Basic Study on Reduction of Measurement Time for Evaluating Thermophysical Properties of Thermal Interface Materials by Steady Temperature Prediction Method

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Abstract
This paper describes an improvement of a measurement method of thermal conductivity in order to shorten the measurement time. A novel thermal interface material (TIM) which has both high electrical insulation performance and high thermal conductivity is strongly demanded. Especially, the novel TIM is strongly needed to achieve the electrical insulation between inverters and water cooling jacket in EVs (Electric Vehicles) and HEVs (Hybrid Electric Vehicles). In order to shorten the development period of the TIMs that has to do many times of the experiment to optimize the composition of the TIMs, an improvement of an evaluation method of the thermal conduction performance of the TIMs should be prepared. However, steady state measurement methods of thermal conductivity generally take very long time. Therefore, we have been focusing on an improvement of measurement method of thermal conductivity in order to achieve the reduction of the measurement time. In this paper, we developed the fast thermal conductivity measurement method by predicting steady temperature from transient temperature history in equipment. Through the investigation, it is found that steady temperature rise in the steady state thermal conductivity measurement can be predicted by using the transient temperature history of the steady state measurement. Information about the optimum time period of the measurement time of the transient temperature response to predict the correct steady state temperature can be obtained.

Keywords: Electric Vehicles, Minimum Measurement Time, Prediction of Steady State Temperature, Thermal Conductivity, Thermal Interface Material

1. Introduction
In recent years, for energy saving and fewer emissions of greenhouse gases, a great demand for electric vehicles or hybrid electric vehicles is continuously increasing. Power devices such as IGBT (Insulated Gate Bipolar Transistor) are widely used for controlling an operation of these vehicles. In an operation of these inverters, the inverters generally generate a large amount of waste heat. Figure 1 shows a schematic of a cooling unit for dissipating heat from the inverters. Generally the cooling unit is composed of a water cooling jacket that includes heat sink for enhancing heat transfer, a ceramic sheet which insulate electricity and a silver solder which decreases contact thermal resistance. However, the complex laminated structure causes an increase in total thermal resistance including thermal contact resistance. In order to decrease the total thermal resistance, a novel insulation heat dissipation sheet, that is one of a thermal interface material (TIM) made by a silicone rubber, was developed. [1] The novel sheet can bond each surface chemically hence the contact
thermal resistance can become almost zero. In addition, the novel sheet has both higher thermal conductivity and good electrical insulation performance. By using the novel insulation sheet instead of the combination of the ceramic sheet and the silver solder, the structure of the cooling unit can become simple and total thermal resistance can be reduced.

However, these physical properties tend to have a trade-off relationship.[2] Hence, in order to optimize the composition of the insulation sheet for achieving both high thermal conductivity and high electrical insulation, many times of the experiments have to be done. To shorten a development period of the novel insulation sheet, an improvement of an evaluation method of the thermal conduction performance of the insulation sheet should be prepared. Many researchers have proposed thermal conductivity measurement of various types of materials.[3–8] One of the most popular thermal conductivity measurement method is a 1-dimensional steady state measurement.[9–11] However, the steady state measurement generally needs very long time to achieve steady state. In order to shorten the measurement time, an evaluation method of thermal conductivity by using transient temperature history have been developed. Hot Disk method is one of the transient thermal conductivity measurement method.[12] However, Hot Disk method cannot evaluate a level of contact thermal resistance. In addition, the measurement time is dependent on a level of thermal conductivity of a test material. Moreover, the measurement system is strongly different from 1-dimensional measurement systems and is strongly complex. If a fast measurement method of thermal conductivity can be developed based on the popular 1-dimensional measurement systems (such as JIS[13]), it will be useful. Ogushi has proposed a quasi-steady state thermal conductivity measurement by using transient temperature data at each measurement time step. The method can reduce the measurement time of thermal conductivity. However, the temperature data is different from temperature at steady state. The prediction accuracy of thermal conductivity by this method may be dependent on the quoted time step. Here, if the steady state temperature can be predicted by using transient temperature response, we can calculate thermal conductivity by using the same temperature as the steady state temperature. This may achieve both fast measurement time and high reliability of the measurement.

From these backgrounds, in order to develop a fast measurement method of thermal conductivity and a level of contact thermal resistance of the TIMs, we tried to develop an optimum thermal conductivity measurement method based on the 1-dimensional steady state measurement system using a predicted steady state temperature data. We tried to predict the steady state temperature of the test material by using transient temperature response from the start of the heating. By using the predicted steady state temperature, thermal conductivity can be calculated by using the same method as the steady state 1-dimensional thermal conductivity measurement (Hereafter we will call the proposed method “Steady temperature prediction method”). An experimental apparatus based on 1-dimensional thermal conductivity measurement system was constructed in a vacuum chamber to prevent heat leak by convective heat transfer. Through the measurement of the test material, the availability of the proposed method was investigated by comparing the prediction results with the steady state result of 3D thermal analysis and the experiment.

2. Experimental Method
2.1 Theory of steady temperature prediction method

Figure 2 shows a schematic of measurement system and the temperature distribution of the system in the steady state condition. Thermal conductivity of a test sheet is derived from the difference of steady temperature between the hotter surface and colder surface of the test sheet.

A prediction method of the steady state temperature by using transient temperature history should be prepared. Generally, a transient temperature rise of simple system can be represented as the following formula.[15]

\[ T_p(t) = RQ \times \left[ 1 - \exp\left(\frac{-t}{\tau}\right) \right] + T_0 \quad \text{[°C]} \quad (1) \]

where \( T_p(t) \) [°C] is the transient temperature rise, \( T_0 \) [°C]

![Fig. 2 Temperature distribution in the proposed measurement system.](image-url)
is the initial temperature, \( \tau \) [s] is time constant, \( R \) [K/W] is thermal resistance and \( Q \) [W] is heat flow. Generally, a relationship between transient temperature and time can be observed as shown in Fig. 3. However, due to the experimental error in the actual equipment such as heat leak from the surface of the test section, the actual transient temperature history is changed from Eq. (1). In addition, Eq. (1) needs \( R \), \( Q \) and \( \tau \) values in order to calculate transient temperature. However, we cannot obtain these values of a test material before the measurement. Moreover, the steady state temperature should be predicted in order to calculate thermal conductivity. However, from Eq. (1), the steady state temperature itself cannot be calculated directly. Therefore, in this paper, we tried to represent the relationship between the transient temperature of a test material and the steady temperature by using the relationship between the tendency of the transient temperature curve, the steady state temperature and the initial temperature. We used the following formula.

\[
T(t) = T_r + (T_{pr} - T_r) \cdot e^{\omega \cdot t}\] (2)

\( \Delta T_r \) is the temperature difference between the initial temperature and the steady temperature. Here, \( \omega \) is a coefficient that defines the rate of the initial temperature rise and \( \sigma(t) \) is a fitting function that is based on the transient temperature history. In Eq. (2), there are 3 unknowns that are \( \Delta T_r \), \( \omega \) and \( \sigma(t) \). However, if \( \omega \) and \( \sigma(t) \) can be predicted by the transient temperature history as shown in Fig. 5, we can predict the whole temperature history curve and obtain \( \Delta T_r \). Therefore, in this study, we tried to calculate \( \omega \) and \( \sigma(t) \) by repeating calculations using transient temperature datum and predict \( \Delta T_r \) by using calculated \( \omega \) and \( \sigma(t) \). \( \omega \) and \( \sigma(t) \) were calculated from the transient temperature datum by using nonlinear least-squares Marquardt-Levenberg algorithm.[16] Figure 3 shows an example of the transient temperature history of the experimental data and the prediction result by using the above algorithm. Eq. (3) is an example of the prediction formula of the transient temperature history by using Eq. (2).

\[
T(t) = 66.8 \times \left[ 1 - \exp \left( -\frac{t}{777.6} \right) \right] + 9.3 \] [°C] (3)

We can see that the prediction data by using Eq. (3) is good agreement with the experimental data.

Figure 4 shows the comparison of Eq. (1) and Eq. (2). In this case, each coefficient of Eq. (1) is as follows. \( Q \) is 10 W, \( R \) is 10 K/W, \( \tau \) is 194 s, \( T_0 \) is 10°C. Eq. (4) is the prediction result which is based on 500 datum of Eq. (1). We can see that the prediction result is good agreement with the Eq. (1).

\[
T(t) = 100 \times \left[ 1 - \exp \left( -\frac{t}{194} \right) \right] + 10 \] [°C] (4)

2.2 Evaluation time period

An evaluation time period for prediction is defined as a time range from 0 to an arbitrary point until the steady state time. Reducing the time period means that the measurement time is reduced. On the other hand, accuracy is tending to be deteriorated. It is important to reduce the time period while keeping the accuracy. In this paper, the
relationship between predicted thermal conductivity and the time period condition was also investigated. Figure 6 shows a flow chart of searching the minimum time period which needs to predict the temperature rise. Firstly, we reduced the time period every 10 seconds. Secondly, we calculated thermal conductivity in every condition. Finally, the relationship between the time period and the prediction error of thermal conductivity was evaluated and the minimum time period was obtained. Here, we defined that the minimum time period was the necessary time period which the prediction error of thermal conductivity by Steady temperature prediction method from that of steady state measurement was less than 2%. When we evaluate the proposed method by analysis, the predicted thermal conductivity by Steady temperature prediction method was compared with the predicted thermal conductivity using the steady state temperature by analysis. However, as for the experiment, the predicted thermal conductivity by Steady temperature prediction method was compared with the predicted thermal conductivity using the steady state temperature by experiment.

2.3 Thermal conductivity

Thermal conductivity is calculated by

\[ \lambda = \frac{Q}{2} \times \frac{d}{\Delta T \times A} \]  \[ \text{[W/(m/K)]} \] 

where \( \lambda \) [W/(m/K)] is thermal conductivity of the test sheet, \( Q \) [W] is supplied heat from the heater, \( d \) [m] is thickness of the test sheet, \( \Delta T \) [°C] is difference of the temperature between the hot surface and cold surface of the test sheet, \( A \) [m²] is the cross sectional area of the contact surface. The reason for using \( Q/2 \) is that the supply heat from the heater is evenly distributed because the test section is constructed symmetrically with respect to the heater. The thermal conductivity is average of calculation results which is obtained by both side test sheets of the test section.

3. Evaluation of Reliability of Proposed Method through Computational Analysis

3.1 Analytical model and method

Firstly, we will evaluate a possibility of proposed Steady temperature prediction method by using transient 3-dimensional thermal conduction analysis. FloTHERM ver. 10.1, which is a commercial CFD solver made by Mentor Graphics Corp. was used as an analysis solver. Figure 6 is an analytical model of the measurement system based on JIS A 1412-2. The analytical domain fits the outer edges of the measurement system in order to represent a thermal insulation. The measurement system model is constituted of the metal blocks, the test sheets, the cooling blocks and the heater. The cross sectional area of each component is 50 × 50 mm². The heater is set at the center of the system and the cooling blocks are set at the top and the bottom of the system. The test silicone sheet is sandwiched between two metal blocks and this unit is sandwiched between the heater and each cooling block. This produces a symmetric structure of the measurement system. Then the heat flows from the heater to each cooling block through each test silicone sheet. This allows 1-dimensional thermal conductivity measurement. As the test material, the silicone sheet which has thermal conductivity of 0.27 W/(m/K) was used. Here, the thermal conductivity was measured by Hot Disk method.[12] The thickness of the silicone sheet was 5 mm. The metal blocks were used for holding the silicone sheets. However these may cause additional thermal conduction resistance and decrease the measurement accuracy. Therefore, the effect of the thickness of the metal blocks on the measurement was also evaluated. In this paper, the thickness of the metal blocks \( h \) was changed between 5 mm and 15 mm. In this analysis, thermal contact resistance at each contact surface was neglected because we aimed to evaluate the influence of the construction of the experimental setup on the measurement time. Physical properties of each block used in the analysis are shown in Table 1.[17] Heat dissipation from the heater was 20 W and temperature of the cooling block was set at 10°C. A period of analysis time was 10,000 seconds in order to calculate transient temperature response of the system until the steady state. The monitoring points of temperature are also shown in Fig. 7. The points were set at the center of the metal blocks, the cen-
ter of the silicone sheets and the contact surfaces between each part.

3.2 Analytical results

Figure 8 shows the relationship between thermal conductivity of the silicone sheet by the Hot Disk method, the thermal conductivity from the steady state temperature of the analytical result and the thermal conductivity by using Steady temperature prediction method using the analytical result. Figure 8 shows the relationship between the minimum time period and the thickness of the metal blocks. To begin with, we confirmed that the thermal conductivity from the steady state temperature of the analytical result was good agreement with that of the Hot Disk method. Therefore, we confirmed the reliability of the proposed analysis. Then we can see that the predicted thermal conductivity by Steady temperature prediction method was also good agreement with that of the Hot Disk method. From these results, we can conclude that the proposed steady temperature prediction method is available for predicting thermal conductivity using transient temperature data. Here, from Fig. 9, the minimum time period was dependent on $h_b$. In the case of $h_b = 5 \text{ mm}$, thermal conductivity can be predicted only in 170 seconds. This result shows that the measurement time is reduced about 98.4% time compare with steady state measurement. Here, when $h_b$ becomes larger, the minimum time period becomes longer dependent on $h_b$. This was caused by the influence of heat capacity. When $h_b$ becomes higher, the heat capacity of the metal blocks becomes larger and temperature response delays. From these analytical results, we can conclude that Steady temperature prediction method can shorten the measurement time of thermal conductivity. However, level of shortening the measurement time is dependent on the heat capacity of the measurement system.

Here, we will confirm the transient temperature change predicted by Steady temperature prediction method. Figure 10 shows the transient response of the temperature difference between the top and the bottom surface of the silicone sheet predicted by Steady temperature prediction method and the steady analysis.

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**Table 1 Physical properties of materials.**

| Material     | Thermal conductivity [W/(m×K)] | Density [kg/m³] | Specific heat [J/(kg×K)] |
|--------------|--------------------------------|-----------------|--------------------------|
| SUS 304      | 14.2                           | 7,920           | 511                      |
| Silicone sheet | 0.27                          | 1,400           | 1,600                    |

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**Fig. 7 Analytical model.**

**Fig. 8** Comparison of thermal conductivities by analysis, prediction result based on analysis and reference value.

**Fig. 9** Relationship between $h_b$ and minimum measurement time in analysis.

**Fig. 10** The transient response of the temperature difference between the top and the bottom surface of the silicone sheet predicted by Steady temperature prediction method and the steady analysis.
dicted transient temperature history by Steady temperature prediction method is good agreement with the steady state analysis. Hence, we can say that Steady temperature prediction method can predict transient temperature history correctly and this achieves the accurate prediction of thermal conductivity.

4. Evaluation of Proposed Method by Experiment

4.1 Experimental apparatus

Secondly, we will try to apply Steady temperature prediction method to the actual experiment. Figure 11 is the schematic of the experimental apparatus of the thermal conductivity measurement, and Fig. 12 is the test section. The experimental apparatus consists of the vacuum chamber, the test section, the vacuum pump and the thermostat chamber.

The structure of the test section is the same as the analytical model. Here, the cooling block is made of copper. The thickness of the cooling block is 20 mm in order to make the duct for the cooling water. The temperature of the cooling water is kept 10°C by the thermostat chamber. The temperature is measured at the plotted point as shown in Fig. 12. T-Type thermocouples that have the wire diameter of 0.2 mm were used. A small amount of silicone grease is put on each contact surface and the test section is loaded 980 N for reducing the contact resistance. The heater is made from a stainless sheet that has the thickness of 50 µm and dissipates heat. Figure 12 shows the schematic of the stainless heater. The heater can dissipate the heat because of the electric resistivity of stainless. The heater causes symmetrical and uniform heat flux because of the structure. The heat dissipation from the heater dropped when the heater temperature increased since the stainless sheet had a temperature dependence of electric resistivity.[18] Considering these influences, we carried out the calibration test and obtained Eq. (6).

$$y = -0.016x + 20.374 \quad [W] \quad (6)$$

Here, $y$ [W] is a value of heat dissipation and $x$ [°C] is the temperature of heater surface. By using this formula, we predicted the accurate heat dissipation from heater temperature and calculated thermal conductivity. The calibration test in which we measured the voltage and current at varied temperature was carried out between 15°C and 100°C with a step of 5°C.

4.2 Result and discussion

Figure 14 shows the relationship between thermal con-
ductivity of the silicone sheet by the Hot Disk method, the thermal conductivity from the steady state temperature of the experimental result and the thermal conductivity by using Steady temperature prediction method using the experimental result. The predicted thermal conductivity by Steady temperature prediction method shows good agreement with the results by the steady state measurement. We can predict the steady temperature by using Steady temperature prediction method although the heat dissipation drops 5% from initial condition. It is considered that the dropping heat dissipation does not influence to the prediction because that the prediction of Steady temperature prediction method is based on mathematical process for the transient temperature history. Here, the measurement results have 10 to 20% of the error from the result of the Hot Disk method. The error slightly increased with an increase in \(h_b\). The reason of the error can be explained as follows. When calculating the thermal conductivity of the test sheet, it was considered that the thickness of the test sheet was 5 mm because it was difficult to measure the actual thickness of the test sheet in the test section. According to an estimation based on Hooke’s law, the thickness of the test sheet decreases to 4.5 mm. Here, the value of Young’s modules of the silicone is 40.3 MPa. When we calculate thermal conductivity, using the revised thickness that includes the deformation of the test sheet, the prediction error can be decreased as shown in Fig.15. It is clear that the gap of the thermal conductivity of the experimental values against the Hot Disk value decreases. And when \(h_b\) increases, the error becomes bigger. The weight of the metal blocks is 100 g, 200 g, 300 g when \(h_b\) is 5 mm, 10 mm, 15 mm, respectively. It is considered that the increase of the error is caused by the increase of weight of the metal blocks. The thickness of the silicone sheets is influenced by the weight of the metal blocks and the cooling block. This suggests the possibility of accuracy improvement by direct measurement of the thickness of test sheets on test section.

Figure 16 shows the comparison of the minimum time period between the experiment and the analysis. The minimum time period of the experiment also decreased from the steady state measurement. Therefore, we can see that Steady temperature prediction method is usable for actual measurement systems of 1-dimensional thermal conductivity to reduce the measurement time. Here, the level of the minimum time period of the experiment becomes longer than that of the analysis. This is caused by the difference of the insulation performance between the experiment and the analysis. In the experiment, the ideal insulation condition cannot be achieved.

Figure 17 shows the comparison of the transient temperature difference between the top and the bottom of the silicone sheets. The symbols are the prediction results by Steady temperature prediction method, and the lines are the experimental results of the steady state measurement. We can confirm that the predicted transient temperature by Steady temperature prediction method has enough accuracy in order to calculate thermal conductivity of the silicone sheet.
5. Conclusion

In this paper, we tried to develop the rapid measurement method of thermal conductivity of TIMs based on the 1-dimensional steady state measurement system by Steady temperature prediction method. Especially, we tried to predict the steady state temperature of the test material by using transient temperature response of the test material and calculate thermal conductivity of the test material by using the predicted steady state temperature. The availability of the proposed Steady temperature prediction method was evaluated by comparing the prediction results of the steady state investigations by the 3-dimensional thermal analysis and the experiment.

Through the research, it is found that Steady temperature prediction method can achieve an accurate evaluation of thermal conductivity of the silicone sheet while shortening the measurement time. By using the proposed relationship between the transient temperature response and the steady state temperature, we can predict the steady state temperature by using the transient temperature history from the short-time experiment. However, the necessary time of the transient temperature measurement is dependent on the thickness of the metal blocks.

In our future research, an evaluation of contact thermal resistance at each contact surface should be done in order to improve the prediction accuracy of Steady temperature prediction method. In addition, an optimum structure of the experimental apparatus that can reduce the prediction error of thermal conductivity by Steady temperature prediction method will be investigated.

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References

[1] T. Ohbu, N. Tada, and K. Hagiwara, “IGBT module for HEV Inverters achieving low loss and high reliability by improvement of heat dissipation,” TOSHIBA review, Vol. 69, No. 4, pp. 37–40, 2014.

[2] Y. Takezawa, “High Thermal Conductive Epoxy Resin Components with Controlled Higher Order Structures,” Hitachi Chemical Thermal Report, No. 53, pp. 5–10, 2009.

[3] T. Hirata, S. Yanamura, S. Watanabe, and T. Ogushi, “Develop of Measuring Method for Thermal Conductivity of Isotropic Conductive -Steady State Com-
32nd International Conference on Digital Printing Technologies; NIP32, Paper No. 112–115, 2016.

[12] K. Konishi, K. Hirose, and T. Fukue, “Measurement of Thermophysical Properties of Several Seafood for Development of Rapid Prediction Method of Freezing Process (in Japanese),” Proceedings of the 51st JSME Tohoku Brunch Annual Conference, Paper No. 114, 2016.

[13] JIS A 1412 – 2, Test method for thermal resistance and related properties of thermal insulations, 1999.

[14] T. Ogushi, “Study of Quasi-Steady State Comparative Longitudinal Heat Flow Method for Thermal Conductive Measurement Using Cartridge Type Specimen (in Japanese),” Thermophysical properties 34, The 34th Japan Symposium 2013, pp. 319–321, 2013.

[15] N. Kunimine and A. Nakamura, “Thermal design and numerical simulation (in Japanese),” Ohmsha, 2016.

[16] J. Racine, “gnuplot 4.0: a portable interactive plotting utility,” Journal of Applied Econometrics, Vol. 21, Issue 1, pp. 133–141, 2006.

[17] The Japan Society of Thermal Properties, “Thermal Properties Handbook (in Japanese),” Yokendo, p. 35, 2008.

[18] G. T. Meaden, “Electrical Resistance of Metals,” Springer, International Cryogenics Monograph Series, 2014.

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