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The Effect of Moisture and Temperature on Thermophysical Properties of Iranian Pistachios

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Abstract: The thermal conductivity, thermal diffusivity and bulk density of Iranian pistachios were measured as functions of temperature (ranging from 50 to 93°C) and moisture content (ranging from 3 to 52% db). Specific heats were then calculated from measured thermal conductivity, diffusivity and bulk density. Results showed that the decreases in moisture content to 11.5% (db) produce reduction in thermal conductivity and specific heat, but decreases in moisture content to 3.3% (db), cause proportional increases in thermal conductivity and specific heat. Average values of thermal conductivity and specific heat were changed from 0.231 to 0.466 W m^{-1} °C and from 1894 to 3820 J kg^{-1} °C in different moisture content, respectively.

Key words: Bulk thermal conductivity, bulk thermal diffusivity, bulk density, specific heat, Line heat source method, Iran pistachio

INTRODUCTION

Over the past fifty years, the production of pistachio (Pistachio Vera l.) in central Iran has increased dramatically so that it is now about 380000 hectares and produces annually 350000 tons of pistachios (DIA, 2007). Iran is the most important pistachio exporter.

The pistachios moisture at harvesting time is about 40 to 50% dry basis according to date and climatic location. However, for storage and consumption pistachios need to dry 5 to 7%. Rate of drying pistachios in free air is slowly and needs 2 or 3 days period that produce conditions in with fungus growth. So pistachios dryers are needed where pistachios in bulk expose hot air at temperatures 50 to 93°C for 3 to 8 h. Huge amount of fossil fuels is being burned annually in these dryers. In Iran, these dryers consume approximately three million litters of mostly diesel fuel each year. Knowledge of thermal properties is important in the solution of these problems. In addition, processing operations on pistachios involve heat transfer. Therefore, information on thermal properties is required.

The objective of the investigation reported in this study was to determine the thermal conductivity, thermal diffusivity and density of pistachio over a wide range of temperature and moisture conditions then values of specific heat were calculated from the relationship:

$$c = \frac{k}{\alpha\rho} \tag{1}$$

The thermal conductivity of various kinds of grain has been determined in a number of ways. Early investigators used one dimension, steady-state heat flow methods. There are two

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disadvantages to these methods, (1) it takes several hours to conduct each test and (2) moisture migration that occurs as the material approaches steady state conditions will produce erroneous results with moist materials. From the fundamental equations it can be shown that transient heat flow in an infinite cylinder of homogeneous material, initially heated by a line heat source may be expressed as:

$$T = \frac{Q}{2\pi k}\int_{\beta}^{\infty}\frac{\exp(-x^2)dx}{x} \tag{2}$$

where, $\beta = r/2\sqrt{\alpha\theta}$. This equation can be transformed and expanded to an infinite series. If β is smaller than 0.16 the temperature change between the times θ_2 θ_1 can be expressed by the first two terms of the series as:

$$T_2 - T_1 = \frac{Q}{4\pi k}\ln(\frac{\theta_2}{\theta_1}) \tag{3}$$

To compensate for the mass and size of the heating element, plot $dT/d\theta$ versus time and obtain a value for the time correction θ_0 at $dT/d\theta = 0$. Equation 3 with the time correction value then becomes:

$$T_2 - T_1 = \frac{Q}{4\pi k}\ln(\frac{\theta_2 - \theta_0}{\theta_1 - \theta_0}) \tag{4}$$

Moysey *et al.* (1977), converted the time correction value to:

$$\theta_0 = \theta_1 \exp(\frac{T^0 - A}{B}) \tag{5}$$

where, θ_1 is a reference time chosen after the temperature time curve becomes linear. A and B are constants for a least squares fit to a natural log function, T^0 is initial temperature minus reference temperature at time θ_1

In the actual test apparatus, the heat source is finite in length and the sample is finite in diameter, the error produced by assuming axial flow mathematically. For the apparatus used in these tests, substitution into equations suggests that the error due to the assumption of axial flow is less than one tenth of 1%.

Nix *et al.* (1969) developed an iteration technique to obtain values of thermal conductivity and thermal diffusivity from a single test. To utilize Eq. 2 to solve for thermal diffusivity it is expanded to an infinite series:

$$T = \frac{Q}{2\pi k}[\frac{-C_e}{2} - \ln\beta - \sum_{n=1}^{\infty}\frac{(-1)^n(\beta^2)^n}{(2n)(n!)}] \tag{6}$$

where, β is as previously defined. β is found by the Newton-Raphson iteration technique. Rao *et al.* (1975) and Singh and Heldman (1993) and α is then calculated for known values of r, θ and β. Suter *et al.* (1975) used this approach in determining the thermal properties of peanut pods, hulls and kernels.

Hsu *et al.* (1991) evaluated physical and thermal properties of pistachios at room temperature. The method of line heat source was employed to determine thermal conductivity and diffusivity but specific heats were measured by method of mixture. Bulk pistachios with apparent mass and temperature throw a Calorimeter full of water with known specific heat. Then pistachios specific heat was calculated by changing the temperature of water, also the specific heat of Iranian pistachio nuts was measured by Razavi and Taghizadeh (2007) for initial moisture content, 25, 15 and 5% w.b. and temperature 25, 40, 55 and 70°C with this method.

No information about thermophysical properties of pistachios at temperatures that confines in drying process with line heat source method was found.

Pistachios used in this study were of Iranian cultivar, obtained from pistachio producers of Rafsanjan located in Kerman province, Iran, during the 2007 harvest season.

MATERIALS AND METHODS

The apparatus used for the thermal conductivity and thermal diffusivity tests consisted of a hollow stainless steel tube 200 mm in diameter and 400 mm long. A 300 watt, 220-volt tungsten-alloy heating wire with 180 mm length sheathes in a copper tube with 6 mm diameter and 300 mm long installed in the axis of the cylinder. Wire temperature was controlled by changing the wire voltage with a 1KVA AC variable power supply. Wattage was read from a LUTRON DW-6060 digital wattmeter in series with the heater with resolution of 1 watt. Temperature was measured midway along the heating wire using two k type thermocouple wire (Fig. 1). These thermocouples were kept parallel in 18 and 40 mm distance from the to the line heat source.

The potential of the thermocouple circuit was measured by a LUTRON TM-915 two-channel thermometer with RS-232 output to USB port and a resolution of 1°C. Temperature readings were recorded on a computer with SW-U001 ver 1.3 software. After temperature of thermocouple A (Fig. 1) was constant, the temperature history of thermocouple B (Fig. 1) 40 mm from the line source was used to determine the thermal diffusivity.

The bulk density of samples was determined by filling a 1091 mL graduate and weighing at room temperature. An attempt was made to fill the graduate in the same manner as the container used for the thermal conductivity and diffusivity tests. Results reported are the average of 6 tests.

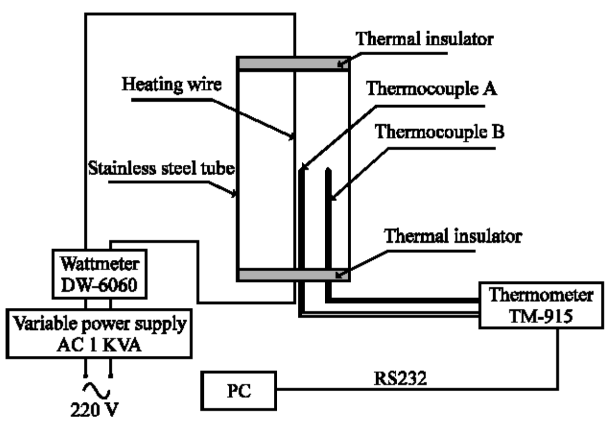

Fig. 1: Schematic arrangement of test apparatus

All of the tests were conducted on the abasali and khani variety of pistachio. The samples obtained from an orchard in Iran, Kerman Province during harvesting season in September 2008.

Initial moisture content of the pistachios was about 40 to 50% dry basis. Samples of about 10 kg each were conditioned either by drying in an oven to obtain different levels of moisture content ranging from about 3.3 to 51.5% dry basis. The moisture content was determined by oven drying according to a standard method (ASAE, 2005). Recorded data computed with Matlab ver 7 software.

RESULTS AND DISCUSSION

Bulk Density

Results of the bulk density tests are shown in Fig. 2. The density of khani pistachios increases from 422.6 to 574.1 kg m^{-3} at 4.3 to 52.8% moisture content (db), respectively. But density of abasali pistachios rises from 417 to 542.9 kg m^{-3} at 3.3 to 51.5% moisture content (db), respectively. Linear regression equation was determined for the data with R^2 = 99.93 as:

$$\rho = 411 + 289\,M \tag{7}$$

From Hsu *et al.* (1991) work the liner model for bulk density of California pistachio at 20°C for the moisture wet basis term was:

$$\rho = 439 + 500.3\,M \tag{8}$$

An F test on the derivative data from Eq. 7 and 8 showed that there was insignificant difference at the 5% level between them.

Thermal Conductivity

The model of thermal conductivity versus temperature in 51.5% moisture content is an exponential but in 31.2% is a quadratic. At first thermal conductivity increases as temperature

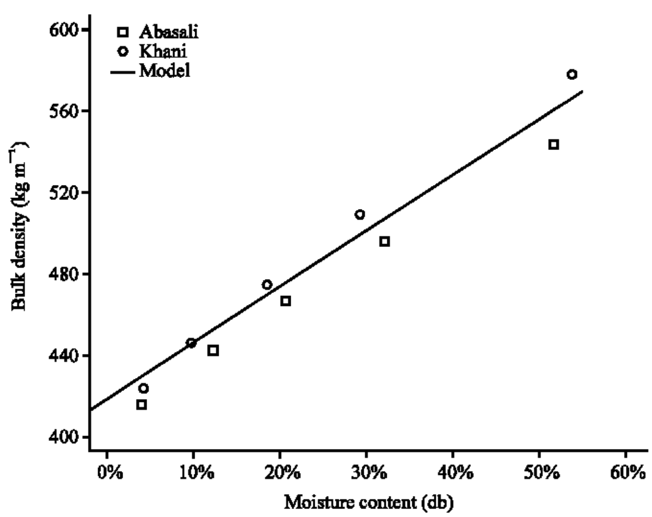

Fig. 2: Effect of moisture content on bulk density of pistachio

rises, then after 70 to 80°C approach descent. In this level of moisture content process of releasing moisture from surface and drying of pistachios have constant rate. In lower moisture as 20, 11.5 and 3.3% dry basis thermal conductivity cause to move in the opposite direction of temperature. In this level of moisture content drying process have descend rate commonly. Average values of thermal conductivity at 50 to 93°C were changed from 0.231 to 0.466 W m^{-1} °C in different moisture content. Polynomial regression equations were determined for the data with $R^2 = 0.95$ as follows:

$$k = -5427.82 + 10703.87\exp\left(\frac{1}{T}\right) - 5276.85\exp\left(\frac{2}{T}\right) \quad M = 51.5\% \tag{9}$$

$$k = -2.1 + 0.064T - 0.0004T^2 \quad M = 31.2\% \tag{10}$$

$$\frac{1}{k} = 0.234 + 0.034T \quad M = 20\% \tag{11}$$

$$\frac{1}{k} = 0.43 + 0.032T \quad M = 11.5\% \tag{12}$$

$$\frac{1}{k} = 0.265 + 0.047T M = 3.3\% \tag{13}$$

Results of the thermal conductivity are shown in Fig. 3 for 51.5%, Fig. 4 for 31.2%, Fig. 5 for 20%, Fig. 6 for 11.5% and Fig. 7 for 3.3% moisture contents.

Thermal Diffusivity

Thermal diffusivity of pistachios reduces at higher temperature but differences are low. Differences of thermal diffusivity at 55 to 95°C in any moisture content are under 0.01 cm^2 sec^{-1}. Average values of thermal diffusivity at previously mentioned temperatures were changed from minimum 2.293×10^{-7} m^2 sec^{-1} to maximum 4.385×10^{-7} m^2 sec^{-1} on various moisture content. Polynomial regression equations were determined for the data with R^2, all thermal diffusivity are converse function versus temperature as follows:

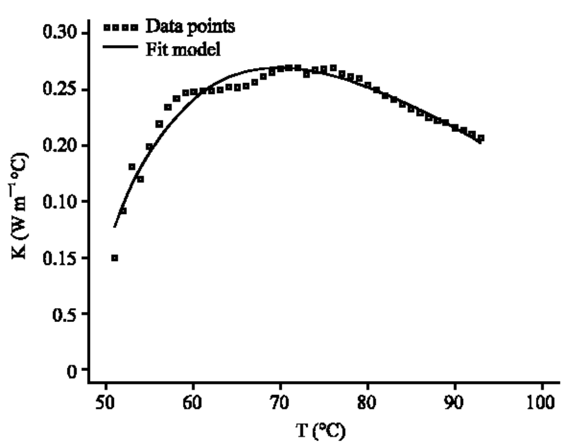

Fig. 3: Thermal conductivity vs. temperature in 51.5% moisture content

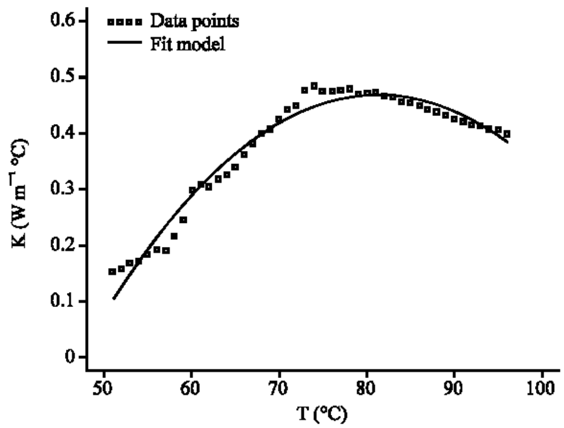

Fig. 4: Thermal conductivity vs. temperature in 31.2% moisture content

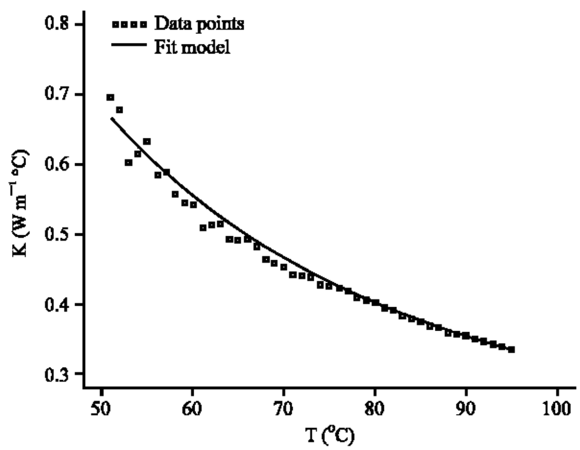

Fig. 5: Thermal conductivity vs. temperature in 20% moisture content

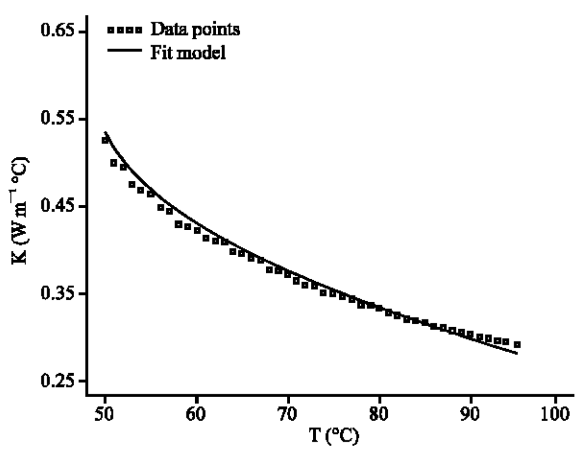

Fig. 6: Thermal conductivity vs. temperature in 11.5% moisture content

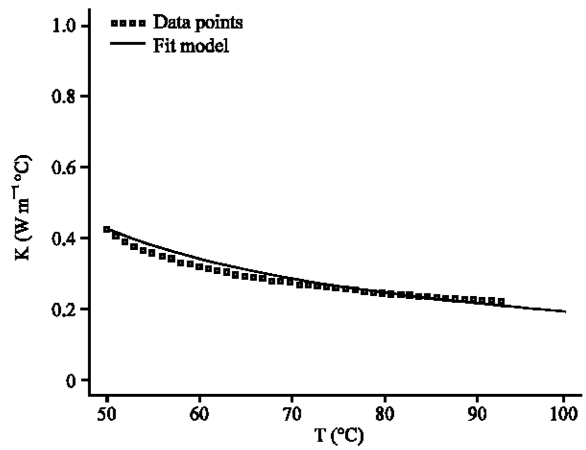

Fig. 7: Thermal conductivity vs. temperature in 3.3% moisture content

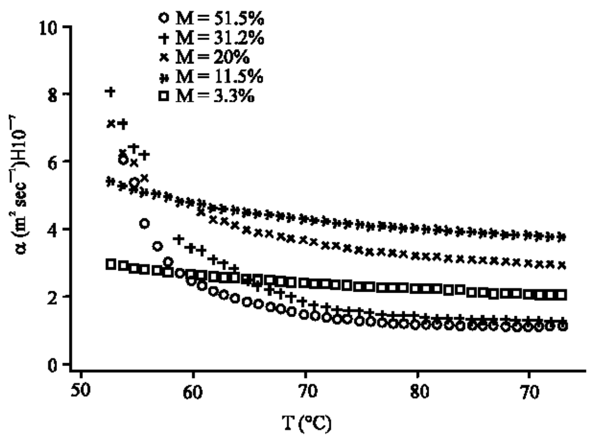

Fig. 8: Thermal diffusivities vs. temperature in various moisture

$$\frac{1}{\alpha} = -8311460 + 205178T \quad M = 51.5\% \tag{14}$$

$$\frac{1}{\alpha} = -7956650 + 183085T \quad M = 31.2\% \tag{15}$$

$$\frac{1}{\alpha} = -1012020 + 50101.6T \quad M = 20\% \tag{16}$$

$$\frac{1}{\alpha} = 799010 + 20961.9T \quad M = 11.5\% \tag{17}$$

$$\frac{1}{\alpha} = 1649090 + 35375T \quad M = 3.3\% \tag{18}$$

Results of the thermal diffusivity are shown in Fig. 8.

Specific Heat

It is obviously showed that bulk pistachios specific heat increases at similar temperatures with reduction moisture content on 31.2%, then in lower moisture content the specific heat decreases at same temperatures but in 3.3% moisture content rises again. Average values of specific heats at 50 to 93°C were changed from minimum 1894 to maximum 3820 J kg^{-1} °C on various moisture content. Polynomial regression equations were determined for the data with R^2>0.97 as follows:

$$c = -25292.68 + 707.023T - 4.2576T^2 \quad M = 51.5\% \tag{19}$$

$$c = 376092.7 - 21410.09T + 442.0305T^2 - 3.91237T^3 + 0.012639T^4 \quad M = 31.2\% \tag{20}$$

$$c = -33770560 + 66641420\exp(\frac{1}{T}) - 32874220\exp(\frac{2}{T}) \quad M = 20\% \tag{21}$$

$$c = 1653.91 + 12.47T - 0.1199T^2 \quad M = 11.5\% \tag{22}$$

$$c = 2530.41 + 659441200T^{-3/5} \quad M = 3.3\% \tag{23}$$

Results of the specific heats are shown in Fig. 9 for 51.5%, Fig. 10 for 31.2%, Fig. 11 for 20%, Fig. 12 for 11.5% and Fig. 13 for 3.3% moisture contents.

The line heat source method was used to determine thermal conductivity and diffusivity. Specific heats were calculated from measured thermal conductivity, diffusivity and bulk density.

Present results showed that the specific heats of pistachios were changed from 1.894 to 3.820 kJ kg^{-1} °C in different moisture content. The study of Razavi and Taghizadeh (2007) for initial moisture content, 25, 15 and 5 w.b. and temperature 25, 40, 55 and 70°C with method mixture showed that the range of 0.419-2.930 kJ kg^{-1} °C, however, the effect of moisture content was greater than both variety and temperature.

For bulk pistachios in 51.5 and 31.2% moisture content, the thermal conductivity increases when temperature rises, then after 70 to 80°C approaches to descent. In this level

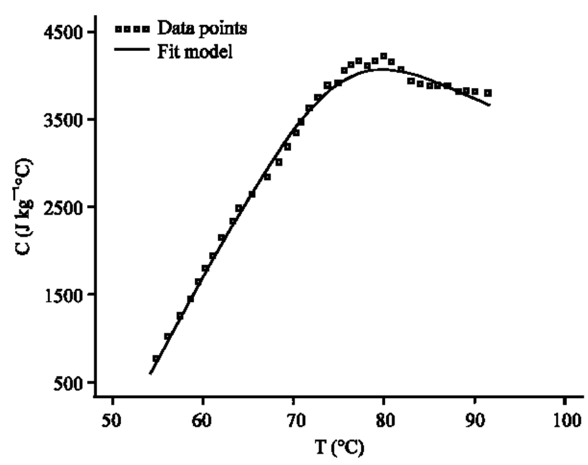

Fig. 9: Specific heat vs. temperature in 51.5% moisture content

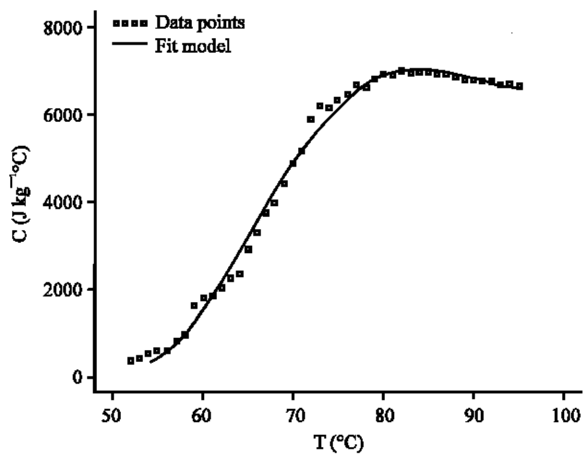

Fig. 10: Specific heat vs. temperature in 31.2% moisture content

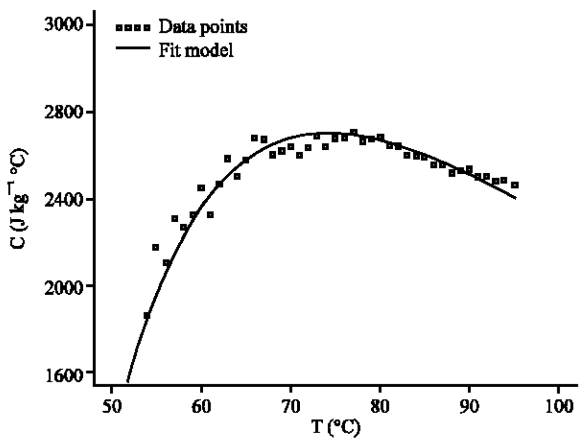

Fig. 11: Specific heat vs. temperature in 20% moisture content

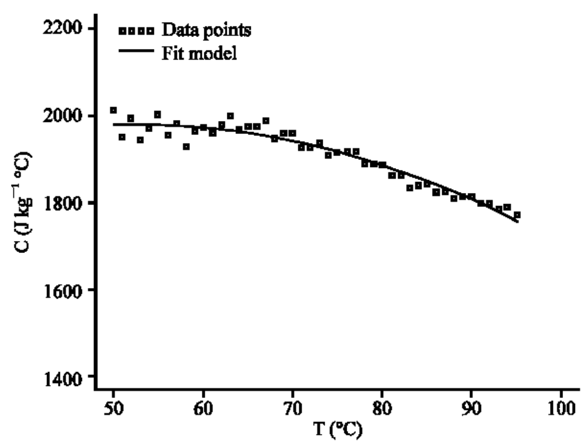

Fig. 12: Specific heat vs. temperature in 11.5% moisture content

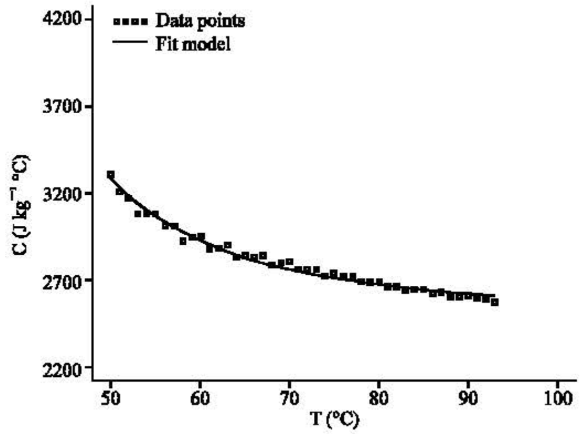

Fig. 13: Specific heat vs. temperature in 3.3% moisture content

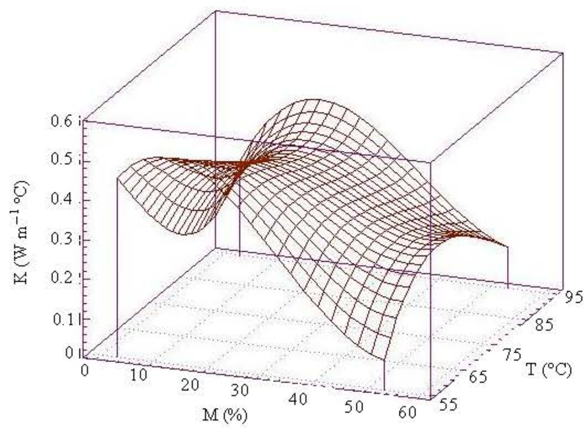

Fig. 14: Thermal conductivities of pistachios vs. temperature and moisture content

of pistachios moisture content drying process are in phase 1 and in lower moisture such as 20, 11.5 and 3.3% thermal conductivity moves in the opposite direction of temperature. In this level of pistachios moisture content drying process are in phase 2.

For the results, bulk specific heat and thermal conductivity were determined as function of temperature and moisture by multiple regressions as:

$$\begin{aligned} &k = -8.066769M + 0.05493T - 8.5956M^2 - 0.001284T^2 + 0.271137MT + \\ &10.622738M + (7.590181\times10^{-6})T^3 - 0.037529M^2T - 0.001569T^2M \\ &R^2 = 96.17 \end{aligned} \tag{24}$$

$$\begin{aligned} &c = -150559.3M + 387.87837T + 283301.6M^2 - 7.46351T^2 + 2315.373851MT - \\ &281406.5M^3 + 0.038866T^3 - 947.32602M^2T - 10.165614T^2M \\ &R^2 = 95.11 \end{aligned} \tag{25}$$

Equations 24 and 25 are valid for temperatures between 50 to 93°C and moisture between 3 to 53% dry basis. Results are shown in Fig. 14 and 15.

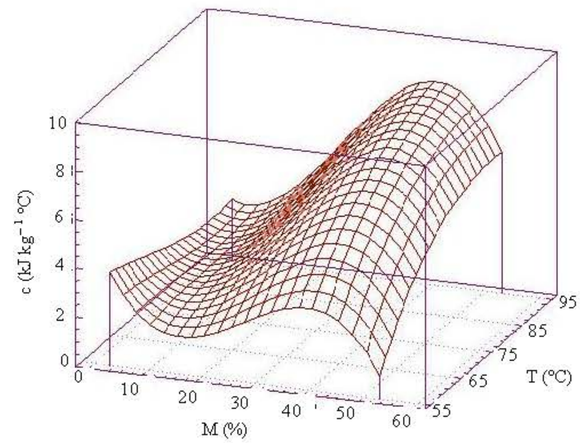

Fig. 15: Specific heats of pistachios vs. temperature and moisture content

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NOMENCLATURES

c	= Specific heat (J kg^{-1} °C)
Q	= Heat input (W m^{-1})
α	= Thermal diffusivity (m^2 sec^{-1})
r	= Distance from heat source (m)
k	= Thermal conductivity (W m^{-1} °C)
θ	= Heating time (sec)
ρ	= Density (kg m^{-3})
C_e	= Euler's constant (0.5772157)
M	= Moisture content (dry basis)
θ_2, θ_1, θ_0	= Time (sec)
T	= Temperature field (°C)
n	= Positive integers
T^0	= Initial temperature (°C)
x	= Dummy variable
β	= Dimensionless

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