Rapid Measuring and Studying on The Thermophysical Properties of Anisotropic Material

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Abstract. This paper describes a rapid technique to measure the thermal conductivity of anisotropic material. It is a new analytical solution is developed for anisotropic materials. With experimental data as the boundary condition of the physical model is substituted into the calculation, The experimental data of the measured point temperature is automatically compared with the calculated result, and the thermal property value of the anisotropic material is determined when the minimum error is reached. We in order to ensure the feasibility of the method, three boundary conditions type(A),type(B) and type(C) were set using the same experimental conditions for comparison reference. The results prove that the method is effective and feasible.

1.Introduction
Recently, advances in science and technology, a great variety of materials have been used for industrial products. Among those, there are many anisotropic materials, which are widely used in mechanics, electronics, chemical industry and aerospace. It is well known that materials like wood, paper, clothes, laminated material, reinforced fibers composite material, woven fabric composite material, crystalline material, nano-film, nano-wire and nano-tube, often have strong direction-dependent properties, but their thermal property values are not well known[1,2]. However, In the design of the product, the thermal property value of the material is very important and greatly affects the product's function or safety. In order to understand the thermal conduction behavior of an anisotropic material, anisotropic thermal conductivity must be obtained. However, determining anisotropic thermal conductivity is a very difficult and rather lengthy process compared to the determination of isotropic thermal conductivity. For the isotropic material, the method of measuring the thermal conductivity is applied more frequently, such as the steady state method, the laser flash method[3]. Hot wire/strip method[4,5] and 3ω method[6], both measure the anisotropic thermal conductivity by changing the test direction of the sample. The transient plane source method could measure the in-plane thermal conductivity and through plane thermal conductivity of anisotropic materials through one single test once the volumetric heat capacity is known[7]. The transient plane source method can be applied to anisotropic materials in which the thermal properties along two
orthogonal axes and the principal axis are the same (in-plane thermal conductivity) but different from the thermal properties along the third axis (through planar thermal conductivity) with known volumetric heat capacity\[8-14\]. It is a very difficult problem to accurately control and determine the volumetric heat capacity in the experiment. The main difficulty is the inability to achieve absolute thermal insulation and determine the data of escape thermal.

In addition, in the conventional thermal diffusivity measurement method, which has been measured average value of the whole material is obtained. Therefore, when the thermophysical properties value varies depending on the direction as an anisotropic material, that is necessary to cut out specimens from various directions and perform individual measurements. However, in particular in the measurement of thermal diffusivity, skill is required, so that is a high possibility of including a measurement error for each measuring. Therefore, in order to reduce the measurement error, a method capable of multidirectional measurement at a time is required. Moreover, in the conventional analysis method, only thermal diffusivity in two orthogonal directions is taken into consideration. When analysing the thermal conductivity of an anisotropic material, it is necessary to take not only the two directions but also the thermal diffusivity in multiple directions.

The detailed theoretical analysis and effective measuring of the anisotropic thermal properties is the main focus of this study. We are studying a method to simultaneously measure orthogonal direction thermal diffusivity using this method. We first need to smoothing the surface of the experimental material, ensures that clearance and reduces errors when contact is made on the heat exchange surface. The effective boundary conditions for the surface temperature data acquisition of materials into analytical physical models. Then, the calculated temperature result is compared with the experimental result to adjust the parameter, and the measured thermal property value is determined until the error minimum value is determined.

2. Measurement principle

2.1 Experimental Apparatus and Method

Fig.1 shows a schematic diagram of the thermal conductivity measuring device. The apparatus consists of a main part, a heating part, a cooling part, and a constant temperature circulating water tank. Aluminum was used as a material for heating surface and cooling surface. The measuring part was sandwiched between a heating part and a cooling part. As the dimensions of the measuring part of the wood, a cube having the height of 32 mm, the length of 32 mm and the width of 32 mm was used as an experimental sample. In addition, the dimensions of the heat insulting material were 32 mm in height and 35 mm in wall thickness, and the material was polystyrene foam. Silicon rubber was 21 mm high, 100 mm long, 100 mm wide. The surroundings of the sample are covered with insulation to ensure that the majority of the heat flowed through the wood to the cooling section. Water of constant temperature was supplied from the thermostatic chamber to the heating part and the cooling part. The temperature difference between the heating/cooling section was set at about 20°C and operation was continued until the steady state was reached.
2.2 Physical models

A numerical analysis model and a coordinate system are shown in Fig. 2. As shown in the figure, an orthogonal coordinate system with an origin O is used. For analysis, only the region of $x,y,z>0$ was considered. In the calculation, the temperature condition is given as the upper side heating, the lower side cooling, the side surface gives as heat insulation. In this analysis, as a two-dimensional analysis, it is omitted for the $z$ direction and it is a two-dimensional analysis in the $x$-$y$ direction.

Sandwich the copper block between the heat exchanger and the sample. Three types of (A), (B) and (C) were set according to these heating conditions. In the $x$ direction where the heating block was dimensionless, ((A) 0 to 0.2, (B) 0.4 to 0.6, (C) 0.8 to 1.0) was arranged.

Fig. 3 shows the temporal change of the heating point and the temperature of the upper part of the sample during step heating. In the heating section, it becomes steady 30 minutes after the start of the experiment. When observing the temperature change of the cooling process, it becomes steady after 50 minutes from the start of the experiment at the cooling part on cooling step. Also, at the sample internal measurement point, it becomes steady in 50 to 60 minutes.
In considering various measurement errors in the experiment, estimation of the inflow and outflow of heat from the heat insulating material and the copper block in the experiment. In the unsteady state obtained from experiments, boundary conditions of step heating of the heating part and cooling part were input to the calculation program.

Nondimensionalized basic equations used in this analysis are shown below.

\[
\frac{\partial T^+}{\partial t^+} = \frac{\partial^2 T^+}{\partial x^2} + \frac{\lambda_y}{\lambda_x} \frac{\partial^2 T^+}{\partial y^2}
\]  

(1)

The thermal conductivity ratio is shown as follows.

\[
\frac{\lambda_y}{\lambda_x} = AYX
\]

(2)

The equation for dimensionless time \( t^+ \) and dimensionless temperature \( T^+ \) is again shown.

\[
t^+ = \frac{a_x t}{L^2}
\]

(3)

\[
T^+ = \frac{T - T_{\text{min}}}{T_{\text{max}} - T_{\text{min}}}
\]

(4)

In the analytical model, the experimental results were captured for the upper and lower sample boundary conditions, reproduced in the same way as the experiment, and calculated while automatically changing the calculation parameters. We tried to automatically obtain the thermal
conductivity ratio and the temperature conductivity by comparing the temperature of the representative point obtained numerically by experiment with the experiment result.

3. Results and Discussion
Fig. 4 shows the temperature flowchart of the observation point in the middle of the wood. As shown in the figure, the thermal diffusivity is obtained by using temperature error $\varepsilon_{ut}$ in the non-stationary region, and the thermal conductivity ratio is obtained by using temperature error $\varepsilon_{st}$ in the steady condition region. We attempted to automatically obtain thermal conductivity ratio and temperature conductivity by incorporating experimental results into calculation.

Fig. 4 Flow chart of calculation and experiment

Fig. 5 shows the absolute value $|\varepsilon_{st}|$ of the difference between the steady-state temperature of the calculation result and the experimental result when calculated by varying the thermal conductivity ratio. In type(A) and type(B), the steady temperature error is the minimum when the thermal conductivity ratio $AYX = 1.5 \sim 1.6$, but in type(C) it became the minimum when the thermal conductivity ratio $AYX = 1.4$.

Fig. 5 Changing of $|\varepsilon_{st}|$ with thermal conductivity ratio

Fig. 6 shows the sum $\Sigma |\varepsilon_{ut}|$ of the difference between the calculation result and the experiment result at each time in the non-stationary region calculated by changing the temperature conductivity.

As can be seen from the figure, in type (A), type (B), the value of $\Sigma |\varepsilon_{ut}|$ is the minimum when the temperature conductivity is 0.08mm$^2$/s. type (C), the temperature conductivity is almost 0.08 mm$^2$/s.
Fig. 6 Changing of $\sum |\varepsilon_{ut}|$ with thermal diffusivity

Fig. 7 Comparison between experimental result and numerical result

With the above method, Fig. 7 shows the comparison of experimental results and calculated results with a thermal conductivity of 1.56 and a temperature conductivity of $a = 0.08 \text{ mm}^2/\text{s}$. From the figure, it was found that steady state temperature or unsteady temperature change in experiment and calculation coincided well qualitatively.

4. Conclusions

Thermophysical properties of anisotropic materials were measured and analyzed using an unsteady method while changing the heating and cooling positions. The method for measuring the thermal conductivity ratio and thermal diffusivity proposed for single direction is extends to the plane relationship of two orthogonal directions on anisotropic materials. The major conclusions are as follows:

① From the numerical simulations using the estimated thermophysical properties and comparisons with the measured temperatures, the validity of the present measurement method is confirmed.

② The results obtained by using the method improved by automatically calculating the thermal conductivity ratio and the temperature conductivity by incorporating the experimental results into the calculation and comparing it with the analysis agree well with the experimental results.

③ From the error estimation for the error control in a certain range, the method is found to be applicable at least for thermal conductivity measurements of anisotropic materials.

References

[1] C. Gobbe, S. Iserna, B. Ladevie, Int. J. Therm. Sci. 43 (2004).
[2] T. Ohmura, M. Tsuboi, T. Tomimura, Int. J. Thermophys. 23 (2002).
[3] W.-Z. Fang, L. Chen, J.-J. Gou, W.-Q. Tao, Int. J. Heat Mass Transf. 92 (2016).
[4] J.-J. Gou, H. Zhang, Y.-J. Dai, S. Li, W.-Q. Tao, Compos. Struct. 125 (2015).
[5] G. Kalaprasad, P. Pradeep, G. Mathew, C. Pavithran, S. Thomas, Compos. Sci. Technol. 60 (2000).
[6] M.G. Miller, J.M. Keith, J.A. King, B.J. Edwards, N. Klinkenberg, Polym. Compos. 27 (2006).
[7] H. Zhang et al. International Journal of Heat and Mass Transfer 108 (2017)
[8] M.G. Miller, J.M. Keith, J.A. King, B.J. Edwards, N. Klinkenberg, D.A. Schiraldi, Polym. Compos. 27 (2006).
[9] A. Berge, B. Adl-Zarrabi, E. Hagentoft Carl, Frontiers Architect. Res. 2 (2013).
[10] Suleiman, M. Ul-HAQ, Karawacki, Maqsood, A. and Gustafsson S.E, Physical Review B, 48 (1993)
[11] J. Sulistyo, T. Hata, M. Fujisawa, K. Hashimoto, Y. Imamura, T. Kawasaki, J. Mater. Sci. 44 (2009).
[12] Y. Jannot, A. Degiovanni, V. Felix, H. Bal, Meas. Sci. Technol. 22 (2011).
[13] T. Tian, K.D. Cole, Int. J. Heat Mass Transf. 55 (2012).
[14] M.Gustavsson, H. Nagai, T. Okutani, Solid State Phenom. 124 (2007).