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Thermal conductivity, specific heat, thermal diffusivity, and emissivity of stored canola seeds with their temperature and moisture content

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ABSTRACT

Density (ρ), specific heat (c_p), thermal conductivity (k), diffusivity (α), and emissivity (ε) of canola seeds (*Brassica napus* L.) are important engineering parameters in the design of storage, heating, and cooling systems. The properties were determined at moisture content (MC) ranging from 5% to 11% (M/M) wet basis (w.b.) and temperature from 40 to 90 °C. Bulk (ρ_b) and particle (ρ_p) densities of stored canola seeds decreased with temperature and ranged from 654.0 to 664.8 kg m^{-3} and 1047 to 1131 kg m^{-3}, respectively. The c_p of stored canola seeds increased with temperature and MC, and ranged from 2180 to 3498 J kg^{-1} °C^{-1}. The k of stored canola seeds at ρ_b and ρ_p increased with temperature and MC and ranged from 0.06 to 0.13 W m^{-1}·°C^{-1} and 0.15 to 0.25 W m^{-1} °C^{-1}, respectively. The α of stored canola seeds at ρ_b and ρ_p were calculated from the measured k, c_p, and ρ, and ranged from 0.40×10^{-8} to 5.7×10^{-8} m^2 s^{-1}, and 6.1×10^{-8} to 8.0×10^{-8} m^2 s^{-1}. The α of stored canola seeds at ρ_b increased with temperature and MC. The α of stored canola seeds at ρ_p exhibited descending–ascending trends with increasing MC at different temperatures except 40 °C. The ε of stored canola seeds decreased with MC and temperature and ranged from 0.93 to 0.99. Based on the experimental data, regression models for all the properties were developed.

1. Introduction

Canada is a major producer of canola as well as other countries such as European Union, the United States, Australia, China, and India. The Foreign agricultural service (FAS) reported 58.4 million tons of canola seed were produced in the 2010–2011 season around the world (FAS, 2011). Approximately 90% of canola produced in Canada is exported to markets around the world with a worth of billions of dollars. The contribution of canola to Canadian economy is $19.3 billion each year including more than $12.5 billion in wages, and 249,000 Canadian jobs (Canola Council of Canada, 2014). Rapeseed was modified to canola to improve seed quality using traditional plant breeding methods. There are significant differences in agronomic characteristics and yield between rapeseed and canola (Canola Council of Canada, 2015).

Heat transfer in a material is governed mainly by its thermal properties, such as thermal conductivity (k), specific heat (c_p), and thermal diffusivity (α). If radiation heat exchange is significant, the emissivity (ε) of the material surface should be included. Therefore, knowledge of these properties is essential to study and design thermal processes, like heating and cooling, handling, storage, and drying of the canola seeds.

Thermal properties, k, c_p, and α of canola (*cultivar NX4-105 RR*) at different temperatures (−20 to 30 °C), moisture contents (6–16%), and storage times (0, 30, and 60 days) have been reported (Jian et al., 2012, 2013). The research was targeted to study the effect of temperature on thermal properties of canola seeds for storage, but not for the heating and drying.

Thermal properties at higher temperature range needs to be studied for heating or drying processes, but no comprehensive researches have been reported.

Recently, many novel techniques for measurements of k of materials have been developed. Sparrow et al. (2012) developed two novel methods for measurement of k. One of the methods is for high-conductivity media (all metals) and the other is for low conductivity (as air). Among many techniques, two different methods (non-steady-state and steady-state) have been used frequently to determine k of biological materials (Mohsenin, 1980; Nesvadba, 1982). A line heat source method, based on transient heat transfer (non-steady-state), has been widely used to measure k of biological materials due to its convenience, fast measurement, relatively small sample size, and etc. (Yang et al., 2002).

The thermal radiation exchange is significant when there was temperature gradient between surroundings and object surface

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Notation

c_p	specific heat (J kg^{-1} °C^{-1})
DF	degree of freedom
DSC	differential scanning calorimetry
E	thermal radiation (W m^{-2})
h	height (m)
I	electric current (A)
k	thermal conductivity (W m^{-1} °C^{-1})
k_b	thermal conductivity at bulk density (W m^{-1} °C^{-1})
k_p	thermal conductivity at particle density (W m^{-1} °C^{-1})
M	mass (kg)
MC	moisture content (% = M/M, wet basis)
MDSC	modulated differential scanning calorimeter
q	heat transfer rate (W)
R	electric resistance (Ω)
r	radial axis (m)
r_s	sample radius (m)
R^2	coefficient of determination
RMSE	root mean square error
SD	standard deviation
T	absolute temperature (K)
T	temperature (°C)
t	measuring time (s)
T_0	initial sample temperature (°C)
ΔT	temperature increase (°C)
U_{atm}	theoretical camera output voltage for a blackbody of temperature (V)
U_{obj}	calculated camera output voltage for a blackbody of temperature (V)
U_{ref}	theoretical camera output voltage for blackbody of temperature (V)
U_{source}	thermal camera output signal (V)
U_{total}	measured camera output voltage for the actual case (V)
W	radiation power from blackbody (W m^{-2})
W_{atm}	radiation emitted by the atmosphere (W m^{-2})
w.b.	wet basis (%)
W_{obj}	radiation emitted by object (W m^{-2})
W_{ref}	radiation from the surroundings reflected by the material surface (W m^{-2})
W_{source}	radiation power from a source (W m^{-2})

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
α_b	thermal diffusivity at bulk density (m^2 s^{-1})
α_p	thermal diffusivity at particle density (m^2 s^{-1})
ε	emissivity
θ	transmittance of the atmosphere
ρ	density (kg m^{-3})
ρ_b	bulk density (kg m^{-3})
ρ_p	particle density (kg m^{-3})
σ	Stefan–Boltzman constant (5.670373×10^{-8} W m^{-2} K^{-4})
ω_{cp}	variations in the measurements of c_p
ω_k	variations in the measurements of k
ω_ρ	variations in the measurements of ρ

temperatures. Thus, the emissivity of canola seeds should be known as functions of temperature and moisture content. However, no related studies have been reported. Particle and bulk densities and porosity are also important properties not only for heat and mass transfer analysis of drying and heating but also for the determination of storage and packing volume, resistance through beds, shrinkage of food, etc. (Giri and Prasad, 2006; Hatamipour and Mowla, 2003; Senadeera et al., 2000).

Hence, our research focuses on the determination of thermo-physical properties of stored canola seeds with temperature and moisture content for drying and heating. The specific objectives of this study were (1) to measure and analyze k, c_p, α, ε, ρ_b and ρ_p of stored canola seeds under various temperatures (40–90 °C) and MCs (5–11%), and (2) to develop regression models to predict these properties from readily measurable physical quantities, namely temperature and MC.

2. Materials and methods

2.1. Sample treatment

Top quality canola seeds (*Brassica napus* L.) at initial MC of 9% (w.b.) were supplied by our industrial partner Viterra Inc., Regina, SK, Canada. The seeds were transported in polypropylene bags and were stored in a cold storage at 4 °C before using them.

A standard method (ASABE, 2010; Brusewitz, 1975) was used to determine the MC of the bulk canola seeds. To calculate the average initial MC, seeds weighing 10 g were poured into each of five aluminum moisture dishes followed by placing them in a hot air oven for 24 h at 103 °C.

The samples of the canola seeds of different MCs, 5%, 7%, 9%, and 11% wet weight basis were prepared separately. Samples at 5% and 7% were prepared by drying a known mass of canola seeds at initial MC to the pre-calculated weight in a hot air oven (Despatch, Despatch Industries, MN, USA) set up at 40 °C followed by storing them at cold storage (4 °C) until used. Samples at 11% were prepared by spraying a pre-calculated amount of distilled water on known mass of the seeds at initial MC contained in a glass jar. The jar was constantly shook and rotated while spraying with water. The air-tight jars were left at room temperature (23 °C) for 3 days with periodic tumbling to achieve an equilibrium MC followed by cold storage (4 °C) until used. A digital scale with an accuracy of ±0.01 g (Symmetry, PR4200, Cole-Parmer Instrument Co., IL, USA) was used for all weighing. The samples at different MCs from the storage were left at room temperature for 1 h and the final MC of samples were checked before using them for experiments.

2.2. Measurement methods

2.2.1. Densities (ρ) and porosity

The ρ_b and ρ_p of stored canola seeds were determined by measuring mass of known volume using a precision steel cylinder and a gas pycnometer as functions of temperature at MC of 5%, 7%, 9%, and 11%, respectively. To calculate ρ_p, a certain mass of the seeds was poured into large cell after calibration and conditioning of the pycnometer. Nitrogen gas was passed into the reference cell until the pressure reached to about 17 psig. Then, nitrogen gas was allowed to flow into the large cell containing the test seeds. Based on the Archimedes principle, the initial gas pressure decreased to a new lower equilibrium pressure depending on the volume of the sample. A gas equation was used to calculate the particle volume using initial and final pressures, and the known volumes of reference and sample cells.