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Rheological properties of coarse food suspensions in tube flow at high temperatures

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Abstract

The effects of particle concentration and carrier fluid temperature on rheological behavior of model food suspensions consisting of 1.5% CMC solution and green peas (15–30% v/v) were investigated using a tube viscometer. The flow behavior of the suspensions was represented by the power law model. The suspension consistency coefficient (m^*) increased with particle concentration and decreased with temperature, whereas the opposite trends were observed for the suspension flow behavior index (n^*). Among various theoretical, semi-empirical, and empirical equations tested for suspension apparent viscosity (μ^*) estimation, the third order expansion of Einstein equation, which was derived via the hydrodynamic approach, provided the best estimates for μ^*. Of equations tested for m^* estimation, those in which n^* was included offered better estimates of experimental values, with an empirical equation obtained based on the Einstein equation and the incorporation of n^* term providing the best m^* estimation. These findings suggest that, for concentrated coarse suspensions subjected to conditions presented here, the dependence between m^* and n^* is of importance and should be considered in order to achieve a better m^* estimation. Besides, better representations for power law parameters of such suspensions may be obtained based on a theoretical expression derived for μ^* via the hydrodynamic approach. The study presented here provides a much-needed insight toward the flow behavior of concentrated coarse food suspensions at high temperature, information of which is vital for various food processes.

Keywords: Non-Newtonian fluids; Rheological properties; Coarse suspension; Particulate foods

1. Introduction

Designing an aseptic process requires information about flow properties of the foods. Flow properties have significant effects on the residence time distribution and heat transfer of the particulate food system as reported by several researchers (Awuah, Ramaswamy, Simpson, & Smith, 1996; Ramaswamy, Awuah, & Simpson, 1996; Sandeep & Zuritz, 1994). A number of studies have been done on rheological behavior of fluid foods and many are summarized by Holdsworth (1971). However, only a few studies on rheological behavior of coarse food suspensions can be found in the literature, especially with the carrier fluids that exhibit non-Newtonian behavior (Bhamidipati & Singh, 1990; Martinez-Padilla, Cornejo-Romero, Cruz-Cruz, Jaquez-Huacuja, & Barbosa-Canovas, 1999; Pordesimo, Zuritz, & Sharma, 1994).

Due to the larger particle size, only few types of viscometers can be used in characterizing the flow behavior of coarse suspensions. These include tube viscometers (Bhamidipati & Singh, 1990), wide-gap parallel plate viscometer (Pordesimo et al., 1994), wide-gap rotational viscometer (Martinez-Padilla et al., 1999). The above-mentioned equipments are although functional, difficulties still exist especially in the studies for dense suspensions. Some of the difficulties could be caused by the interference to the equipment parts by the large particles as reported by Martinez-Padilla et al. (1999), centrifugal effects in the parallel plate viscometer as pointed out by Pordesimo et al. (1994), or simply large amount of materials and floor space required to run the tests using the tube viscometer. This leads to the scarcity of the knowledge on the flow behavior of coarse food suspensions. More insight on the flow behavior of

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Nomenclature

D	tube diameter, m
L	length, m
L_e	entrance length, m
m	fluid consistency coefficient, Pa s^n
m^*	suspension consistency coefficient, Pa s^n
n	fluid flow behavior index
n^*	suspension flow behavior index
P	pressure, Pa
Q	volumetric flow rate, m^3/s
Q_{ws}	volumetric flow rate without slip, m^3/s
Q_m	measured volumetric flow rate, m^3/s
r	tube radius, m
Re	Reynolds number
T	temperature, °C
Greek characters	
β	slip coefficient, m Pa^{-1} s^{-1}
ϕ	particle volume fraction
ϕ_m	maximum particle volume fraction
$\dot{\gamma}$	shear rate, s^{-1}
$\dot{\gamma}_w$	wall shear rate, s^{-1}
μ^*	suspension apparent viscosity, Pa s
μ_f	fluid apparent viscosity, Pa s
μ_r	relative viscosity (μ^*/μ_f)
τ	shear stress, Pa
τ_w	wall shear stress, Pa

coarse food suspensions particularly in the conditions applicable to aseptic processing is clearly desirable. The objectives of this study were (1) to characterize the flow behavior of model food suspensions consisting of non-Newtonian carrier fluid and high concentration of large particulates at high temperatures, (2) to investigate the effect of particle concentration and temperature on flow behavior of non-Newtonian coarse suspensions, and (3) to investigate the applicability of several mathematical expressions in explaining the effect of particle concentration on the flow behavior of coarse suspensions.

2. Materials and methods

2.1. Food system

Green peas were used as model particulate phase because of their commercial availability and their applications in real food in the market. Frozen green peas were purchased from Purdue University food store. Green peas were thawed and drained prior to each experimental run.

An aqueous solution (1.5% w/v) of sodium carboxymethylcellulose (CMC) (TIC Gum, Inc., Belcamp, MD) was selected as the carrier fluid. The CMC solution was prepared by slowly adding the desired amount of CMC powder into a mixing tank filled with water continuously agitated by a mechanical mixer. The mixture was agitated for approximately 45 min then left overnight (12–15 h) for the CMC to dissolve. Prior to the experimental run, the CMC solution was mixed with green peas to attain the specified particle volume fractions (15–30%v/v). Due to the delicate texture of green peas, the CMC-pea suspension was made in several small batches of 0.0379 m^3 to achieve the desired particle concentration. The suspension was mixed manually to ensure the uniform distribution of green peas in the suspension and then delivered into the pump feeder during the experimental run. The physical properties of the food materials are summarized in Table 1.

Table 1
Physical properties of model food system

Property	Value
Green peas	
Average diameter (m)	0.0084 ± 0.0025
Density (kg/m^3)	1026 ± 9.770
CMC solution (1.5% w/v)	
Density (kg/m^3)	1022 ± 5.000

2.2. Experimental setup

The rheological characterization of the fluid food, with or without particulates in aseptic processing conditions was performed using an in-line tube viscometer. The schematic diagram of the experimental setup is shown in Fig. 1. The system consisted of a 150 l feed tank, a moving pocket type pump (Moyno® Product Progressive cavity pump, Robbins and Myers, Inc., Springfield, OH), a helical double tube heat exchanger (46.3 m long, 0.032 m I.D.) as a heater, a helical double tube heat exchanger (33.5 m long, 0.032 m I.D.) as a cooler (Stork, Amsterdam, Netherlands), an electromagnetic flow meter (Promag 33, Endress and Hauser Inc. Greenwood, IN), an insulated straight stainless steel tube (0.022 m I.D.), a differential pressure transducer (Rosemount Model 3051 Smart Pressure Transmitter, Rosemount Inc., Eden Prairie, MN), resistance temperature devices (RTD's), and a programmable logic controller (PLC, 5-15, Allen-Bradley Co., Inc. Milwaukee, WI) for control and data acquisition. The tube viscometer (2.89 m long) is located in the straight tube