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Determination of thermal properties of ambient and cryoground black pepper

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Abstract

The effects of temperature (-40°C to 55°C) and particle size (71-492 μm) on thermal properties of black pepper ground at ambient and cryogenic conditions were investigated. The specific heat decreased non linearly whereas the thermal conductivity and thermal diffusivity increased non linearly with the increase in temperature range of black pepper powder for different grades of both grinding conditions. The specific heat at ambient conditions varied from 2.3×10^4-2.2×10^4 J/kg-K, 2.5×10^4-2.3×10^4 J/kg-K and 2.2×10^4-2.1×10^4 J/kg-K and at cryogenic conditions it varied from 3.03×10^4 -2.9×10^4 J/kg-K, 3.2×10^4 -3.2×10^4 J/kg-K and 3.24×10^4 -3.20×10^4 J/kg-K, for three grades I, II, III respectively. The thermal conductivity varied from 0.044-0.061W/m-K, 0.043-0.059 W/m-K and 0.041-0.076 W/m-K at ambient conditions while in cryoground conditions it varied from 0.046-0.078 W/m-K, 0.045-0.077 W/m-K and 0.045-0.067 W/m-K at different grades. The thermal diffusivity varied from 38.79×10^{-8}- 58.69×10^{-8} m^2/s, 39.57×10^{-8}-58.56×10^{-8} m^2/s and 45.37×10^{-8}-85.59×10^{-8} m^2/s in ambient conditions and during cryo conditions varied from 28.94×10^{-8}-49.37×10^{-8} m^2/s, 27.41×10^{-8}-46.74×10^{-8} m^2/s and 27.72×10^{-8}-42.36×10^{-8} m^2/s, respectively at different temperature and grades.

Key words : Black pepper, DSC, liquid nitrogen, specific heat, thermal conductivity, thermal diffusivity

Introduction

Black pepper (*Piper nigrum* L) is known as 'king of spices' and 'black gold' due to its specific pungent flavor, taste and chemical/medicinal characteristics. It is a perennial climbing vine or shrub (Murthy & Bhattacharya, 2008). It is consumed in the form of whole, cracked, coarse to fine powder and oleoresin. Generally, the mechanical process of grinding is used for producing black pepper powder. In ambient grinding, temperature of the powder raises to as high as 90°C resulting in losses of essential oils, aroma and colour *i.e.* quality deterioration. Recently, the concept of cryogenic grinding technique is highly employed to harness the benefits by retaining its volatile oil, flavour and colour of spices (Singh & Goswami, 2000). Thus thermal properties of food a material especially spices are very important. Thermal properties *viz.* specific heat, thermal conductivity and thermal diffusivity are essential for design of cryogenic grinding system, modelling and simulation of heat transfer phenomenon during grinding, transport and packaging. In early work, the effect of temperature and moisture content on specific heat (Tang *et al.,* 1991; Singh & Goswami, 2000) and methods for mixing, for the measurement of specific heat of agricultural materials (Mohsenin, 1980) were carried out. Sharma and Thompson (1973) reported that the heat of hydration released when the materials absorb moisture from the calorimeter can introduce error in measurements. Ojha *et al.* (1967) and Dua and Ojha (1969) used cylindrical devices to employ the one-dimensional, steady state heat transfer equation in cylindrical coordinates to ascertain the bulk thermal conductivity of agricultural materials. Similarly, a cylindrical device with a line heating source at the centre was used to determine the thermal conductivity of varieties of materials based on transient heat transfer analysis (Kazarian & Hall, 1965; Chandra & Muir, 1971). The differential scanning calorimetry (DSC) facilitates the measurement of specific heat as a function of temperature. Various investigators have studied the thermal properties

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*Corresponding author email: balaciphet@gmail.com of food and agricultural materials using DSC and thermal conductivity meter for cumin seed (Singh & Goswami, 2000), gram (Dutta *et al.,* 1988), ground and hydrated cowpea (Taiwo *et al.,* 1996), meat (Karunakar *et al.,* 1998), cassava (Njie *et al.,* 1998), mushrooms (Shrivastava & Datta, 1999), borage seeds (Yang *et al.,* 2002), minor millet grains and flours (Subramanian & Viswanathan, 2003), guna seed (Aviara *et al.,* 2008). The effect of moisture content and temperature on the specific heat of potato using DSC was studied by Wang and Brennan, 1993. The effect of specific heat, thermal conductivity and diffusivity with moisture content have been reported in literature, e.g. for corn and wheat (Muir & Viravanichai, 1972; Kazarian & Hall, 1965), pistachios (Hsu *et al.,* 1991), and peanuts (Wright & Porterfield, 1970) etc. The objective of this paper is to study the effect of temperature and different grades of particle size of black pepper powder obtained from ambient and cryogenic conditions on various thermal properties *viz.*, specific heat, thermal conductivity and diffusivity.

Materials and methods

Sample preparation

Black pepper was procured from the local market Ludhiana, Punjab (India). The seeds were cleaned manually and broken, foreign matter, split, deformed and immature seeds were discarded before the samples were prepared for the experiment. The initial moisture content of seed was determined (Ranganna, 1986) and found to be 7.2 % d.b. For experimentation, about 10 kg of black pepper seeds were stored at room temperature (25°C) for 2 to 3 weeks and subjected to grinding process. Black pepper was ground in a pin mill type grinder (100 UPZ, Hosokava Alpine, Germany) at ambient (30°C) and cryogenic conditions (< -50°C) using liquid nitrogen (LN2) at grinder speed of 12, 000 rpm and 1 kg h^{-1} feed rate. For thermal properties measurements, powder was graded into three different sizes particle size analyzer (LA 950, Horiba, Japan) *viz.*,85, 284, 492 µm for ambient and 71, 211, 322 µm for cryogenic grinding conditions.

Experimentation and observation

The ground black pepper samples of both conditions were used for determination of thermal properties of black pepper. The thermal properties of black pepper powder were determined and the experiments were conducted in triplicate at different temperature and grades. Specific heat of the black pepper samples was determined by using Pyris operated differential scanning calorimeter (DSC) (Perkin Elmer 6000, USA). Before conducting the experiments, the DSC was calibrated using indium at a scanning rate of 10°C $min.^{-1}$ For determination of specific heat, about 5 mg samples were kept in an aluminium crucible (10 µL). The aluminium crucible was sealed and the DSC was operated for a temperature range of -150°C to 300°C. The thermograph was obtained for variation of specific heat with temperature. However, the thermograph readings of DSC for the temperature range of -45 to 55°C for discussion to match with the studied temperature range of thermal conductivity measurements.

A thermal conductivity meter (KD-2 PRO, Decagon Devices, INC. USA) was used for the determination of thermal conductivity of ground black pepper samples. Before starting the experiments, about 80 g of samples were taken in 100 ml beaker and tapped for 100 times to minimize the void space. Then the beaker was covered using aluminium foil and stored at -50°C in a deep freezer (U 410-86, New Brunswick Scientific, England) for over night. For obtaining higher temperature (> 0°C), samples were placed in recirculatory type tray dryer (BTPL, Kolkata, India) at 60°C for 6 h. The thermal conductivity meter was calibrated using glycerine. The packed samples were planted with the single needle probe (KS-1, 1.3 mm diameter x 60 mm long) of thermal conductivity meter and taken readings were recorded for every 2 min for the temperature range between -45°C and 5s°C. The bulk density of samples was determined using standard volumetric cylinder method and described as kg/m^3. Thermal diffusivity of black pepper sample was calculated from the experimental values of specific heat, thermal conductivity and bulk density (Singh & Goswami, 2000)

$$\alpha = \frac{k_b}{\rho_b C_p} \quad \dots (1)$$

where, α is the thermal diffusivity (m^2/s), k_b is the thermal conductivity (W/m-K), C_p is the specific heat (J/kg-K) and ρ_b is the bulk density (kg/m^3).

Statistical analysis

Data were analysed using MS-2003 for obtaining the variation of specific heat, thermal conductivity and diffusivity with temperature and grades.

Results and discussion

Specific heat (C_p)

Specific heat of black pepper powder decreased with increase in temperature from -45°C to 55°C and their different grade sizes (Fig. 1). Similar trend was reported for specific heat of neem seeds (Kuye *et al.*, 2010), guna seed (Aviara *et al.,* 2008), soybean (Aviara *et al.*, 2003; Deshpande & Bal, 1999; Deshpande *et al.*, 1996), sheanut kernel (Aviara & Haque, 2001); borage seed (Yang *et al.*,

2002) and ground & hydrated cowpea (Taiwo *et al.*, 1996). It is obvious (Fig.1a) that the specific heat decreased non-linearly from 23293-22166 J/kg-K, 24932-23410 J/kg-K and 21572-21160 J/kg-K of grade size at ambient ground samples. Fig. 1b, depicts that the cryoground samples showed a decreasing trend of specific heat and varied from 30340-29935 J/kg-K, 32337-32123 J/kg-K and 32423-32095 J/kg-K of grade, respectively. It was found from the results that the specific heat was maximum for cryoground samples and it might be due to the higher retention of essential oils and fat (Goswami and Singh, 2003) as compared ambient grinding. Also, the observed decrease in specific heat capacity within this temperature range could be attributed to the latent heat of fusion of the water molecules. A second order polynomial relationship between specific heat with temperature and grades are summarized (Table 1).

Thermal conductivity (k)

Thermal conductivity of black pepper samples at an average interval of temperature and grades are represented (Fig. 2). It is clear that the thermal conductivity increased non-lineally with the increase in temperature from -45°C to 55°C and their different grades. The thermal conductivity ground samples varied *viz.*, 0.044-0.061, 0.043-0.059 and 0.041-0.076 W/m-K for ambient grinding and *viz.*, 0.046-0.078, 0.045-0.077 and 0.045-0.067 W/m-K for different grade I, II and III of cryoground samples, respectively. Thus in this temperature range, the thermal conductivity increased due to the heat generated which was not sufficient to cause vaporization. This increasing trend was reported for the thermal conductivity of guna seed (Aviara *et al.,* 2008), cumin seed (Singh & Goswami, 2000), soybean (Deshpande *et al.,* 1996), sheanut kernel (Aviara & Haque, 2001), borage seed (Yang *et al.,* 2002), rough rice (Yang *et al.,* 2003), and millet grains (Subramanian & Viswanathan, 2003). A second order polynomial relationship between thermal conductivity and temperature for both conditions at different grades are expressed in (Table 1). Also, similar results were reported by Chandra and Muir (1971) for wheat and Singh and Goswami (2000) for cumin seed and for ground and hydrated cowpea (Taiwo *et al.*, 1996) and found that the thermal conductivity increased as a non-linear function of temperature and moisture content.

Thermal diffusivity (α)

Bulk densities of black pepper powder are shown in Table 1. The thermal diffusivity of black pepper samples in the different temperature range and grades were calculated and its variation with temperature and grade particle size is shown in Fig. 3. Thermal diffusivity of ambient ground black pepper samples increased non-linearly in the range of 38.79×10^{-8}- 58.69×10^{-8}, 39.57×10^{-8}-58.56×10^{-8} and 45.37×10^{-8}-85.59×10^{-8} m^2/s with increase in temperature from -45°C to 55°C for grade I, II and III, respectively. Also, thermal diffusivity of cryo ground samples increased non-linearly in the range of 28.94×10^{-8}-49.37×10^{-8}, 27.41×10^{-8}-46.74×10^{-8} and 27.72×10^{-8}-42.36×10^{-8} m^2/s with the increase in temperature and grade I, II and III, respectively. The relationship between thermal diffusivity with temperature and their different grades for both grinding conditions are represented by second order polynomial equations (Table 2). However, in literature, the relationship between thermal diffusivity (á) with respect to temperature and moisture content have been reported in both increasing gram (Dutta *et al.,* 1988)] and decreasing haylage (Jiang *et al.,* 1986), borage seeds (Yang *et al.*, 2002) and cumin seed (Singh & Goswami, 2000)] trends. From Eq. (1), it is clear that the magnitude of á depends on the combined effect of ki, ñ and Cpi. For a material where the value for ki increases faster than that for ñ and Cpi in the same temperature and moisture ranges, such as gram, thermal diffusivity would increase with increase in moisture content (Dutta *et al.,* 1988, Yang *et al.,* 2002).

Conclusions

Thermal properties (C_{pi}, k_i and α) of ambient and cryo ground black pepper seeds were determined with the function of temperature and their grade size. From this study, it may conclude that the temperature had great effect on thermal properties. The particle size also had much effect on the properties studied. The specific heat of black pepper powder decreased non-linearly with the increase in temperature and different grades while thermal conductivity and diffusivity increased within the studied parameters.

Table 1. Bulk density of different grades of ambient and cryoground black pepper

Ambient			Cryogenic		
I	II	III	I	II	III
465.87±1.95	428.09±1.88	419.18±0.77	523.81±2.03	507.69±1.84	490.23±1.86

Plotted average values ±SD

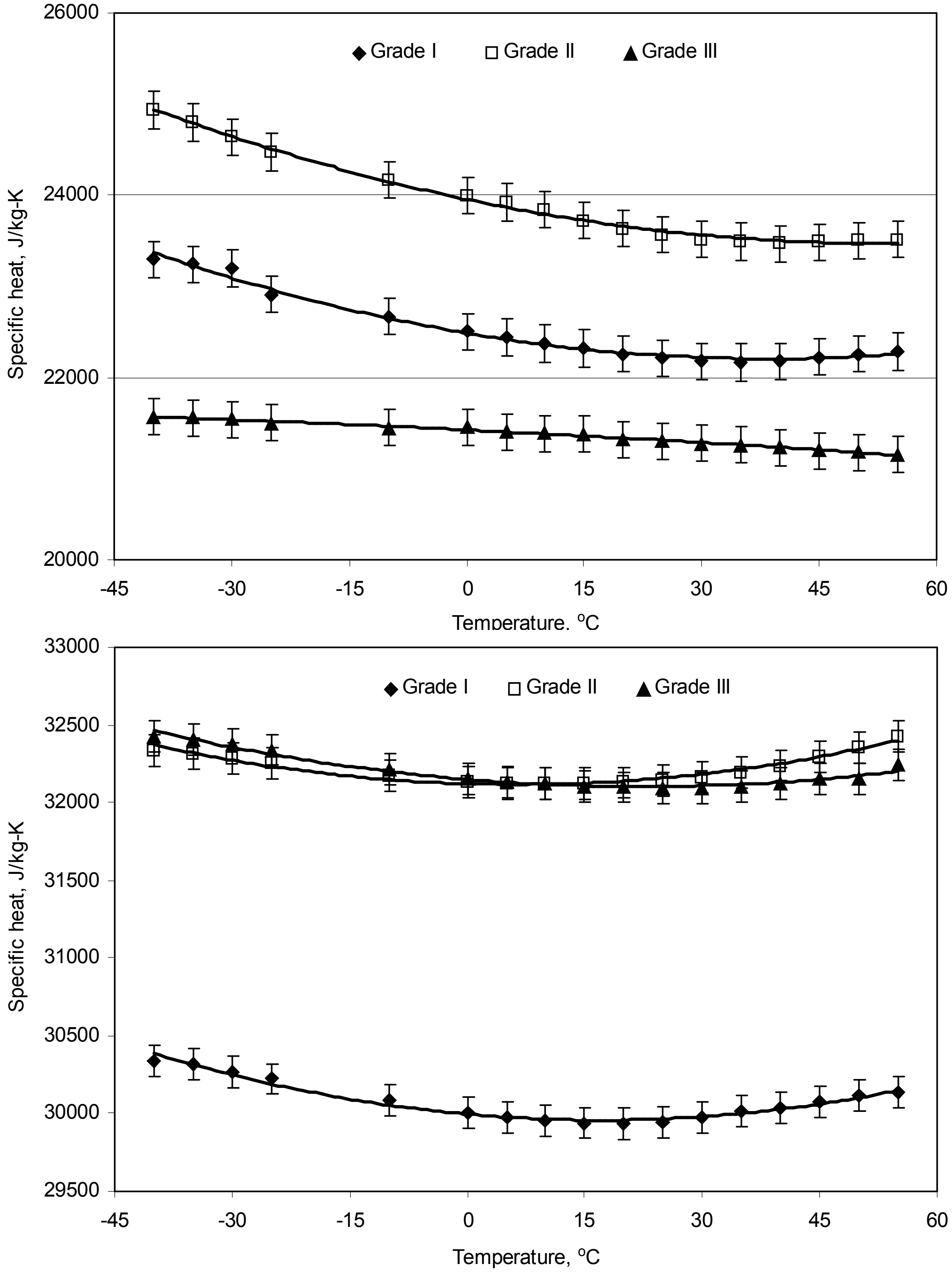

Fig. 1. Variation of specific heat with respect to temperature and grades of black pepper powder obtained through (a) ambient, (b) cryogenic grinding conditions

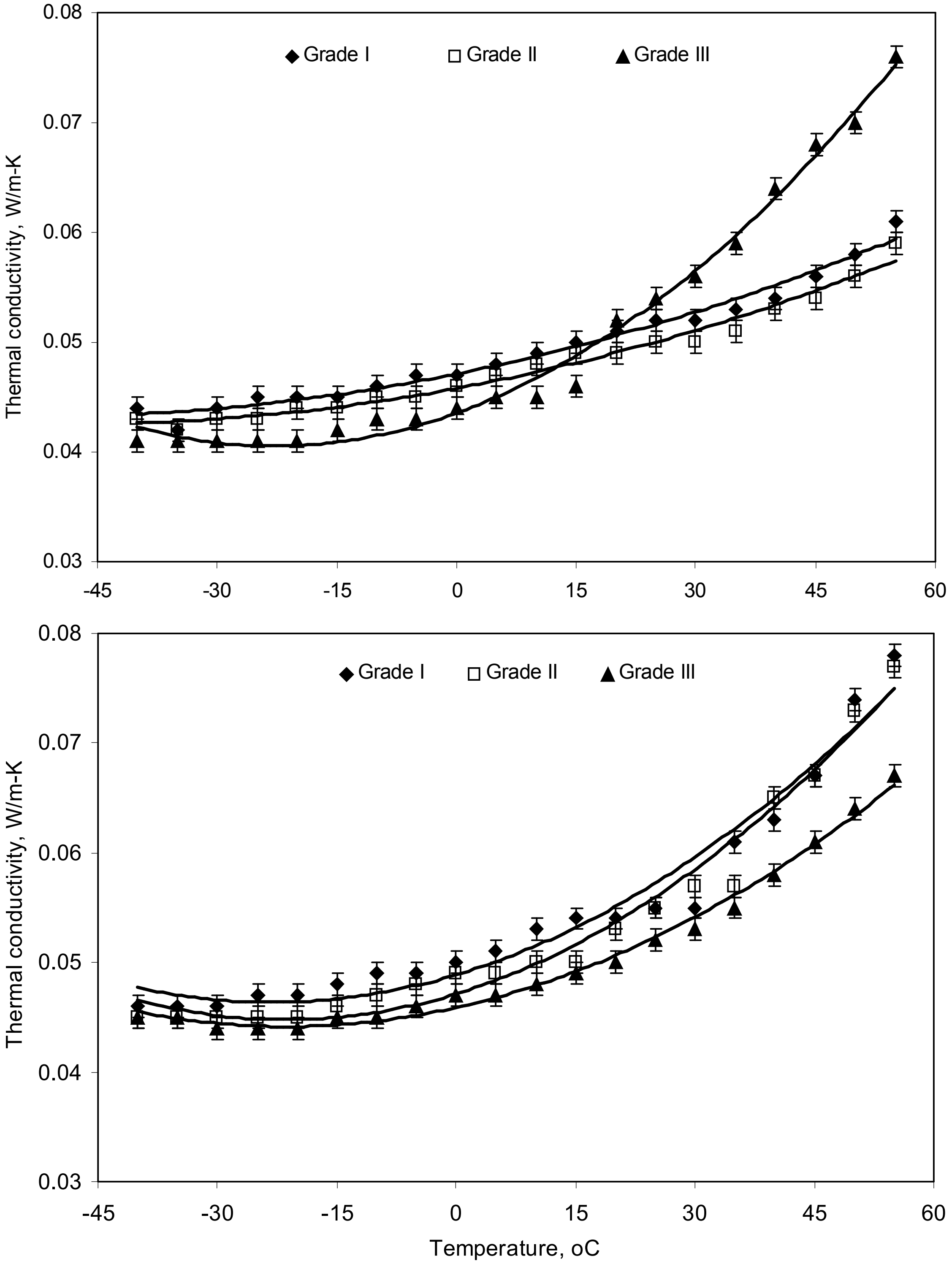

Fig. 2. **Variation of thermal conductivity with respect to temperature and grades of black pepper powder obtained through (a) ambient, (b) cryogenic grinding conditions**

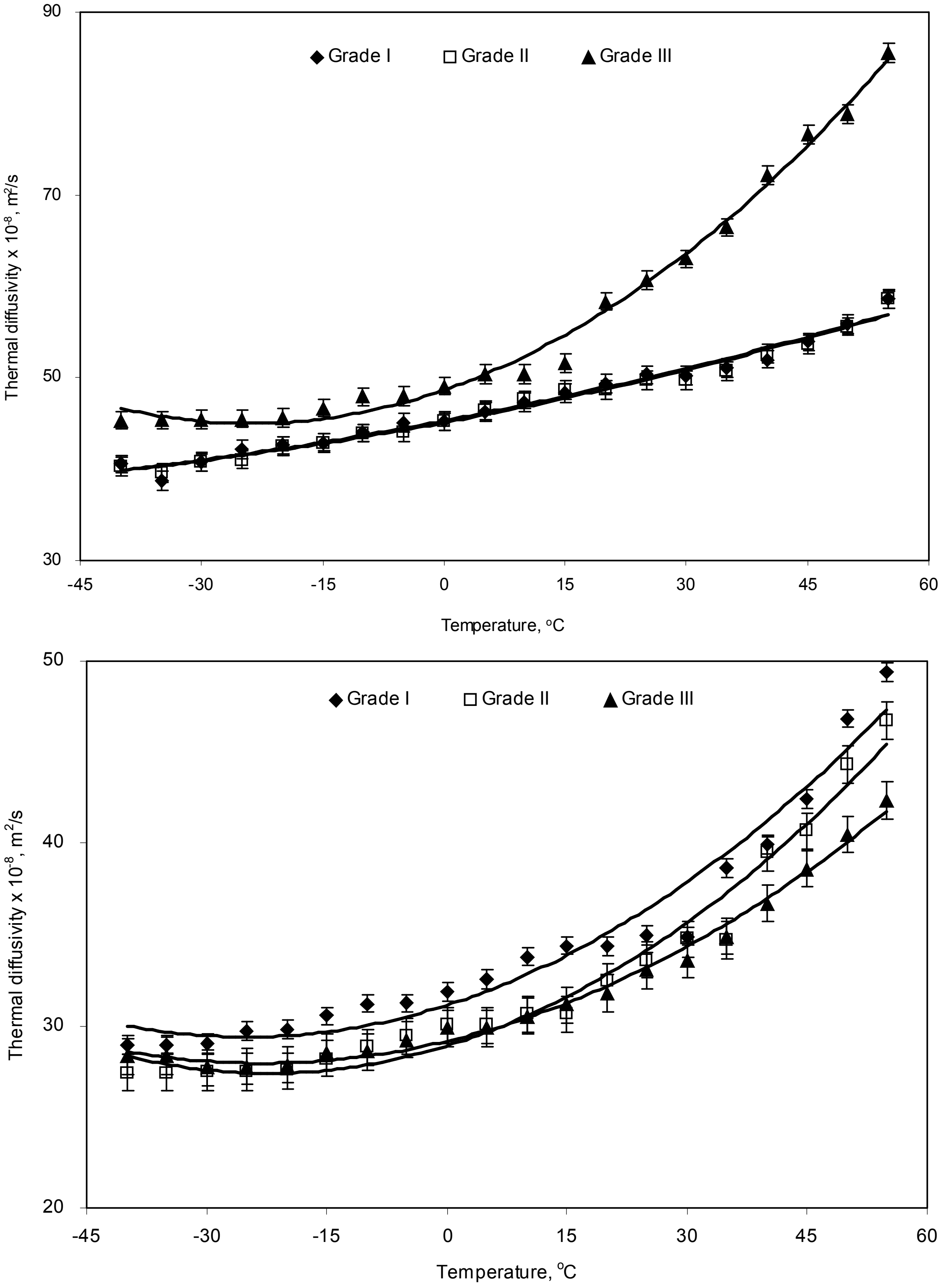

Fig. 3. Variation of thermal diffusivity with respect to temperature and grades of black pepper powder obtained through (a) ambient, (b) cryogenic grinding conditions

Table 2. Polynomial equation of *Cp, kb,* α with respect to temperature of black pepper powder

Grinding conditions	Thermal property					
	C_p	R^2	k_t	R^2	α	F^2
Ambient						
Grade I	$0.188T^2 - 14.54T + 2287$	0.99	$1\times10^{-6}T^2 - 0.0001T + 0.047$	0.98	$0.0008T^2 + 0.168T + 45.3$	0.98
Grade II	$0.168T^2 - 17.99T + 23953$	0.99	$1\times10^{-6}T^2 - 0.0001T + 0.046$	0.98	$0.0009T^2 + 0.166T + 45.01$	0.98
Grade III	$-0.015T^2 - 4.18T + 21426$	0.99	$6\times10^{-6}T^2 - 0.0003T + 0.044$	0.99	$0.0064T^2 + 0.306T + 48.66$	0.99
Cryogenic						
Grade I	$0.132T^2 - 4.47T + 29995$	0.98	$5\times10^{-6}T^2 - 0.0002T + 0.049$	0.96	$0.0028T^2 + 0.140T + 31.13$	0.96
Grade II	$0.119T^2 - 1.48T + 32122$	0.97	$5\times10^{-6}T^2 - 0.0002T + 0.047$	0.97	$0.0030T^2 + 0.135T + 28.90$	0.97
Grade III	$0.092T^2 - 4.14T + 32149$	0.97	$4\times10^{-6}T^2 - 0.0002T + 0.046$	0.99	$0.0023T^2 + 0.105T + 29.15$	0.99

Valid for $-50°C \leq T \leq 60°C$ and $\leq M \leq 7.2\%$ dry basis

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