Journal of Food Engineering 119 (2013) 627–632

Contents lists available at SciVerse ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Effect of low frequency, high power pool ultrasonics on viscosity of fluid food: Modeling and experimental validation

Monica Anese [a], Maria Valeria De Bonis [b], Giorgio Mirolo [a], Gianpaolo Ruocco [b,*]

[a] Dipartimento di Scienze degli Alimenti, Università degli Studi di Udine, Via Sondrio 2/a, Udine 33100, Italy
[b] CFDfood, Scuola d'Ingegneria, Università degli Studi della Basilicata, Campus Macchia Romana, Potenza 85100, Italy

ARTICLE INFO

Article history:
Received 19 January 2013
Received in revised form 22 May 2013
Accepted 17 June 2013
Available online 2 July 2013

Keywords:
Ultrasonics
Viscosity
Non-newtonian
Natural convection
Tomato puree
Computational fluid dynamics

ABSTRACT

Ultrasound induced changes of certain physical and chemical properties of molecules are nowadays exploited at industrial level for food processing and preservation purposes. Deeper knowledge on the mechanisms influencing these changes would contribute to extend implementations of ultrasound to steer structure and functionality of food molecules.

In this study the laws of transfer phenomena were applied in order to investigate on the viscosity changes of a pectin-containing fluid flow, i.e. tomato puree in a cylindrical reactor, induced by low frequency, high intensity ultrasound treatments. In particular, the model for fluid motion was associated to a validating rheological investigation.

Results showed a good agreement between experimental and computational data for temperature and viscosity progresses with time. A new power law for viscosity has been proposed based on reactor aspect ratio and Rayleigh numbers for natural convection.

1. Introduction

Food viscosity is an important processing and formulation parameter, as it may affect some unit operations, such as piping and mixing, as well as the rheological properties of the final product. As well known, viscosity is influenced by physical and chemical properties of polymers naturally contained in the food matrix (e.g. molecular weight, nature and number of functional groups, their position in the molecule).

Preliminary results have shown that ultrasounds (US), that are already applied for food processing and preservation (e.g. emulsification, homogenization, extraction, freezing, etc.), can induce changes in the physical properties (e.g. viscosity, water binding capacity, etc.) of biopolymers such as pectin, starch and proteins (McClements, 1995), to obtain ingredients or semi-manufactured products with tailored functional characteristics. Such effects are due to the cavitation phenomenon, which is the spontaneous formation and collapse of bubbles, that leads to the generation of local extreme temperatures and pressures, that in turn produce intense shear energy waves and turbulence in the vicinity of the material (Mason, 1998; Barbosa-Canóvas and Rodríguez, 2002).

The structural modifications of biopolymers are reported to highly depend on the US intensity and material nature (Vercet et al., 2002a; Tiwari et al., 2010). In particular, power US may cause opposite effects on macromolecules. For instance, pectin, starch or protein containing systems that were exposed to high values of power showed a viscosity decrease due to depolymerization (Seshadri et al., 2003; Jambrak et al., 2009; Zuo et al., 2009). On the contrary, a viscosity increase (fluid thickening) was observed in food matrices such as tomato puree and yoghurt (Vercet et al., 2002a,b; Wu et al., 2008; Anese et al., 2013). It has been speculated that reducing the polymer size would liberate macromolecules and subsequently more polymer chain would be available for bonding (Seshadri et al., 2003). As a consequence US treatment can give rise to a different type of network, which is accompanied by an enhancement of the rheological properties.

The aim of the present paper was to study the interdependence of low frequency, high power US induced viscosity changes and flow field during treatment of a pectin-based fluid food, such as tomato puree. Most of the world's tomato crop is processed into tomato derivatives, such as tomato juice, paste, concentrate and powder (Gould, 1991). Tomato products are sold as convenient food in pre-packed packages or used as ingredients for the manufacture of a wide range of formulated foods.

In exploring the erratic nature of pool US or sonication, it is important to know the active bubbles generation and stronger cavitation patterns (Gogate et al., 2002), but the application of transfer phenomena laws is the key to macromolecular physical properties determination. In particular, process modeling by the Computational Fluid Dynamics (CFD) of the subject Non-Newtonian fluid

* Corresponding author. Tel.: +39 0971 205454; fax: +39 0971 205461.
E-mail address: gianpaolo.ruocco@unibas.it (G. Ruocco).

0260-8774/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jfoodeng.2013.06.020

Nomenclature

c_p	specific heat (J/kg K)
$\mathbf{g}$	gravitational acceleration (m/s^2)
H	vessel height (mm)
k	thermal conductivity (W/m K)
m	consistency index (Pa s^n)
n	power law index
p	pressure (Pa)
$\dot{Q}$	nominal acoustic power (W)
$\dot{q}$	power density (kW/m^3)
R	universal gas constant (kJ/mol K)
Ra	Rayleigh number
t	time (s)
T	temperature (°C)
$\mathbf{u}$	velocity vector (m/s)

Greek

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (1/K)
$\dot{\gamma}$	shear rate (1/s)
η	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
τ	shear stress (Pa)

Subscripts

0	initial, apparent
d	deep geometry
s	shallow geometry
∞	operating parameter

may be useful in assessing the process efficiency and helping establish the optimal configuration parameters.

Lei et al. (2006) introduced an acoustic streaming formulation in determining fluid motion by numerical techniques, including the buoyancy force due to horn heating. Their results focussed on flow fields and heat transfer, but no effects on rheology are reported. This limitation is also found in Laborde et al. (2000), where fluid dynamics phenomena and cavitation induced by power US have been studied, only. A wave equation formulation was then exploited by Klíma et al. (2007), but the flow patterns and their effects on fluid behavior were left unexplored. A similar approach was tried by Kumaresan et al. (2007), who complemented the computational aeroacoustics method with a number of turbulence paradigms. Their work confirmed the highly non-uniform nature of the situation at stake, but did not dig into the fluid alterations. In Xu et al. (2013), the flow field generated by a transducer at frequency of 490 kHz is simulated, by using a finite elements commercial solver. The model solves the harmonic wave field, following the inhomogeneous Helmholtz equation, to describe the acoustic pressure distribution. This is a complete approach to describe the flow field induced by the acoustic pressure, but the structural change of the liquid sample is neglected.

In this work, the physico-chemical thread leading from power US-induced kinetics changes and structure degradation to tomato puree thickening (structure and functionality) is substituted with a fluid dynamics, classical approach. A momentum and heat transfer model is proposed and solved by a commercial finite elements code, incorporating custom notations for rheology. Upon the inherent volumetric heating, a free convection pattern is established which alters the Non-Newtonian shear rate. Through experimental validation and model optimization, the model is able to simulate the local and mean histories of viscosity, velocity and temperature; a modified power law notation for apparent viscosity is then proposed, depending on US intensity and vessel geometry, shedding light on potential use of CFD to simulate complex rheological US-dependent configurations.

2. Experimental set-up and measurements

2.1. Sample preparation and treatment

Commercial tomato puree rates of 450 g (7.3 ± 0.8% dry matter), previously sieved to remove seeds and coarse particles, were poured into two different glass vessels. A schematic representation of the US reactor is shown in Fig. 1. In particular, one geometry had R = 75 mm and H = 70 mm (hereafter called shallow geometry, s), another had R = 50 mm and H = 120 mm (deep geometry, d).

An ultrasonic processor (Hieschler Ultrasonics GmbH, mod. UP400S, Teltow, Germany) with a titanium horn tip with diameter of 22 mm was used (Fig. 1). Treatments were performed for 15 min at US amplitude and frequency of 100 μm and 24 kHz, respectively. The horn was placed in the centre of the vessel, with an immersion depth in the fluid varying between 10 and 20 mm. In order to minimize water evaporation and promote thermal insulation during sonication, the vessel was closed with a Plexiglas lid fitted with holes allowing horn and thermocouple probes to be placed at the desired positions in the tomato puree. The nominal acoustic power was $\dot{Q} = 400$ W, bringing forth two different power densities: $\dot{q}_d = 425$ kW/m^3 or $\dot{q}_s = 324$ kW/m^3.

Sample temperature was kept at 60 °C during the treatment, by means of a thermostatic bath. The temperature history was recorded using copper-constantan thermocouple probes (Ellab, Denmark) connected to a data logger (CHY 502A1, Tersid, Milano, Italy). In particular, the temperature was measured in three fixed points of the sample mass, sufficiently far one another.

Upon treatment, at fixed times the samples were cooled down to 20 °C in an ice bath. After gentle mixing for thermal homogeneity, 50 g of tomato puree were sampled, immediately assayed for rheological measurements, and disposed of after assessment.

An adequate number of samples were taken as controls, by heating them at 60 °C in the same configuration, with no exposure to US. Both heat and US treatments were carried out in duplicate. By comparing the different treatments it was concluded that

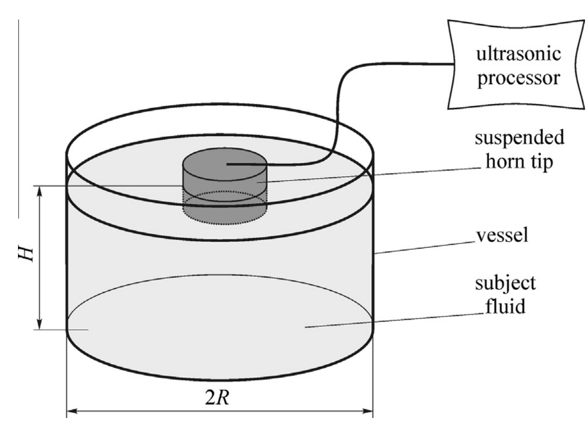

Fig. 1. Schematic representation of the ultrasonic reactor.