Effects of Moisture and Particle Size on Alfalfa's Thermal Conductance, Diffusivity, and Heat Capacity

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Researching the thermal characteristic parameters of alfalfa is of fundamental importance for accurately measuring heat transfer and distribution during the compression process. Therefore, the thermal characteristic parameters were measured using the transient plane heat source method. Additionally, the study examined the impact of moisture content and particle size on the thermal characteristic parameters of alfalfa. The experimental results indicated that the thermal conductivity of alfalfa increased with higher moisture content, and it decreased with the increase of particle size. Similarly, the specific heat capacity increased with higher water content, while the particle size had little effect on specific heat capacity. The thermal diffusion coefficient initially decreased and then stabilized with higher water content. Moreover, the influence of particle size on thermal diffusion coefficient was not significant. The obtained thermal characteristic parameters are valuable for investigating temperature changes during the densification process of alfalfa.

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INTRODUCTION

Alfalfa is a type of forage with high nutritional value, which can provide sufficient protein intake for ruminants such as cattle and sheep (Li *et al.* 2018; Liu 2019; Song 2022). Generally, harvested fresh alfalfa needs to be dried and compressed, and it is modulated into grass products for easy storage and transportation. The heat generated during the process will affect the quality of modulated grass products (Zhang 2019; Lin *et al.* 2020). However, the thermal characteristics parameters are directly related to the heat generated. The thermal conductivity, thermal diffusivity, and specific heat capacity are the basic parameters of thermodynamics. Having measured these parameters, it is possible to provide technical support and a parametric basis for relevant research in the field of alfalfa feed.

In recent years, scholars have focused on the thermal characteristics of materials, measurement techniques for thermal characteristics, and factors affecting the thermal characteristics of materials. Cao *et al.* (2010) measured the thermal conductivity of wheat and investigated the effect of moisture content and temperature on the thermal conductivity of wheat. Zhong and Zhong (2003) studied the relationship between wood thermal diffusivity and temperature, moisture content under certain conditions, and established a model for wood thermal diffusivity. Tan (2017) statistically analyzed the differences in the thermal characteristics of crop straws of different types and regions in northwest China. Feng *et al.* (2021) investigated the effect of moisture content on the thermal conductivity of soils.

Gustafsson (1991) measured the thermal conductivity and thermal diffusion coefficients of solid materials using the transient planar heat source method. Huang and Fang (2003) studied the thermal conductivity of materials using the hot disk thermal analyzer, demonstrating that the analyzer can be adapted to test the thermal characteristics of different materials. Chai (2019) measured the thermal conductivity of soil using the quasi-steady-state plate method to investigate the effect of soil with different moisture contents on thermal conductivity. Hsin Wang *et al.* (2019) used the transient planar source method to assess the thermal conductivity of thermal interface materials. Zhu *et al.* (2021) determined the thermal parameters of plant cellulose reinforced alkali slag gel materials using the hot wire method.

At present, scholars' research on thermal characteristics focuses on solid materials such as straw, soil, *etc.*, while the determination of thermal characteristic parameters of forage grass is rarely reported. Therefore, the thermal characteristic parameters of alfalfa are determined by transient plane heat source method (TPS method) to explore the influence of moisture content and particle size on the thermal characteristics of alfalfa.

EXPERIMENTAL

Program

Taking moisture content and particle size as factors, thermal conductivity, thermal diffusion coefficient, density, and specific heat capacity as evaluation indexes, alfalfa thermal characteristics were tested. The moisture content of alfalfa was divided into four levels of 2.7%, 10%, 20%, and 33%, and the particle size level was divided into four grades, namely 1, 2, 3, and 4.

Materials

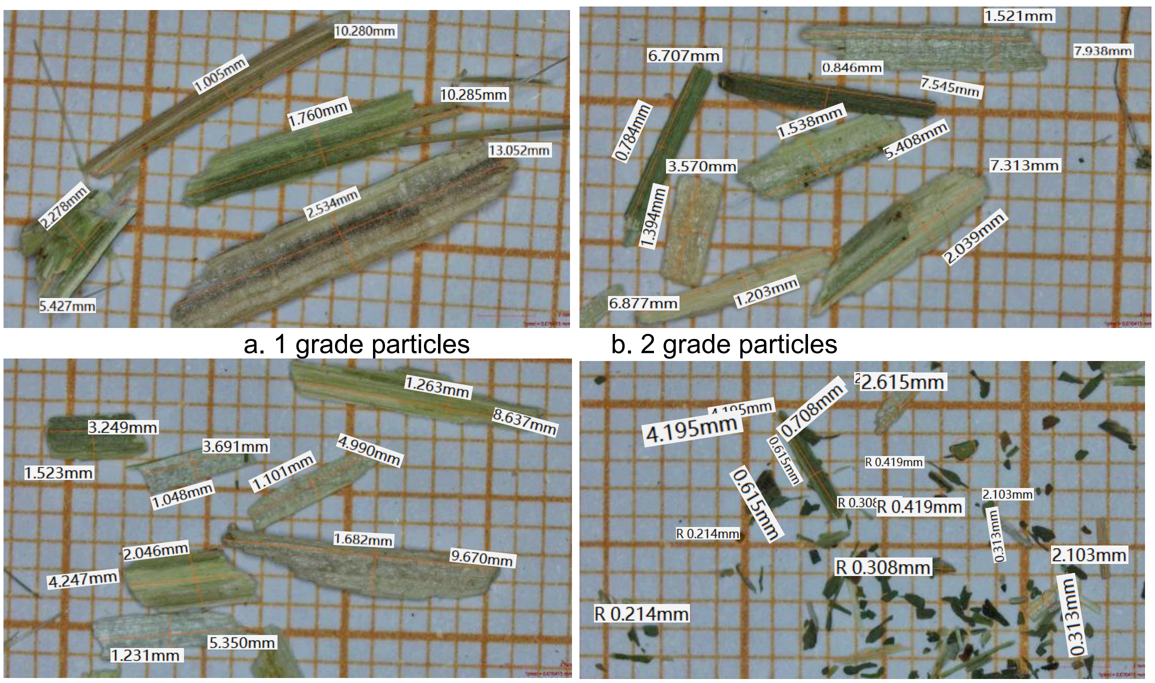
Alfalfa from the experimental field of Inner Mongolia Agricultural University was selected as the experimental material, and the harvested alfalfa was crushed by a 550-type crusher (YUYING, Sichuan, China). Then, the crushed alfalfa was dried in a DHG-9140A oven (YeTuo, Shanghai, China) to obtain dry alfalfa particles with a moisture content of 2.7%. Then water was added to prepare samples with moisture content of 10%, 20%, and 33%. When preparing alfalfa particles with different moisture contents, the self-sealing bag was weighed by an electronic scale, recorded as m_1. An appropriate amount of dry alfalfa particle samples was placed into a self-sealing bag. The mass of self-sealing bags and alfalfa particle samples was weighed and recorded as m_2. The mass of dry alfalfa samples was determined as M_1, $M_1=m_2-m_1$. The total mass of the dried alfalfa sample and the water to be prepared was noted as M_2. M_2 was calculated according to the following formula (1).

$$\text{Moisture Content} = \frac{M_2 - M_1}{M_2} \times 100\% \tag{1}$$

$$m_{\text{water}} = M_2 - M_1 \tag{2}$$

According to Eq. 2, the mass of distilled water added at different water contents can be calculated. Distilled water was evenly sprayed in a self-sealing bag containing alfalfa particles and left for 24 hours before the experiment was carried out.

Alfalfa particles with different moisture contents were sieved through four experimental standard sieves of 6, 8, 14, and 20 meshes to obtain four different grades of particles. The particle size distribution of different grades of alfalfa was observed and measured by a 3800-D high-definition electron microscope (Dongxing Technology, Guangzhou Shenzhen, China), as shown in Fig. 1. The average diameters of particles of grades 1 to 4 were 1.89 mm, 1.41 mm, 1.33 mm, and 0.58 mm, respectively; the average length of particles of grades 1 to 4 was 9.76 mm, 6.48 mm, 5.69 mm, and 1.80 mm, respectively. As the particle grade increases, the particle size decreases.



a. 1 grade particles b. 2 grade particles

c. 3 grade particles d. 4 grade particles

Fig. 1. Crushed alfalfa

The alfalfa particles with different moisture content and particle grades were compressed into blocks on the dense forming equipment. The forming equipment is shown in Fig. 2. The diameter of molding mold was 45 mm, and the height of molding mold was110 mm. A limit switch was arranged at the down stroke stop point of the compression piston to ensure a consistent compression height each time. At this time, the alfalfa particles were compressed at a height of 14 mm. The piston compressed at a speed of 4.8mm/s. Alfalfa particles are elastic materials, when the alfalfa molding block was out of the mold, it would produce elastic deformation. The diameter of the alfalfa molding block was 45 to 47 mm, and the height was 14 to 28 mm. The pressure of compressing alfalfa varied with the moisture content and particle size of alfalfa, which was between 4 and 20 MPa. Figure 3 showed alfalfa molding blocks obtained by compressing different grades of particle sizes with a moisture content of 20.0%.

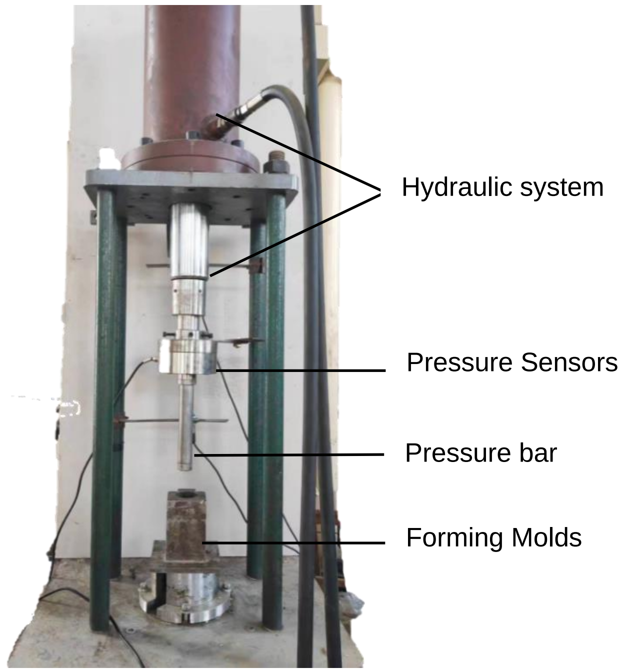


Fig. 2. Biomass dense forming equipment

			
Grade 1 forming block	Grade 2 forming block	Grade 3 forming block	Grade 4 forming block

Fig. 3. Alfalfa forming block

Method

The transient plane heat source method (TPS method) is a patented technology proposed by Gustafsson (1991) on the basis of the hot wire method, The resistance heating temperature measurement method can obtain a larger contact surface in a smaller space and output the thermal conductivity and thermal diffusion coefficient of the sample.

There is the following thermal conductivity, specific heat capacity, density and thermal diffusion coefficient formula,

$$\alpha = k/(C \bullet \rho) \tag{3}$$

where α is the thermal diffusion coefficient (mm^2/s); k is the thermal conductivity ($W/m{\cdot}K$); C is the specific heat capacity ($J/(m^3{\cdot}K)$); and ρ is the density (kg/m^3).

The JTKD-II rapid thermal conductivity meter / thermal conductivity meter (TAILE, Changzhou, Jiangsu, China) uses the transient plane heat source method to measure the thermal characteristic parameters of the material, as shown in Fig. 4. The molded sample was placed in a specific clamping device using a stainless steel clamp, and then the TPS probe was placed in the center of the sample to obtain the thermal conductivity and thermal diffusivity of the alfalfa straw.

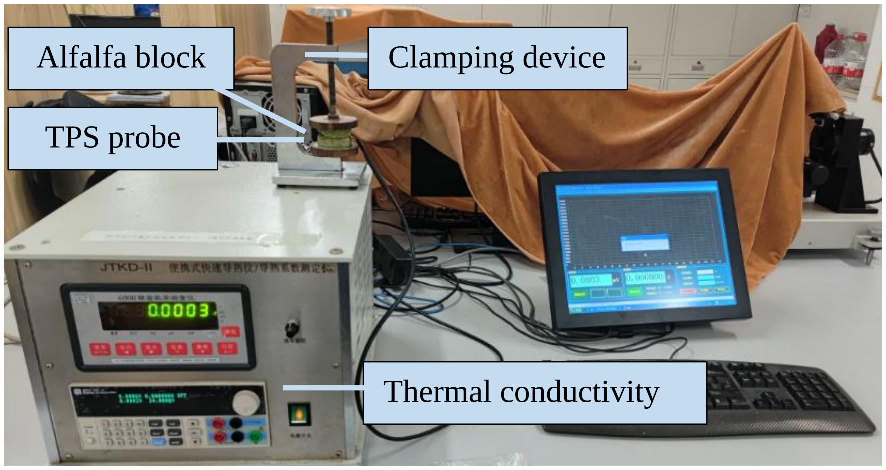


Fig. 4. Measurement of thermal characteristics parameters of alfalfa

RESULTS AND DISCUSSION

Density of Alfalfa Forming Blocks

The moisture content and particle size affected the density of the alfalfa blocks. The forming density is shown in Table 1.

Table 1. Density of Alfalfa Forming Blocks with Different Moisture Contents and Pellet Grades

Granule / Moisture Content	Density(kg/m^3)			
	1 grade particles	2 grade particles	3 grade particles	4 grade particles
2.7%	428	436	458	591
10%	443	433	490	630
20%	463	466	502	645
33%	482	477	566	650

The water contained in alfalfa can play the role of binder. Under the action of pressure, alfalfa particles deformed, slid, and fit into each other, closely bonding together. Therefore, within a certain range, with the increase of water content, the density of alfalfa forming block increased.

Porosity is the percentage of pore volume in a block material compared to the total volume of the material in its natural state. The size of the alfalfa particle directly affects the porosity of the compressed alfalfa block. The larger the alfalfa particles, the smaller the area of interaction between the particles and the relatively weaker the adhesion between the particles in compression (Zhang *et al.* 2015). The smaller the alfalfa particles, the easier the compression molding, the relaxation ratio lower significantly after compression molding, porosity is correspondingly small, resulting in an increase in molding density

(Zhang and Meng 2020). Therefore, as the particle size decreased (grade increased), the density of alfalfa molding blocks increased.

Effect of Moisture Content and Particle Grade on Thermal Conductivity

The effects of moisture content and particle grade on the thermal conductivity of alfalfa are shown in Fig. 5, where the thermal conductivity of alfalfa increased with the increase of water content. Alfalfa is a kind of loose porous medium, its thermal conductivity is smaller than that of water. In compressing, water will fill the holes between alfalfa particles to form convection, which will strengthen the heat transfer and increase the thermal conductivity.

With the increase of particle grade, the thermal conductivity of alfalfa increased. The particle size of alfalfa directly affected the porosity of alfalfa blocks. When the particle size was small (large grade), the molding block was compressed more densely, which reduced the porosity of the molding block. There were less air in the pores, so the thermal conductivity increased with the density of alfalfa blocks.

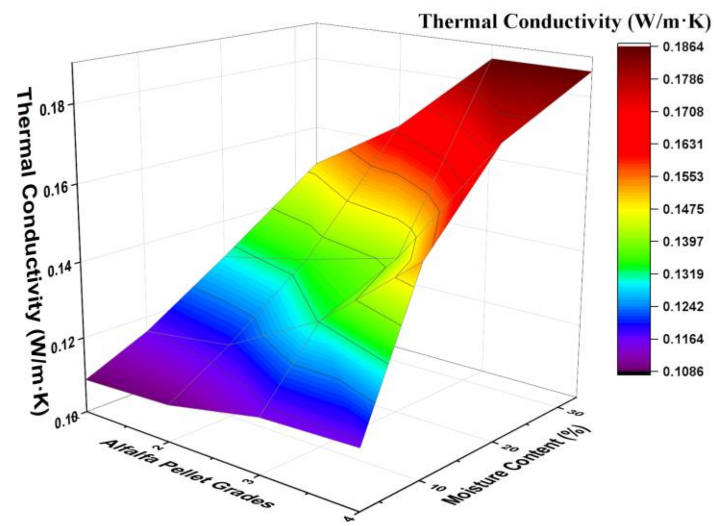


Fig. 5. Effect of moisture content and particle grade on the thermal conductivity of alfalfa

The test results of thermal conductivity of alfalfa with different moisture content and particle grade were analyzed by non-repeated two-factor variance analysis. The results are shown in Table 2. It can be seen from the table that the water content had an extremely significant effect on the thermal conductivity of alfalfa particles, and the particle grade had a significant effect on the thermal conductivity of alfalfa particles.

Table 2. Thermal Conductivity Analysis of Variance Table

	Source of Difference	SS	df	MS	F	P-value
Alfalfa Forming Block	Moisture content	0.0083	3	0.0027	26.6224	8.29E-05
	Grain grade	0.0021	3	0.0007	6.8811	0.0104
	Error	0.0009	9	0.0001		
	Total	0.0114	15			

Note : $p < 0.01$ indicates an extremely significant effect ; $p < 0.05$ indicates a significant effect.

Effect of Moisture Content and Particle Grade on Specific Heat Capacity

The effect of moisture content and particle grade on specific heat capacity of alfalfa is shown in Fig. 6. Normally, the specific heat capacity of water is greater than the general solid material, so the specific heat capacity of the block increased with the increase of water content. Because the specific heat capacity is an inherent property of the material, the particle grade had no effect on the specific heat capacity of alfalfa straw particles.

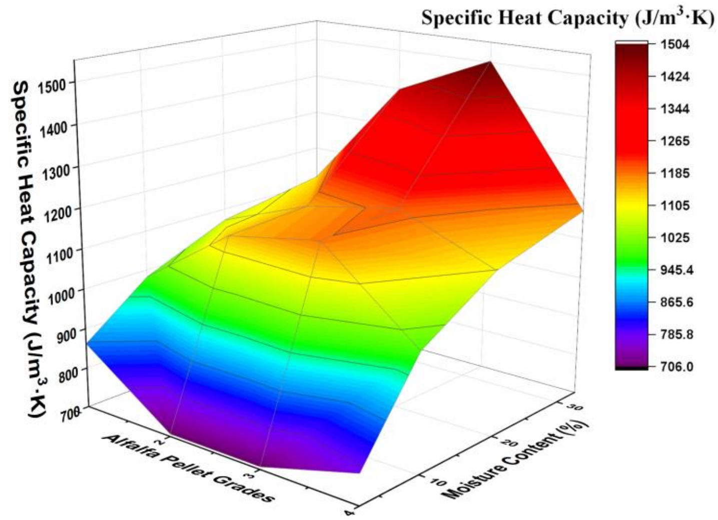


Fig. 6. Effect of moisture content and particle grade on specific heat capacity of alfalfa

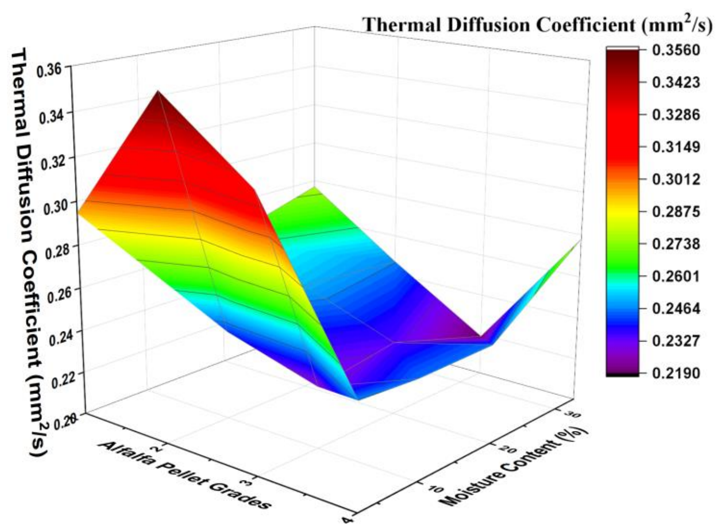


Fig. 7. Effect of moisture content and particle grade on specific heat capacity of alfalfa

The specific heat capacity test results of alfalfa with different moisture content and particle grade distribution were analyzed by non-repeated two-factor variance analysis. The results are shown in Table 3. It can be seen from the table that the moisture content had a very significant effect on the specific heat capacity of alfalfa particles. The effect of particle grade on specific heat capacity was not significant.

Table 2. Specific Heat Capacity Analysis of Variance Table

	Source of Difference	SS	df	MS	F	P-value
Alfalfa Forming Block	Moisture content	601751.3	3	200583.8	17.8403	0.0004
	Grain grade	57854.04	3	19284.68	1.7152	0.2330
	Error	101189.5	9	11243.28		
	Total	760794.9	15			

Note : $p < 0.01$ indicates an extremely significant effect; $p < 0.05$ indicates a significant effect

Effect of Moisture Content and Particle Grade on Thermal Diffusion

The effect of moisture content and particle grade on thermal diffusion of alfalfa, as shown in Fig. 7.

The thermal diffusivity of alfalfa samples with different moisture content was analyzed by fitting, as shown in Fig. 8. The thermal diffusivity of alfalfa particles usually decreased with the increase of water content. The reason was that the thermal diffusivity of water was very small. The increase of water content caused some air in alfalfa samples to be replaced by water, resulting in the decrease of thermal diffusivity of alfalfa straw. Alfalfa contained a large amount of cellulose, and the existence of water at the fiber saturation point was different, so the variation of thermal diffusivity varied within different ranges of water content (Li *et al.* 2021). Below the fiber saturation point, the thermal diffusivity decreased with the increase of moisture content. It can be seen in the diagram that the thermal diffusivity of alfalfa samples decreased greatly at first, and then increased slightly with the increase of moisture content. However, the overall trend was towards a stable level.

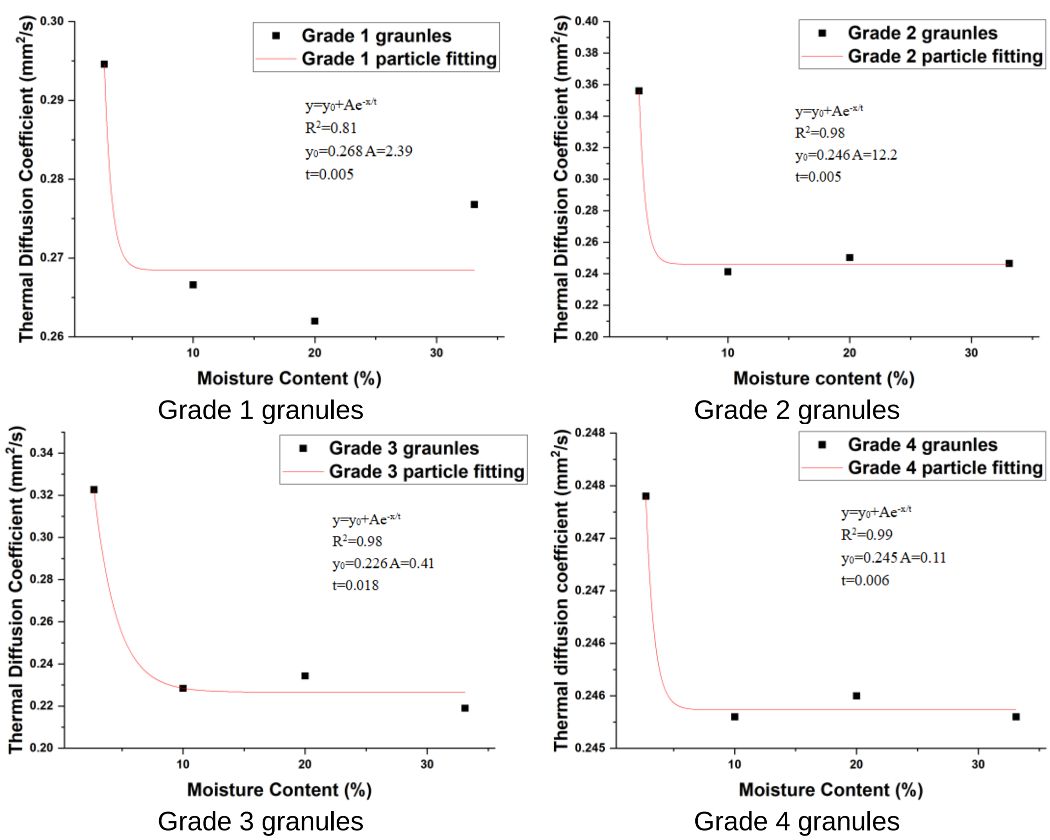


Fig. 8. Fit analysis of thermal diffusion coefficients for alfalfa with different moisture contents

The thermal diffusivity of alfalfa was not obviously affected by the particle grade, and it showed a complex change rule under the interaction of water content and particle size. Alfalfa straw belongs to porous media. Therefore, it is necessary to further study the complex relationship between the thermal diffusivity of porous media and the influencing factors.

CONCLUSIONS

1. The thermal conductivity of alfalfa increased with increasing moisture content, and the thermal conductivity increased with decreasing particle size (increasing grade).
2. As the moisture content of alfalfa rose, its specific heat capacity also increased. However, particle size had no influence on specific heat capacity.
3. The moisture content and the presence of moisture in alfalfa straw had a significant impact on the thermal diffusivity, which decreased with the increase of moisture content; However, after the moisture content reached the fiber saturation point, the presence of water in alfalfa straw varied, resulting in a slight increase in the thermal diffusivity. The influence of particle size on the thermal conductivity coefficient had no obvious pattern.

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