Journal of Food Engineering 127 (2014) 16–23

Contents lists available at ScienceDirect

Journal of Food Engineering

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

Inverse method to sequentially estimate temperature-dependent thermal conductivity of cherry pomace during nonisothermal heating

Ibrahim Greiby [a], Dharmendra K. Mishra [a], Kirk D. Dolan [a,b,*]

[a] Department of Biosystems & Agricultural Engineering, Michigan State University, East Lansing, MI 48824, United States
[b] Department of Food Science & Human Nutrition, Michigan State University, East Lansing, MI 48824, United States

ARTICLE INFO

Article history:
Received 15 January 2013
Received in revised form 27 October 2013
Accepted 29 October 2013
Available online 11 November 2013

Keywords:
Cherry pomace
Thermal conductivity
Moisture
Inverse problem
Parameter estimation

ABSTRACT

Fruit and vegetables are a rich source of many bio-active compounds from which value-added nutraceuticals can be produced. The objective of this work was to estimate temperature-dependent thermal properties of cherry pomace. Differential scanning calorimetric was used to estimate the specific heat. Samples of tart cherry pomace at different moisture contents were canned and heated at 126.7 °C in a steam retort. Ordinary least squares and sequential estimation methods were used for estimating the parameters in MATLAB with Comsol. Thermal conductivity at 25 °C (k_1) and 125 °C (k_2) during 90 min heating for 70%, 41% and 25% MC were: 0.49 and 0.55; 0.20 and 0.39; and 0.15 and 0.28 W/m °C, respectively, with errors less than 3%. Results are useful for (a) processors desiring to use cherry pomace to make value-added by-products at elevated temperatures common in extrusion and other food drying methods; and (b) researchers desiring a convenient, rapid method to estimate thermal properties of thick and solid foods at elevated temperatures under dynamic conditions.

1. Introduction

Thermal processing of foods involves heating to temperatures typically from 50 to 150 °C. Anthocyanin stability is a main focus in many studies. This stability is not only a function of final processing temperature but also of other properties (intrinsic) like pH, storage temperature, product moisture content, chemical structure of the anthocyanins and its initial concentration, light, oxygen, presence of enzymes, proteins and metallic ions (Patras et al., 2010). There are many studies examining these factors individually or a combination of one or more of them on degradation of food components. There is limited information available on the effect of high temperature processing at different moisture contents on the stability of these pigments in solid food products. A challenge in collecting this information is the confounding decrease in moisture during heating at temperatures greater than 100 °C. A study on the change in physical properties of ground beef during cooking showed that thermal conductivity of ground beef varied between 0.35 and 0.41 W/m °C in a temperature range of 5–70 °C (Pan and Singh, 2001). Many studies have been done on this subject for estimating these properties for different kinds of food materials. Some studies used measured temperature profiles for estimation of the thermophysical properties in inverse heat conduction problems (Beck and Woodbury, 1998; Yang, 1998). Estimation methods for thermal conductivity are classified into two main methods: steady- and transient-state heat transfer methods. Steady-state methods require long times, and moisture content changing with time introduces significant error (Dutta et al., 1988).

Equations (quadratic models) were developed for predicting thermal conductivity of a meat with a given water content and temperature at different ranges (Rahman, 1992; Sweat, 1975). Thermal conductivity of carrot and potato (solid food) were measured as well, using the probe method at a temperature range 30–130 °C. A correlation equation was established for predicting the thermal conductivity (Gratzek and Toledo, 1993). The thermal conductivity of porous foods, which have complex structure is difficult to predict (Sweat, 1995).

Specific heat of borage (Borago officinalis) seeds was measured by differential scanning calorimetric (DSC) and ranged from 0.77 kJ/kg K to 1.99 kJ/kg K. The thermal conductivity increased with moisture content and contributed the most to the uncertainty of thermal diffusivity. A quadratic equation was established for estimating these thermal properties (Yang et al., 2002). A study on wheat, corn and rice flour proposed an equation to predict the specific heat of these products as function of temperature,

* Corresponding author. Address: Department of Food Science & Human Nutrition, Michigan State University, 135 Trout Food Science Building, East Lansing, MI 48824, United States. Tel.: +1 517 355 8474x119; fax: +1 517 353 8963.
E-mail address: dolank@msu.edu (K.D. Dolan).

0260-8774/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jfoodeng.2013.10.039

Nomenclature

Cp_s	specific heat of sample (J/g °C)
Cp_{st}	Sapphire specific heat (J/g K)
H	length of the cylinder (can), m
H_r	heating rate (10 °C/min)
H_s	heat flow of sample (mJ/s)
H_{st}	heat flow of Sapphire (mJ/s)
k	thermal conductivity (function of temperature) (W/m K)
k_1	thermal conductivity at T_1 (W/m K)
k_2	thermal conductivity at T_2 (W/m K)
k_s	calibration constant (dimensionless) $k_s = Cp_{st}\frac{H_r \times W_{st}}{H_{st} \times 60}$
MC	moisture contents (%, wb)
n	number of data
d	number of parameters
r	radial coordinate of the cylinder (m)
R	radius of the cylinder (m)
t	time (s)
t_f	end of process time (s)
T	temperature of the sample at time (°C)
Ti	initial temperature at time 0 (°C)
T_1	particular value of T (low value (°C))
T_2	particular value of T (high value (°C))
T_{obs}	measured temperatures at can center (°C)
T_{prd}	predicted temperature at can center (°C)
T_{rt}	retort temperature (°C)
T_s	surface temperature on the can (°C)
W_{st}	sapphire weight (mg)
W_s	sample weight (mg)
X'	scaled sensitivity coefficient (°C)
Z	axial coordinate of the can (m)
60	conversion constant (min to s), in Eq. (1)

Greek

ρCp	volumetric heat capacity (J/m^3 K)
ρ	density (kg/m^3)
α	thermal diffusivity (m^2/s)

moisture content and protein content. The DSC method was used in this study at a temperature range from 20 to 120 °C and moisture content of 0–70% dry basis and 20 atm pressure (Kaletunc, 2007). In a study on fruit juices, the specific heat and thermal conductivity of the juices had linear dependency on water content and temperature, while the density was nonlinearly related to water content (Gratao et al., 2005). Simultaneous estimation of volumetric heat capacity and thermal conductivity of solid food was established using a nonlinear sequential parameter estimation method. Transient temperature measurements with known heat flux at the boundary for one-dimensional conduction food samples were used to conduct the study (Mohamed, 2009). Thermal properties of coffee bean powder were determined: specific heat was determined in a temperature range of 50–150 °C, and thermal conductivity in the range of 20–60 °C. Bulk density was determined. Its change was negligible at temperature of roasting. A linear model for specific heat was given as a function of temperature, and for density as a function of moisture content. (Singh et al., 1997). Thermal conductivity of cherry (9–60 °Brix) and sweet-cherry (12–50 °Brix) juices and other fruits was studied by a coaxial-cylinder technique (steady state) at a temperature range 20–120 °C. A prediction model as function of temperature or temperature with concentration was established for predicting the thermal conductivity (Magerramov et al., 2006a,b).

Most processing and cooking operations are not isothermal. Therefore, changes in chemical and physical characteristics in foods during heating because of temperature rise might affect the level of reactants and products concentrations in the process. Competition between growth and degradation was indicated during a chemical process or reaction that peaked at high temperatures. A model was used to describe a dynamic rate reaction and to simulate a process under non-isothermal conditions (Peleg et al., 2009).

Cherry pomace, left over after cherry juice processing, is a rich source of anthocyanins, a functional food, and hence can be used as an ingredient in the food industry. Examples include cherry powder added as a nutraceutical and colorant to breakfast cereals, snacks, drink mixes and pet foods, and as a slow-release antioxidant in packaging films. In the past decade, health properties of cherries have become more prominent (McCune et al., 2011). Therefore, the objective of this study was to estimate specific heat and thermal conductivity of cherry pomace at different levels of moisture content during non-isothermal heating.

2. Materials and methods

2.1. Sample preparation

Tart cherry pomace was obtained from Cherry Growers Inc., (Grawn, MI, USA). The moisture content (McCune et al.) of the samples was measured using a Sartorius Moisture Analyzer MA30 (Sartorius AG, Goettingen, Germany). The initial MC of cherry pomace was 70% (wet basis, control). Two additional samples with lower MC (41% and 25%) were prepared using a pilot-scale cabinet dryer (Proctor and Schwartz Inc. K12395, Philadelphia, PA, USA) at 45 ± 2 °C. Pomace samples were identified as MC-70, MC-41, and MC-25 representing pomace with 70%, 41%, and 25% MC, respectively. Each of the three cherry pomace samples were filled in duplicate (total 6 cans) and sealed (Dixie Seamer, Athens, Georgia) under vacuum (20-mmHg) in 54 × 73 (mm) steel cans (Fig. 1), and heated at 126.7 °C using a still steam retort (FMC Steritort Laboratory Sterilizer, Madera, CA, USA) for 25, 40, 60 and 90 min. Each can was fitted with a needle-type thermocouple (Ecklund-Harrison Technologies Inc., Fort Myers, FL, USA) to measure the center temperature. All experiments were done in duplicate.

2.2. Measurement of bulk density and specific heat

The bulk density of cherry pomace was determined by weighing of the pomace in each can, which had effective volume of 136 cm^3 (volume measured by water replacement in the can) (Hsu et al., 1991). Samples at the three different moisture contents were used to determine the bulk density; ten replications were made for each moisture level.

Specific heat was measured using the differential scanning calorimetric (DSC) method following a similar procedure to that described by Gill et al. (2010), Singh et al. (1997), and Yang et al. (2002). Samples in triplicate of each moisture content of cherry pomace were weighed. Each sample for each MC was placed in the hermetically sealed aluminum pans (baseline) and analyzed using the DSC. The samples were first cooled from 10 °C to −50 °C and then heated at a ramp of 10 °C/min from 10 °C to 130 °C with a standard material (reference sample sapphire (Archer, 1993)). The heat flow curves are shown in Fig. 2. Dry nitrogen gas flow was used to minimize the condensation in the cell during