Heat Transfer Analysis for Vehicle Electronic Parts

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ABSTRACT This paper focuses on Junction Blocks (JBs) composed of circuit boards. Fuses and relays are built into a JB with high density. They are connected to electrical circuits which are also built into the JB. Circuits can be constructed of bus bars, wires, or circuit boards. In some cases using a bus bar is superior, while other cases circuit board is superior. The choice depends on the specification of each car. Vehicle electronic systems are getting larger in scale every year. This is increasing the importance of thermal management and thermal countermeasures applying heat transfer. One of the most important requirements for a computer simulation of a JB is the compatibility of easy modeling and accuracy [1), 2)]. This paper is intended to provide that compatibility. A new approach to modeling and transformation software for CAD files has been developed successfully. The error level of the simulation is approximately ±5 % in this case.

1. INTRODUCTION

Progress in the vehicle electronics field has been remarkable. The number of circuits increased by four times and the length of harnesses increased three times from 1980 to 1990. As a result, the heat generated from the connected loads, the junction parts and the circuits has increased dramatically. If the heat generated increases simply four times, four times the surface area is needed to release it. Actually, the surface heat transfer coefficient depends on shape and size. However, the former assumption is true as an approximation. Thus, a four times larger area is required, which is equivalent to eight times greater volume with similar figures. In practical applications, heat generated has been successfully reduced. Therefore, the heat to be released is not actually four times. The future expansion of vehicle electronics systems means countermeasures for heat transfer issue will remain important. In particular, JBs with relays and fuses which are generators of heat, cannot release the heat easily into the ambient atmosphere. The components (relays and fuses) are packed into a compact box, and design consideration to heat transfer is especially important. The appearance of a JB with a comparatively large circuit scale is shown in Figure 1. Historically, since the margin was large and the heat generated was small, the design could initially be on the safe side. In such a situation, the design does not need to be based on a precise heat analysis. On the other hand, an analytical approach has become indispensable in recent years. Moreover, since it is necessary to respond quickly to a minor design change during the development period, it is required that satisfactory accuracy should be reconciled with simplicity and practicality of operation.

In this paper we report the results of a heat analysis technology developed based on these factors. An analytical approach using a computer was adopted for the circuit board type JB. However, efforts are made to develop an analytical tool that is as flexible as possible and is not limited to a specific structure. The trade-off to develop a simple tool was understood in the process. Finally, a moderately general-purpose and specialized pre-processor is adopted. Specifically, limitations of form are applied. For example, if software can respond easily to changes in the arrangement of parts or the number of boards, even if it is applied to an object composed of two or more circuit boards with several parts, the software is still useful in practice. If further software development is performed, a very flexible software module group can be built in the future.

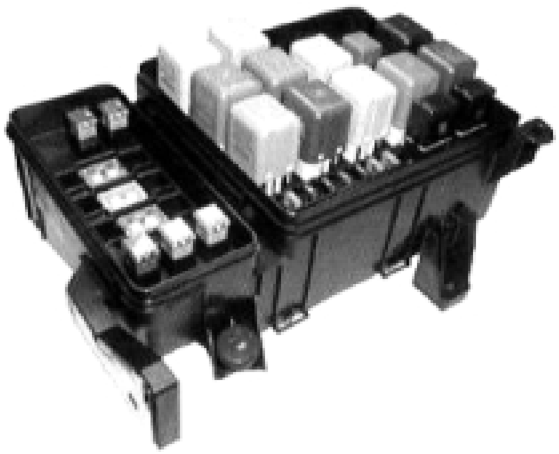

Figure 1 Appearance of a junction block.

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2. CIRCUIT BOARD-BASED JB DESIGN WITH HEAT TRANSFER ANALYSIS

The thermal design of a typical JB is based on following conditions.

- Relation between total heat generated and heat-releasing ability of a JB.
- Local temperature rise induced by Joule effect in circuit leads.
- Local temperature rise induced by heat generated from components.

The following are descriptions of a circuit board-based JB.

(1) Relation between Total Heat Generation and Releasing Ability

Let $\dot{Q}$[W] be the estimated value of total heat generation, α[W/m²K] be mean heat conductance, A[m²] be effective surface area, and ΔT[K] be mean value of temperature rise. Then we get

$$\dot{Q}=\alpha A \Delta T$$

That is

$$\Delta T=\dot{Q}/\alpha A$$

ΔT should be smaller than design value of the temperature rise. Otherwise you should modify the original design.

(2) Local Temperature Rise Induced by Joule Effect in the Circuit Lead

Figure 2 shows the permitted current for the cross-section of a conductor in circuit leads. The essential design policy is to know the temperature rise under a balanced state. The thermal calculation approach is almost the same for circuit boards and electric wires. However, a board itself can release heat as a heat sink. A thicker Cu foil is more effective for releasing heat. The effect also depends on the gaps between circuit leads. These factors should be considered when deciding the optimum thickness of Cu foil. However, in an actual design, ease of supplying material etc. is required to be considered when determining Cu foil thickness.

(3) Local Temperature Rise Induced by Heat Generated from Components

Mounting components usually have a complicated internal structure. Therefore, too much time and effort is need for exact modeling. Moreover, it is troublesome that not only heat generated but also heat resistance depends on connection method. Typical connection methods are plug-socket, soldering, and welding. The following section explains this in a little detail in terms of simplification of modeling[3].

3. MODELING OF COMPONENTS

Relays and fuses are the main components of a JB. In particular, relays have relatively complicated internal structures. Thus, inputting geometry data is a time-consuming process, and model simplification is necessary. Moreover, relays are the main heat sources in some types of car due to their advanced electronic systems. In such cases, an accurate simulation is required with a simple calculation model. The following two concrete subjects have been taken up for modeling relays. These are "Simple modeling of an internal structure" and "Modeling of a terminal connection".

As a result, we have succeeded in a calculation model, which is verified for accuracy. Each is described below.

(1) Simplified Modeling of Internal Structure

If the internal structure of a relay is disregarded, calculation accuracy does not reach a practical level. Our investigation into the internal structure of a relay led to the following conclusion. That is, a thermal resistance network can describe the actual thermal resistance of a relay. Accuracy is sufficient for practical use. The thermal resistance network is shown in Figure 3. Overall thermal resistance is calculated from each divided ingredient. Let R_1 and R_2 be heat conduction resistance of current terminals. R_5 is the heat conduction resistance of the shell of a relay. Let R_3 and R_6 be radiation heat transfer resistance and R_4 and R_7 be convection heat transfer resistance. Overall resistance R_{overall} can be calculated by the following formula.

$$\frac{1}{R_{\text{overall}}}=\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{\dfrac{1}{\dfrac{1}{R_3}+\dfrac{1}{R_4}}+R_5+\dfrac{1}{\dfrac{1}{R_6}+\dfrac{1}{R_7}}}$$

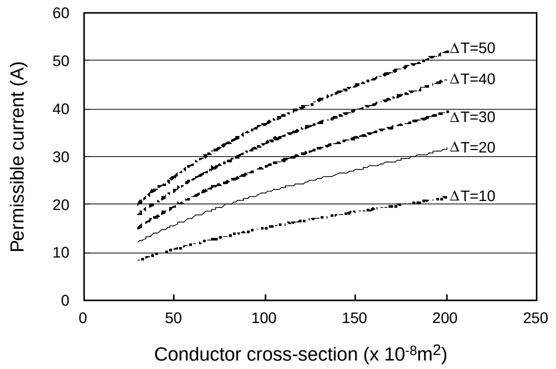


Figure 2 Permissible current vs. cross-section of conductor.

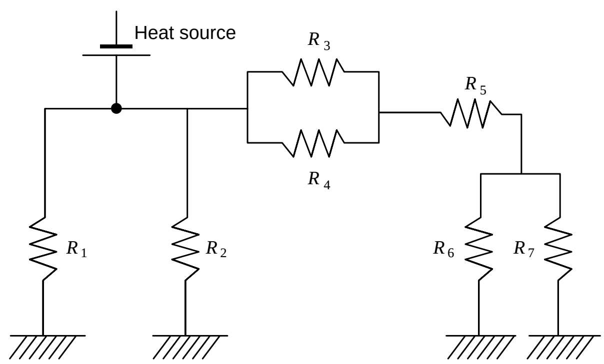
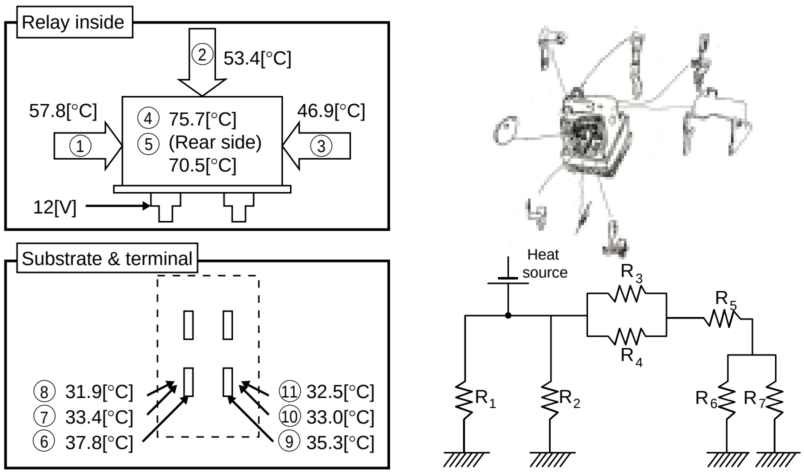


Figure 3 Thermal resistance network of a typical relay.



Thermal resistance estimated from measurement: 23.7[K/W]

Thermal resistance derived from calculation model: 24.9 [K/W]

Figure 4 Comparison between measured and calculated thermal resistances.

Conduction resistance is strictly defined by sizes and material properties. While natural convection resistance depends on the temperature difference between an object and ambient atmosphere, radiation resistance depends on the temperature itself. Therefore, a device is required for the calculation. Generally, heat transfer resistance is calculated by assuming the temperature of each part, and then the temperature of each part is calculated from the value of heat transfer resistance. Furthermore, it is necessary to repeat the exercise until the temperature values converge.

Nevertheless, the accuracy level of the temperature required for the resistance calculation is not very high. Actually, a rough temperature distribution value is sufficient for practical use. Because the atmosphere temperature itself does not change significantly, especially in a case of the same kind of JB, heat transfer resistance can be calculated easily.

Comparison of heat transfer resistance based on the measured temperature and the heat transfer resistance calculated from a heat resistance network is shown in Figure 4. The error is less than 10 %. Therefore, the modeling concept of relays has been justified.

(2) Modeling of the Solder Joints

Solder joint is one of various connecting methods for components and a board, and it is popular in many applications. There are roughly two types of solder joint: lead through type and surface mount type. The surface mount type is better for high density packaging, while the lead through type makes it easier to achieve a reliable design. In particular, some heavy components are not suitable for the surface mount type. Although the situation is expected to change in the future, the lead through type joint will still be required for a while. That means modeling joints is troublesome, because the structure of a lead-through joint has a complicated three-dimensional structure. The joint is composed of current lead, solder material, and pad on a circuit board. Thus we propose a virtual surface mount joint, which is applicable for design modifications. Figure 5(a) shows an actual lead-through model and shown in Figure 5(b) is a virtual surface mount joint. These two models have the same heat transfer resistance. By adopting such a model, the construction process of geometric shape and also design modification process can be executed smoothly.

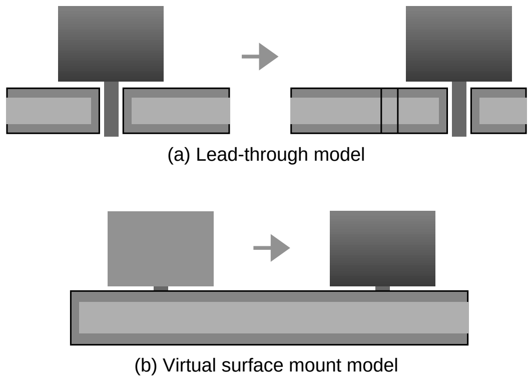


Figure 5 Model construction of a joint.

With this method, the microscopic heat flux in a joint is not very reliable. This is the weak point of the method. On the other hand, macroscopic temperature distribution presents no problems, even when using this virtual surface mount joint model. Therefore, it can be used for a thermal simulation, except if a microscopic view at the joint segment is required. The problem should be improved in the next stage.

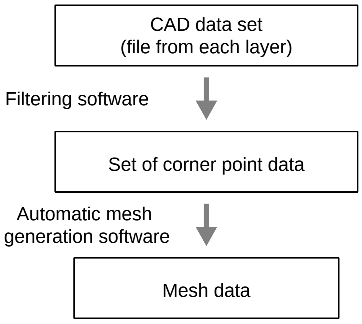


Figure 6 Automatic mesh generation flow.

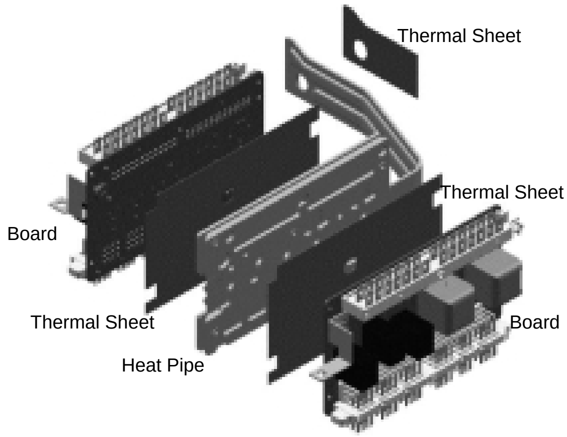


Figure 7 Inner structure of a junction block.

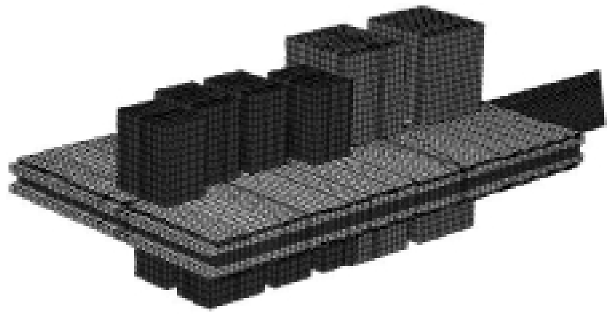


Figure 8 An example of mesh generation.

4. AUTOMATIC MESH GENERATION PROGRAM

CAD drawings are required for manufacturing. The drawings are desired to be materials that can be used directly for a computer analysis. An essential problem at this stage is as follows: a fact that is very clear to a human is not always clear to a computer. For example, automatic recognition of a structure with a narrow crevice or a laminated structure is very hard to perform. A human can make a judgment about a crevice, and a decision on whether or not to fill it, and if it is the premise that a 3-dimensional form is given by a point set that can be understood by a computer, automatic division can be performed based on developed predecessors [4), 5)]. If there is neither a narrow crevice nor an overlap structure (when the lid is put on a box etc.), commercial software that can carry out automatic generation of a mesh from a quite complicated CAD drawing has also appeared on the market recently. However, it is not necessarily completely satisfactory. That is, commercial automatic mesh generation software fundamentally applies tetrahedral mesh generation. There are some disadvantages with the finite element method using a tetrahedral mesh. At least, a hexahedral mesh enables us to make a model with fewer nodes. Moreover, in some kinds of analysis, a tetrahedral mesh cannot provide sufficient accuracy. Automatic mesh generation of a hexahedral mesh is still being developed by several groups and has not yet been completed. Since our present subject is mainly constructed of rectangles, a hexahedral mesh is more suitable and a tetrahedral is not intended to to be used.

We developed the procedure shown by the flow in Figure 6 for mesh generation. The method can be applied for some objects whose character is limited in a finite range. The CAD drawings to begin with are somewhat different from conventional CAD drawings. Two-dimensional line drawings are provided from each layer. This data set of line drawings is defined as a "CAD" here. Filtering software can provide the minimum geometrical information from the CAD file. The minimum geometrical information can be defined using "corner points". Mesh generation software can generate a calculation mesh from the corner points. The filtering and mesh generation software are our original product. The role of filtering software is to purge unused information and to provide useful geometrical information from each layer of line drawings. The automatic mesh generation software reconstructs a three-dimensional structure from the vertices and generates a hexahedral mesh using a structured method. The structured method is suitable for a rectangular based object [6), 7)]. Figure 7 shows the inner structure of a JB.

It is confirmed that this method is effective for circuit board-based JBs and similar cases. A mesh generation example is shown in Figure 8. In spite of limited applicable objects, this method is suitable for many types of JB because the components used in JBs are mostly rectangular. For other types of JB, other types of software should be applied.

5. ANALYSIS RESULT

(1) Heat Transfer Analysis

The temperature of the several points located on the board surface is compared between measured and calculated values. Figure 9 compares calculated and measured temperature distribution on a board. Figure 10 takes calculated values along the horizontal axis, and takes actual measured values along the vertical axis, and plots some points on a board. Also in the Figure, ΔT expresses a temperature rise value, and the unit is Kelvin. In this example, the maximum error between measurement and calculation is approximately ±5 %, which is sufficient for practical pur-

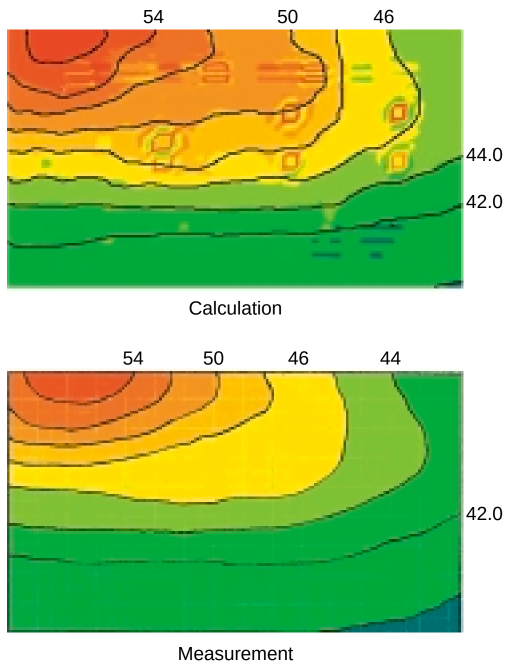


Figure 9 **Comparison between calculated and measured temperature distributions with numerals corresponding to ΔT.**

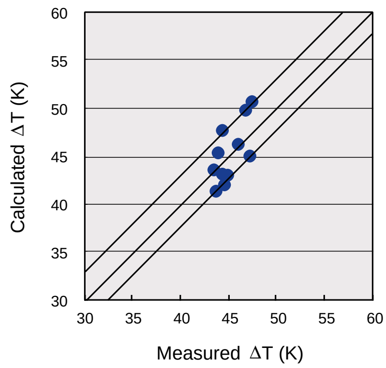


Figure 10 **Comparison between calculated and measured temperature distributions.**

poses. However, in actual application, we may be interested in the temperature of a very fine structure of about 1 mm, and may be unable to use the present model. Although it is in the main factor for having simplified the model, making a precise model will produce problems of disagreements with a simple tool. This should be solved in the following stage.

(2) Calculation Time

Analysis time can roughly be divided into model creation time and calculation time. Among commercial solvers, calculation times are not so long in normal cases. Moreover, as model creation time is usually overwhelmingly taken for a long time rather than calculation time in a heat transfer analysis, it is meaningful to shorten this. Although calculation time also depends on the quality of a mesh, about 30 minutes is typically considered and it does not interfere with the process. Even in the worst case, it can be shortened to 1.5 days with the developed software from 3 days with conventional software.

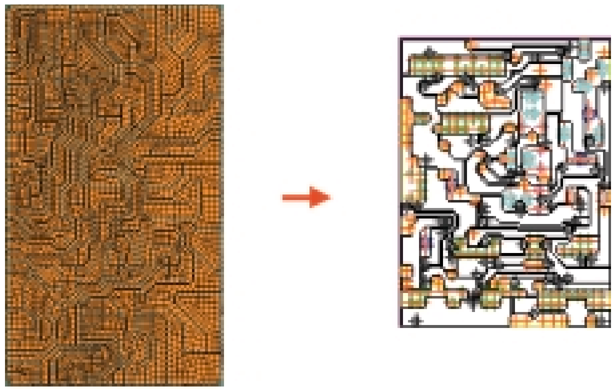


Figure 11 **An example of design optimization.**

6. DESIGN OPTIMIZATION

The developed software tool is applied to the design optimization of a circuit board. With a manual calculation, the temperature distribution cannot be easily obtained. Therefore, predicting the optimum arrangement of the components is not easy. On the other hand, a three-dimensional computer analysis makes this possible. Figure 11 shows an example of design optimization. In this case, the projection area of the board is reduced by 20 %.

7. CONCLUSION

In this paper, we present a new modeling method and a transformation software from CAD for a JB FEM analysis. This simulation tool is based on the structured mesh generation method and we obtained the following conclusions.

(1) Error level is ±5 % or less in thermal analysis of a circuit board based Junction Block.
(2) Total simulation time is reduced by 50 %.
(3) Design optimization reduces weight by approximately 20 %.

In the future, the software tool should have a simpler interface that is compatible with sufficient accuracy. The authors also intend to get higher performance for a wider range of applications.

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REFERENCES

1) T. Ikeya et al., Thermal Simulation of the Electrical Distribution Box, SAE 2001-01-0690, 2001.
2) Y. Oka et al., Investigation and Evaluation of the Wire Harness for the High Performance Components in the Vehicle, The Institute of Electronics Information and Communication Engineers, Technical Report R97-32, pp19-22, 1998.
3) K. Mashimo et al., New Approach of Computer Simulation for Heat Transfer in Automotive Parts, IPC2001D053, Nov. 2001, Shanghai.
4) T. Taniguchi, Automatic Mesh Generation Methods of Arbitrary 3D Domain, J. of Simulation Vol. 18, No.2, 1999.
5) T. Taniguchi and E. Fillion, Numerical Experiments for 3-dimensional Flow Analysis in a Fractured Rock with Porous Matrix, Advances in Water Resources Vol. 19, No. 2, pp 97-107, 1996.
6) M. de Berg et al, Computational Geometry, Springer, 2000.
7) Okabe et al., Spatial Tessellations 2nd ed., John Wiley & Sons, 1998
8) K. Mashimo et al., Development of the Simulation Tool for Vehicle Electronic Parts, SAE 2002 World Congress, Mar. 2002, Detroit