Thermal properties of ambient ground fenugreek (*Trigonella foenum-graceum* L.)

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ABSTRACT

The present investigation was done to study the thermal properties, namely, thermal conductivity, specific heat and thermal diffusivity, as a function of temperature. These properties were determined for ambient ground (30 °C) fenugreek powder of following varieties *viz*., AM, RMT- 305 and RMT-1 for temperature range from -30 °C to 30 °C. Thermal conductivity was evaluated using thermal conductivity meter, specific heat by differential scanning calorimeter and bulk thermal diffusivity by standard relation. It was found that thermal conductivity increased with the increase in temperature from -30 °C to 30 °C, thus depicting a direct correlation between the two. Also the overall specific heat of the spice varieties decreased initially from -30 °C to 10 °C and then increased from temperature 20 °C to 30 °C. Thermal diffusivity showed an increasing trend with the increasing temperature for all the three varieties. Mathematical modelling of thermal properties as a function of temperature resulted in polynomial expressions, mainly of sixth order, which may be applicable for easy fabrication of ambient grinding system, for spices and development of advanced grinding systems, conserving the essential spice properties (**Keywords:** Thermal conductivity, specific heat, ambient ground fenugreek, thermal diffusivity, bulk density).

INTRODUCTION

Fenugreek (*Trigonella foenum- graceum* L.) is an annual herb of family *fabaceae* of order leguminosea. Fenugreek seed is the ripe fruit of an annual herb. Fenugreek is used as food, food additive and also used in medicines. Seed extract is used in imitation vanilla, butterscotch and rum flavouring. It is used in colic flatulence, dysentery, diarrhoea, chronic cough, rickets, gout and diabetes. Fenugreek oil is used in the manufacture of hair tonics (Spice board of India). The grinding of spices result in increased surface area for the availability of constituents (such as oil inside the cells, fragrance and flavouring components). During the conventional grinding, the grinding temperature rises as high as 90 °C causing loss of essential oils, flavour and colour (Singh and Goswami, 2000). Thermal properties of product are important in studying the heat transfer during the grinding process and hence useful for optimization of grinding losses with minimal volatile losses of the oil. Thermal properties *viz*., thermal conductivity, thermal diffusivity and specific heat are important engineering properties essential for designing of any grinding system, simulation and modelling of heat transfer phenomenon during grinding transport and packaging. Chandrasekar *et al*. (1999) reported that the thermal conductivity as well as specific heat increased and the thermal diffusivity decreased with increasing moisture content (9.9 - 30.6 % wb) among the Arabica and Robusta parchments (coffee) varieties. Yang *et al.* (2002) found that the specific heat and thermal conductivity of borage (*Borago officinalis*) increased with increase in moisture content (1.2 - 30.3 % db) and temperature (6 - 20 °C). Several similar experimental studies on determination of thermal properties of food and agricultural materials were reported in literature: cumin seed (Singh and Goswami, 2000), minor millet grain and flours (Subramanian and Viswanathan, 2003), sweet potato (Farinu and Baik, 2007), cassava, yam and plantain (Nije *et al.,* 1998), sheanut kernel (Aviara and Haque, 2001) and black pepper (Meghwal and

Goswami, 2011). There are many methods available for the measurement of thermal properties of food (Singh, 1982; Mohsenin, 1980).

Some empirical equations have also been proposed for determining the specific heat (Lamb, 1976; Miles *et al.*, 1983). Experimental values of specific heat are available for some food products and food processing materials (Lewis, 1987; Jowitt *et al.*, 1983), but most of them are restricted to a certain temperature and/or water content. Experimentally differential scanning calorimeter is used for determining the specific heat of the food but it is an expensive method (Sweat, 1995; Telis-Romero *et al.,* 1998). However, the accuracy and sensitivity of this method makes it as a popular one for studying the specific heat. Thermal conductivity of food is determined by thermal conductivity probe based on line heat source principle (Sweat and Haugh, 1974). This method is used widely, because of its simplicity, rapidity in measurement, and suitability for small food samples (Gratzek and Toledo, 1993; Rahman, 1995). Advantages of this method are, less time consumption for the experiments and that the same sample can be employed either to determine thermal conductivity at several temperatures or to make several replicates at the same conditions. There is no literature evidence on thermal properties of fenugreek powder which is useful for designing and fabricating advance grinding system such as cryogenic system for fenugreek powder. This study was to investigate the thermal properties *viz*., specific heat, thermal conductivity and thermal diffusivity of ambient ground fenugreek powder as a function of temperature for a given particle size range. The temperature range for the study was selected from -30 °C to 30 °C, as it includes both cryogenic temperature (-30 °C) involving glass transition of the fenugreek components and the ambient grinding as well as the storage temperature (30 °C).

MATERIALS AND METHODS

Sample preparation

Fenugreek (AM, RMT-305, RMT-1) seed was obtained from National Research Centre on Seed Spices (NRCSS), Ajmer (India). The seeds were cleaned manually to remove foreign matter, broken, split, deformed and immature seeds for sample preparation. The initial moisture content of seed was determined (7.56 % db) by the vacuum oven method (Ranganna, 1986). In this method, sample was heated up to 72 °C for 24 h until a constant weight was obtained and then the moisture content is calculated. Sample was stored at room temperature (30±1 °C) for three weeks. For experiments, about 10 kg of fenugreek was taken for grinding at ambient temperature (30 ± 1 °C).

Grinding and particle size analysis

The fenugreek seed was ground using a pin mill grinder (100 UPZ, Hosokava Alpine, Germany) at ambient temperature (30 ± 1 °C) with a constant grinder speed of 12000 rpm and 2 kg h^{-1} feed rate. The fenugreek powder obtained was used for studying the thermal properties. The ground sample was stored in sealed, moisture free and water proof flexible polythene bags. For particle size analysis, ground fenugreek was subjected to particle size analyzer (LA 950, Horiba, Japan) and the thermal properties are measured in the temperature range of -30 °C to 30 °C and at particle size (400 -420 μ) for AM, RMT-305 and RMT-1 varieties.

Bulk thermal conductivity

Thermal conductivity is the ratio of heat flux density to temperature gradient in a material. Bulk thermal conductivity refers to the thermal conductivity of a sample of bulk material. The bulk thermal conductivity of fenugreek samples for a temperature range of -30 °C to 30 °C was determined using a thermal conductivity meter (KD-2 PRO, Decagon Devices Inc, USA). This method works on the transient hot wire method. Sample for the experiments were prepared by compact pack made by tapping in a 100 mL beaker, covered using aluminium foils. The thermal conductivity meter was calibrated using glycerine and the thermal conductivity was checked for 0.285 W/m^{-1}°C. After calibration, probe (KS-1, 1.3 mm diameter × 60 mm long) of thermal conductivity meter was penetrated in the sample and reading was taken at interval of 3 min.

Specific heat

Differential scanning calorimeter (Perkin Elmer 6000, USA) was used for determining the specific heat of fenugreek powder using Pyris software. The DSC was calibrated using indium before conducting the experiments. The samples were dried in vacuum drying oven at 72 °C (recording moisture content at every 15 min interval) to achieve 5 % db moisture and were studied for a temperature range of -150 °C and 300 °C. Samples (5 ± 0.1 mg) were placed in the aluminium hermetic sealed pans (cap.10 µL). The sample was brought to the initial temperature of -150 °C using liquid nitrogen with holding temperature at -150 °C for 1 min and then scanned dynamically at the rate of 10 °C min^{-1} over the selected temperature range along with an empty pan as reference in the DSC. The thermograph was obtained and analysed. The specific heat data was obtained between -30 °C to 30 °C for ambient ground fenugreek.

Bulk density and bulk thermal diffusivity

Bulk density is the physical property which may be defined as the mass of the material divided by the total volume they occupy. It is expressed in kg per cubic meter (kg m^{-3}). For fenugreek powder, tap bulk density was calculated using a container of known volume. The powder was compactly packed in the container and the total weight was noted down. The bulk density was calculated using the undermentioned equation:

$$\text{Bulk density} = \frac{\text{mass (kg)}}{\text{volume } (m^3)} \qquad (1)$$

The bulk thermal diffusivity was calculated from the experimental results as described by Singh and Goswami (2000).

$$\alpha = \frac{k}{\rho C_p}$$

where, α is the thermal diffusivity (m^2 s^{-1}), k is the thermal conductivity (W m^{-1} °C), C_p is the specific heat (kJ kg^{-1} °C) and ρ is the bulk density (kg m^{-3}).

Statistics

Data were analysed with Statistica 6.0.

RESULTS AND DISCUSSION

Thermal property *viz*., thermal conductivity, specific heat and thermal diffusivity for different varieties of fenugreek samples (AM, RMT- 305 and RMT-1) at an average interval of temperature are represented in Table 1.

Table 1. Thermal properties (thermal conductivity (k), specific heat (Cp) and thermal diffusivity (α)) for three varieties of fenugreek powders ground under temperature conditions of -30 °C to 30 °C

Property	AM	RMT- 305	RMT-1
Thermal Conductivity (W m^{-1} °C)	0.055 (±0.007) -0.065 (±0.005)	0.054 (±0.005) 0.066 (±0.004)	0.052 (±0.003) -0.063 (±0.006)
Specific Heat (kJ kg^{-1} °C)	28.31 (±0.10) -28.16 (±0.09)	26.98 (±0.05) -26.83 (±0.06)	28.94 (±0.04) -28.96 (±0.07)
Bulk density (ρ) (kg m^{-3})	575.7 (±0.09)	8608.2 (±0.10)	256.8 (±0.06)
Thermal diffusivity ($\alpha \times 10^{-6}$) (m^2 s^{-1})	3.37 (±0.05) -3.99 (±0.04)	3.29 (±0.03) -4.04 (±0.08)	7.00 (±0.06) -8.50 (±0.09)

Thermal conductivity (k)

Figure 1 (a) shows the effect of temperature on thermal conductivity of the varieties of fenugreek powder. The values of thermal conductivity were found to be in range of 0.054 - 0.063, 0.053 - 0.065 and 0.052 - 0.0547 W m^{-1} °C for AM, RMT-305 and RMT-1 respectively. From the results, it is evident, that thermal conductivity increased nonlinearly with the rise in temperature from -30 °C to 30 °C, which is similar to the reported studies cumin seed (Singh and Goswami, 2000), soybean (Deshpande *et al.,* 1996), sheanut kernel (Aviara and Haque, 2001), borage seed (Yang *et al.,* 2002), rice flour (Mahapatra *et al.*, 2011) and millet grains (Subramanian and Viswanathan, 2003). According to Emami *et al.* (2007), it was explained that this trend could be due to the increase of atomic activity with temperature which enhances the ability of transfer heat. Also among the three varieties, RMT-305 showed highest thermal conductivity followed by AM and RMT-1. This trend is attributed to the bulk density of the varieties. With the increase in bulk density, void space is decreased resulting in less retention of air. Since air is a bad conductor of heat, decrease of it increases the bulk thermal conductivity of sample. Equations are developed to describe the effect of temperature on thermal conductivity of fenugreek powder. The polynomial equations for thermal conductivities have been tabulated in (Table 2) with R^2 values 0.989, 0.991 and 0.994 for AM, RMT- 305 and RMT-1 respectively. The relationship between the thermal conductivity and the temperature mostly fit into the sixth order polynomial equations. From the (Table 3), it has been deduced that temperature has more effect on thermal conductivity than varietal difference, as F value is higher for temperature.

Specific heat (C_p)

From the study, it was observed that the specific heat ranged as 28.10 - 28.37, 26.76 - 27.01 and 28.87 - 29.19 kJ kg^{-1} °C for the fenugreek variety AM, RMT-305 and RMT-1 respectively. The overall specific heat of the spice varieties initially decreased from -30 °C to 0 °C and then increased from 5 °C to 30 °C. It has been observed that there is no clear trend between the specific heat and temperature, irrespective of fenugreek varieties. However, it has been cited elsewhere that there was a direct relationship between them along moisture content for borage seeds (Yang *et al.,* 2002), cumin seeds (Singh and Goswami, 2000), coriander and anise seeds (Hacikuru and Kocabiyik, 2008) and sheanut kernel (Aviara and Haque, 2001). However, it has been studied that below initial freezing temperature, the specific heat varies greatly because of complex processes involved during freezing. This might be the reason for the non linear relationship of specific heat with temperature for the range -30 °C to 30 °C. The relationship between overall specific heat and

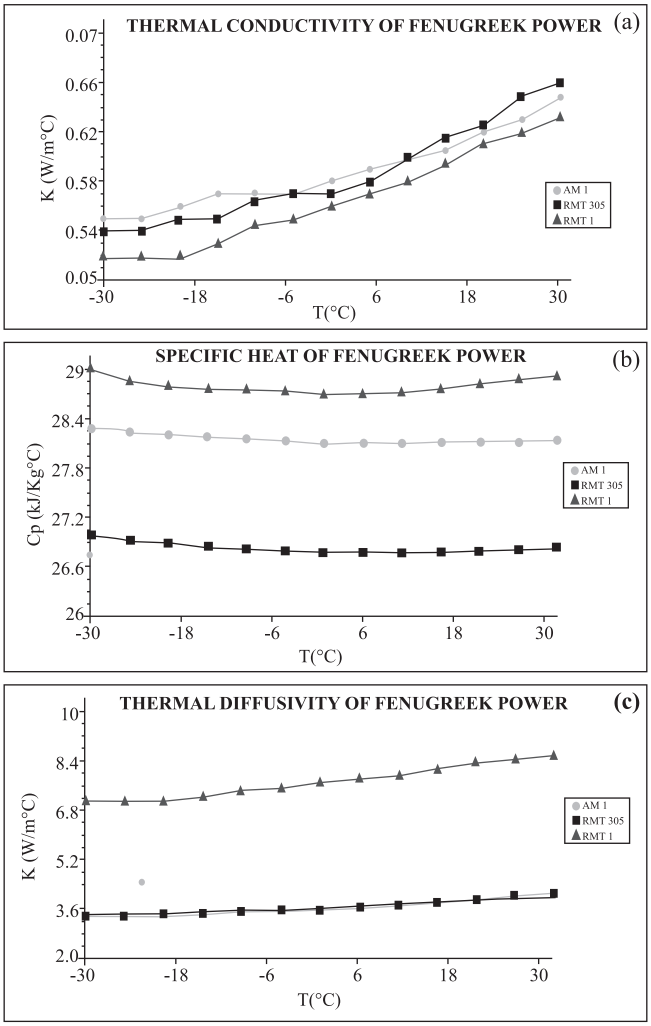

Figure 1. Variation of thermal properties viz. thermal conductivity (a), specific heat (b) thermal diffusivity (c) among different fenugreek varieties with the temperature

Table 2. Polynomial expressions for the thermal conductivity (k), specific heat (Cp) and thermal diffusivity (α) for three varieties of fenugreek powders ground under ambient condition

Fenugreek variety	Polynomial expressions	R^2
AM	$k = -3\times10^{-12}T^6 - 1\times10^{-10}T^5 + 2\times10^{-9}T^4 + 2\times10^{-7}T^3 + 2\times10^{-6}T^2 + 0.058$	0.989
	$Cp = -1\times10^{-10}T^6 - 2\times10^{-9}T^5 + 1\times10^{-7}T^4 + 4\times10^{-6} T^3 + 9\times10^{-5} T^2 -0.004T + 28.12$	0.996
	$\alpha = -2\times10^{-1}0T^6 - 8\times10^{-9}T^5 + 1\times10^{-7}T^4 + 1\times10^{-5} T^3 +0.007T+ 3.585$	0.991
RMT 305	$k = 4\times10^{-12}T^6 - 2\times10^{-10}T^5 - 8\times10^{-9}T^4 + 3\times10^{-7}T^3 + 7\times10^{-6}T^2 +0.057$	0.991
	$Cp = -8\times10^{-11}T^6 - 2\times10^{-9}T^5 + 7\times10^{-8}T^4 + 3\times10^{-6}T^3 - 0.002T + 26.76$	0.998
	$\alpha = 4\times10^{-11}T^6 - 1\times10^{-8}T^5 - 2\times10^{-7}T^4 + 1\times10^{-5}T^3 +0.009T+ 3.525$	0.993
RMT 1	$k = 1\times10^{-12}T^6 - 2\times10^{-10}T^5 - 2\times10^{-9}T^4 + 2\times10^{-7}T^3 + 2\times10^{-6}T^2 +0.056$	0.994
	$Cp = -1\times10^{-10}T^6 - 8\times10^{-9}T^5 + 1\times10^{-7}T^4 + 1\times10^{-5}T^3 -0.002T+ 28.74$	0.992
	$\alpha = -2\times10^{-8}T^5 + 5\times10^{-8}T^4 + 2\times10^{-5}T^3 + 0.024T+ 7.589$	0.998

Note: -30 °C $\leqslant$ T $\leqslant$ 30 °C

Table 3. Analysis of variance for specific heat, thermal conductivity and thermal diffusivity

Source of variation	Thermal conductivity			Specific heat			Thermal diffusivity		
	DOF	F	P	DOF	F	P	DOF	F	P
Temperature	12	89.41*	<0.0001*	12	32.81*	<0.0001*	12	11.80*	<0.0001*
Variety	2	49.39*	<0.0001*	2	21.84*	<0.0001*	2	9.273*	<0.0001*
Error	24			24			24		
Total	38			38			38		

temperature was found to fit into sixth order polynomial equations with R^2 values 0.996, 0.998 and 0.992 for AM, RMT-305 and RMT-1 respectively (Table 2).

Thermal diffusivity (α)

From the study, it was found that the thermal diffusivity ranged as 3.31 - 3.99 × 10^{-6}, 3.223 - 4.04 × 10^{-6} and 6.94 - 8.35 × 10^{-6} m^2 s^{-1} for AM, RMT- 305 and RMT-1 respectively. From the Figure 1, it is understood, that the thermal diffusivity of fenugreek powder increased with increase in temperature. This may be due to the combined effect of thermal conductivity, specific heat and bulk density on the thermal diffusivity. The relationship between thermal diffusivity (α) with temperature and moisture content trends were reported (Dutta *et al.,* 1988; Jiang *et al.,* 1986; Yang *et al*., 2002; Singh and Goswami, 2000; Mahapatra *et al*., 2011). RMT-1 showed higher thermal diffusivity than the other two varieties, because it had lower bulk density than the other two. It was visible from the standard equation of thermal diffusivity, that it was inversely proportional to the bulk density. The relationship between the thermal diffusivity and the temperature was expressed in sixth order polynomial equations with R^2 values 0.991, 0.993 and 0.998 for AM, RMT-305 and RMT-1 respectively (Table 2). From the (Table 3), it was deduced that temperature had more effect on thermal diffusivity than varietal difference as F value was higher for temperature.

CONCLUSION

The measured thermal properties of the three fenugreek varieties *viz*., AM, RMT-305, RMT-1 for the temperature range of -30 °C to 30 °C showed that the thermal conductivity increased non-linearly. The specific heat capacity decreased followed by increase. The thermal diffusivity showed an increasing trend with the increase in temperature, which was significant at 0.01 % level. All the properties were following polynomial model with the temperature. This data derived from this study may be useful for grinding, processing storage and quality assessment of the fenugreek powder.

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