**International Journal Of Engineering Research And Development**
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 14, Issue 9 (September Ver. II 2018), PP.35-52

# Basic Study on Thermo physical Properties Measurement of Layered Anisotropic Materials

Qing-Ming ZHANG [1], Koichi HIROSE [2], Qiang-Sheng WANG[3]
[1] *Department of Mechanical Engineering, Civil and Environmental Engineering, Graduate School of Iwate University, Morioka, Iwate 020-8551, Japan*
[2] *Department of Systems Innovation Engineering, Iwate University, Morioka, Iwate 020-8551, Japan*
[3] *Department of Mechanical and Electrical Engineering，Henan Institute of Technology, Henan, 453003,China*
*Corresponding Author: Qing-Ming ZHANG*

**ABSTRACT:** *A method for measuring the thermal properties of anisotropic materials is proposed. In this study, we use wood with significant anisotropic characteristics as a research object, and combine the experimental data to simulate an effective analytical method. The purpose of obtaining the thermal conductivity and thermal diffusivity of the material in the orthogonal direction quickly and automatically has been achieved. According to the characteristics of wood, the variation law of the thermal conductivity at the significant angle of the wood grain change is obtained. Based on the measurement data and the characteristics of the molar stress circle, the maximum thermal conductivity and the minimum thermal conductivity distribution direction of the unknown internal structure are found.*

**KEYWORDS:** *Anisotropy, Thermal conductivity, Thermal diffusivity, Numerical simulation, Thermophysical Property*

---

Date of Submission: 18-12-2018 Date of acceptance: 31-12-2018

---

## I. INTRODUCTION

Exploring the heat transfer problem is especially important for understanding of the status of the design and phenomena of the equipment. Many problems due to damages caused by materials and thermal efficiency in industrial products, but clarifying these causes and taking appropriate measures to solve the problems will improve product quality and prolong the service life. The thermophysical properties of the material form the basis for the heat transfer characteristics of the product. Since the physical property values such as the thermal conductivity are accurately known, it is possible to improve the calculation accuracy of the thermal efficiency and create better product development and facilitating countermeasures to various products. In recent years, as the thermal conductivity and thermal diffusivity of typical values of thermophysical properties, and with the progress of measurement equipment, measurement with high accuracy becomes possible. Thermal conductivity is a physical property value that indicates the ease of heat flow in a material. In the industrial world, in order to solve the problem of heat resistance and operation efficiency of precision equipment and combustion equipment, it is considered very important to grasp the thermal conductivity of the material. Recent electronic devices have been miniaturized, but power consumption increases, resulting in increased accidents in the equipment and acceleration of defects, which has been reported numerous. In order to solve thermal problems such as heat radiation and heat transfer, it is necessary to make fully utilize of the thermal properties of the material, and the industry has begun to re-examine the value of the thermal properties obtained by the previous measurement methods.

The research so far, many studies on the mechanical properties of anisotropic materials have been conducted, and it seems that evaluation methods have basically been established. For the thermal design of systems using anisotropic materials and for evaluating thermally designed systems, establishment of techniques such as local thermal diffusivity measurement and thermal conduction analysis is increasingly expected in the future it seems to be necessary. In the conventional thermal diffusivity measurement method, In the conventional thermal diffusivity measurement method, the average value of the whole material is obtained. Therefore, when the value of thermal properties that varies depending on the direction of the anisotropic material varies, it is necessary to cut out the test piece from various directions and perform individual measurements. However, especially in the measurement of the thermal diffusivity, certain skills are required to be operated. Therefore, in order to reduce the measurement error, it is necessary to be able to measure multiple directions at a time. Moreover, in the conventional analysis method, only the thermal diffusivities in two orthogonal directions are considered. When analyzing the thermal conductivity of an anisotropic material, not only two directions, but also the thermal diffusivity of multiple directions are considered, which is very challenging with current technology. To overcome this problem, M. Fujii [1-2] et al. proposed a non-contact measurement method using lasers and infrared thermometers, as well as the simultaneous measurement of thermal conductivity and the thermal diffusivity of isotropic materials, and further tested the error in measurement. This method was based on the fact that the change in surface temperature with time after step heating depends on the thermal properties of the material, and therefore, non-contact (non-invasive) heat was achieved by combining laser heating with the surface temperature measured by an infrared thermometer. The measurement of physical properties becomes possible. M. Fujii [3] et al. the method proposed for isotropic materials was extended to measure anisotropic materials by performing three-dimensional transient numerical simulation and by measuring the two-dimensional surface temperature distributions. The measurement results are compared with those obtained by Takegoshi [4] et al. and Eiji NEMOTO [5] et al. propose a thermal conductivity measurement of a two-dimensional anisotropic heat conductor using an unsteady point source of heat. It simplifies the calculation of two principal thermal conductivities and the principal rotating angle from the measured coordinates. Generally, the experimental materials used to test the thermal properties of anisotropic materials used special experimental materials or special measured equipment, which makes the thermal physical properties test of anisotropic materials difficult to achieve [6-9]. Therefore, It is particularly important to propose a method for easily measuring the thermal properties of common anisotropic materials.

In this study, the method proposed for isotropic materials was extended to measure anisotropic materials by performing two-dimensional transient numerical simulation and by measuring the two-dimensional temperature distributions. We used wood with significant anisotropic material as the experimental sample, which has a major thermal property value and thermal conductivity and thermal conductivity were measured. Due to its low thermal conductivity and anisotropy, we were measured the position of temperature measurement, how to apply heat flux etc with the experiment and explored. Also, in numerical analysis, we analyzed it so as to the experimental conditions can be reproduced as much as possible and made it possible to obtain a more accurate thermophysical property value. Then, actually calculating the thermal conductivity ratio ($AYX = \lambda y / \lambda x$) and the thermal diffusivity, when the steady state temperature and unsteady temperature change obtained from the experimental results were incorporated into numerical analysis, the calculation parameters were changed, availability auto thermal gain conductivity ratio and thermal diffusivity, by using the measured thermal properties in two directions to calculate the principal thermal conductivity direction and value.

## II. ANALYTICAL AND EXPERIMENTAL METHOD

### 2.1 Physical Model and Coordinate System

Physical model and coordinate system of analysis used in this study are shown in Fig.1 and Fig.2. As shown in the figure, both models use the orthogonal coordinate system , and its coordinate origin is set at the position of O. The upper part(Red block) of the analytical model is the heating part, and the lower part(Green block) is the cooling part. Other boundaries are set as adiabatic conditions.

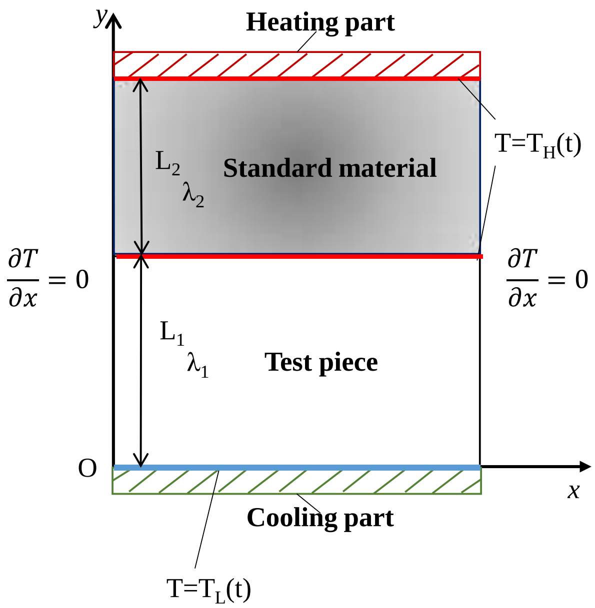



**Fig.1** One-dimensional physical model and coordinate systems.

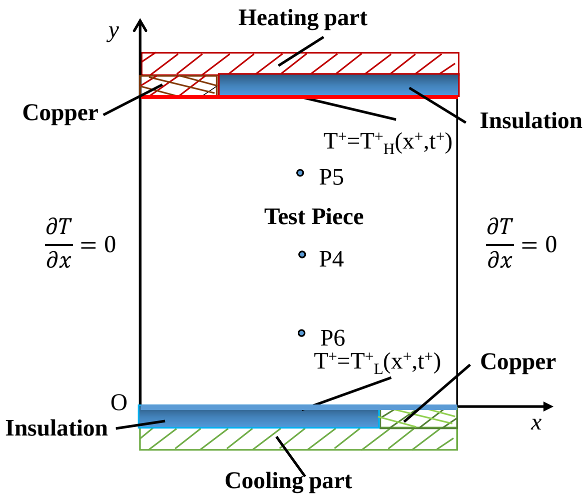



**Fig.2** Two-dimensional physical model and coordinate systems.

The physical model of Fig.1 is the same as the method of measureing the thermophysical properties in the single direction for isotropy material. The location of the heat source and the cooling site in the physical model of Fig.2 is arranged asymmetric, resulting in that the heat flux inside the sample to be measured also cannot be uniform, and the internal temperature distribution changes accordingly.

## 2.2 Measuring Principle

When using the model of Fig.1 to measure the thermophysical properties of the measurement sample, it must be between the heat source and the measurement sample place a standard material that is with the same surface area as the tested substance and known thermal conductivity. By implementing the standard material with known thermal conductivity, the sample target thermal conductivity easured can be extracted without heat flow measurement as shown in Eq.(1), and the associated error due to heat flow easurement can thus be eliminated. Since the heat flux through the standard material is equal to the heat flow through the measurement sample target, the thermal conductivity of the measurement sample target are defined as the following:

$$\lambda_1 = \lambda_2 \frac{\Delta T_2 L_1}{\Delta T_1 L_2} \tag{1}$$

Where, subscript 1 and 2 are associated with the measurement sample and the standard material, respectively, λ representative thermal conductivity. ∆T represents the temperature difference between the upper and lower surfaces, L represents the thickness of the measurement sample. However, efforts are still needed to ensure equal heat flow between the standard material and the testing specimen.

The non-dimensionalized unsteady 2-dimensional heat conduction equation for anisotropic material used in this analysis are defined as the following:

$$\frac{\partial T^+}{\partial t^+} = \frac{\partial^2 T^+}{\partial x^{+2}} + \frac{\lambda_y}{\lambda_x}\frac{\partial^2 T^+}{\partial y^{+2}} \tag{2}$$

Also, the thermal conductivity ratio AYX is shown as follows.

$$\frac{\lambda_y}{\lambda_x} = AYX \tag{3}$$

The equation for dimensionless time $t^+$ and dimensionless temperature $T^+$ are shown.

$$t^+ = \frac{\alpha_x t}{L^2} \tag{4}$$

$$T^+ = \frac{T - T_L}{T_H - T_L} \tag{5}$$

The boundary conditions on both sides are defined as adiabatic condition as the following:

$$\frac{\partial T^+}{\partial x^+} = 0$$

(6)

The following approximate expression was used as the boundary condition between the top and bottom of the analysis model are defined as the following:

$$T^+ = T_H^+(x^+, t^+) \tag{7}$$

$$T^+ = T_L^+(x^+, t^+)$$

(8)

In the experiment, as shown in Fig.2, copper and heat insulating material were sandwiched between the sample and the heat exchanger, and partial heating or partial cooling using a copper block was carried out. The insulating layer is on the side of the original copper block, but in fact there is a little heat flow into the upper part and a little heat flow out the lower part. For this reason, we need to use boundary conditions similar to experiments for the top and bottom surfaces in this analysis, which incorporates the experimental values into the calculation and compares the representative point temperatures to automatically obtain the thermal conductivity ratio and the thermal diffusivity. In order to faithfully reproduce the boundary temperature of the sample in the experiment and obtain the thermal conductivity ratio and the thermal diffusivity of the sample, the following approximate expression was used as a boundary condition between the upper part and the lower part of the analysis model. Also, in the same way, the lower part of the sample was approximated as a function.

Therefore, the upper part is given as an approximate function $T^+ = T_H^+(x^+,t^+)$ as a whole and the lower part was given an approximate function $T^+ = T_L^+(x^+,t^+)$ in the same way. It shows the temperature boundary condition converted to the approximate expression based on the experimental results of the upper part and the lower part, respectively. In the approximate expression on the position $x^+$, that is a variable which is approximated by using a sixth-order polynomial equation, and the deviation from the boundary temperature in the experiment is minimized as much as possible. In addition, the data is continuously collected under unsteady state temperature, in order to reduce the deviation of the theoretical value from the experimental value when the boundary temperature changes with time. The approximation formulas can only be converted into analytical calculations at a limited each fixed time interval.

In this analysis, we tried to automatically obtain the thermal conductivity ratio and the thermal diffusivity by incorporating the experimental results into the calculations. Since the steady state temperature of the sample is determined by the magnitude of the thermal conductivity ratio($\lambda_y/\lambda_x$=AYX). The steady temperature of a certain representative point is obtained with respect to each thermal conductivity ratio, when the thermal conductivity ratio is changed in the calculation. Comparing the value with the experimental value, the thermal conductivity ratio of the sample was obtained. Specifically, when the calculation starts to set the initial conditions， we don't know anything about those values, so we just was arbitrary choice set a value， that were thermal conductivity ratio AYX and minute change thermal conductivity ratio ΔAYX are input, and AYX is increased or decreased by ΔAYX. In general, when the thermal conductivity is relatively large, the representative point temperature decreases. On the contrary, when the thermal conductivity is small, the representative point temperature increases. Therefore, when the experimental result is compared with the calculated result, the difference is used to calculate AYX as ΔAYX increases or decreases. For example, as shown in Fig.3. When the AYX value is increased so that the error $\varepsilon_{ST}$ between the experimental results and the calculated results become minimum value, the AYX at this time is the required value.

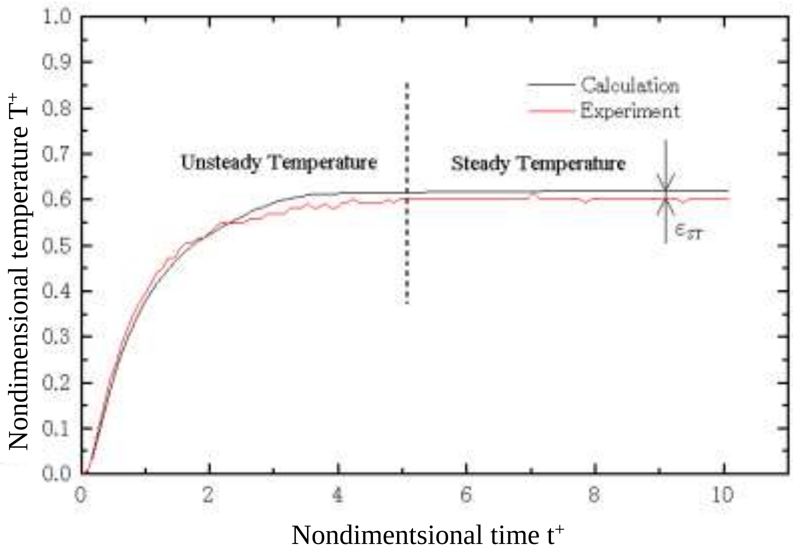



**Fig.3** Description of the method for judging the thermal conductivity ratio

The thermal conductivity ratio was determined as described above, and then the thermal diffusivity was determined. According to the above Eq.(4), the dimensionless time $t^+$ in the analysis can be changed by changing the term of α. For example, as shown in Fig.4

below, by changing $\alpha_x$ for the sample with the thermal diffusivity α, the gradient of the rising temperature becomes steep or gentle.

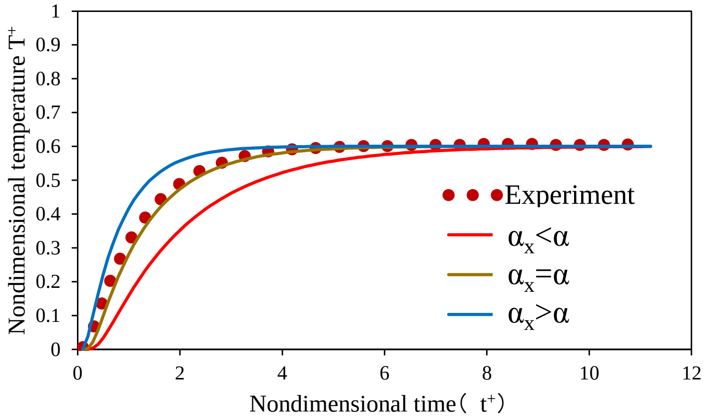



**Fig.4** Effect of thermal diffusivity on temperature rise

As shown in the Fig.4, regarding the thermal diffusivity, the temperature rises rapidly when the thermal diffusivity is high, and the temperature slowly rises when the thermal diffusivity is low. Therefore, as shown in the Fig.5 for the thermal diffusivity, as in the case of obtaining the thermal conductivity ratio AYX, by changing the thermal diffusivity $\alpha_x$ by $\Delta\alpha_x$, taking the difference between the experimental value and the calculated value for the rising temperature and using the summation. The thermal diffusivity so that the summation is the smallest was obtained, the formula for this relationship is expressed as:

$$E_{UT}=\sum_{i=1}^{ST}\varepsilon_{UT}=\sum_{i=1}^{ST}(T_{Ex}-T_{Cal})_i \tag{9}$$

By calculating the optimal thermal conductivity ratio and the optimal heat dissipation coefficient, the exact thermal conductivity on the x and y directions is calculated according to the equation is expressed as:

$$\lambda_y=\lambda_x AYX=\alpha_x c\rho AYX \tag{10}$$

Where c is the specific heat and ρ is the density.

Calculated using a two-dimensional conduction program to determine the thermal conductivity ratio, and then the thermal diffusivity was determined in the same way. The combination of the actual measurement results corresponding to the above theoretical analysis can only obtain the thermal conductivity and heat dissipation coefficient of orthogonal anisotropy in both x and y directions on the rectangular coordinates. However, as a general anisotropic material, there are always inconsistent thermal properties in each direction. Therefore, exploring the maximum and minimum thermal conductivity of anisotropic materials has become a characteristic research direction.

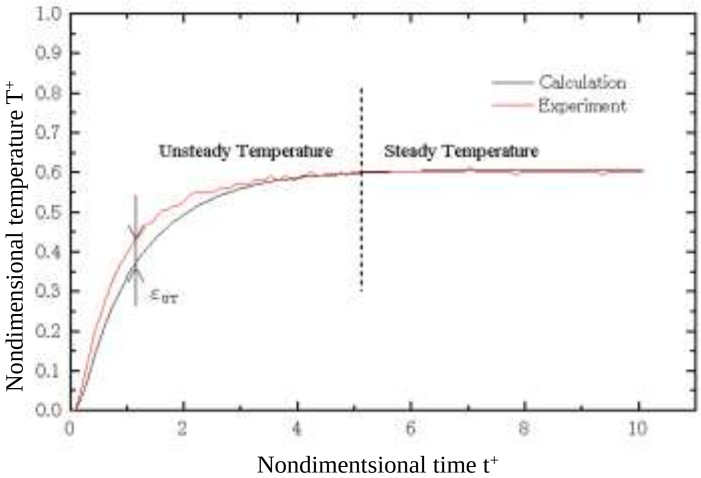



**Fig.5** Description of the method for judging the thermal diffusivity

The thermal conductivity inside the anisotropic material is no longer a scalar independent of direction. From this point of view, the formula for the components of the heat flow vector along the various directions in the Cartesian coordinate system is expressed as:

$$q_x = -\lambda_{xx}\frac{\partial T}{\partial x} - \lambda_{xy}\frac{\partial T}{\partial y} \tag{11}$$

$$q_y = -\lambda_{yx}\frac{\partial T}{\partial x} - \lambda_{yy}\frac{\partial T}{\partial y} \tag{12}$$

Where ∂T/∂x is the temperature gradient in the x direction, ∂T/∂y is the temperature gradient in the y direction, $q_x$ is heat flux in the x direction, $q_y$ is heat flux in the y direction, $\lambda_{xx}$ is thermal conductivity in the x direction, $\lambda_{yy}$ is thermal conductivity in the y direction, $\lambda_{xy}$ and $\lambda_{yx}$ is the matrix components of thermal conductivity assigns to the valid x-y domain.

Introduces a local Cartesian coordinate(ζ, η) where the ζ-axis is along the direction of the maximum thermal coefficient of the anisotropic material. If the direction of the principal direction of the thermal conductivity and the current coordinate system do not coincide, there existed an inclined angle between the local Cartesian coordinate(ζ, η) and the basic Cartesian coordinate(x, y). $q_\varphi$ is integrated heat flux in the x-y yields, φ is the angle between the integrated heat flux and the y-axis, β is the angle between the principal axis direction of the maximum thermal conductivity and the x-axis. The position relation is as shown in the Fig.6 .

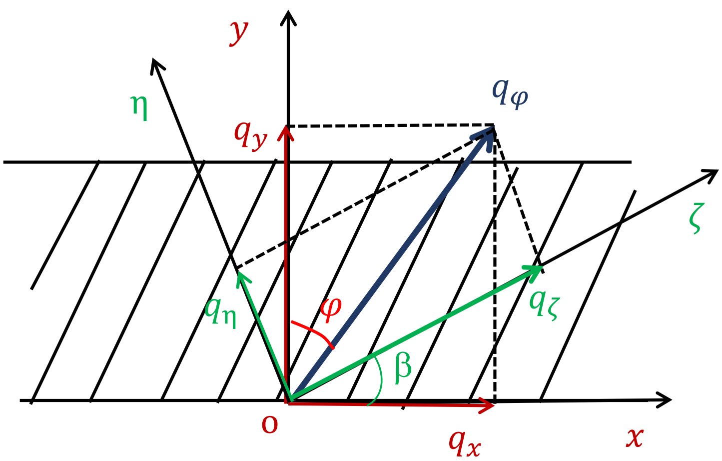



**Fig.6** Anisotropic principal axes(ζ, η) and coordinate systems(x,y)

The heat flow component in the principal coordinate system is expressed as:

$$q_\zeta = -\lambda_\zeta \frac{\partial T}{\partial \zeta} \tag{13}$$

$$q_\eta = -\lambda_\eta \frac{\partial T}{\partial \eta} \tag{14}$$

The thermal flow components in the coordinate(x,y) system are expressed as:

$$\begin{bmatrix} q_x \\ q_y \end{bmatrix} = -\begin{bmatrix} \lambda_{xx} & \lambda_{xy} \\ \lambda_{yx} & \lambda_{yy} \end{bmatrix} \begin{bmatrix} \dfrac{\partial T}{\partial x} \\ \dfrac{\partial T}{\partial y} \end{bmatrix} \tag{15}$$

According to the conversion relationship of the thermal conductivity matrix in different coordinate systems, it can be expressed as:

$$\begin{bmatrix} \lambda_{xx} & \lambda_{xy} \\ \lambda_{yx} & \lambda_{yy} \end{bmatrix} = C \begin{bmatrix} \lambda_\zeta & 0 \\ 0 & \lambda_\eta \end{bmatrix} C^T \tag{16}$$

In the above formula, C represents the transformation matrix between the coordinate system($\zeta$, $\eta$) and the coordinate system(x,y).

$$C = \begin{bmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{bmatrix} \tag{17}$$

Substituting Eq.(17) into Eq.(16), after matrix multiplication we can get the following expression as:

$$\lambda_{xx} = \lambda_\zeta \cos^2\beta + \lambda_\eta \sin^2\beta \tag{18}$$

$$\lambda_{xy} = \lambda_{yx} = \left(\lambda_\zeta - \lambda_\eta\right)\cos\beta\sin\beta \tag{19}$$

$$\lambda_{yy} = \lambda_\eta \cos^2\beta + \lambda_\zeta \sin^2\beta \tag{20}$$

Substituting Eq.(18), Eq.(19), Eq.(20) into Eq.(11) and Eq.(12), we can get the following expression as:

$$q_x = -(\lambda_\zeta \cos^2\beta + \lambda_\eta \sin^2\beta)\frac{\partial T}{\partial x} - \left(\lambda_\zeta - \lambda_\eta\right)\cos\beta\sin\beta\frac{\partial T}{\partial y} \tag{21}$$

$$q_y = -(\lambda_\eta \cos^2\beta + \lambda_\zeta \sin^2\beta)\frac{\partial T}{\partial y} - \left(\lambda_\zeta - \lambda_\eta\right)\cos\beta\sin\beta\frac{\partial T}{\partial x} \tag{22}$$

The tensor of thermal conductivity has a certain relationship with a mathematically correct Mohr circle [6], which produce relation of Mohr's circle between thermal conductivity and rotating angle as shown in the Fig.8.

Arbitrarily choose a piece of material 1(Cartesian coordinate (x,y)) to rotate in its direction by $\delta$(in this case $\delta$ = 45°) and select a material 2(Cartesian coordinate ($x_z$,$y_z$)) of the same size as the measuring material as shown in Fig.7.

According to the material selection conditions combined with the Mohr circle analysis method can be established as shown in the Fig.8, we can be inferred that the relationship between the thermal conductivity in each direction and the principal angle[5,6,10]. The maximum and minimum of thermal conductivity are the abscissas of the points A and B where the circle intersects the $\lambda_{ii}$-axis. The maximum of thermal conductivity $\lambda_1$ is always the greatest absolute value of the abscissa of any of these two points. Likewise, the minimum of thermal conductivity $\lambda_2$ is always the lowest absolute value of the abscissa of these two points. Finding thermal conductivity $\lambda_{11}$ and $\lambda_{22}$ on x-y axis($\lambda_{11}$=$\lambda_{xx}$, $\lambda_{22}$=$\lambda_{yy}$ corresponding to the Eq.(16)), involves the determination of a point on the Mohr circle called the pole(A) or the origin of planes. Any straight line drawn from the pole will intersect the Mohr circle at a point that represents the state of stress on a plane inclined at the same orientation (parallel) in space as that line. Therefore, knowing the thermal conductivity on any particular experimental sample, one can draw a line parallel to that horizontal and vertical of experimental sample through the particular coordinates thermal conductivity on the Mohr circle and find the pole as the intersection of such line with the Mohr circle. As an example, let's assume we have a state of thermal conductivity with thermal conductivity components $\lambda_{11}$, $\lambda_{22}$and $\lambda_{12}$, $\lambda_{21}$($\lambda_{12}$=$\lambda_{21}$=$\lambda_{xy}$=$\lambda_{xy}$ corresponding to the Eq.(16)), as shown on Fig.8. Any straight line drawn from the pole will intersect the Mohr circle at a point that represents the state of thermal conductivity a plane inclined at the same orientation (parallel) in space as that line. The intersection of any of these two lines with the Mohr circle is the pole. Once the pole has been determined pole(A)minor principal thermal conductivity $\lambda_2$($\lambda_2$=$\lambda_\eta$ corresponding to the Eq.(16)), to find the state of stress on a plane making an angle $\phi$ with the vertical, or in other words a plane having its normal vector forming an angle $\phi$ with the horizontal plane, then we can draw a line from the pole parallel to that plane(as Fig.8). The thermal conductivity and thermal conductivity components on that plane are then the coordinates of the point(C,D) of intersection between the line and the Mohr circle.

Finding the orientation of the principal angle approach relies on the fact that the angle $\phi$ ,which is the normal vectors to any two physical planes passing through A(Fig.8) is half the angle between the central angle at which two lines joining their thermal conductivity points (C,D) and circle diameter AB intersect at the centre of the Mohr circle. The orientation of the planes where the maximum and minimum principal thermal conductivity act, also known as principal planes, can be determined by measuring in the Mohr circle the angles. Considering the principal axes ($\lambda_{ii}$, $\lambda_{jj}$) as the coordinate system, instead of the general coordinate system.

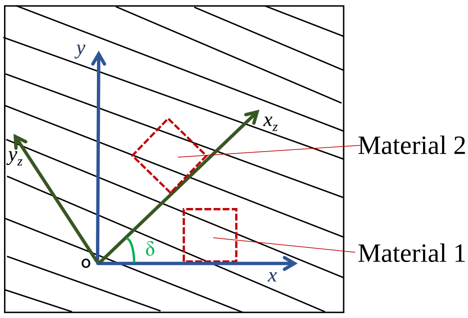



**Fig.7** Experimental materials selected on materials whose principal axis is unknown

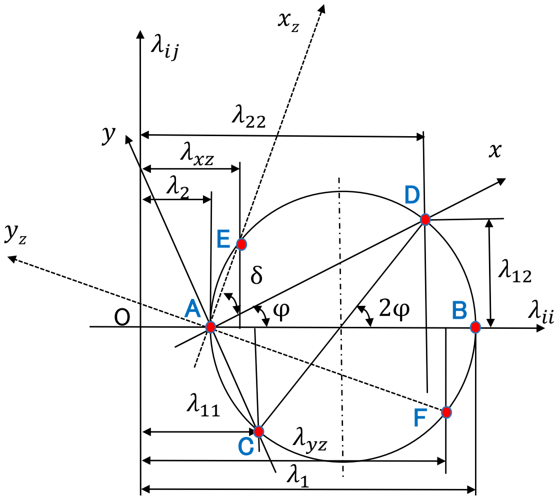



**Fig.8** Relation of Mohr's stress circle between thermal conductivity and rotating angle

The maximum thermal conductivity $\lambda_1$ and minimum thermal conductivity $\lambda_2$ expression is expressed as:

$$\lambda_{\zeta} = \lambda_1 = \frac{\lambda_{11} + \lambda_{22}}{2} + \sqrt{\left(\frac{\lambda_{22} - \lambda_{11}}{2}\right)^2 + \lambda_{12}{}^2} \tag{23}$$

$$\lambda_{\eta} = \lambda_2 = \frac{\lambda_{11} + \lambda_{22}}{2} - \sqrt{\left(\frac{\lambda_{22} - \lambda_{11}}{2}\right)^2 + \lambda_{12}{}^2} \tag{24}$$

$$\tan 2\phi = \frac{2\lambda_{12}}{\lambda_{22} - \lambda_{11}} = \frac{2\lambda_{xy}}{\lambda_y - \lambda_x} \tag{25}$$

$$\lambda_{xy} = \lambda_{12} = \sqrt{\frac{(\lambda_{22} - \lambda_{11})^2 \cos^2\phi \sin^2\phi}{1 - 4\cos^2\phi \sin^2\phi}} \tag{26}$$

The thermal conductivity of the two directions of the experimental material can be determined experimentally. The relationship between the maximum thermal conductivity and the minimum thermal conductivity of the material and the thermal conductivity of the new coordinate direction can be obtained by the geometric relationship on the Fig.8, as shown in the following equation.

$$\lambda_{22} = \lambda_1 - (\lambda_1 - \lambda_2)\sin^2\phi = \lambda_1 \cos^2\phi + \lambda_2 \sin^2\phi \tag{27}$$

$$\lambda_{11} = \lambda_2 + (\lambda_1 - \lambda_2)\sin^2\phi = \lambda_2 \cos^2\phi + \lambda_1 \sin^2\phi \tag{28}$$

$$\lambda_{11}/\lambda_{22} = \left(AYX_{ext}{}^2 \cos^2\phi + \sin^2\phi\right) / \left(\cos^2\phi + AYX_{ext}{}^2 \sin^2\phi\right) \tag{29}$$

where $AYX_{ext} = \lambda_1/\lambda_2$ (maxmum and minimum thermal conductivity ratio). Now, Eq.(29) is an expression of the thermal conductivity ratio of material 1. From the above relationship of Eq.(29), the expression of material 2 [substituting ($\phi = \phi + \delta$, $\delta = 45°$) into the Eq.(29)] can be obtained as write that:

$$\lambda_{yz}/\lambda_{xz} = \left(1 + \sin 2\phi + AYX_{ext}{}^2 (1 - \sin^2\phi)\right) / \left(1 - \sin 2\phi + AYX_{ext}{}^2 (1 + \sin^2\phi)\right) \tag{30}$$

In general, relations Eq.(29) and Eq.(30) can be applied to any combinations of ($\lambda_{11}/\lambda_{22}$, $\lambda_{yz}/\lambda_{xz}$) provided they are measured exactly, meaning that they are measured on exactly the same sample and there is no error associated with the measuring technique. Of course, in reality there is always a difference in geometry between two samples and there is always some measuring technique error.

Eliminate the unknown quantity $AYX_{ext}$, and simplify the two equations(Eq.(29) and Eq.(30)) into the following formula, we could rewrite Eq.(30) as follows:

$$\lambda_{yz}/\lambda_{xz} = \frac{(B+1)\tan^2\phi + (1-B)\tan^2\phi\sin 2\phi + (1-B)\sin 2\phi - (B+1)}{(B+1)\tan^2\phi + (B-1)\tan^2\phi\sin 2\phi + (B-1)\sin 2\phi - (B+1)} \tag{31}$$

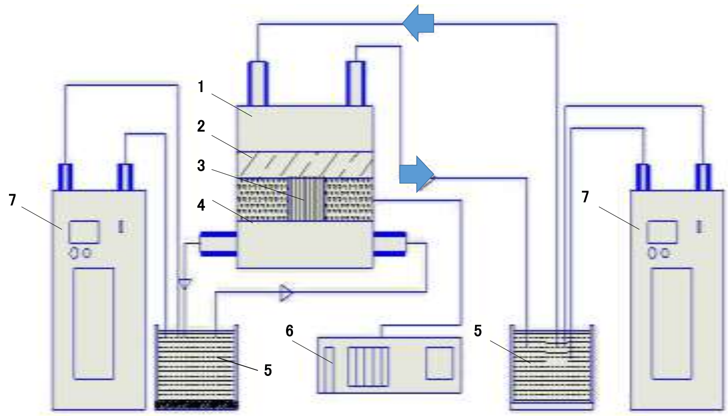
where B = $\lambda_{11}/\lambda_{22}$ (the experimental thermal conductivity ratio of material 1 on x,y axis in Fig.8). The function Eq.(31) is an equation for determining the azimuth of the principal axes, where in the thermal conductivities $\lambda_{11}$, $\lambda_{22}$, $\lambda_{xz}$ and $\lambda_{yx}$ respectively correspond to the x,y-direction thermal conductivity and $x_z$,$y_z$-direction thermal conductivity measured in the previous method with Eq.(10). Therefore, based on the value of $\lambda_{yz}/\lambda_{xz}$ and value of B are measured, the specific angle of the principal axis in the Eq.(31) can be calculated.

**2.3 Experimental Apparatus and Method**

The Schematic diagram of the experimental apparatus is shown as Fig.9. Roughly, the experimental apparatus could be divided into the constant temperature circulation section, measuring ection and data acquisition section. The constant temperature circulation section controls the water by the heating and cooling device under the temperature difference between the heating and cooling section was set ΔT at about 20°C. And operation was continued until the steady state was reached, and then connects to the heat exchange element by using the thermal insulation tank. The contact surface on the heat exchange element was aluminum has been used as a material for heating surface and cooling surface. The measuring ection is sandwiched between a heating part and a cooling part. A cube having a height of 30mm, a length of 30mm and a width of 30mm was used as an experimental sample of the wood measurement part. In order to allow most of the heat to pass through the wood and flow to the cooling section, the surroundings of the sample were covered with thermal insulation. In addition, the dimensions of the heat insulating material were 30mm in height and 35mm in wall thickness, and the material was polystyrene foam. Silicon rubber was 21mm high, 100mm long, 100mm wide. The temperature change values of the test materials are all transferred by thermal couple, transmitted and recorded in the data collector.

In this study, Hiba wood has been used as measurement sample. The reference direction is the direction in which the body grows toward the sky. This direction is defined as the fiber direction. In this study, the horizontal plane perpendicular to the direction of the fiber is selected, and the direction through the tree (bone marrow) on the plane is defined as the radial direction. And the direction perpendicular to them and tangential to the annual rings is defined as the wiring direction. They are identified as three main directions.

In the analytical model, the internal structure and components of the measurement sample are ignored and uniformly identified as unknown material analysis. However, the direction of wood grain and heat flux in the experiment will affect the accuracy of the results. Then, in the heat introduction method, according to placement position of the heating parts and cooling parts are divided into 6 types, as shown in Fig.10.




1 Heat exchanger (Heater)    2 Silicone panel   3 Test section
4 Heat exchanger (Cooler)    5 Constant temperature bath
6 Data logger    7 Heating or cooling device

**Fig.9** Schematic diagram of experimental apparatus.

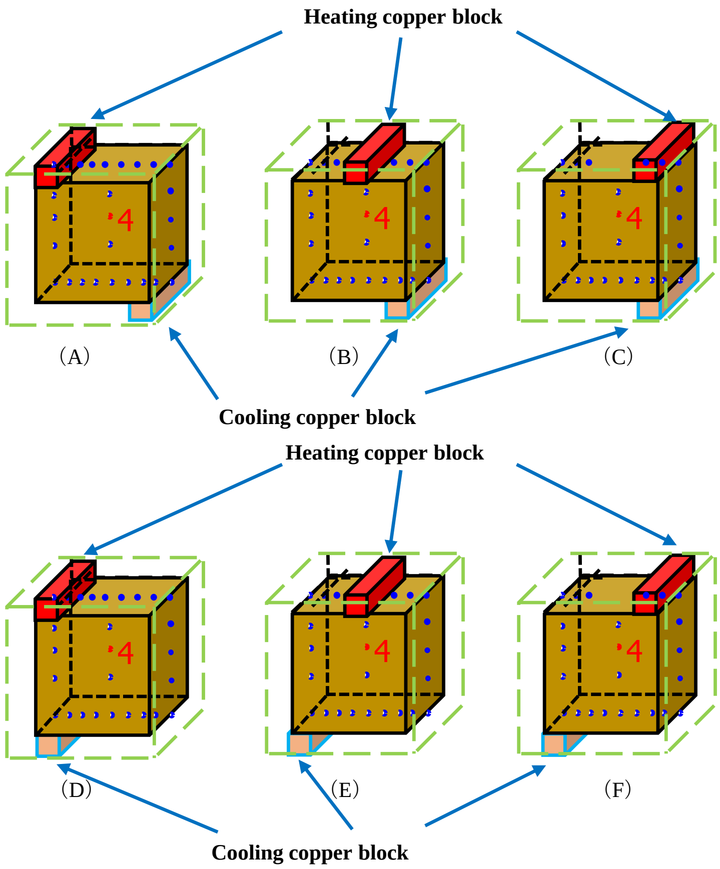



**Fig.10** Physical model and coordinate system

## III. RESULTS AND DISCUSSIONS

The results we will be discussed hereafter are all in two dimensions, In order to reduce the deviation of the accurate measurement sample of the result data, the test piece should not be replaced frequently. The thermal conductivity and thermal diffusivity of materials 1 and materials 2 were measured in the same experimental method under the condition that the material remained in the same position and only heating parts and cooling parts.

### 3.1 Thermal conductivity ratio and thermal diffusivity

The upper and lower boundary conditions in the analytical model are collected experimental data, and fed back to the analytical process. The state of the experiment is reproduced during the parsing process. The experimental data was selected for the time period correction method. The boundary condition data was collected at intervals and then calculated according to a high order function fitting equation into the analysis. Take the experimental model C for material 1 as an example, the temperature trend and data before steady state are recorded, Fig.11 and Fig.12 are data records of the surface temperature of the heating part at the upper end of the test piece and the cooling part at the lower end, respectively.

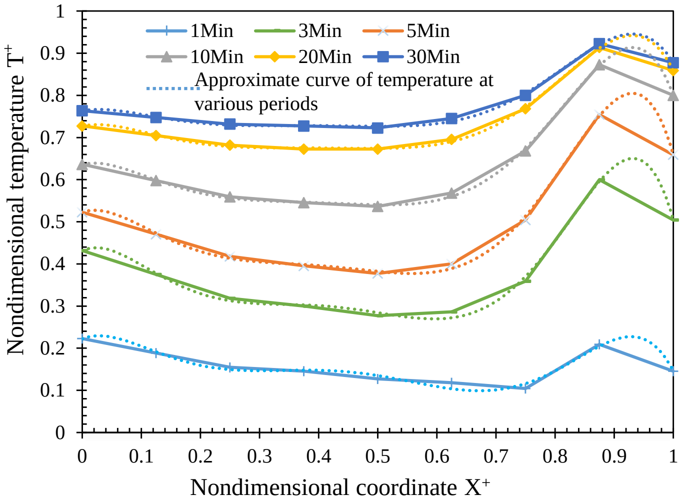



**Fig.11** Approximate curve for temperature distribution transformation at the upper boundary

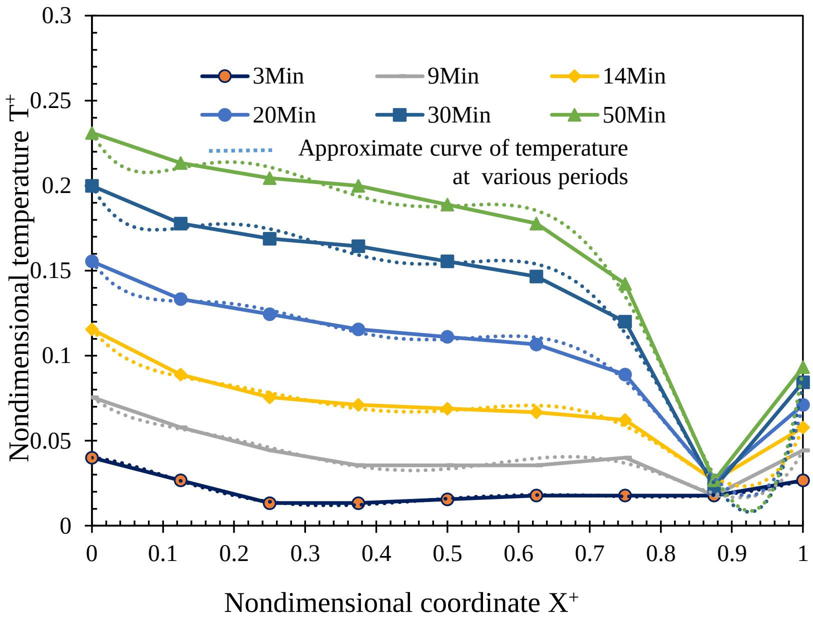



**Fig.12** Approximate curve for temperature distribution transformation at lower boundary

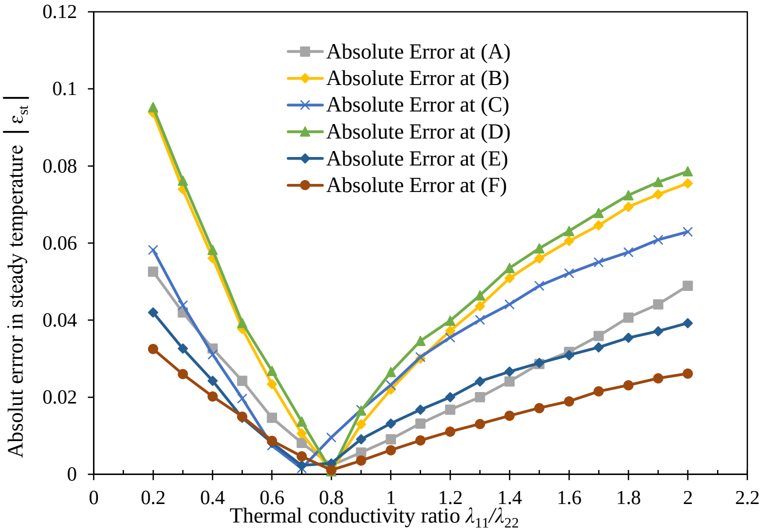



**Fig.13** Changing of│Ɛst│with thermal conductivity ratio on material 1

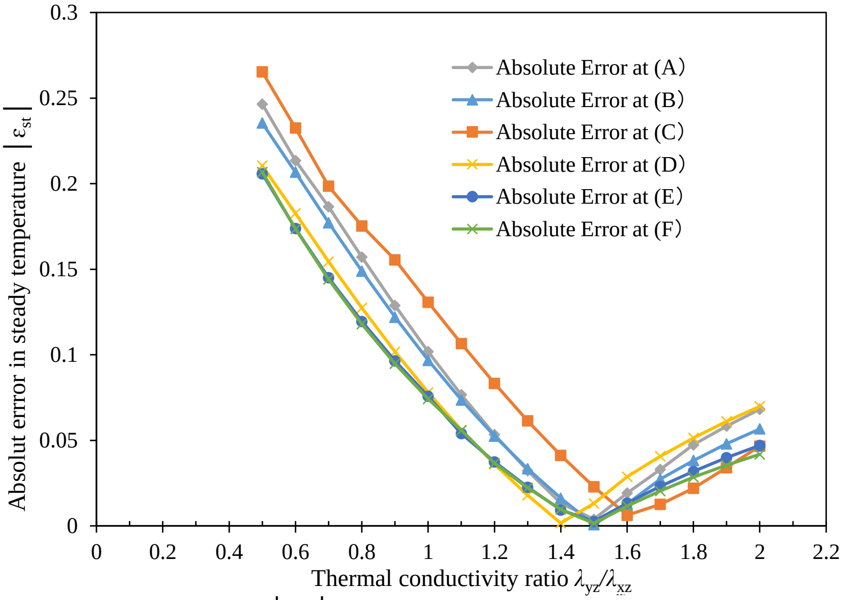



**Fig.14** Changing of│Ɛst│with thermal conductivity ratio on material 2

Fig.13 shows the relationship between thermal conductivity ratio and the error |Ɛst| of that easurement results and the calculated results of the six models under steady-state conditions, and determines the thermal conductivity ratio of the material 1. According to the Fig.13, the thermal conductivity ratio of the heating surface and the cooling surface on the same side the result of model C is around 0.7. The result of heating surface and cooling surface the diagonally distributed model A,B and E,F is closer to the area between 0.8. Considering that the heating cooling surface has a large amount of heat loss when the model C and model D is distributed on the same side, the thermal conductivity ratio of the material is finally determined according to the average value of the model A,B,E and F. Hence, We can determine the thermal conductivity ratio of the material 1 was 0.8. Fig.14 shows the relationship between thermal conductivity ratio and the error |Ɛst| of that easurement results and the calculated results of the six models under steady-state conditions, and determines the thermal conductivity ratio of the material 2. The thermal conductivity ratio of the heating surface and the cooling surface on the same side the result of model C is around 1.6, the result with this model D is at 1.4. The experimental results under the remaining model conditions all return to the minimum error at 1.5. We can determine the thermal conductivity ratio of the material 2 was 1.5.

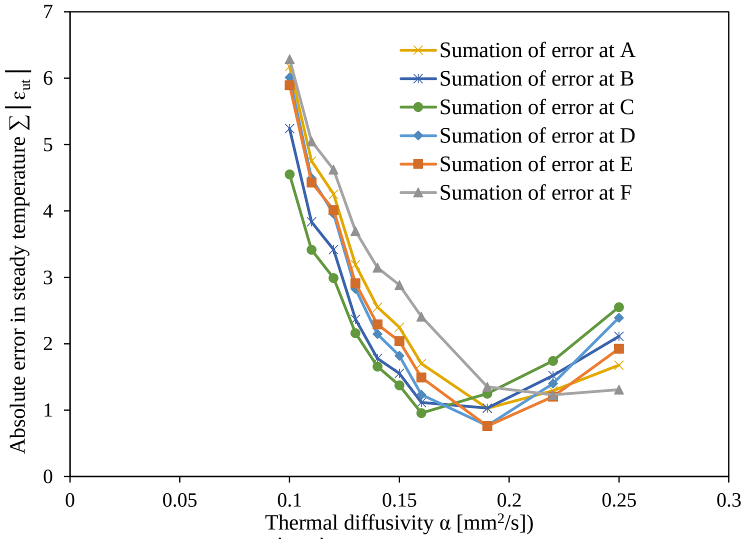



**Fig.15** Changing of $\sum|\mathcal{E}_{ut}|$ with thermal diffusivity on material 1

According to the convergence determination method of Eq.(9), the results of our set of experiments are processed as shown in Fig.15. It shows that the sumation Σ|Ɛut| of the difference between the calculation result and the experiment result at each time in the unsteady temperature region calculated by changing the thermal diffusivity. model A and B,D,E,F the value of Σ|Ɛut| is the smallest when the thermal diffusivity is 0.19mm$^2$/s. model C the thermal diffusivity is almost 0.15mm$^2$/s. According to the statistical results of Fig.15, combined with the method of Eq.(10), the measured thermal conductivity and thermal diffusion of any material in the x-y direction can be obtained.

### 3.2 Principal thermal conductivity and principal angle

According to the graph of mohr circle, the amount that can be accurately obtained through the experiment is the thermal conductivity in the two directions of the materials at x-axis and y-axis(Fig.7), which is $\lambda_{11}$ and $\lambda_{22}$ in the Fig.8.

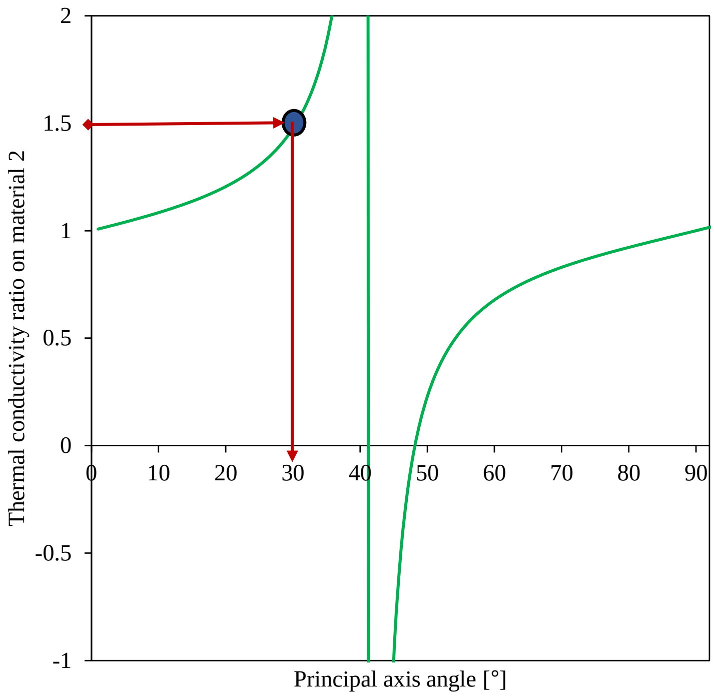



**Fig.16** The relationship between the Principal angle and the thermal conductivity ratio

Randomly select a sample(material 1) of an unknown wood grain angle for measurement. According to the thermal conductivity coefficient method described above with experimental measurement, It's not a difficult get the result of Fig.13(the thermal conductivity ratio is 0.8) so the thermal conductivity ratio is B in Eq.(31) can be determined as 0.8, and combined with the thermal diffusivity of Fig.15 and Eq.(10). The thermal conductivity of the material 1 can be obtained the thermal conductivity $\lambda_{22}$ is 0.16W/(mk) and $\lambda_{11}$ is 0.128W/(mk).

At this time, selecting a piece of wood(material 2) that is to rotate the 45° angle in the counter-clock-wise direction with the above test piece as the experimental material 1. According to the thermal conductivity coefficient method described above with experimental measurement, according to the result of Fig.14(the thermal conductivity ratio is 1.5). When the thermal conductivity ratio is $\lambda_{yz}/\lambda_{xz}$ in Eq.(31) be determined as 1.5(according to the result of Fig.14)， and combined with the thermal diffusivity of Fig.15 and Eq.(10), the thermal conductivity of the material 2 can be obtained the thermal conductivity coefficient $\lambda_{yz}$ is 0.172W/(mk) and $\lambda_{xz}$ is 0.115W/(mk),.

According to Eq.(31), a dependency relationship diagram between the principal axis angle and the thermal conductivity ratio can be drawn. The ordinate is the thermal conductivity ratio $\lambda_{yz}/\lambda_{xz}$ in Eq.(31) that has been measured and determined, so that the unknow principal axis angle corresponding (abscissa corresponding) to curve can also be determined. When the curve y-coordinate is determined to be 1.5(thermal conductivity ratio is $\lambda_{yz}/\lambda_{xz}$), the only x coordinate value is 30°(principal axis angle), and the line segmentation mark appears in Fig.16. Thus it was then determined that the direction of the dominant thermal conductivity axis of the initial measurement material was inclined at 30°(angle$\varphi$) to the material 1. Then, if the determined principal angle was arbitrarily substituted into Eq.(29) or Eq.(30), the maximum of thermal conductivity ratio on the principal direction can be obtained was 1.6. The wood grain on the study plane appears parallel. The foundation of principles that is angle between the wood grain arrangement and the x-axis direction is used as a basis for judging the differential classification of experimental samples. This experiment selected four types of wood grain with 30°, 45°, 75°and 90° angles. Analysis conditions are divided into seven categories of angle between wood grain and x-direction: 0°, 15°, 30°, 45°, 60°, 75°and 90°.

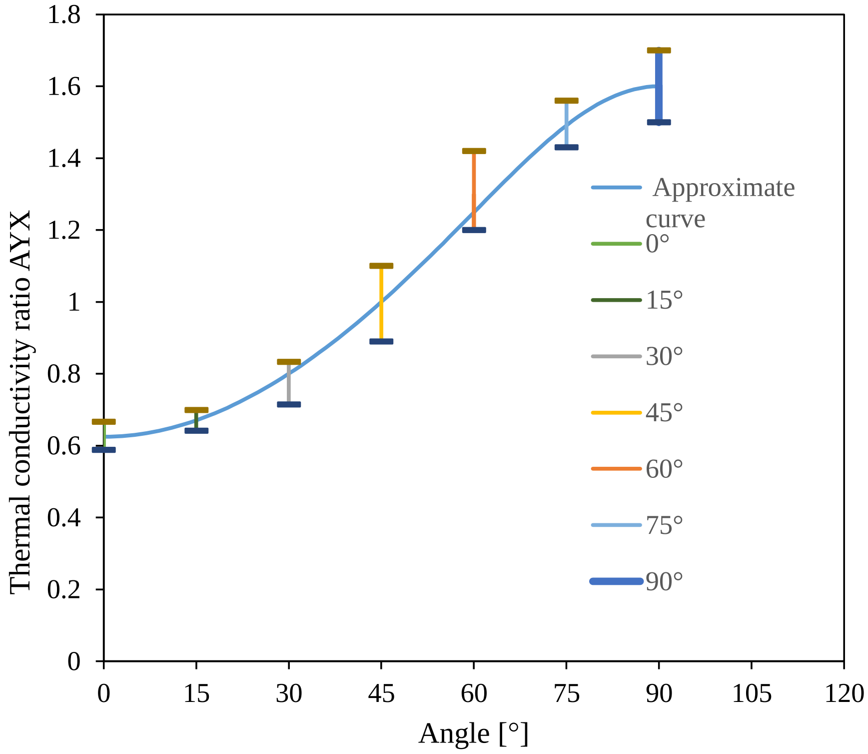



**Fig.17** Thermal conductivity ratio at different angles between the wood grain and x-direction

As shown in Fig.17, statistics show that the ratio of thermal conductivity of all materials at a known angle by experiment. As the angle increases, the thermal conductivity ratio also appears to grow in similar bands. The numerical results of each angle are counted, it is easy to obtain a suitable curve fitting into a parabolic line with AYX change reaction in the Fig.17. The approximate extremum obtained from the curve is the thermal conductivity ratio of maximum extremum 1.6 and minimum extremum 0.62. According to the data, it is known that the material has a thermal conductivity ratio of at maximum 1.67 and a minimum of 0.6. In order to verify the feasibility of the above-mentioned modeling method, all existing materials are measured and recorded for comparison. In Fig.17 it can be observed that the material with a thermal conductivity ratio of 0.8 that is determined to have an angle of maximum thermal conductivity of 30° from the horizontal x-axis, which verifies that the above calculation results are conform to reality.

We present the results for the fully analysed the principal angle to be determined for the original sample. In the coordinate systems (x,y) and ($x_z$,$y_z$), the special case that cannot be judged exists. Only when one of the selected materials has a thermal conductivity ratio equal to 1(with the same result of measurement on Fig.17), it indicates that the material is mistaken for the isotropic material to have no thermal conductivity major axis. So continue to add a new angle to the material measurement and re-measure.

## IV. SUMMARIES

In this paper, we have explored the multi-directional thermal coefficient and thermal diffusivity methods for measuring anisotropic materials. In particular, we seek out the maximum thermal conductivity and the direction of principal thermal conductivity when the internal structure is unknown. In addition, With a simple experimental method and analytical method, the thermal conductivity coefficient and temperature diffusion coefficient in the orthogonal direction are automatically obtained. Finally, the possibility of predicting confirmed that the direction of principal thermal conductivity and its value can be detected.

First, by comparing the analysis results with that of the experiment, we found that the qualitative features of the present numerical analysis were reasonable and thus the validity of the numerical analysis was confirmed. Second, we found that the randomness of the thermal diffusivity is strong and can only measure the approximate range and is easily affected by the experimental environment. Finally, according to the Mohr stress circle law combined with the experimental and analytical results, the basic information of the maximum thermal conductivity and the minimum thermal conductivity of an orthotropic material can be successfully analyzed.

As our further study, we can extend the three-dimensional structure analysis of anisotropic materials according to the existing methods. Further explore the influence of unknown materials on thermal diffusivity and accurate measurement methods.

## REFERENCES


[1]. M. Fujii, T. Tomimura, X. Zhang, and S. Park, "A Non-contact Measurement of Thermal Conductivity and Diffusivity of Solids(in Beijing)" Thermophysical Properties (International Academic, Beijing), pp.120-125, 1992.

[2]. M Fujii, S. Park, T. Tomimura,and X. Zhang, "A noncontact method for measuring thermal conductivity and thermal diffusivity of anisotropic materials, (in Japanese)" International Journal of Thermophysics, Vol. 18,No. 1, pp.251-267,1997.

[3]. 藤井丕夫,朴寿泉,富村寿夫,張興, "異方性物質の熱伝導率と熱拡散率の非接触同時測定" Netsu Bussei, Vol. 9, No. 4,pp.231-236,1995.

[4]. E Takegoshi, S Imura, T Takenaka, Y Hirasawa, "A Method of Measuring the Thermal Conductivity of Orthogonal Anisotropic Materials by the Transient Hot Wire Method , (in Japanese)" Transactions of the Japan Society of Mechanical Engineers, Vol.48,No.433, pp.1743-1750, 1982.

[5]. E Nemoto， K Kawashimo "Principal Thermal Conductivity and Rotating Angle Measurement of Two-Dimensional Anisotropic Heat Conductor Using an Unsteady Point Source of Heat (in Japanese)"Transactions of the Japan Society of Mechanical Engineers Part B , Vol.62,No.603, pp:3905-3911,1996

[6]. P.L.Woodfield., M.Monde,Y.Mitsutake, "Implementation of an analytical two-dimensional inverse heat conduction technique to practical problems", International Journal of Heat and Mass Transfer, Vol.49, No.1-2, pp. 187-197, 2006.

[7]. Beck, J.V., Cole, K.D, Haji-Sheikh, A. and Litkouhi, B., Heat Conduction Using Green's Functions, p.221, 1992.

[8]. Swift, D.L., "The thermal conductivity of spherical metal powders including the effect of an oxide coating", International International Journal of Heat and Mass Transfer ,Vol.9, No.10, pp. 1061-1074,1966

[9]. Kunii, D. and Smith, J.M., "Heat transfer characteristics of porous rocks", American Institute of Chemical Engineers, Vol.6, No.1, pp.71-78,1960.

[10]. Parry, Richard Hawley Grey. "Mohr circles, stress paths and geotechnics (2 ed.)". Taylor & Francis. pp. 1-30,2004.


Qing-Ming ZHANG. "Basic Study on Thermo physical Properties Measurement of Layered Anisotropic Materials" International Journal Of Engineering Research And Development , vol. 14, no. 09, 2018, pp 35-52