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Nano-fluid thermal processing of watermelon juice in a shell and tube heat exchanger and evaluating its qualitative properties

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ABSTRACT

Due to specific thermophysical properties of nanofluids, compared with conventional thermal fluids (steam and hot water), their application in diverse industries, to improve heat transfer and to save energy, has increased. One important aspect of applying nanofluid thermal processing is shortening the process time which could have high potentials in the food industry since nutritional and bioactive components would be maintained much higher than common thermal processes. In this project, possibility of replacing water with alumina-water nanofluids (2 and 4% concentrations) during high temperature short time processing (75, 80 and 85 °C for 15, 30 and 45 s) of watermelon juice in a shell and tube exchanger regarding its qualitative properties (lycopene, vitamin C, color, pH and TSS) was investigated. Reduction in process time when applying 2 and 4% nanofluids, up to 24.88 and 51.63%, had considerable effects on maintaining qualitative properties for watermelon juices. For instance, thermal processing by 0, 2 and 4% nanofluids at 75 °C for 15 s could keep 81.15, 84.81 and 91.28% of lycopene and 61.11, 63.70 and 67.04% of vitamin C, respectively. pH and TSS indices of processed watermelon juices were in the range of 5.58–5.82 and 9.0–9.4, respectively, showing no considerable correlation with the heating media used in thermal processing. Our results revealed that nutritional and physicochemical properties of watermelon juice processed with alumina nanofluids were better than common thermal processing by water with 9.89, 6.18 and 50.38% higher lycopene, vitamin C and color retention in the final product, respectively.

Industrial Relevance: Even so thermal processes are effective in preventing microbial spoilage of fruit juices, high volume of energy transfer in long durations into food products with heat sensible ingredients or properties results in biochemical and nutritional losses, development of unpleasant reactions, changes in overall quality of food products, and high energy consumption. Nowadays, consumers demand for food products with long shelf lives, high quality and proper prices are increasing. So, to meet these demands, food industries are looking for alternative thermal technologies to reduce losses in food characteristics and process costs, and introduce a fresh, nutritious, healthy and affordable food produce.

Thermal conductivity of conventional fluids is much lower than metals and oxidized metals. For example, thermal conductivities of copper and alumina are 700 and 60 times higher than the thermal conductivity of water, respectively. Accordingly, fluids with suspended particles of metals or oxidized metals benefit from better heat transfer properties. The term of Nanofluid refers to each stable two-phase compound that includes both base fluids and nanoparticles (lower than 100 nm, at least in one dimension).

There is no research dealing with effects of adding nanoparticles to conventional thermal fluids for fruit juices processing. So, the goal of this research was to introduce nanofluid technology for thermal processing of food products for the first time, increasing heat transfer efficiency in shell and tube exchangers by nanofluids and frugality in energy consumption for pasteurization, reducing thermal processing duration and better quality retention of food products.

1. Introduction

Fruit juices are usually pasteurized by batch or continuous thermal processes. These processes might be carried out before or after packaging of products in their containers. In batch pasteurization, given volume of products is processed in steel jacketed vessels. These vessels could be used for warming (by steam or hot water) or cooling (by cold water). Continuous pasteurization is implemented by passing fruit

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juices through heat exchangers (including preheating, heating, holding and cooling stages). At now, High Temperature Short Time (HTST) pasteurization is the conventional method for thermal processing of fruit juices, in which temperature of 76.6–87.7 °C is deployed for 25–30 s (Moyer & Aitken, 1980).

Even so thermal processes are effective in preventing microbial spoilage of fruit juices, high volume of energy transfer in long durations into food products with heat sensible ingredients or properties results in biochemical and nutritional losses, development of unpleasant reactions, changes in overall quality of food products, and high energy consumption (Chen, Shaw, & Parish, 1993; Dehnad, Jafari, & Afrasiabi, 2016). Nowadays, consumers demand for food products with long shelf lives, high quality and proper prices are increasing. So, to meet these demands, food industries are looking for alternative thermal technologies to reduce losses in food characteristics and process costs, and introduce a fresh, nutritious, healthy and affordable food produce (Espachs-Barroso, Barbosa-Canovas, & Martin-Belloso, 2003; Hendrickx & Redd, 1995).

Watermelons are composed of about 93% water, 6.4% carbohydrates, 590 IU vitamin A and 8.1 mg/100 g vitamin C. Lycopene as a carotenoid is a strong antioxidant and responsible for the red color of watermelon (Rao & Agarwal, 1999). Watermelon contains about 2.3–7.2 mg/1000 g lycopene, which is among rich resources of this bioactive colorant and could be a suitable substitute for tomato products. Not only is lycopene in watermelon 40% higher than its content in raw tomato, but also its absorption is higher than lycopene in tomato (Fish, Perkins-Veazie, & Collins, 2002). Also, watermelons contain vitamin C, an essential substance to synthesize collagen and to protect our body against oxidative damages (Block, 1991; Fontham et al., 1988; Ness, Khaw, Bingham, & Day, 1996).

Consumers' demands for functional foods led to producing derivatives of watermelon juices. These products supply antioxidants, vitamins and other nutritious and functional compounds which provide excellent sensorial and nutritious characteristics (Stern, 1998). However, considering low acidity and suitable conditions for microorganisms' growth, watermelons juices should be pasteurized before consumption. Color is the first factor affecting consumers' decisions when purchasing; thus, fruit juices are usually packaged in transparent bottles (Khanzadi et al., 2015). But, thermal pasteurization might influence color and appearance of fruit juices adversely by colorants degradation. Also, heat sensitive vitamin C contents dwindle during pasteurization of watermelon juices. Replacing conventional thermal fluids (steam or hot water) with nanofluids might be an appropriate solution to remove these problems.

Thermal conductivity of conventional fluids is much lower than metals and oxidized metals. For example, thermal conductivities of copper and alumina are 700 and 60 times higher than the thermal conductivity of water, respectively (Heris, Etemad, & Nasr Esfahani, 2006). Accordingly, fluids with suspended particles of metals or oxidized metals benefit from better heat transfer properties (Lee, Choi, Li, & Eastman, 1999). This term was used for the first time by Choi (1995) who called suspensions of nanopowders in fluids as nanofluids and put forward their distinctive properties. The term of Nanofluid refers to each stable two-phase compound that includes both base fluids and nanoparticles (lower than 100 nm, at least in one dimension).

Recently, Longo Giovanni, Righetti, and Zilio (2016) developed a new raw milk dispenser based on nanofluid technology, although they focused merely on time and energy savings of their systems, and not quality aspects of the product. They concluded that their system could achieve 63–70% energy savings compared with traditional system; besides, the duration required by the new system to complete the process was half the time required by the traditional one. Also, Jafari, Jabari, Dehnad, and Shahidi (2017a, 2017b) investigated heat transfer enhancement in nanofluids processing of tomato juice. They applied three different variables of temperature (70, 80, and 90 °C), alumina nanoparticle concentration (0, 2, and 4%), and time (30, 60, and 90 s) and showed that time reduction, brought about by nanoparticle incorporation, caused energy saving rates of 22.3 and 48.76% for 2 and 4% nanofluids, respectively. However, there is no research dealing with effects of nanofluids, compared with conventional thermal fluids, on qualitative properties of fruit juices. So, the goal of this research was to introduce nanofluid technology for thermal processing of food products for the first time, increasing heat transfer efficiency in shell and tube exchangers by nanofluids and frugality in energy consumption for pasteurization, reducing thermal processing duration and better quality (lycopene, vitamin C, color, brix, pH and total microbial count) retention of food products.

2. Materials and methods

2.1. Preparing the product

Fresh watermelons (*Citrulus lanatus*) were purchased from a local market (Gorgan, Iran) and stored in a cool and dark place. Watermelon rinds were washed with pure ethanol before juice extraction. Watermelons were cut into two parts, and the flesh was scooped out and cut into small cubes. The cubes were placed in a juice processor (Hamilton model No. FH–145). Extracted juice was filtered through six layers of cheese cloth (VWR, West Chester, PA), processed immediately by HTST method (76.6–87.7 °C, 25–30 s) after putting in autoclaved screw–top glass bottles, and then placed inside an ice bath (Alam, Hoque, Morshed, Shahriar, & Begum, 2012).

2.2. Nano-fluid preparation

Alumina nano-particles with 99% purity (US research nano-materials, Inc.) were purchased and dispersed with different volume concentrations of 0, 2 and 4% W/V in deionized distilled water according to our previous study (Jafari, Saremnejad, Dehnad, Rashidi, 2017). Details of nanoparticles characteristics have been represented in Table 1. Then, it was stirred completely for an hour with a heater-stirrer at 1500 rpm in order to ensure nano-fluid stability. No sedimentation was observed in the prepared nanofluid after 24 h.

2.3. Intelligent thermal processing system

This system contains a shell and tube heat exchanger, two separate reservoirs, one for a liquid food, and the other one equipped with a 1 kw heater for heating the fluid (water or nano-fluid) and flow loop tubes for transferring the fluids from the reservoir to the heat exchanger. All the components were made of 316 L stainless steel, and were insulated with aluminum foam to reduce heat loss. Required power to overcome the pressure drop was supplied by two 0.55 kw steel centrifugal pumps (3 pH. induction motor, Western Electric, Australia). Control, return and drain valves were installed in proper places. Heating performance and temperatures of nano-fluid and liquid foods were controlled by thermocouples to regulate fluids flow (Fig. 1a) (Jafari et al., 2017a, 2017b).

Nanofluid and food liquid exchanged their thermal energy through passing 13 tubes with external diameter, thickness and length of 8, 2 and 800 mm (respectively) and passing a shell with internal diameter of 100 mm in a countercurrent way. Controlling flow speed of two fluids

Table 1
Thermophysical Properties of alumina nanoparticles and base fluid of water.

Properties	Alumina	Water
Average particle diameter (nm)	50	0.384
Density (kg m^{-3})	3880	971
Heat capacity (J kg^{-1} K^{-1})	773	4197
Thermal conductivity (W m^{-1} K^{-1})	36	0.669