Thermal properties measurement of cut tobacco based on TPS method and thermal conductivity model

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Abstract Drying process of biomass porous media is widely involved in agricultural products processing. Accurate measurement of thermal properties and prediction of thermal conductivity variation at different conditions is the key of heat transfer simulation and optimization for drying process. The present work measured the thermal properties of cut tobacco in a constant temperature experimental platform by transient plane source method (TPS method), and developed a model to predict thermal conductivity of cut tobacco at different conditions. The results showed that there was a high test precision for thermal properties measurement of cut tobacco by TPS method. Thermal conductivity of cut tobacco increased significantly with the increase of temperature and moisture content at the range of 25–65 °C and 12.5–25 %. Volume heat capacities showed a similar trend. The model predictions of thermal conductivity showed strong correlation coefficient with experimental values. The deviation of model predictions is less than 10 %, which indicated that the established model had a good prediction precision for thermal conductivity of cut tobacco.

Keywords Thermal properties · Cut tobacco · Transient plane source method (TPS method) · Thermal conductivity · Model

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Introduction

Agro-processing widely involves biomass wet porous media, such as grains, seeds, fruits, vegetables, fodder, and tobacco drying process. Thermal properties of the processed materials are key factors affecting drying quality. The heat transfer between materials and dryer, as well as the variation of moisture content and temperature are closely associated with the thermal conductivity, heat capacity, and other thermal parameters of materials. Therefore, the accurate determination of thermal properties of the biomass wet porous media is the key of simulating heat and mass transfer during drying process to optimize process parameters. It is especially important for processing quality control of thermo-sensitive materials.

Two kinds of methods including steady state and non-steady state methods are generally used to determining thermal properties of materials. Non-steady state method is suggested to have a shorter test time and can obtain multiple parameters within a measurement [1, 2], which make it increasingly used in the thermal properties testing of different materials, such as metallic materials, ceramics, building materials, fabrics, and other non-metallic porous materials [3–5]. Transient plane source method (TPS method) developed in recent years is a non-steady state testing methods for thermal properties of materials [6–8]. Compared with the transient hot wire method and hot strip method, TPS method is based on the average temperature measurement of the heated surface of sample [9], which is particularly important for anisotropic materials such as biomass porous media. It also has a wider measurement range of thermal conductivities between 0.01 and 500 W m^{-1} K^{-1}. Although it has been applied to thermal properties studies of different materials [10–12], the TPS method for measuring thermal properties of agriculture
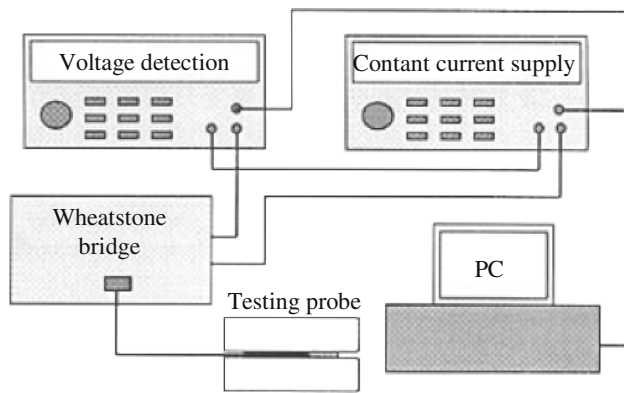
Fig. 1 Schematic diagram of TPS system

products has been rarely reported. Thermal properties of wet porous media are closely related to its particle composition, moisture content, and stacking behavior [13–15]. As porous materials with high moisture content are always involved in agriculture products, moisture loss for these materials during measuring would affect the accuracy of thermal properties results, especially at relatively high testing temperature. In the present work, thermal properties of flue cured tobacco as the typical biomass porous media materials were investigated in a constant temperature and humidity experimental platform based on the TPS method. And a model is established for predicting thermal conductivity of cut tobacco at different temperature and moisture content conditions. The results of predicted model and experimental measurement by TPS method were further analyzed.

Materials and methods

Test materials

A kind of cut tobacco (flue cured tobacco from Sichuan province of China) was chosen as experimental materials. The raw material is pretreated as follows: by adding a calculated amount of distilled water to cut tobacco, moisture content of cut tobacco was adjusted to the desired level of moisture content. In this work, moisture content of the testing cut tobacco was set as 22.5, 20, 17.5, 15, and 12.5 % , respectively (on the wet basis). After adjusting the moisture content, cut tobacco was bagged and put into isothermal and equal humidity equipment to balance moisture for 48 h.

TPS test principle

The principle of non-steady state method is to add thermal interference to the heat balance sample, and then record the

temperature response of sample to the thermal interference. According to the response curve, thermal properties parameter values can be determined based on unsteady heat conduction differential equation [6]. TPS method for the determination of thermal properties is based on the transient temperature response of an infinite medium during step heating, and the TPS test system consists of a constant current power supply, voltage test unit, Wheatstone bridge, and the Hot Disk probe, as have been shown in Fig. 1.

During the work process, the constant current power is connected to the probe, while the Wheatstone bridge with constant output power heats the sample. When the probe is electrically heated, its thermal resistance value is a function of time as the following equation:

$$R(t) = R_0\{1 + \alpha[\Delta T_i + \Delta T_{ave}(\tau)]\} \tag{1}$$

where R_0 is the resistance of the probe before the test temperature, α is the test probe's thermal resistance coefficient of nickel plate, ΔT_i is the temperature difference between the protective layers, and ΔT_{ave} is the temperature response of material contacting the probe.

Hot Disk probe is used as heating source and temperature sensor to measure the mean temperature distribution of the material surface contacting with the probe. In the testing process, due to temperature change, there are changes in the resistance value, which will result in the voltage changes across the probe. By recording the change of the voltage during the test, the probe resistance changes with time can be obtained, which will result in the acquisition of the probe surface temperature rise. The heat exchange between the disk-shaped probe and the sample can be viewed as a heating conduction process of limited scale surface heater in the infinite medium. By using the Green function method to derive the unsteady two-dimensional heat conduction problem [2], the variation of temperature with time of the materials can be obtained:

$$\Delta T(\tau) = \frac{P_0}{\pi^{3/2} r \lambda} D(\tau) \tag{2}$$

where P_0 is total power output of the probe, a is radius of the probe, and λ is thermal conductivity of the material being tested. $D(\tau)$ is function of dimensionless time τ, which can be obtained by the following equations:

$$\tau = \sqrt{\frac{t}{\Theta}} \tag{3}$$

$$\Theta = \frac{a^2}{k} \tag{4}$$

where t is test time, Θ is characteristic time, and k is the thermal diffusivity of the test sample.

By changing different τ, when the squared deviations of linear fitting between the theoretical temperature rise and measured value is the smallest, the optimal τ value will be

Fig. 2 Constant temperature experimental platform. *1* Mercury thermometer *2* high temperature test probe *3* K-type thermocouple *4* temperature indicator *5* waterproof rubber gasket *6* TPS host computer *7* GPIB test data line *8* RS232line *9* PC machine
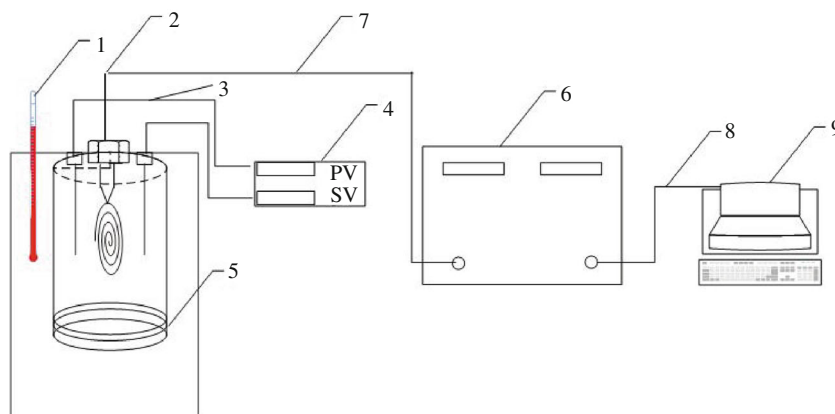
obtained. Thus the thermal conductivity can be got by the slope values of the fitted line. The thermal diffusivity k can be obtained by Eq. (4), and according to the formula $k = \lambda/c$, the volume heat capacity c can also be achieved.

Experimental platform

To ensure the constant temperature and moisture content condition for TPS test, the experimental platform as shown in Fig. 2 has been established in which the water bath method is used. After modulating and balancing cut tobacco moisture content to the set level, load the cut tobacco in a waterproof aluminum container quantitatively and uniformly, then place the probe in the middle of the sample to form a sandwich structure. To avoid the moisture migration during testing, the inner surface of the sample container lid was sealed with waterproof material. When sample was loaded into the container, pressed downward the sealing cover of container uniformly until the top surface of loaded sample reached the same height of barrel, which could ensure the certain filling volume for each test. Due to the same loading mass on dry basis and filling volume, the loading density of dry-based sample in the container can be controlled to the same level. After all these preparations, the aluminum containers will be placed in the water-bath pot, and two K-type thermocouple is added to record the temperature of tobacco, correspondingly, a mercury thermometer is used to measure the temperature of container wall.

Before the test, by adjusting the water-bath temperature, the temperature of cut tobacco in the container is stably controlled at test level. Effect of temperature was investigated by the measurement of each 10 °C step, and the test temperature levels are 25, 35, 45, 55, and 65 °C, respectively. Pre-experiment shows that moisture migration within the container is smaller enough to believe the moisture content is stable during testing. And when the bath temperature is about 10 °C higher than the tobacco system, the temperature changes of the experimental system at the highest temperature level within the 5 min is less than 1 °C
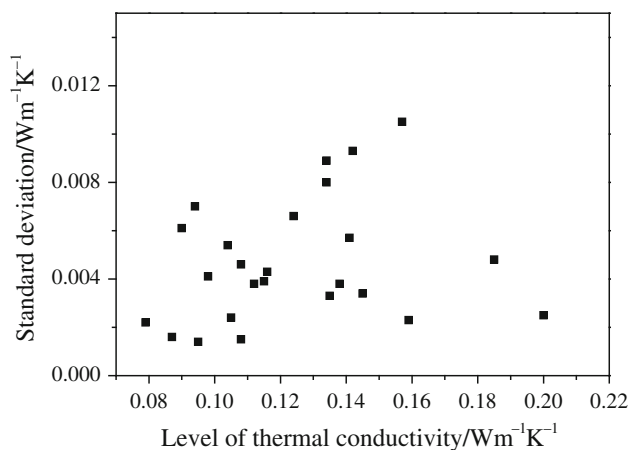

Fig. 3 The correlation of standard deviation and the level of thermal conductivity

around the test level. Because of the small thermal conductivity of cut tobacco, according to the contrast experiment, output power of probe was set as 0.025 W, in which the stability of obtained data is best. The test time is 70 s and more than 100 data points is collected in order to ensure the representative of a single thermal conductivity.

Results and discussion

Analysis of the test results

During the drying and rehydration process, wet basis moisture content of cut tobacco varies from 22.5 to 12.5 %, and the temperature is lower than 70 °C. Therefore, different temperature and wet basis moisture levels of cut tobacco are set within the range, which are 25, 35, 45, 55, 65 °C and 22.5, 20, 17.5, 15, 12.5 %. Four times parallel test were carried out to get the cut tobacco thermal conductivity and volume heat capacity at different temperatures and moisture levels. According to the test result, the standard deviation distribution of the thermal conductivity and the volume heat capacity for different conditions are shown in Figs. 3 and 4.
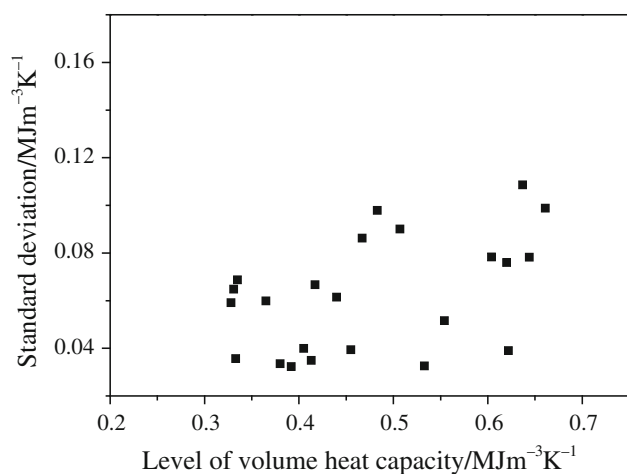
Fig. 4 The correlation of standard deviation and the level of volume heat capacity

As has been shown in Figs. 3 and 4, the thermal conductivity of cut tobacco within the investigated range of moisture content and temperature is about 0.08–0.2 W m^{-1} K^{-1}, and standard deviation values under different conditions are no more than 0.01 W m^{-1} K^{-1}. Volume heat capacity is about 0.35–0.7 MJ m^{-3} K^{-1}, while standard deviation values are no more than 0.1 MJ m^{-3} K^{-1}. During test, due to the probe heating, possible evaporation of some water in sample particles contacting the probe will result in the changes of moisture content and gas humidity in per unit volume. This maybe has larger influence on the variation of heat capacity per unit volume than that of thermal conductivity, which is related with the larger standard deviation values of volume heat capacity. Under the same conditions, the thermal conductivity measurement results by TPS method are higher than that by quasi-steady method based on the heating flat plate [16], while close to that by transient-state-plate method [17]. For quasi-steady method, there is heat dissipation because of exposure of heating flat plate to the atmosphere, which maybe causes the result differences from TPS method.

Standard deviation of parallel determination for different test conditions can reflect the precision of the test method. For the thermal conductivity and volume heat capacity, there is no dependent relationship between the results precision and their level. When the mean value of standard deviations for different testing conditions is viewed as repeatability standard deviation of the test methods, the thermal conductivity repeatability standard deviation is 0.0047 W m^{-1} K^{-1}, while for volume heat capacity it is 0.0625 MJ m^{-3} K^{-1}.

Thermal conductivity and heat capacity constant at different temperatures and moisture content levels are shown in Table 1. There is an increasing tendency for

thermal conductivity with the increase of temperature and moisture content. The effect of moisture content is more significant when the cut tobacco at higher temperature levels, and so does temperature effect. These experimental results are consistent with the conclusion by Xu et al. [18] in rice husk, straw, and other biomass material with hotline method or steady plate method. For stacking cut tobacco, the raise of sample temperature means the increasing heat transport within and between cut tobacco particles, and the heat conduction of gas phase also will be enhanced, all of which will lead to the increase of the thermal conductivity. Since the thermal conductivity of water is about 0.61 W m^{-1} K^{-1}, higher than that of tobacco skeleton, higher moisture content of biomass particles also causes the increases of thermal conductivity. Volume heat capacity of stacking tobacco under high temperature and high moisture conditions also shows increasing trend, which is related to the raise moisture content in per unit volume and the increasing humidity in the gas phase.

Thermal conductivity prediction model

The thermal conductivity of material is the key parameter in all thermal properties parameters that will affect processing quality of the heat treatment. During the actual dehydration and humidification process, thermal conductivity will change with the different material temperature, moisture content, and particle stacking state. Therefore, it is the foundation for the simulation analysis and optimization of heat transfer process to accurately predict thermal conductivity of materials under different conditions by theoretical model.

Stacking cut tobacco consists of wet solid particles and gas phases among cut tobacco particles. Thermal properties of materials under this state are affected by the combined effect of thermal conductivity of solid and gas phase, as well as the stacking porosity. As loose stacking cut tobacco is exposure to the continuously non-moving gas as Fig. 5a, gas–solid dispersion model can be used to analyze the thermal conductivity of loose slope tobacco. By assuming that the porous material is built up by in a bouquet of long cylinder, Krupiczka [19] used numerical method to solve the heat balance equations, which involved heat transfer between solid particles, convective heat transfer in fluid and heat exchanger between fluid and solid. An approximate solution of thermal conductivity model for stacking porous media was obtained as following:

$$k_e = k_g (k_s/k_g)^{a - b \log(1-\varepsilon) + c \log(k_s/k_g)} \tag{5}$$

where k_g is the thermal conductivity of gas, k_s is the thermal conductivity of wet solid particle, ε is the porosity value of stacking material which can be determined

Table 1 Testing results of cut tobacco thermal properties

Temperature/°C	Thermal properties	Mosiure content/%				
		12.5	15	17.5	20	22.5
25	λ/W m^{-1} K^{-1}	0.0790	0.0867	0.0954	0.0984	0.1046
	c/MJ m^{-3} K^{-1}	0.3283	0.3306	0.3864	0.4068	0.3271
35	λ/W m^{-1} K^{-1}	0.0906	0.0939	0.1034	0.1075	0.1149
	c/MJ m^{-3} K^{-1}	0.3921	0.4134	0.3347	0.5538	0.4552
45	λ/W m^{-1} K^{-1}	0.1126	0.1076	0.1232	0.1086	0.1429
	c/MJ m^{-3} K^{-1}	0.3653	0.6216	0.4402	0.6374	0.5074
55	λ/W m^{-1} K^{-1}	0.1158	0.1341	0.1343	0.1316	0.1448
	c/MJ m^{-3} K^{-1}	0.4673	0.4165	0.5329	0.6035	0.4827
65	λ/W m^{-1} K^{-1}	0.1376	0.1408	0.1568	0.1853	0.1996
	c/MJ m^{-3} K^{-1}	0.6196	0.6608	0.6439	0.7588	0.9351

Fig. 5 Structure diagram of stacking cut tobacco and cut tobacco particle

(a) Stacking cut tobacco particles

(b) Interior of cut tobacco particle
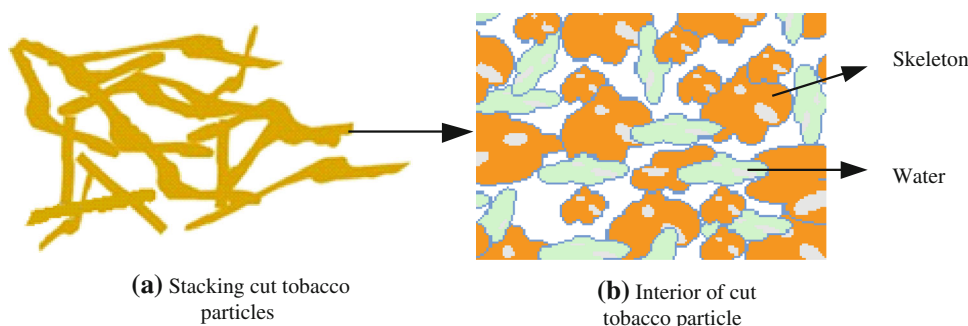
Skeleton

Water

according to the stacking density and particle density of cut tobacco, and a, b, and c are constants.

Thermal conductivity of wet tobacco particle is mainly affected by the inner tobacco skeleton and the water filled in it. Wet biomass particles like cut tobacco is a kind of fiber absorbent porous material. In the particle, water mostly filled in the interspace which is formed by skeleton fibrous of the material. Considering this, on the basis of hypothesis that it is a randomly scattered distribution state for tobacco skeleton and liquid water in cut tobacco particle as Fig. 5b, Tavman model [20] is used to describe thermal conductivity of the wet tobacco particle:

$$k_s = k_w^{V_w} k_b^{(1-V_w)} \tag{6}$$

where k_w is the thermal conductivity of water in the tobacco, k_b is the thermal conductivity of solid skeleton part, V_w is the volume fraction of water in the tobacco particle which can be determined according to the moisture content and skeleton density of cut tobacco.

Thermal conductivity of solid material changes with the temperature, and for most homogeneous solid material the thermal conductivity have a linear relationship with the temperature, that is:

$$k_b = k_{b0}(1 + dT) \tag{7}$$

where k_{bo} is the thermal conductivity of the solid at temperature 0 °C, d is coefficient which is a positive value for most non-metallic materials.

The fitting correlation between k_g and temperature as well as the correlation between k_w and temperature can be obtained according to the IAPWS data [21].

$$k_g = 7.8091 \times 10^{-5}T + 0.02409 \tag{8}$$

$$k_w = -1.18759 \times 10^{-5}T^2 + 0.025T + 0.5561 \tag{9}$$

by combining the equations from (5) to (9), the thermal conductivity of biomass porous media in stacking state with different moisture and temperature can be calculated.

Predicted results of thermal conductivity model

Stacking density of cut tobacco as well as particle density and skeleton density on dry basis was measured, which were 250, 1,084 and 1,311 g cm^{-3} respectively. The ε in Eq. (5) can be obtained according to tobacco stacking density and particle density, while the V_w in Eq. (6) can be calculated according to skeleton density and moisture content of cut tobacco. According to the Eq. (7), to get the best linear relationship between k_b and T was taken as the constraint and then solve Eqs. (5) and (6) to determine the
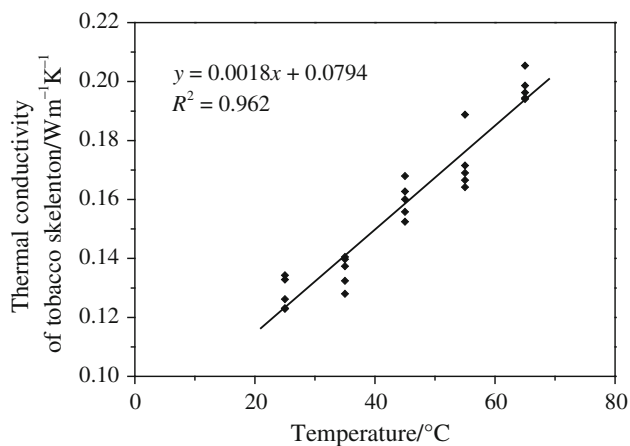
Fig. 6 The correlation of thermal conductivity of cut tobacco skeleton and temperature

proper values of parameter a, b, and c. When parameter values of a, b, and c were determined, the values of k_s can be figured out by Eq. (5) based on test values of k_e, and

Table 2 The comparison of predicted thermal conductivity values and experimental values

Temperature/°C	Moisture content/%	Predicted λ value/W m⁻¹ K⁻¹	Experimental λ value/W m⁻¹ K⁻¹	Relative deviation/%
25	22.5	0.1025	0.1046	−2.02
25	20	0.0940	0.0980	−4.12
25	17.5	0.0863	0.0952	−9.35
25	15	0.0793	0.0866	−8.45
25	12.5	0.0772	0.0786	−1.80
35	22.5	0.1227	0.1149	6.75
35	20	0.1117	0.1077	3.80
35	17.5	0.1019	0.1036	−1.63
35	15	0.0930	0.0940	−1.05
35	12.5	0.0903	0.0898	0.54
45	22.5	0.1441	0.1420	1.48
45	20	0.1305	0.1345	−3.02
45	17.5	0.1183	0.1237	−4.38
45	15	0.1074	0.1075	−0.11
45	12.5	0.1041	0.1124	−7.45
55	22.5	0.1666	0.1589	4.86
55	20	0.1501	0.1448	3.66
55	17.5	0.1355	0.1343	0.91
55	15	0.1224	0.1341	−8.71
55	12.5	0.1184	0.1156	2.49
65	22.5	0.1901	0.1996	−4.73
65	20	0.1707	0.1853	−7.89
65	17.5	0.1534	0.1568	−2.15
65	15	0.1381	0.1408	−1.93
65	12.5	0.1333	0.1376	−3.11

then the values of k_b (the skeleton values) can also be obtained according to Eq. (6).

By the above method, when the optimal linear fitting R^2 of k_b versus temperature is 0.962 as Fig. 6, values of a, b, c, k_{b0}, and d are determined as 0.009, 0.1065, 0.82, 0.0495, and 0.03434, respectively. The test conditions including the different temperature and moisture content levels were introduced into Eqs. (6)–(9) to calculate the predicted values of k_s and k_g. And the porosity value of stacking material (ε) can be determined according to the test stacking density and particle density of cut tobacco. Then the predicted values of stacking cut tobacco can be calculated by Eqs. (5). The predicted values and experimental values of thermal conductivity were compared, as shown in the Table 1.

As can be seen from Table 2, there is a high linear correlation between the predicted and measured values. The correlation coefficient is up to 98.2 %. Within the investigated range of temperature and moisture content, maximum deviation of predicted thermal conductivity by model is no more than 10 % from the experimental values, which indicates that the established thermal conductivity model has a good prediction precision. For some other porous materials with loose stacking state, the model can also be used to predict the effect of temperature, moisture content and stacking density on the thermal conductivity. The model predictions can provide the basis for optimization of drying process parameters.

Conclusions

Thermal properties of flue cured tobacco as the typical biomass porous media materials were investigated in a constant temperature and humidity experimental platform based on the TPS method. A predicting model of thermal conductivity is established for cut tobacco at different temperature and moisture content conditions. The results of predicted model and experimental measurement by TPS method were analyzed.

The results showed that the TPS method could be well used to measure thermal properties of biomass wet porous media such as cut tobacco, and there is a high test precision. For cut tobacco, the repeatability standard deviation of measured thermal conductivity is 0.0047 W m⁻¹ K⁻¹, while for volume heat capacity it is 0.0625 MJ m⁻³ K⁻¹. Thermal conductivity of cut tobacco increased significantly with the increase of temperature and moisture content at the range of 25–65 °C and 12.5–25 %. Volume heat capacities showed a similar trend. A thermal conductivity prediction model for stacking cut tobacco is established, and there is a strong correlation coefficient between estimated values and experimental values. The maximum

deviation of model predictions is less than 10 %, which indicates that the established model has a good prediction precision for thermal conductivity. The above results can be referred for thermal properties test and thermal conductivity prediction of biomass porous media with loose stacking state.

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