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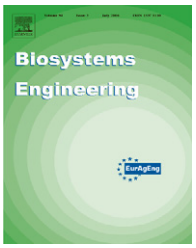


Research Paper: PH—Postharvest Technology

# Determination of thermal properties of the rhizome of *Podophyllum peltatum* for drying and ethanol extraction

*M. Izadifar, O.D. Baik**

*Department of Agricultural & Bioresource Engineering, College of Engineering, University of Saskatchewan, Saskatoon, Sask., Canada*

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The rhizome of *Podophyllum peltatum* is a major source of podophyllotoxin which is an antitumour compound and obtained by ethanol extraction in a packed bed. Thermal conductivity of a packed bed of rhizome particles was determined using the line heat source method at temperatures ranging from 25 to 55 °C, moisture contents from 0.138 to 0.70 dry basis (db) and effective densities from 512 to 1354 kg m$^{-3}$. The measurement was done with the pores of the bed filled with air or ethanol. Specific heat of rhizome particles was measured using differential scanning calorimetry (DSC) for moisture contents, 0.1486–0.621 dry basis (d.b.) and temperatures, 35–80 °C. Depending on temperature, moisture content and effective density, the effective thermal conductivity ranged from 0.06 to 0.25 W m$^{-1}$ °C$^{-1}$. Likewise, specific heat and thermal diffusivity ranged from 1118 to 2932 J kg$^{-1}$ °C$^{-1}$ and $0.82 \times 10^{-7}$ to $1.53 \times 10^{-7}$ m$^2$ s$^{-1}$, respectively. Descending–ascending trends of thermal diffusivity with moisture content ranging from 0.14 to 0.60 dry basis (d.b.) were observed for all tested temperatures. Simple regression models were developed based on the experimental data and the regression models were further improved to enhance their predictability using genetic algorithm (GA).



## 1. Introduction

Podophyllotoxin is a medicinal component that has outstanding antiviral (Bedows & Hatfield, 1982) and antitumour activities (Markos, 2001). Podophyllotoxin can be effectively used in the treatment of Wilms tumours, different types of genital tumours, non-Hodgkin (Ayres & Loike, 1990) and other lymphomas, and lung cancer (Subrahmanyam *et al.*, 1998). Furthermore, Pugh *et al.* (2001) described immunostimulatory activities of podophyllotoxin.

Podophyllotoxin is traditionally isolated from *Podophyllum* rhizome. *Podophyllum emodi* (Indian podophyllum) and *Podophyllum peltatum* (American podophyllum) are two major sources of podophyllotoxin (Giri & Narasu, 2000). *P. peltatum* is a native plant to North America. The rhizome of this plant must be dried and stored carefully in order not to degrade podophyllotoxin during the processing. Thermal conductivity, specific heat and thermal diffusivity are the most important properties, which must be used in detailed studies and precise designs of all heat transfer-related processes such as drying, cooling and non-isothermal solvent extraction of podophyllotoxin. Thermal properties of many biological novelty medicines are not available in the literature. For the rhizome of *P. peltatum* no thermal properties data have been reported.

The objective of this study is to determine thermal conductivity, specific heat and thermal diffusivity of *P. peltatum* rhizome as functions of temperature, moisture content and bulk density. In addition, since packed bed ethanol extraction of podophyllotoxin from rhizome particles

*Corresponding author.
E-mail address: oon-doo.baik@usask.ca (O.D. Baik).
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**Nomenclature**

| | |
|---|---|
| $A$ | Constant |
| $C$ | volumetric fraction, $m^3\,m^{-3}$ |
| $C_p$ | specific heat, $J\,kg^{-1}\,^\circ C^{-1}$ |
| $D$ | difference, % |
| $E$ | electric resistance, $\Omega\,m^{-1}$ |
| $H$ | thermal energy, J |
| $I$ | electric current, A |
| $k$ | thermal conductivity, $W\,m^{-1}\,^\circ C^{-1}$ |
| $M$ | mass, kg |
| $n$ | an intermediate variable |
| $q$ | heating rate, W |
| $r$ | radial axis, m |
| $S$ | slope |
| $T$ | temperature, °C |
| $t$ | time, s |
| $X$ | moisture content, kg $[H_2O]\,kg^{-1}$ [dry solid] |
| $\alpha$ | thermal diffusivity, $m^2\,s^{-1}$ |
| $\varepsilon$ | porosity, $m^3\,m^{-3}$ |
| $\rho$ | density, $kg\,m^{-3}$ |
| $\omega_\alpha$ | uncertainty in thermal diffusivity |
| $\omega_{C_p}$ | uncertainty in specific heat |
| $\omega_k$ | uncertainty in thermal conductivity |
| $\omega_\rho$ | uncertainty in density |

*Subscripts*

| | |
|---|---|
| *air* | associated with air |
| *eff* | effective |
| *est* | estimated |
| *ethanol* | associated with ethanol |
| *exp* | experimental |
| *i* | initial |
| *p* | particle |
| *s* | sample |

requires sufficient information about thermal conductivity of the packed bed, determination of the effective thermal conductivity of a packed bed of the rhizome particles and ethanol is addressed in this study as a function of temperature, ethanol concentration and particle moisture content. Throughout the manuscript, the unit of particle moisture content is kg$[H_2O]$ $kg^{-1}$[dry solid].

## 2. Thermal properties measurement fundamentals

The line heat source method is the common method based on transient heat transfer for the measurement of thermal conductivity of biological materials. This method uses a bare wire or thermal conductivity probe as heating source to calculate the thermal conductivity based on the rate of temperature increase in the core of the sample (Yang *et al.*, 2002). The rate of heat generation, which is produced by the electrical wire in the core of a sample, is given as

$$q = EI^2, \tag{1}$$

where $q$ is the heating rate in W; $I$ is the electric current in A; and $E$ is the electric resistance in $\Omega\,m^{-1}$.

If the thermal conductivity of the sample is assumed to be constant and assuming the sample has a long cylindrical geometry and is isotropic and homogenous and also the mass of the wire in the core of the sample is negligible, the governing equation for heat conduction in the sample is

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right), \tag{2}$$

where $T$ is the sample temperature in °C; $r$ is the radial axis in m; $\alpha$ is thermal diffusivity of the sample in $m^2\,s^{-1}$; and $t$ is time in s. The analytical solution of Eq. (2) is (Hooper & Lepper, 1950):

$$T - T_i = \frac{q}{2\pi k}\left(A - \ln(rn) + \frac{(rn)^2}{2} - \frac{(rn)^4}{8} + \cdots\right), \tag{3}$$

$$n = \frac{1}{2\sqrt{\alpha t}}, \tag{4}$$

where A in Eq. (3) is a constant. To be able to evaluate Eq. (3) by the first two terms in the right side, $r$ and $n$ must have negligibly small values. If the sample temperature is measured in a position very close to the sample centre where the wire is located and also if heating time adopts a large value, $r$ and $n$ will become small enough to approximate Eq. (3) by the first two terms of right side as follows:

$$T - T_i = \frac{q}{2\pi k}(A - \ln(rn)). \tag{5}$$

Substituting $n$ from Eq. (4) into Eq. (5) followed by expanding Eq. (5) results in:

$$T - T_i = \frac{q}{2\pi k}A - \frac{q}{2\pi k}\ln\left(\frac{r}{2\sqrt{\alpha}}\right) + \frac{q}{4\pi k}\ln(t). \tag{6}$$

Eq. (6) shows a linear relationship between temperature change, $(T–T_i)$, at the measuring position and natural logarithm of heating time ln(t) with a slope of $q/4\pi k$. Calculating $q$ from Eq. (1) and obtaining $(T–T_i)$ as well as ln(t) from experimental data enable the thermal conductivity to be determined as follows:

$$k = \frac{EI^2}{4\pi S}, \tag{7}$$

where S is the slope that is obtained from experimental data and $k$ is thermal conductivity.

Differential scanning calorimetry (DSC) is an accurate and rapid method for measuring specific heat (Yang *et al.*, 2002). In DSC the thermal response of an unknown sample is measured and compared to a standard when both of them are uniformly heated at a constant temperature rate over the temperature range of interest. For the same mass of sample and standard and no reaction and phase change, any temperature difference between the unknown sample and the standard is related to differences in specific heat. The specific heat of sample is calculated based on