, circulating in closed loop, facilitate heat transfer. As a result of forced heat diffusion in turbulent flow, thermal energy is distributed uniformly in the stream within seconds. The entropy of moving liquid is increasing. This combined effect of cavitation and volumetric heating in the moving liquid could be defined as hydrothermodynamic (HTD) effect. However, to our knowledge, there is no research on the synergetic effect of cavitation and heat on biochemical, physical and microbiological properties of foods.

This research aims to fill this gap in knowledge. The effect of novel HTD technology on food properties was evaluated using wild blueberries, which are rich source of bioactive phenolics, such as anthocyanins, flavonoids and phenolic acids with health-promoting effects (Wu and Prior, 2005; Basu and Lyons, 2012). Most of them are located in the fiber matrix (Parada and Aguilera, 2007) and could not be extracted in juice cold pressing (Satanina et al., 2014). At the same time, bioactive phenolics are very sensitive to matrix disintegration. Once fruit is crushed, the enzyme polyphenol oxidase (PPO), initially separated from vacuolar phenolics in intact cell, becomes available for phenolic oxidation. Temperature is another significant factor of polyphenol degradation. Negative effect of thermal processing on blueberry phenolics was reported by Skrede et al. (2000), Lee et al. (2002), and Brownmiller et al. (2008). For example, Lee et al. (2002) reported 87% anthocyanin degradation in clarified pasteurized juice; and Satanina et al. (2014) reported only 43% retention of anthocyanin in thermally processed berries compared to 81% retention in berries processed using the HTD technology. Heat accelerates chemical and enzymatic oxidation, which is perceived as a problem in manufacturing health promoting fruit-based foods with acceptable shelf life (Srivastava et al., 2007).

The hypothesis of this research was that simultaneous crushing, agitation and heating of whole blueberries would release bioactives from the matrix, while reduced oxygen environment would protect them from oxidation. To test this hypothesis, we evaluated effects of HTD processing on the quality and shelf-life of processed blueberry.

2. Materials and methods

2.1. Experimental apparatus

Food processing was done using a pilot-scale HTD processor, initially designed for crushing and dispergation of plant seeds (Osipenko, 2008). The physical principle of HTD is based on phenomena of high turbulence and cavitation in viscous liquid (Fig. 1).

High turbulence in active area (cavitation zone) was created due to a number of parallel bypass pipes of a smaller cross section (nozzles), adapted to take the liquid from the mainstream and return it back as a disturbing stream (Osipenko, 2008). Liquid at high velocity enters cavitation zone, where the disturbing streams induce local turbulence that generates multi-phase cavitation bubbles (nuclei). In this way, cavitation is focused on the center of the stream, preventing erosion of metal surfaces. Further growth of cavitation nuclei occurs downstream due to the pressure drop at the orifice. Big bubbles are unstable and collapse right after going through the active area of the cavitator. The quick collapse of the cavitation bubbles creates local shear forces and releases energy for crushing, homogenizing and heating of the fluidized product. The primary advantage of HTD for whole food processing is volumetric heating, leading to uniform product pasteurization and thermal inactivation of enzymes. Single-unit operation minimizes product deterioration by excluding multiple processing steps. A prototype of pilot-scale HTD processor (Tekmash, Ukraine) is shown in Fig 2. It consists of the tank (1), electric motor (2), centrifugal pump (3), pressure gauges (4), temperature sensors (5), cavitator (6) and pressure relief valve (7).

The pilot-scale processor was designed for batch operation. The capacity of the processor, including free volume of tank and pipes, was 5.5×10^{-3} m^3. Three-phase AC electric motor (2.2 kW, 1500 rpm) was connected to centrifugal pump. The pump with outlet pressure of 1.41 MPa provided circulatory motion of the liquid product with flow rate of 0.5×10^{-3} m^3/s (Osipenko and Lesnikov, 2009). With 38 mm diameter of main pipe, velocity of the liquid was 0.45 m/s, reaching 1.5 m/s in the active area of cavitation. Reynolds number depended on product viscosity and velocity. For liquid blueberry, it was in the range from 0.52 to 0.92×10^5, reaching 6.5×10^5 in the active area of cavitation. Due to the high turbulence, mechanical energy of the stream was converted into heat and accumulated in a form of thermal energy. After each cycle of the circulatory motion, the temperature of the liquid product increased from 0.2 to 0.3 °C. The food temperature