

Article

Parameter Estimations on Measurement Accuracy for Thermal Conductivity of Wood Using the Transient Plane Source Method

Hongxu Meng, Xinxin Yu, Bonan Chen, Pengyuan Ren and Jingyao Zhao *

Key Laboratory of Bio-Based Material Science and Technology, Northeast Forestry University, Ministry of Education, Harbin 150040, China; mmmmenghx@hotmail.com (H.M.); 28977880@nefu.edu.cn (X.Y.); chenbonan@nefu.edu.cn (B.C.); 2021220709@nefu.edu.cn (P.R.)

* Correspondence: zjy_20180328@nefu.edu.cn; Tel.: +86-0451-82191765

Abstract: In order to enhance the reliability and accuracy of the results from the transient plane source (TPS) method for measuring the thermal conductivity of wood, this paper investigates setting parameters and measurement methods to improve measurement accuracy. Criteria are proposed to determine the optimal parameters such as the power output, heating time, and time window. The measurement results of the TPS method and the HFM method are compared. The results show that the total to characteristic time, temperature increase in the probe, mean deviation, and temperature drift graph are valid indicators for evaluating the detection reliability of the TPS method. The optimal parameters for measuring the thermal conductivity of wood using the TPS method are as follows: power output of 0.05 or 0.1 W, heating time of 120 s, and time window covering 60% to 80% of the heating time. The thermal conductivity measured with the TPS method was higher than that measured by the steady-state method in all grain angle directions. The standard uncertainties after optimization were 18.9% to 59.5% lower than before optimization. The optimized TPS measurement method can be applied to other tree species as well.

Keywords: transient plane source; heat flow meter; thermal conductivity; anisotropic; wood



Citation: Meng, H.; Yu, X.; Chen, B.; Ren, P.; Zhao, J. Parameter Estimations on Measurement Accuracy for Thermal Conductivity of Wood Using the Transient Plane Source Method. *Forests* **2024**, *15*, 1820. <https://doi.org/10.3390/f15101820>

Academic Editors: Rene Herrera Diaz and Rafael De Avila Delucis

Received: 21 September 2024

Revised: 6 October 2024

Accepted: 15 October 2024

Published: 17 October 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Thermal properties are an integral part of the physicochemical properties of wood. For instance, during processing or usage, heat and mass exchanges between the wood and its environment facilitate moisture movement. Thermal properties of wood such as thermal conductivity, thermal diffusivity, and specific heat capacity are crucial, with thermal conductivity being particularly significant [1]. It greatly influences the efficiency and quality of wood processing methods such as drying, heat treatment, and hot pressing [2]. Moreover, thermal conductivity is critical for the insulation effectiveness of wooden structures, as well as for reducing energy consumption and improving indoor comfort. Therefore, accurately evaluating the thermal conductivity of wood is crucial for the scientific and rational implementation of processing and application [3].

There are two main approaches for determining the thermal conductivity of materials: theoretical and experimental. The theoretical approach consists of the equivalent modeling method, numerical simulation method, and inverse analysis method. The equivalent modeling method analogizes the pore structure of wood to an electrical resistance circuit, converting thermal behavior to electrical behavior for calculation [4,5]. Thermal conductivity is computed using equivalent series and parallel resistances. The numerical simulation method uses thermal control equations to simulate thermal behavior based on the actual pore structure of wood. This method determines the macroscopic thermal conductivity at a microscopic scale by calculating the heat flux per unit time and area according to Fourier's law [6,7]. The inverse analysis method combines experimentation and simulation to determine material properties. It applies numerical techniques to solve

Fourier's second law for temperature variation and distribution in wood [8,9]. These methods effectively measure the thermal conductivity of wood through various computational models, but the results still require experimental validation. The complex derivations and numerous assumptions involved in constructing theoretical models can impact the accuracy of simulations. Therefore, research on measurement techniques for thermal conductivity is practically important.

Experimental methods for measuring thermal conductivity primarily include steady-state and transient methods. The steady-state method calculates the thermal conductivity by measuring heat flux under constant heat source conditions, with the heat flux method (HFM) being most frequently used [10–12]. However, it has limitations such as requiring large sample sizes, long measurement periods, and susceptibility to variations in material moisture affecting accuracy. The transient method rapidly heats the material with an external heat source and calculates thermal conductivity using a heat conduction model [13,14]. It is typically categorized into three methods based on the heat source: the transient plane source (TPS) method, the hot wire method (HWM), and the laser flash apparatus (LFA). The TPS method is more suitable for materials with low thermal conductivity like wood owing to its advantages in specimen size, measurement range, and applicability. Related research has been conducted by Nouemsi, Gaiser, Lagüela, and Duplex [15–18]. However, parameters such as the power output, heating time, and time window in the testing process of the TPS method significantly impact the measurement results. The effect of these parameters on the stability of measurement results has not been adequately reported. Furthermore, differences in the calculation methods and detection results between the TPS and steady-state methods have not been elaborated upon, which is detrimental to optimizing the stability and accuracy of the TPS method.

The objective of this work is to provide a reference for standardizing the application of the TPS method in measuring the thermal conductivity of wood. The total to characteristic time, temperature increase in the probe, mean deviation, and temperature drift graph are used as evaluation indicators to inspect the reliability of the measurement results. The measurement accuracy for the thermal conductivity of wood is verified by comparing the results of the TPS method with those of the steady-state method.

2. Theoretical Basis

The sandwich structure consists of identical material samples on both the top and bottom, with a centrally placed probe that ensures uniform temperature distribution. A constant current is applied to the probe to maintain steady heating power, resulting in dynamic temperature changes in the samples. The temperature rise over time is recorded as a temperature–time curve using an electronic system and computer software. The probe functions as both a heater and a temperature sensor, serving as a self-heating element. The thermal conductivity and thermal diffusivity of the sample are calculated from the temperature–time curve based on the mathematical model and the boundary conditions of the probe.

In the heat conduction equation, the conductive double helix structure of the probe is typically idealized as a set of concentric rings and equally spaced line heating sources [19]:

$$\Delta T_{(\tau)} = P_0 \left(\pi^{\frac{3}{2}} r \lambda \right)^{-1} D_{(\tau)} \quad (1)$$

where P_0 is the heating power output from the probe; r is the average radius of the outermost heating ring of the probe; λ is the thermal conductivity of the sample; and τ^2 is a dimensionless parameter in the TPS method known as the characteristic time ratio or the total to characteristic time, which is the ratio of heating time to characteristic time. The fit of the temperature rise curve to the dimensionless characteristic time function plays a crucial role in calculating thermal conductivity. According to Equation (1), the average temperature rise of the sensor is linearly related to dimensionless time, allowing the determination of material thermal conductivity from its slope.

To determine the time window required for measuring thermal conductivity and diffusivity from a single temperature rise, sensitivity theory must be applied [20]. This theory involves calculating the partial derivatives of the temperature rise with respect to thermal conductivity or diffusivity. Extensive experimental data indicate that measurements of thermal conductivity are more stable when the total to characteristic time ranges from 0.3 to 1.0.

$$\tau = \left(\frac{t}{\theta} \right)^{\frac{1}{2}} \quad (2)$$

where $\theta = r^2/\alpha$; α is the thermal diffusivity; and $D_{(\tau)}$ is the dimensionless time-specific function defined as follows [21,22]:

$$D_{(\tau)} = [m(m+1)]^{-2} \int_0^\tau \sigma^{-2} \left[\sum_{l=1}^m l \sum_{k=1}^m k \exp \left(\frac{-(l^2 + k^2)}{4m^2\sigma^2} \right) I_0 \left(\frac{lk}{2m^2\sigma^2} \right) \right] d\sigma \quad (3)$$

where m is the number of spirals in the sensor, σ is the integration variable, and I_0 is the modified Bessel function.

A resistance-measuring circuit is used to collect the temperature rise of the TPS probe in relation to time. The resistance measurement scheme can be based on either a bridge circuit or a series circuit. No matter what kind of resistance measurement scheme is used, during the measurement process, it is necessary to ensure that the resistance value of the standard resistance in series with the probe is strictly unchanged. The resistance value R_s of the standard resistor should be as close as possible to the sum of the resistance values of the probe and its leads to keep the power supplied to the probe constant. Figure 1 shows a schematic diagram of the probe resistance measurement.

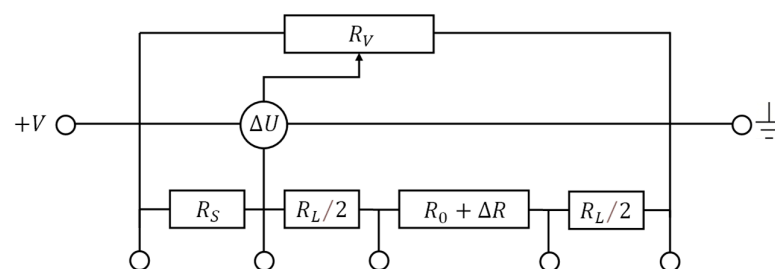


Figure 1. Schematic diagram of the electronic measurement circuit.

The average temperature rise on the surface of the detector is recorded by the detector itself when the TPS method is used to measure the thermal conductivity of the material. This is based on the relationship between the change in resistance value and temperature increase:

$$R_{(t)} = R_0 \left(1 + \beta \Delta \bar{T}_{(\tau)} \right) \quad (4)$$

where $\Delta \bar{T}_{(\tau)} = (T_t - T_0)$ is the average temperature rise of the probe, R_0 is the initial resistance value at the starting temperature T_0 , and β is the temperature coefficient of resistance (TCR) of the probe. Furthermore,

$$\Delta T_{(t)} = \frac{(R_S + R_L + R_0) \Delta U_{(t)}}{\beta \Delta R_0 (J_0 R_S - \Delta U_{(t)})} \quad (5)$$

where R_s is the resistance of the series resistor; R_L is the total resistance of the leads; R_0 is the initial resistance value of the probe; R_V is the variable resistance; $\Delta U_{(t)}$ is the variation in potential difference measured by the voltmeter in the bridge due to the increase in resistance; and J_0 is the initial current through the probe, which can be easily obtained by measuring the total voltage value of the probe, leads, and series-connected standard

resistor before heating and then dividing it by their series-connected total resistance value ($R_S + R_L + R_0$).

The temperature rise $\Delta\bar{T}_{(\tau)}$ on the sensor surface can be accurately obtained from Equation (4), and the relationship between the test time t and dimensionless time τ can be used to obtain the curve of $\Delta\bar{T}_{(\tau)}$ versus $D_{(\tau)}$. After the input power and detector are selected, P_0 and r can be known, so the thermal conductivity can be found. The value of τ is calculated from the equation $\tau = \sqrt{\alpha t}/r$. However, the thermal diffusion of the material is unknown, so it is impossible to determine a suitable value of τ before testing. Iterative calculations during testing are required to obtain τ . The thermal diffusion α is predicted so that a value of τ can be obtained and a curve of $\Delta\bar{T}_{(\tau)}$ as a function of $D_{(\tau)}$ plotted until $\Delta\bar{T}_{(\tau)}$ is linear with $D_{(\tau)}$. The iterative process is implemented by software during the time measurement process until an optimized value of τ is found. Finally, the thermal conductivity of the material is obtained from the slope and parameters selected [20].

The reliability of the results is evaluated using the total to characteristic time, temperature increase, mean deviation, and temperature drift graph. The evaluation criteria for setting parameters are clearly marked in the subsequent analysis, including the specified range for each criterion. The above calculations are built into the instrument. The evaluation criteria for setting parameters are as follows [19,20,23]:

- (1) Total to characteristic time: The ratio of the heating time to the characteristic time is the total to characteristic time, also named the time ratio. The total to characteristic time takes values between 0.3 and 1.0, with the ideal value near 0.6, for easier access to stable thermal conductivity.
- (2) Temperature increase: This consists of the most direct observation data of the TPS method, and its value is generally controlled in the range 0.3–5 K for low thermal conductivity of materials. If the temperature increase is too small, detecting the change between the probe and the material's surface becomes difficult. Conversely, a large increase can damage the probe. It is essential to carefully control the temperature rise by adjusting the power output and rounding off the initial data points to minimize residual dispersion.
- (3) Mean deviation: This is the difference between the actual temperature measured by the probe and the temperature predicted by the fitted curve using the TPS method. A smaller residual indicates a more credible fitted curve. The result of the mean deviation should be as small as possible and is required to be within 10^{-4} .
- (4) Temperature drift graph: The residual plot depicting the temperature deviation shows the difference between the fitted curve and the original curve data. The difference value can be positive or negative. The curve is an aid in judging the effectiveness of the fit. As a general principle, the better the randomness of the discrete points, the better the fit.

3. Materials and Methods

3.1. Sample Preparation

Three insulating building materials from the market were tested: polypropylene (PP), extruded polystyrene (XPS), and polymethyl methacrylate (PMMA). They are used as reference materials to validate the measurement methodology. Their properties (declared thermal conductivity, measured density, specific heat capacity, and thermal diffusivity) are gathered in Table 1 [24]. All materials were measured in dry state after being dried in a ventilated oven.

Two wood species commonly used in structural materials were selected, poplar (*Populus adenopoda* Maxim) from Heilongjiang Province, China, with an absolute density of $0.371 \pm 0.024 \text{ g}\cdot\text{cm}^{-3}$, and camphor pine (*Pinus sylvestris* var. *mongolica* Litven.) from the greater Khingan mountains, with an absolute density of $0.427 \pm 0.026 \text{ g}\cdot\text{cm}^{-3}$, with all samples sourced from a single trunk of each tree species, both approximately 25 years in age. Before each measurement, the samples were placed in the drying box at $103 \pm 2 \text{ }^\circ\text{C}$ for 24 h to ensure that they were oven-dried wood. The wood samples were initially sanded

with 180 mesh sandpaper for preliminary smoothing, followed by repeated sanding with 1500 mesh sandpaper for a finer finish. The flow of preparing the samples is shown in Figure 2, with the dashed line showing the direction of sawing.

Table 1. Thermophysical properties of measured materials.

	ρ , $\text{kg}\cdot\text{m}^{-3}$	λ , $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$	α , $\text{mm}^2\cdot\text{s}^{-1}$	c_p , $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
PP	920	0.22	0.17	1883
XPS	32.3	0.028	0.72	1239
PMMA	1189	0.197	0.13	1464

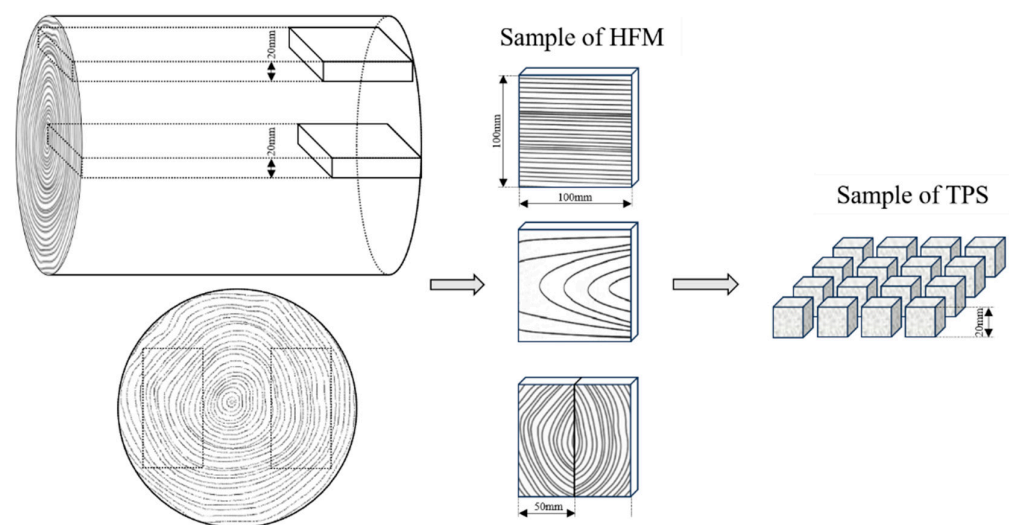


Figure 2. Preparation of samples for testing the thermal conductivity of wood. (TPS: transient plane source; HFM: heat flow meter).

Because of the size requirements of the steady-state method equipment, the wood was cut into 100 mm × 100 mm × 20 mm radial and tangential boards. These boards were used to measure the tangential and radial thermal conductivity using the steady-state method. For axial thermal conductivity measurements, two 100 mm × 50 mm × 20 mm pieces were sawed from the wood cross section and tightly joined together. Three samples of each type were used for measurement. To reduce the impact of wood property variations on measurement results, samples used in steady-state measurements were further cut into small 20 mm × 20 mm × 20 mm samples for TPS measurement, with 16 selected samples per group.

The samples of the three directions of grain angle of the poplar and camphor pine were used to investigate the method of measuring thermal conductivity. Subsequently, to evaluate the effectiveness and reliability of the optimization parameters, this study compared data from poplar, eucalyptus, radiata pine, and oak before and after correction of the TPS method. These samples were eucalyptus (*Eucalyptus grandis*) from Guangdong Province, China, with an absolute density of $0.641 \pm 0.047 \text{ g}\cdot\text{cm}^{-3}$; radiata pine (*Pinus radiata* D. Don) from North Island, New Zealand, with an absolute density of $0.417 \pm 0.031 \text{ g}\cdot\text{cm}^{-3}$; and oak (*Xylosma racemosum*) from Heilongjiang Province, China, with an absolute density of $0.546 \pm 0.043 \text{ g}\cdot\text{cm}^{-3}$. These species were chosen for their widespread use and to represent a broad range of densities.

3.2. Thermal Conductivity Measurement by the TPS Method

The structure of the measuring device for the TPS method (TPS 2500S, SETARAM, Caluire-et-Cuire, France) is shown in Figure 3. The method is suitable for materials having values of thermal conductivity, λ , in the approximate range of $0.001 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$

to $1800 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ and values of thermal diffusivity, α , in the approximate range of $0.05 \text{ mm}^2 \cdot \text{s}^{-1}$ to $100 \text{ mm}^2 \cdot \text{s}^{-1}$, and for temperatures, T , in the range of 170 K to 393 K. The type of TPS probe selected was P32126, and the probe diameter was 12.6 mm.

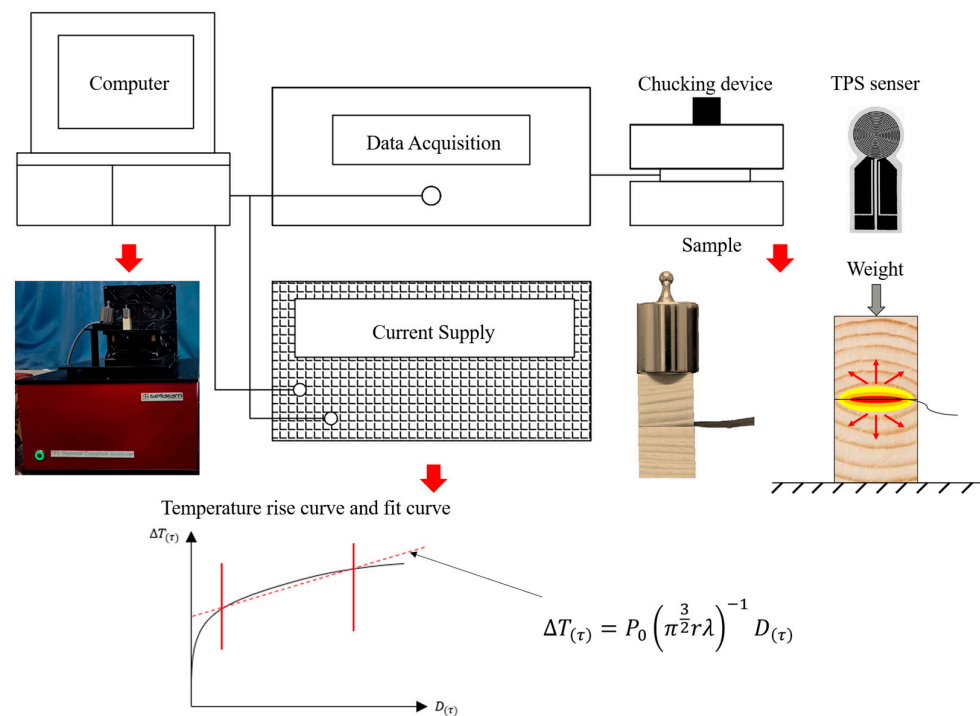


Figure 3. Equipment and structure schematic of the TPS method.

A common disc-shaped TPS probe generally consists of a double helix of hot wires etched from metal foil, an insulating film covering both sides of the wire, and an outer wrapping of epoxy resin coating. The probe was placed between the two samples and held in place by weights during the measurement. The 100 g weight was placed at the top of the sample for constant pressure control. Subsequently, the power output and heating time of the device were set, thereby obtaining the temporal evolution of temperature. Within the temperature rise curve segments, attempts were made to select a time window to determine the reliability of the test results using the total to characteristic time, temperature increase in the probe, mean deviation, and temperature drift graph. The power output settings were 0.05, 0.1, 0.2, and 0.5 W. The heating time settings were 20, 60, 120, and 200 s. The time windows were set to 50%, 60%, 70%, 80%, and 90% of the total heating time. Full factorial experiments on power output and heating time were performed to determine the optimal parameters according to the evaluation index (Section 2). The 80 sets of test conditions include all combinations of the levels of the three factors, as shown in Table 2.

Table 2. Experimental factors and their levels.

Factor	Levels
Power output	0.05, 0.1, 0.2, and 0.5 W
Heating time	20, 60, 120, and 200 s
Time window	50%, 60%, 70%, 80%, and 90%

The optimal temperature rise interval was determined by adjusting the time window. Ultimately, the parameters suitable for the detection of the thermal conductivity of wood were obtained. The setting parameters of the TPS method in the research were the mean values of the three directions of grain angle of the two wood species. For the statistical anal-

ysis of the measurement results, we employed standard deviation to assess the significance of differences among the means.

3.3. Thermal Conductivity Measurement by the HFM Method

Thermal conductivities measured by the TPS method were compared with those measured on a device using the HFM method (DRH-V, Xiangtan Instrument Co. Ltd., Xiangtan, China). This method is suitable for materials having values of thermal conductivity, λ , in the approximate range of $0.001 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ to $3.000 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$.

The plate was placed on the heating plate, pressurized, and fixed. The temperature of the cold plate was controlled by circulating cooling water from a low-temperature thermostatic water tank. Once the measurement started, the hot plate was heated until the temperature of both the hot plate and the sample stabilized. The thermal conductivity of the sample was then measured using a device that maintained the cold plate and hot plate temperatures at 20.0°C and 40.0°C , respectively [12]. From Fourier's law of thermal conductivity, it is known that the amount of heat Q that passes through a cross section of the sample is proportional to the temperature gradient perpendicular to that cross section. The one-dimensional steady-state thermal conductivity is obtained as

$$\lambda = \frac{Qd}{S(T_2 - T_1)} \quad (6)$$

where d is the thickness of the sample being tested, S is the sample area, T_2 is the hot plate temperature, and T_1 is the cold plate temperature.

4. Results and Discussion

4.1. Validation of TPS

Table 3 shows the mean thermal conductivity measured on dry insulating materials with the TPS method and the HFM method. Mean thermal conductivity values were calculated for standardized material from all experiments, which were compared to the reference value of Table 1. For thermal conductivities of PP, XPS, and PMMA, a good agreement was found between both methods. Similarly, the maximal difference observed cannot exceed 5%. Thermal conductivity of isotropic insulating materials can be accurately measured with the TPS device.

Table 3. Mean thermal conductivity measured on dry insulating materials with TPS and HFM devices.

Material	TPS			HFM		
	Mean	Std. Dev.	Difference	Mean	Std. Dev.	Difference
PP	0.2526	2.92%	1.85%	0.2382	1.39%	3.95%
XPS	0.0322	0.41%	3.87%	0.0305	0.84%	1.61%
PMMA	0.1947	1.18%	1.17%	0.1934	1.52%	1.83%

The reliability of the results can be evaluated using the total to characteristic time, temperature increase, mean deviation, and temperature drift graph. Accordingly, we adopted the method of setting parameters (such as power output, heating time, and time window) required for the detection process for correcting the measurement accuracy of the TPS method. Thermal conductivity of wood is affected by factors such as density, moisture content, temperature, and grain direction; the range of thermal conductivity of all types of wood is basically between that of XPS and soapstone. It is possible to refer to the setting parameters of XPS, PMMA, and soapstone for setting parameters of different materials, shown in Table 4.

Table 4. Recommended power output and heating time.

Range of Thermal Conductivity	≥ 20	10–20	1–10	0.1–1	≤ 0.1
Examples of materials	brass	steel	soapstone	PMMA	XPS
Thermal conductivity	115	15.4	5.5	0.197	0.028
Probe radius	14	6.3	6.3	6.3	6.3
Power output	3	1	0.5	0.1	0.1
Heating time	3	7	10	120	60

The TPS method in previous studies was used to measure the thermal conductivity of wood based on the reference setting parameters listed in Table 4. However, measurement errors are significantly observed, and the repeatability of results needs improvement. Therefore, the correction of the setup parameters such as power output, heating time, and time window on the measurement results of the thermal conductivity of wood using the TPS method needs to be investigated.

4.2. Power Output

The curves of total to characteristic time, temperature increase in the probe, and mean deviation with power output for different heating times are shown in Figure 4. Figure 4a shows that the total to characteristic time decreases slowly with the increase in power output under all heating times except 200 s. According to the evaluation criteria for total to characteristic time (0.3–1.0), only the power outputs under a heating time of 120 s and the powers of 0.2 and 0.5 W under 200 s meet the requirements. Similarly, according to the evaluation criterion of the probe temperature increase (0.3–5 K), only the powers of 0.05 W and 0.1 W meet the standard, as shown in Figure 4b. The entire curve of temperature rise vs. power output shows a significant upward trend. Figure 4c shows the mean deviation at different powers, with smaller values indicating more reliable measurement. The mean deviations were similar and significantly smaller than the other values for both power outputs, 0.05 W and 0.1 W. The mean deviation decreased slowly with increasing power output at heating times of 20 s and 60 s. It is the case that increasing the temperature difference within a certain range will favor the fitting of the temperature rise curve. However, at heating times of 120 s and 200 s, the mean deviation was minimized at a power output close to 0.1 W and then rapidly increased beyond the fitting residual rating criterion ($<10^{-4}$). It is possible that sustaining a high power for long periods of time affects the accuracy of the temperature increase determined for the probe by allowing heat to escape. To summarize, it can be initially judged that a power output setting of 0.05 W or 0.1 W is appropriate.

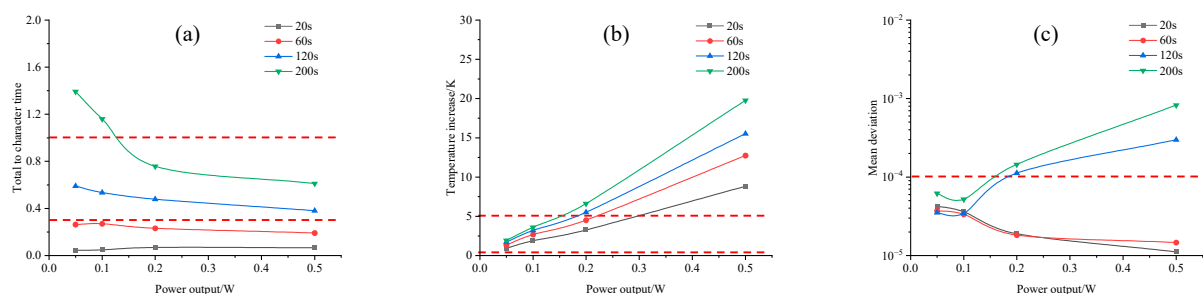


Figure 4. Relationship between power output and measurement reliability index. (a) Total to characteristic time. (b) Temperature increase. (c) Mean deviation.

Temperature drift graphs at different power outputs are shown in Figure 5. The scatter points show a random distribution trend at heating powers of 0.05 W and 0.1 W. This indicates that the sample is isothermal and there is no disturbance from other heat sources. However, in the case of longer heating time, when power output exceeds 0.2 W,

the temperature drift graph is less random. In particular, when the heating power reaches 0.5 W, the differential scatter plot tends to a curve. The reason is that excessive power output results in less heat being transferred to the wood than to the probe itself, causing the temperatures of the sample and the probe to rise out of synchronization.

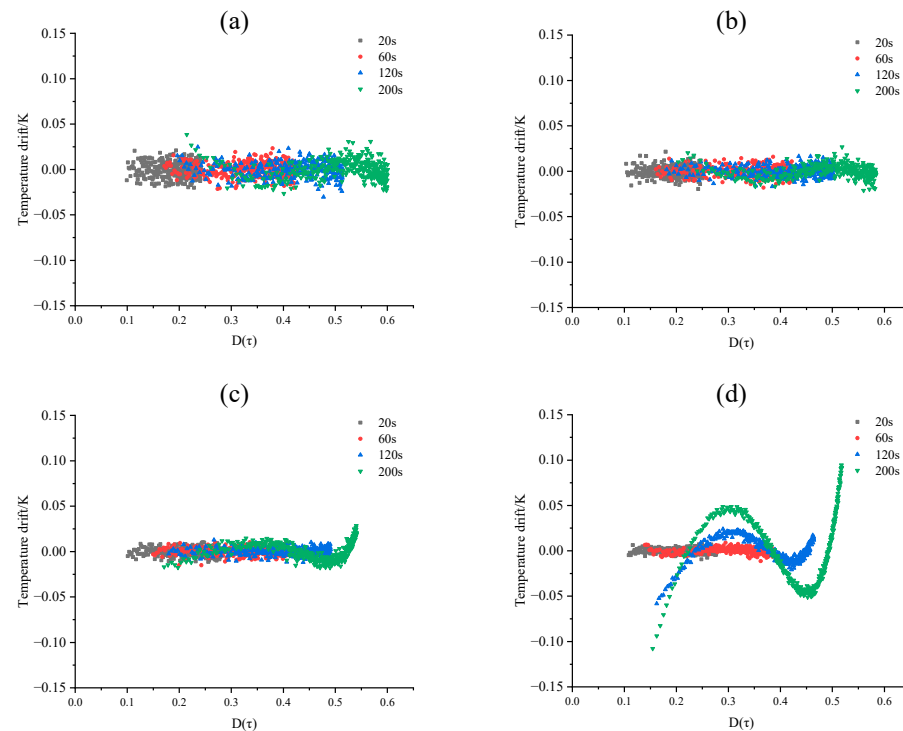


Figure 5. Temperature drift graphs for power outputs of (a) 0.05 W, (b) 0.1 W, (c) 0.2 W, and (d) 0.5 W.

4.3. Heating Time

Heating time is another important factor affecting the detection accuracy of the TPS method. The curves of total to characteristic time, temperature increase in the probe, and mean deviation with heating time for different powers are given in Figure 6. From Figure 6a, the total to characteristic time increases linearly with heating time, and this conclusion can also be drawn from Equation (2). According to the rating criterion of total to characteristic time (0.3–1.0), heating times of 20 s, 60 s, and 200 s should be excluded. Figure 6b shows the temperature increase in the probe at different heating times. The temperature increase in the probe has a more gently growth trend at longer heating times. This is due to the more significant effects of heat dissipation from the specimen surface during long measurements with lower power output. However, when the power output is increased to 0.5 W, prolonged heating still causes the temperature increase in the probe to continue to trend upward. Figure 6c shows the mean deviation at different heating times, with the fitted residuals increasing slowly with heating time at power outputs of 0.05 W and 0.1 W and meeting the rating criterion ($<10^{-4}$) for all 200 s of heating time. At power outputs of 0.2 W and 0.5 W, the mean deviation increases rapidly after the heating time exceeds 60 s, deviating from the requirement of the evaluation criterion. The contact thermal resistance between the specimen and the probe can cause prolonged heating to induce severe hysteresis in the temperature rise curve, compromising the accuracy of the fit to measurement data. Additionally, excessive heating might lead to heat leakage outside the specimen, rendering the fitted data unreliable.

Temperature drift graphs for different heating times are shown in Figure 7. The longer the heating time is, the wider the distribution of data points in the horizontal coordinate is. When the heating time is 20 s or 60 s, the distribution of data points is more concentrated, and it is more scattered after the heating time exceeds 120 s. It is clearly seen from the figure

that the randomization of the temperature drift graph is better with a lower power output selected for a heating time of 120 s. In contrast, the differential random scattering is less effective when the heating time is 200 s. This is probably because heating the sample for an extended period causes it to lose more heat to the air, resulting in a significant temperature difference between the sample and the probe.

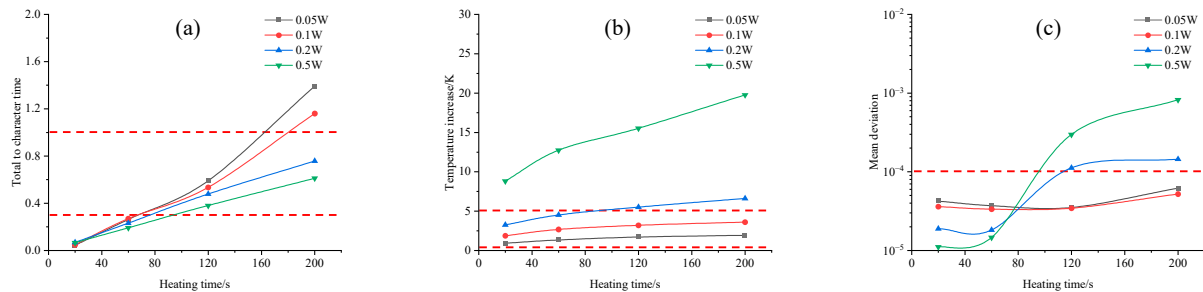


Figure 6. Relationship between heating time and measurement reliability index. (a) Total to characteristic time. (b) Temperature increase. (c) Mean deviation.

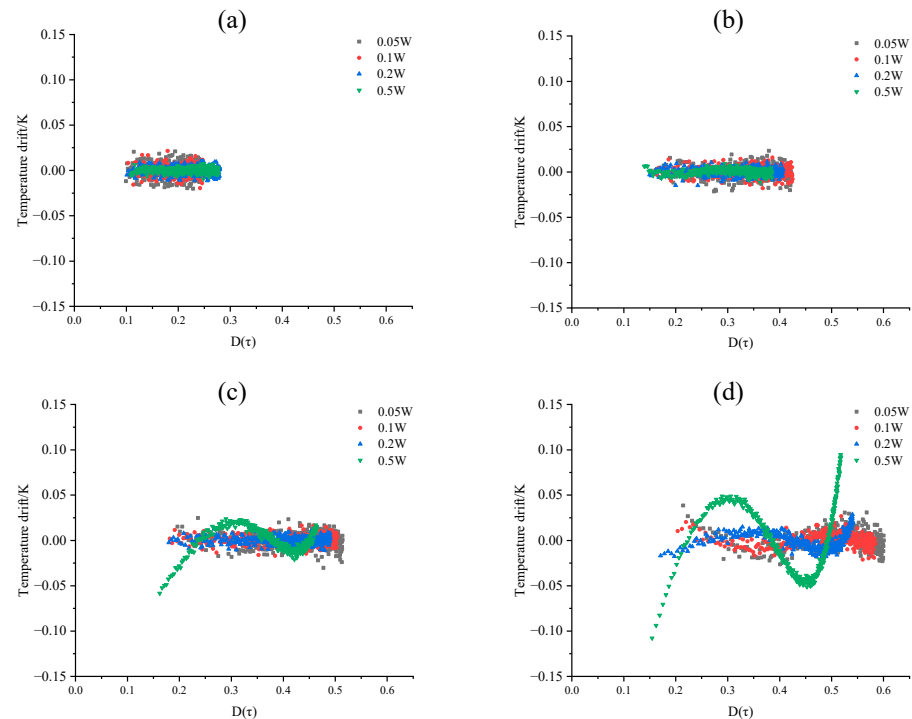


Figure 7. Temperature drift graphs for heating times of (a) 20 s, (b) 60 s, (c) 120 s, and (d) 200 s.

With the above analysis, it can be clearly seen that the total to characteristic time is about 0.5344, the temperature increase in the probe is about 3.1952 K, and the mean deviation is about 3.4443×10^{-5} for the parameter settings (0.1 W, 120 s). All of them are in the middle of the reasonable intervals, the average deviation is within the order of 10^{-4} , and the stochasticity of discrete points in the temperature drift graph is better, which is in line with the evaluation criteria. For the parameter settings (0.05 W, 120 s), the total to characteristic time is about 0.5898, the temperature increase in the probe is about 1.7004 K, and the mean deviation is about 3.5139×10^{-5} , which are also in the reasonable ranges. The distribution of the temperature drift graph is uniform, which is basically in line with requirements. Therefore, the parameter settings (0.1 W, 120 s) and (0.05 W, 120 s) are more in accordance with requirements of the evaluation index.

4.4. Time Window

The selection of the time window is another critical factor affecting the accuracy of the TPS method. Initial and end intervals are chosen to calculate thermal conductivity for each measurement. Initial and final stages of heating are generally excluded owing to significant temperature fluctuations between the heating probe and the specimen at the start and substantial heat loss at the end from environmental influences. The impact of time window selection on the evaluation index is less significant than that of power output and heating time. As shown in Figure 8, the evaluation indicators all tend to increase with the proportion of the time window. Total to characteristic time increases slowly with the proportion of the time window, but the effect is not significant. The positive correlation of the temperature increase in the probe with the proportion of the time window is more pronounced. This is because increasing the time window increases the number of data points in the temperature rise curve that are involved in the calculation. Therefore, when the temperature increase in the probe does not meet the requirements, the position of the heated initial section can be appropriately adjusted. With a larger proportion of the time window, the temperature rise segments have a slightly smaller effect on mean deviation, and the more data points are rounded off from the temperature rise curve, the smaller the fitting residuals become. Therefore, if the mean deviation is too large, it is appropriate to round off more temperature rise data, specifically to shorten the proportion of the time window selected.

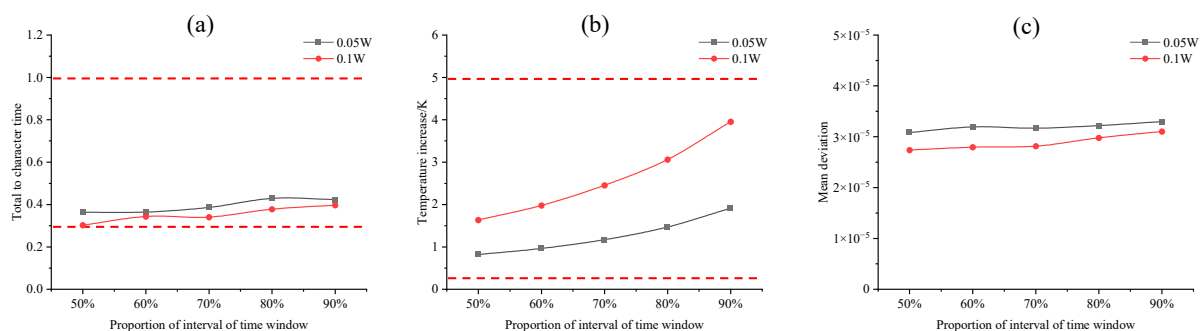


Figure 8. Relationship between the proportion of the time window and measurement reliability index. (a) Total to characteristic time. (b) Temperature increase. (c) Mean deviation.

Temperature drift graphs for different time windows are shown in Figure 9. It is obvious that increasing the time window selected will result in a wider distribution area of the differential scatter plot, but at the same time the randomness becomes worse. The distribution area of data points is wider and the data fitting is more significant when the power output is 0.05 W. However, the temperature difference value is larger, leading to an increase in the mean deviation. The temperature difference values are smaller and mean deviations are lower when the power output is 0.1 W, but the data points are distributed over a narrower area. If the selected time window is excessively narrow, the small distribution range of data points will lead to insufficient calculated data points, affecting the validity of the measurement results. If the selected time window is excessively long, the temperature drift graph is less randomized. The selection of time window had little effect on total to characteristic time and mean deviation, and there was some effect on the temperature increase in the probe, but it was not outside the range of the rating criterion. With the parameter settings (0.1 W, 120 s) and (0.05 W, 120 s), 60%–80% of the total time window is appropriate.

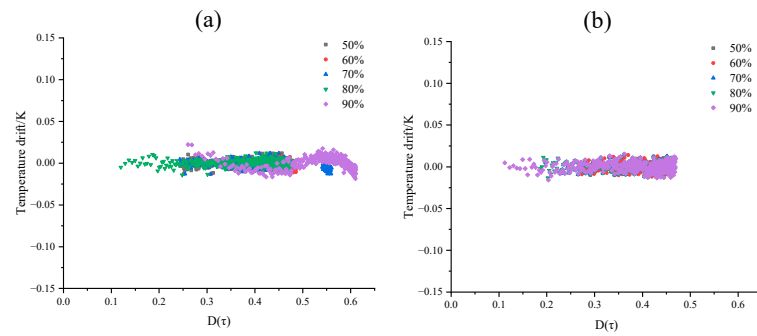


Figure 9. Relationship between the proportion of the time window and temperature drift graph. (a) (0.05 W, 120 s). (b) (0.1 W, 120 s).

4.5. Comparison with Measurement Results

For verifying the measurement accuracy of the result of the TPS method, the relationship between the thermal conductivity of wood obtained by the TPS method and that obtained by the HFM method was investigated. Figure 10 gives the measurement results for the thermal conductivity of poplar and camphor pine in different grain directions according to these two methods. It shows that the TPS measurement results in all directions are greater than those of the HFM method; the detection results of the TPS measurement range from 0.122 to 0.207 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, and the HFM measurement results range from 0.069 to 0.081 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$. From Figure 10, the axial thermal conductivity of TPS is 1–1.4 times higher than that of HFM, the radial thermal conductivity is 0.9–1.4 times higher than that of HFM, and the chordal thermal conductivity is 0.9–1.3 times higher than that of HFM. Previous studies have shown that the thermal conductivity measured by the TPS method is 0.2 to 1.5 times higher than that of the HFM method, and the reason for the difference in the results of the studies is that the tree species studied are different and the testing parameters chosen are different [10–12,25–27].

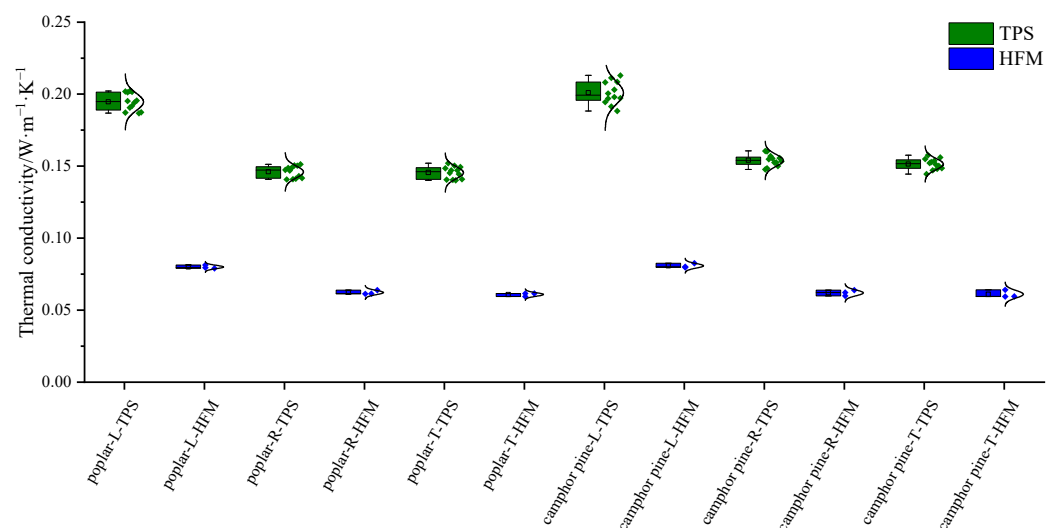


Figure 10. Comparison of thermal conductivity measured by HFM and TPS method.

The differences between TPS and HFM measurement results mainly stem from differences in their computational models and testing environments. According to Equation (1) in the TPS computational model, the thermal conductivity increases as the temperature rise of the probe decreases. The thermal resistance between the sample surface and the probe reduces the amount of heat supplied to the sample, thereby lowering the temperature rise of the probe. Additionally, heat exchange between the sample, the probe, and the surrounding environment also causes a decrease in the temperature rise of the probe [27].

The accuracy of the thermal conductivity obtained by the TPS method may vary significantly depending on the calculation method. The measurement method was optimized by adjusting the settings of power output, heating time, and time window. Evaluation indexes such as the total to characteristic time, temperature increase in the probe, mean deviation, and temperature drift graph were used to judge whether the measurement results of the thermal conductivity of wood were reliable or not. The optimized TPS measurement method can also be extended to other tree species. In this study, the data of poplar, eucalyptus, radiata pine, and oak before and after TPS correction were compared, as shown in Figure 11. The range of measurements before optimization was 0.145–0.329 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, and the range of measurements after optimization was 0.145–0.328 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$. The optimized TPS measurements basically did not change the result for the thermal conductivity of wood. However, the standard uncertainties ranged from 1.57% to 2.36% before optimization and ranged from 0.79% to 1.28% after optimization, and the standard uncertainties after optimization were 18.9%–59.5% lower than those before optimization. Research shows that the accuracy of the corrected thermal conductivity is significantly better than that of the uncorrected measurements. Measurements before and after correction do not change significantly as a result of the calibration, but the correction greatly improves the repeatability of sample measurements. The TPS method can be considered an efficient and accurate method for measuring the thermal conductivity of wood.

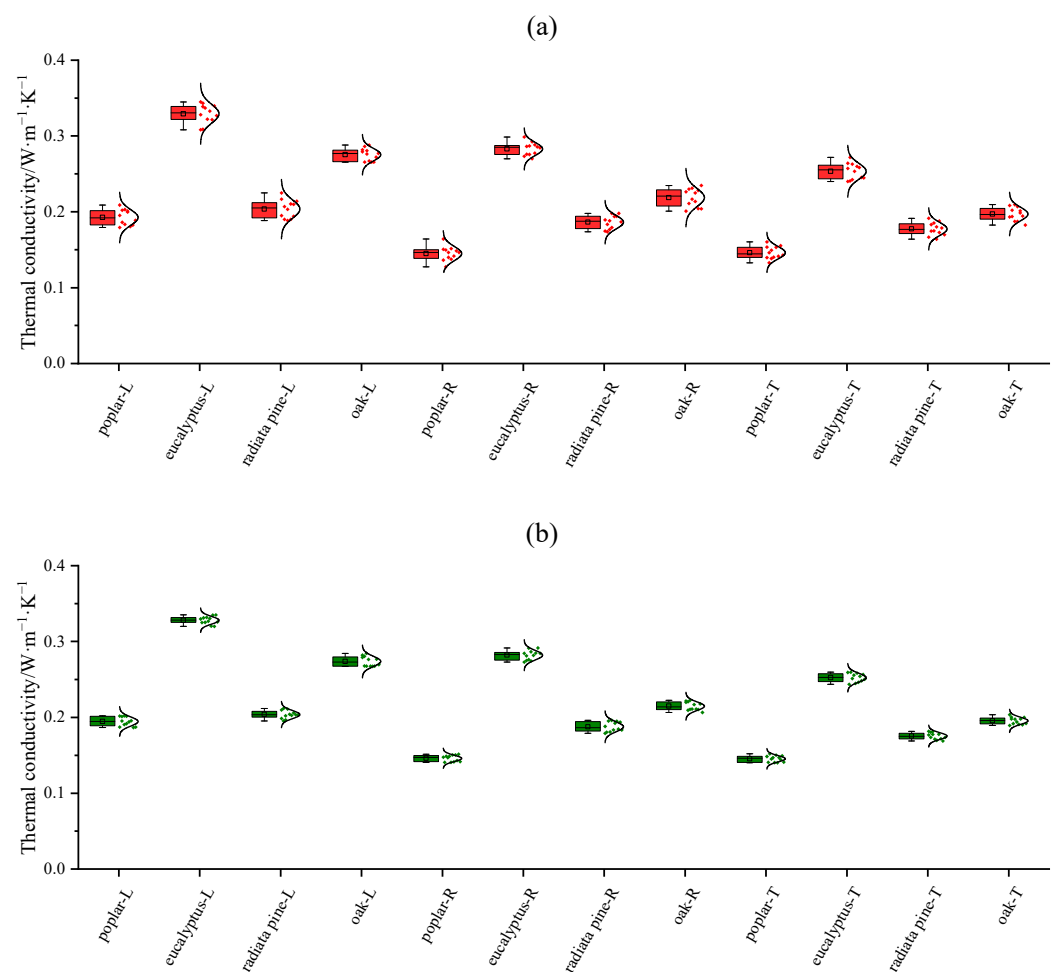


Figure 11. Comparison of thermal conductivities measured before and after correction of the TPS method. (a) Before correction. (b) After correction.

5. Conclusions

The TPS method was utilized to study the method of setting parameters (such as power output, heating time, and time window) required for the detection process for assessing the reliability of the index test measurements and to compare the data obtained by the TPS method with the results of the steady-state method. The following conclusions were drawn.

The optimal parameters for measuring the thermal conductivity of wood were determined to be the following: a power output of 0.05 or 0.1 W, heating time of 120 s, and time window covering 60% to 80% of the entire heating time. Measurements of the thermal conductivity of wood by the HFM method were approximately 40%–120% of those obtained by the TPS method. The thermal conductivity measured by the TPS method exceeds that of the HFM method in all directions of grain angle.

The total to characteristic time, temperature increase in the probe, mean deviation, and temperature drift graph are valid indicators for evaluating the detection reliability of the TPS method. The TPS method is an effective way to achieve efficient and accurate measurement of the thermal conductivity of wood. The subsequent optimization of its measurement process can start from the calculation model, contact thermal resistance, and testing environment.

Multiple tree species, including poplar, eucalyptus, radiata pine, and oak, were measured both before and after the optimization of the TPS method. The overall range of thermal conductivity measurements remained consistent, but there was a significant reduction in standard uncertainties.

Author Contributions: Conceptualization, methodology, writing—original draft, H.M.; investigation, formal analysis, X.Y.; validation, B.C.; data curation, P.R.; supervision; resources, project administration, writing—review and editing, J.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China [grant no. 32271786] and National Undergraduate Training Programs for Innovations [grant no. 202310225510].

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Giannotas, G.; Kamperidou, V.; Barboutis, I. Tree bark utilization in insulating bio-aggregates: A review. *Biofuels Bioprod. Biorefin.* **2021**, *15*, 1989–1999. [\[CrossRef\]](#)
2. Srivaro, S.; Börcsök, Z.; Pásztor, Z. Temperature dependence of thermal conductivity of heat-treated rubberwood. *Wood Mater. Sci. Eng.* **2021**, *16*, 81–84. [\[CrossRef\]](#)
3. Li, Y.; Lattimer, B.Y.; Case, S.W. Measurement and modelling of thermal and physical properties of wood construction materials. *Constr. Build. Mater.* **2021**, *284*, 122780. [\[CrossRef\]](#)
4. Tanaka, T. Simple geometrical model of thermal conductivity and bound-water diffusion coefficient in resin-rich regions of softwood plywood. *Wood Sci. Technol.* **2018**, *52*, 331–342. [\[CrossRef\]](#)
5. Zhao, J.Y.; Guo, L.Y.; Cai, Y.C. A novel fractal model for the prediction and analysis of the equivalent thermal conductivity in wood. *Holzforschung* **2021**, *75*, 702–711. [\[CrossRef\]](#)
6. Chai, Y.; Liang, S.Q.; Zhou, Y.D.; Lin, L.Y.; Fu, F. 3D Microscale Heat Transfer Model of the Thermal Properties of Wood-Metal Functional Composites Based on the Microstructure. *Materials* **2019**, *12*, 2709. [\[CrossRef\]](#)
7. Diaz, A.R.; Flores, E.I.S.; Yanez, S.J.; Vasco, D.A.; Pina, J.C.; Guzmán, C.F. Multiscale modeling of the thermal conductivity of wood and its application to cross-laminated timber. *Int. J. Therm. Sci.* **2019**, *144*, 79–92. [\[CrossRef\]](#)
8. Zhao, J.Y.; Fu, Z.Y.; Jia, X.R.; Cai, Y.C. Inverse determination of thermal conductivity in lumber based on genetic algorithms. *Holzforschung* **2016**, *70*, 235–241. [\[CrossRef\]](#)
9. Cai, L.P.; Garrahan, P. Inverse determination of thermal conductivity in frozen lumber. *Wood Sci. Technol.* **2006**, *40*, 665–672. [\[CrossRef\]](#)
10. Vay, O.; Busquets-Ferrer, M.; Emsenhuber, G.; Huber, C.; Gindl-Altmutter, W.; Hansmann, C. Thermal conductivity of untreated and chemically treated poplar bark and wood. *Holzforschung* **2021**, *75*, 1125–1135. [\[CrossRef\]](#)

11. Assaad, M.E.L.; Colinart, T.; Lecompte, T. Thermal conductivity assessment of moist building insulation material using a Heat Flow Meter apparatus. *Build. Environ.* **2023**, *234*, 110184. [[CrossRef](#)]
12. Troppová, E.; Švehlík, M.; Tippner, J.; Wimmer, R. Influence of temperature and moisture content on the thermal conductivity of wood-based fibreboards. *Mater. Struct.* **2015**, *48*, 4077–4083. [[CrossRef](#)]
13. Wang, J.Y.; Hou, S.Y.; Shen, Z.L.; Wen, J.L.; Qi, C.S. Thermal Characteristics and Simulation of Enzymatic Lignin Isolated from Chinese Fir and Birch. *Forests* **2022**, *13*, 914. [[CrossRef](#)]
14. Wu, S.S.; Tao, X.; Xu, W. Thermal Conductivity of Poplar Wood Veneer Impregnated with Graphene/Polyvinyl Alcohol. *Forests* **2021**, *12*, 777. [[CrossRef](#)]
15. Nouemsi, E.S.; Ngouloure, Z.N.M.; Bidoung, J.C.; Kamseu, E.; Rossignol, S.; Leonelli, C. Dependence of the insulating behavior of some common woods to the pore network and packing density of their fibers: A microstructural approach. *Transp. Porous Med.* **2021**, *138*, 309–336. [[CrossRef](#)]
16. Gaiser, J.; Stripf, M.; Henning, F. Enhanced Transient Hot Bridge Method Using a Finite Element Analysis. *Int. J. Thermophys.* **2019**, *40*, 12. [[CrossRef](#)]
17. Lagüela, S.; Bison, P.; Peron, F.; Romagnoni, P. Thermal conductivity measurements on wood materials with transient plane source technique. *Thermochim. Acta* **2015**, *600*, 45–51. [[CrossRef](#)]
18. Dupleix, A.; Kusiak, A.; Hughes, M.; Rossi, F. Measuring the thermal properties of green wood by the transient plane source (TPS) technique. *Holzforschung* **2013**, *67*, 437–445. [[CrossRef](#)]
19. Sun, S.C.; Jin, X.; Liu, C.L.; Meng, Q.G.; Zhang, Y. Study on in-situ measurement method of THF hydrate thermal conductivity. *Int. J. Heat. Mass. Transf.* **2018**, *127*, 88–96. [[CrossRef](#)]
20. Gustafsson, S.E.; Mihiretie, B.M.; Gustavsson, M.K. Measurement of Thermal Transport in Solids with the Hot Disc Method. *Int. J. Thermophys.* **2024**, *45*, 1. [[CrossRef](#)]
21. He, Y. Rapid thermal conductivity measurement with a hot disk sensor. *Thermochim. Acta* **2005**, *436*, 122–129. [[CrossRef](#)]
22. Jannot, Y.; Acem, Z. A quadrupolar complete model of the hot disc. *Meas. Sci. Technol.* **2007**, *18*, 1229–1234. [[CrossRef](#)]
23. Bohac, V.; Gustavsson, M.K.; Kubicar, L.; Gustafsson, S.E. Parameter estimations for measurements of thermal transport properties with the hot disk thermal constants analyzer. *Rev. Sci. Instrum.* **2000**, *71*, 2452–2455. [[CrossRef](#)]
24. Grimvall, G. *Thermophysical Properties of Materials (Enlarged and Revised Edition)*; Elsevier: Amsterdam, The Netherlands, 1999. [[CrossRef](#)]
25. Jang, E.S.; Kang, C.W. The Relationship Between Bulk Density and Thermal Conductivity in Various Korean Woods. *Wood Res.* **2022**, *67*, 178–186. [[CrossRef](#)]
26. Sonderegger, W.; Hering, S.; Niemz, P. Thermal behaviour of Norway spruce and European beech in and between the principal anatomical directions. *Holzforschung* **2011**, *65*, 369–375. [[CrossRef](#)]
27. Maeda, K.; Tsunetsugu, Y.; Miyamoto, K.; Shibusawa, T. Thermal properties of wood measured by the hot-disk method: Comparison with thermal properties measured by the steady-state method. *J. Wood Sci.* **2021**, *67*, 20. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.