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Thermal Properties of Soybean Pod as a Function of Moisture Content and Temperature

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Abstract In this study, specific heat, thermal conductivity, and thermal diffusivity of soybean pod were evaluated as a function of moisture content and temperature. Specific heat and thermal conductivity of soybean pod were measured by mixture method and transient state heat transfer apparatus respectively while thermal diffusivity was calculated using formula method. The experiments were done at four moisture levels [14.5, 21.5, 25.5, and 30.5 (w.b.%)] and four temperature levels [50, 150, 250, and 350 ℃] with 3 repetitions. Results showed significant variations in thermal properties values with changing moisture and temperature. Increasing moisture content and temperature increased specific heat and thermal conductivity from 1.856 to 4.39 kJ.kg^{-1} ℃$^{-1}$ and 0.038 to 0.338 W.m^{-1} ℃$^{-1}$ respectively. At all levels of temperature, thermal diffusivity decreased by increase in moisture content and at moisture increased by increase in temperature. The maximum amount of thermal diffusivity was obtained in the temperature and moisture content of 350 ℃ and 14.5 (w.b.%) ,respectively, which was equal to 2.62×10^{-7} m^2. S^{-1} and the minimum amount of thermal diffusivity was obtained in the temperature and moisture content of 50 ℃ and 30.5% (w.b.%) ,respectively, which was equal to 7.18×10^{-8}. Maximum thermal diffusivity coefficient in 350 ℃ and 14.5% (w.b.) was 2.62×10^{-7} m^2. S^{-1} and minimum in 50 ℃ and 30.5% (w.b.) was 7.18×10^{-8} m^2. S^{-1}.

Keywords: *soybean pod, specific heat, thermal conductivity, thermal diffusivity, mixture method, transient state*

1. Introduction

In general, soybeans are harvested in the cold season with high relative humidity and possibility of rainfall. These conditions, makes the moisture content of soybean pod is high, so that the grain combine harvester can` t properly thresh and separate the bean from it` s pod. Since the farmers should harvest and sell soybean on time and also they have to prepare land for the next cultivation, having a pre-threshing dryer unit which can reduce some moisture content of soybean pod in field for proper working of combine is necessary. This study due to determination of thermal properties of soybean pod were done. The aim of this study was to determine the thermal properties of soybean pods.The result are useful in fabrication of pre-threshing dryer on combine harvester or dryers. The transient heat conduction during drying material is an important heat transfer mechanism in materials. Also, in the food industry, thermal properties are important parameters to determine in designing equipment or its parts, and, in computer simulation, to analyze, optimize, and control of the temperature during the elaboration, storage, transport and commercialization of foods is very important. The design and control of equipment are difficult due to the lack of information on the behavior of the thermo physical properties with composition and temperature. Equipment size is usually overestimated to compensate the lack of information, leading to a non-ideal design with cost implications as well as inferior quality of the product. These thermal controls can only be put in practice by the precise knowledge of the thermo- physical characteristics of the food stuffs. These works are realized to foresee how the heat and mass transfers occur in the products with the final objective of the optimization of these processes. There are numerous methods to measure the thermal properties proposed in the literature. The specific heat, thermal conductivity and thermal diffusivity of soybean pod were determined by method of mixtures, conductivity prob flow and the method proposed by Mohsenin, respectively [1].

Several papers discussed present results of thermal characterization of different materials such as: peanut [2], apple [3], coconut milk [4], bread dough [5], liquid egg products [6], borage Seeds [7]), potato starch [8], rough Rice [9], sandwich bread [10], sheanut kernel [11]. Previous literature data indicated the major factors influencing thermal properties of materials: temperature, water content, fat, state of pressure and density. Materials with lower porosity have lower thermal conductivity. Also, heat conductivity of solids increases with moisture content [7,12,13].

The objective of this research was to determine thermal conductivity, thermal diffusivity and specific heat in soybean pod. Results are useful in drying soybean and the pod before threshing and thereby reducing losses during harvesting.

2. Materials and Methods

2.1. Sample Preparation

Soybeans harvested from the experimental farm in Gorgan, Iran, were used in the study. Samples were stored in a refrigerator at 5℃ prior to the drying experiments. Three 100g samples were dried in an oven at 105℃ for 24h to determine initial moisture content.

2.2. Thermal Conductivity Determination

The thermal conductivity of soybean was determined using a line heat source method, the most commonly used transient-state heat transfer method. For an infinitely long line heater in an infinite, homogeneous, and isotropic medium the temperature rise at a radial distance (r) from the line, heat source can be represented by the following equation:

$$\Delta T = \frac{Q}{4\pi K}\left[\ln(t) + \ln\left(\frac{4\alpha}{r^2 e^{0.5772}}\right)\right] \tag{1}$$

Where, ΔT is temperature rise at a distance r from the line-heat source probe (℃); t is the time (s), Q is the heating power/unit of probe length ($W.m^{-1}$); k is thermal conductivity ($W.m^{-1}$ $℃^{-1}$); α is thermal diffusivity ($m^2 s^{-1}$); r is the distance from central axis probe (m).

Eq. (1) means that the gradient of a plot of (ΔT) versus natural logarithm of time, ln (t), is equal to $S = Q.(4\pi k)^{-1}$. The thermal conductivity can then be calculated as:

$$k = \frac{Q}{4\pi}\frac{\Delta \ln(t)}{\Delta T} \tag{2}$$

Since $Q = I^2R$, the above equation can be rearranged as:

$$k = \frac{I^2 R}{4\pi S} \tag{3}$$

where, I is the electric current; R is the electric resistance per unit length (Ω/m).

A hot-wire thermal conductivity apparatus used in this study is shown in Figure 1. The apparatus consisted of a Pyrex cylinder 83mm in height and 29mm in inner diameter, with a removable rubber top and bottom cover.

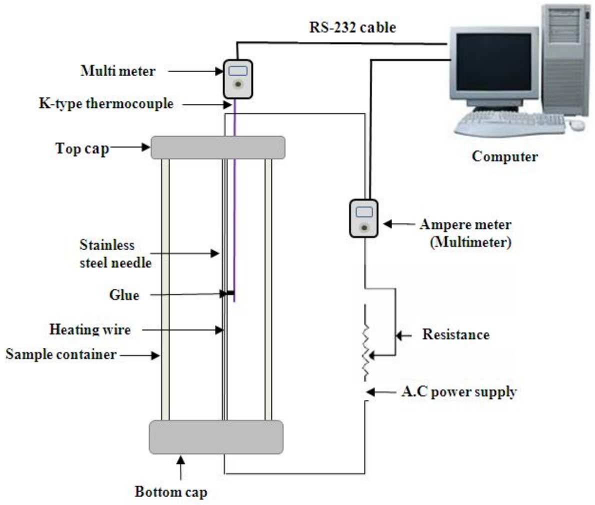

Figure 1. Schematic of the apparatus used for measuring thermal conductivity

A nichrome resistance heating wire with a diameter of 0.150mm and length of 235mm ($30.37\Omega.m^{-1}$) was connected to constant DC power source (0-12V) and the desired current adjusted by resistor. A pre-calibrated 0.8mm diameter K-type thermocouple were installed for measuring the core temperature and glued approximately 1mm from heating wire at the middle of the heating wire. The assumption of an infinite medium required that the surface temperature of the sample holder was constant during the experiments. To validate this assumption, a second thermocouple was attached to the outer surface of the cylinder to monitor its temperature. A data logger multi-type thermometer (ET-2230, Minipa, China) was used to collect the temperature data. The thermocouple temperatures were recorded by the data logger every second for 5min. A digital multi-meter was used to monitor the current (ET-2230, Minipa, China). The recorded temperature values were then plotted against the natural logarithm of elapsed time. The slope (S) and the coefficient of determination (R^2) were determined successively for each experimental run using different data intervals. The slope for the highest R^2 was selected from the data intervals and used in the thermal conductivity determination. Slopes with R^2 values of less than 0.990 were not used in the thermal conductivity determination.

Before measuring the samples, the probe was calibrated with 0.5% agar gel and glycerin. The expected values of 0.5% agar gel and glycerin at 30℃ was 0.628 and 0.289 $W.m^{-1}$ $℃^{-1}$, respectively [4]. The measured average thermal conductivity of 0.5% agar gel at 30℃ was 0.624±0.007 $W.m^{-1}$ $℃^{-1}$, an approximately 0.64% deviation from the expected value. The measured average thermal conductivity of glycerin at 30℃ was 0.286 ± 0.008 $W.m^{-1}$ $℃^{-1}$, an approximately 0.81% deviation from the expected value.

2.3. Specific Heat Determination

The method of mixtures has been the most common technique reported in the literature for measuring the specific heat of agricultural/food materials [1,14,15]. The apparatus consisted of cylindrical aluminum capsules for holding the samples with 15.2mm diameter, 52.6mm height and 2.1mm wall thickness which were provided with a threaded lid to ensure no moisture was lost from the sample and no water entered into the capsule during the experiment, T-type thermocouples with a temperature indicator, 250cm^3 capacity insulated vacuum thermo-flasks and a hot air oven. The heat capacity of the calorimeter was determined experimentally by adding a known quantity of distilled water at a known high temperature (maximum 100℃) to the calorimeter. As the system was assumed to be adiabatic, , the heat capacity of the calorimeter was determined by following equation:

$$H_f = \frac{M_{cw}C_w\left(T_e - T_{cw}\right) - M_{hw}C_w\left(T_{hw} - T_e\right)}{\left(T_{hw} - T_e\right)} \tag{4}$$

where, H_f is the heat capacity of flask (cal. $℃^{-1}$), M_{cw} is the mass of cold water (kg), M_{hw} is the mass of hot water (kg), C_w is the specific heat of water ($cal.kg^{-1}$ $℃^{-1}$), T_{cw} is the temperature of cold water (℃), T_{hw} is the temperature of hot water (℃), and T_e is the temperature of equilibrium cold water (℃).

The heat capacity of cylindrical aluminum test capsule was also determined experimentally. For this purpose the capsule at a known high temperature was added to the calorimeter that containing a known quantity of distilled water at a known low temperature (room temperature). The system was assumed to be adiabatic. Therefore, the heat capacity of the capsule was given by equation (5):

$$H_c = \frac{\left(H_f + M_{cw}C_w\right)\left(T_e - T_{cw}\right)}{\left(T_c - T_e\right)} \qquad (5)$$

where, H_c is the heat capacity of capsule (cal ℃$^{-1}$), and T_c is the temperature of capsule (℃).

To determine the specific heat of the soybeans, the test capsule was filled with the soybeans and was maintained into hot air oven at desired temperature for at least one hour. Then the filled capsule was dropped into the calorimeter containing a known quantity of distilled water at a known low temperature and equilibrium temperature was recorded. The specific heat of soybeans was calculated using the following heat balance equation:

$$C_p = \frac{\left(H_f + M_{cw}C_w\right)\left(T_e - T_{cw}\right) - H_c\left(T_m - T_e\right)}{M_m\left(T_m - T_e\right)} \times 4.1868 \qquad (6)$$

where, C_p is the specific heat of soybeans (kJ.kg^{-1} ℃$^{-1}$), M_m is the sample (kg), and T_m is the temperature of sample (℃).

In this technique, certain assumptions were required as there was no heat loss from the capsule containing the material, during transfer from the hot air oven to the calorimeter, the capsule and the pods attained uniform temperature throughout the mass at the end of heating, there was no evaporation loss in the calorimeter during equilibration period, and the heat capacities of the calorimeter and the capsule remained constant within the range of temperature studied.

2.4. Thermal Diffusivity Determination

Thermal diffusivity of soybean was calculated by the relationship given in equation (7).

$$\alpha = \frac{k}{pC_p} \qquad (7)$$

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

The bulk density (ρ) of soybeans was determined by filling a container with sample from a height of 150mm at a constant rate and weighing the contents. The volume of the container was estimated by filling the container with water and measuring it with 80ml measuring cylinder. The bulk density is the ratio of the mass of a sample of a sample to its total volume.

3. Results and Discussion

The effects of moisture content and temperature on specific heat, thermal conductivity, and thermal diffusivity of soybean pod are shown in Figure 2, Figure 3, Figure 4 through response surface diagrams. It is observed that the specific heat and thermal conductivity values increased with increase in moisture content and temperature of soybean pod. At all temperatures tested, increase in moisture content caused decrease in thermal diffusivity and increase in temperature caused increase in thermal diffusivity.

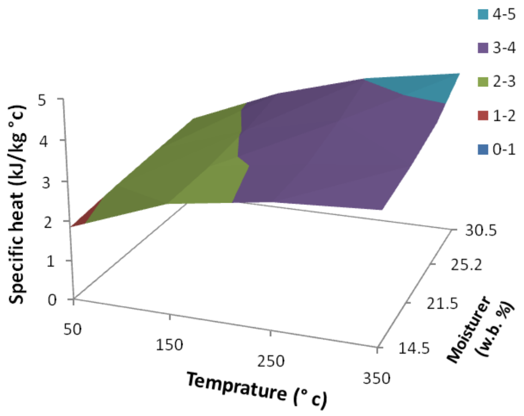

Figure 2. Effects of different moisture and temperature on specific heat

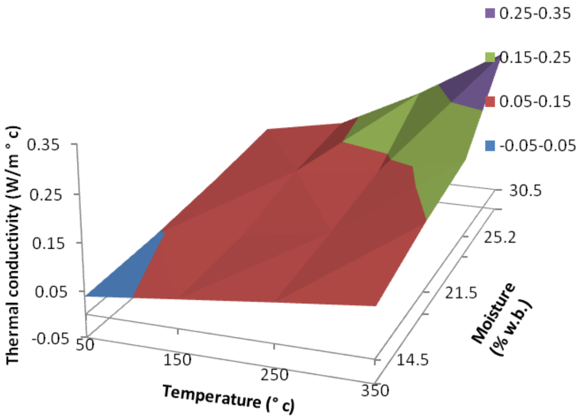

Figure 3. Effects of different moisture and temperature on thermal conductivity

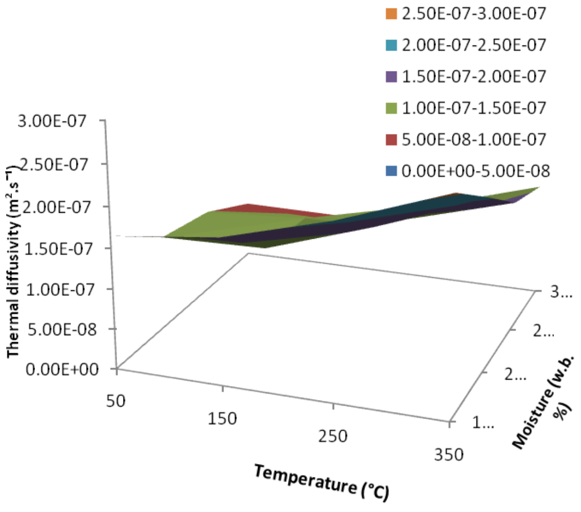

Figure 4. Effects of different moisture and temperature on thermal diffusivity

Also, the specific heat, thermal conductivity and thermal diffusivity of soybean pod from 1.865 to 4.390 kJ.kg^{-1} ℃$^{-1}$, 0.038 to 0.338W.m^{-1} C^{-1}, 2.62×10^{-7} to

7.18×10^{-8} m^2.s^{-1} respectively for the experimental range of variables studied.

According to Table 1 which shows variance analyses of specific heat, thermal conductivity, and thermal diffusivity effect of moisture content and temperature on specific heat, thermal conductivity, and thermal diffusivity was significant. The relationship between the thermal properties and moisture content for each temperature can be expressed by the regression equations (Table 2). Linear relationship between thermal properties and temperature for each moisture content were presented in Table 3. Also eq..8-10 gaves the linear relationship between thermal properties, moisture content and temperature:

$$C = 0.256M + 0.529T + 1.120 R^2 = 0.916 \tag{8}$$

$$K = 0.039M + 0.044T - 0.089 R^2 = 0.815 \tag{9}$$

$$\alpha = 2.741\times10^{-5}T - 3.49\times10^{-5}M + 1.6\times10^{-4} R^2 = 0.926 \tag{10}$$

Researchers measured the specific heat of Cassava, Yam, and Plantain as a function of moisture content and temperature. Almost in all cases, there was a similarity in the specific heat values of three crops and for each crop, and the specific heat increased with increasing both moisture and temperature [16]. Shrivastava and Datta also indicated the similar results for mushrooms, but they found that the moisture content in compared with the temperature had a highly significant effect on specific heat [17]. Singh and Goswami s evaluated the specific heat of cumin seed at various temperature (70 to 50 ℃) and moisture content (1.8–20.5% d.b.) levels. Specific heat was found to be both moisture and temperature dependent and increased from 1.330 to 3.090 (kJ kg $^{-1}$ K^{-1}) with increase in temperature and moisture content [14]. The effect of variation in moisture content (3.32–20.70% d.b.) and temperature (303–363 K) on thermal properties of Sheanut kernel was investigated and found that the specific heat values increased linearly with moisture content and temperature in the range of 1.792–3.172 (kJ kg $^{-1}$ K^{-1}) [11].

Table 1. Variance analyses of specific heat, thermal conductivity, and thermal diffusivity under different initial moisture content and temperature

Source of variation	Degrees of freedom	Sum of squares	Mean square		
			specific heat thermal	conductivity thermal	diffusivity
Moisture (Mc)	3	4.133	1.377^{**}	0.034^{**}	$2.503\times10^{-8**}$
Temperature (T)	3	18.001	6.00^{**}	0.039^{**}	$1.626\times10^{-8**}$
T ×Mc	9	0.492	0.054^{**}	0.003^{**}	$3.741\times10^{-10**}$
Error	32	0.0038	0.00012^{**}	$6\times10^{-6**}$	$9.361\times10^{-12**}$

Table 2. Relationships related to thermal properties calculation of soybean pod in different temperature

Equation			Tem. (℃)
Specific heat	Thermal conductivity	Thermal diffusivity	
$C=0.032M+1.379$, $R^2=0.994$	$K=0.003M-0.017$, $R^2=0.924$	$\alpha=-5.60\times10^{-9}M+2.436\times10^{-7}$, $R^2=0.994$	50
$C=0.032M+2.173$, $R^2=0.878$	$K=0.004M-0.011$, $R^2=0.873$	$\alpha=-6.50\times10^{-9}M+2.704\times10^{-7}$, $R^2=0.878$	150
$C=0.032M+2.202$, $R^2=0.861$	$K=0.008M-0.057$, $R^2=0.832$	$\alpha=-7.18\times10^{-9}M+3.163\times10^{-7}$, $R^2=0.861$	250
$C=0.032M+2.158$, $R^2=0.894$	$K=0.014M-0.122$, $R^2=0.833$	$\alpha=-7.8\times10^{-9}M+3.754\times10^{-7}$, $R^2=0.894$	350

C= Specific heat of soybean pod (kJ.kg^{-1} ℃$^{-1}$), K= Thermal conductivity of soybean pod (W.m^{-1} C^{-1}), α =Thermal diffusivity of soybean pod (m^2.s^{-1}), M= Percent of moisture content (14.5-30.5w.b.)

Table 3. Related relationships to thermal properties calculation of soybean pod in different moisture content

Equation			Moisture (w.b.%)
Specific heat	Thermal conductivity	Thermal diffusivity	
$C=0.0004T+1.834$, $R^2=0.873$	$K=0.0002T+0.027$, $R^2=0.990$	$\alpha=3.00\times10^{-10}T+1.39\times10^{-7}$, $R^2=0.954$	14.5
$C=0.0004T+1.973$, $R^2=0.934$	$K=0.0003T+0.024$, $R^2=0.973$	$\alpha=3.37\times10^{-10}T+8.35\times10^{-7}$, $R^2=0.897$	21.5
$C=0.0005T+2.108$, $R^2=0.935$	$K=0.0004T+0.049$, $R^2=0.984$	$\alpha=1.95\times10^{-10}T+8.78\times10^{-7}$, $R^2=0.861$	25.2
$C=0.0006T+2.183$, $R^2=0.959$	$K=0.0008T+0.029$, $R^2=0.956$	$\alpha=2.43\times10^{-10}T+4.82\times10^{-7}$, $R^2=0.894$	30.5

C= Specific heat of soybean pod (kJ.kg^{-1} ℃$^{-1}$), K= Thermal conductivity of soybean pod (W.m^{-1} C^{-1}), α =Thermal diffusivity of soybean pod (m^2.s^{-1}), T=Temperature (50-350 ℃)

Thermal conductivity, specific heat, and thermal diffusivity of borage seeds were obtained by Yang et. al. They determined by increase in moisture from 1.2 to 30.3% (w.b.%) thermal conductivity will increase from 0.11 to 0.28 W.m^{-1} °K^{-1} and specific heat will change from 0.77 to 1.99 kJ.kg^{-1} K^{-1} and thermal diffusivity will go from 2.32×10^{-7} to 3.18×10^{-7}m^2 S^{-1} [7]. Verma and Prasad experiments on corn showed that when moisture go from 10% to 50% thermal conductivity, specific heat and thermal diffusivity increased from 0.125 to 0.193 W.m^{-1} ℃$^{-1}$ and from 2.002 to 2.996 kJ.kg^{-1} ℃$^{-1}$ and from 8.33×10^{-8} to 10.17×10^{-8} m^2 S^{-1} respectively [18]. Studies on pod, seed and shell of peanut showed, specific heat changed from 2.1 to 3.3, 1.9 to 2.8 and 2.7 to 4.1 kJ.kg^{-1} ℃$^{-1}$ respectively, however moisture content increased from 5.2 to 23.7, 5 to 30.6 and 3.5 to 28.7% (d.b.). Thermal conductivity of pod, seed and shell increased from 0.12 to 0.16, 0.15 to 0.19 and 0.11 to 0.18 W.m^{-1} ℃$^{-1}$ respectively and by increase in moisture content. Thermal diffusivity of pod and seed in that moisture range reduced from 2.8×10^{-8} to 2.3×10^{-8} and 1.1×10^{-8} to 1×10^{-8} m^2. S^{-1} and thermal diffusivity of shell increased from 5.9×10^{-8} to 6.7×10^{-8}m^2 S^{-1} [12]. Researchers used mixture method to determine specific heat of peanut pod and reported that specific heat of pod increased by increase in moisture content and temperature [19]. According to Singh and Goswami reports, specific heat of cumin seed increase from 1.330 to 3.090kJ.kg^{-1} K^{-1}. Thermal conductivity will change from 0.046 to 0.223 W.m^{-1} °K^{-1} while temperature and moisture content go from -70 to 50℃ and 1.8 to 20.5% (d.b), and while temperature change from -50 to 50 ℃ and moisture is 7.8% (d.b.) thermal diffusivity increase from 6.53$\times 10^{-8}$ to 16.64$\times 10^{-8}$ m^2. S^{-1}, but in 10 ℃ temperature and moisture content increase from 1.8 to 11.1% (d.b.) thermal diffusivity decrease from 14.72$\times 10^{-8}$ to 12.87$\times 10^{-8}$$m^2$ S^{-1} [14]. Results of work on minor millet grains and flours showed that by increase in moisture from 10 to 30% (w.b.) specific heat and thermal conductivity increase from 1.33 to 2.4 kJ.kg^{-1} $℃^{-1}$ and 0.119 to 0.223 W.m^{-1} $°K^{-1}$ respectively, but thermal diffusivity decrease from 0.734 to 0.55 m^2 h^{-1} [20]. Experiment on palm seed has shown that specific heat (by mixture method), thermal conductivity (by line heat source) and thermal diffusivity by increase in moisture from 5.2% to 25.4% (d.b.) will increase from 2.508 to 3.1177$\times 10^{-3}$ kJ.kg^{-1} $℃^{-1}$, 0.078 to 0.152 W.m^{-1} $℃^{-1}$ and 13.92 to 18.33 m^2 S^{-1}, respectively [21]. Work of researchers on timothy hay illustrated that increase in moisture in range of 7.7% to 17.1% will cause increase in thermal conductivity and thermal diffusivity from 0.284 to 0.0605 W.m^{-1} $℃^{-1}$ and 1.024 to 3.031$\times 10^{-7}$ m^2. S^{-1}, respectively [22]. Also, reports has shown thermal conductivity increase of barely, barley, lentils, and peas as follow, 0.169 to 0.232 W.m^{-1} $°K^{-1}$, 0.187 to 0.249 W.m^{-1} $°K^{-1}$ and 0.187 to 0.257 W.m^{-1} $°K^{-1}$ respectively. In all of them range of moisture increase from 9 to 23% [23].

4. Conclusions

1. Thermal properties of soybean pod were determined for the typical ranges of moisture content, and temperature. The results showed the significant variations in thermal properties values with changing these variables.
2. By increasing in moisture content from 14.5 to 30.5 (%w.b.) and temperature from 50 to 350 ℃, specific heat increased from 1.856 to 4.39 kJ.kg^{-1} $℃^{-1}$.
3. Thermal conductivity increased from 0.038 to 0.338 W.m^{-1} $℃^{-1}$ with increase in temperature from 50 to 350 ℃ and moisture content from 14.5 to 30.5 (%w.b.).
4. Thermal diffusivity decreased from 2.62$\times 10^{-7}$ to 7.18$\times 10^{-8}$ m^2. S^{-1} by increase in moisture content from 14.5 to 30.5 (%w.b.) and temperature from 50 to 350 ℃.
5. The developed models can be also used to estimate the thermal properties of soybean pod within the range of variables studied.

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