# The Application of the Thermal Simulation Technology to the Products in the Energy and in the Automotive Fields

*Mamoru Shimada*, Masami Ikeda**

**ABSTRACT** Furukawa Electric is providing the heat sink products which are applicable from the cooling of the several watts (W) elements in the electronics field to the several kW of heat treatment in the energy field. At first, the thermal simulation technology started as the technology for the product design in the electronics field. Then, it came to play an important role in the time reduction of the product design and the optimization of the designing. At present, it is used in the designing of almost all the fields from the energy to the automotive fields. In these fields, the thermal simulations were difficult because the heat values of the elements (which were the cooling goals) were larger than those in the electronics field, and because the sizes of the heat sinks (which were the analysis goals) were large. In this paper, we will explain the improvements in the analysis methods and in the analysis accuracy when applying the simulation technology to the designing focusing on the heat sinks in the energy field, and we will introduce the development of the simulation technology to the automotive field.

## 1. INTRODUCTION

Furukawa Electric has commercialized heat sink products which are applicable in various fields, focusing on heat-pipe-based products. By running a simulation using thermo-fluid software, the number and the costs of the test production are reduced and the designs are optimized simultaneously. In the first place, the simulation started to be applied for the products in the electronics field such as in notebook PCs. At present, it is used for the designing of various heat sink products and heat control products. In recent years, along with the wide spread understandings of the importance of the thermal designing, advanced heat sink designing, which uses the limited space efficiently, became essential[1].

Figure 1 shows the heat values and the heat densities of various semiconductor elements. The main cooling goals among electronics devices are the arithmetic elements for the signal processing such as the central processing units (CPUs) and the graphics processing units (GPUs). They have properties of having a small element size and a large heat density.

On the other hand, as the Figure 1 shows, the cooling goals in the energy and in the automotive fields are the power devices which have large heat values such as thyristors, insulated gate bipolar transistors (IGBTs) and diodes. A heat sink for the energy field, which is commercialized as a POWER KICKER, is used for their cooling[2]. Thick heat pipes of 12.7 mm or more in diameter are mainly used for the cooling of these elements, and they are making a significant contribution because they can transport a large heat value at a small heat resistance. In particular, the adoption of the heat- pipe-based cooling devices is increasing and replacing the conventional ebullient cooling device for the railway power sources. That is because they have the advantages that they are environmentally friendly and can save the weight of the heat sink systems.

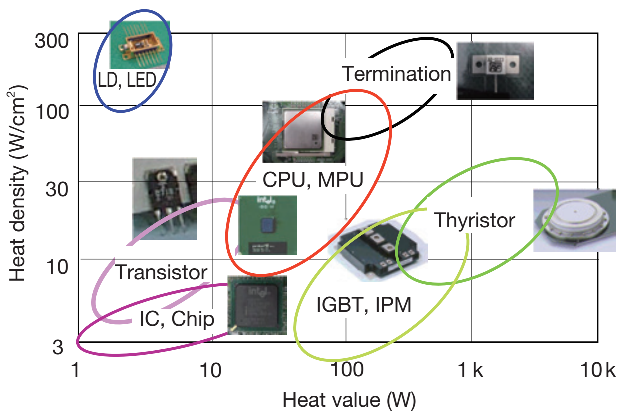


**Figure 1** Heat values and heat densities of typical semiconductor devices.

The thermal simulation in the energy field, especially the heat sinks for railway power sources, had the difficulties which were different from the ones in the electronics

* Automotive System & Device Laboratories, Research & Development Division

products. However, the accuracy which is equivalent to that in the thermal simulation in the electronics field became possible. This paper will explain the application methods of the thermal simulation technology to the designing of the heat sink products in the energy field, and will introduce the analysis examples of the heat sink devices for automobiles.

## 2. THE HEAT PIPES AND THE VARIOUS HEAT SINK COMPONENTS IN THE THERMAL SIMULATION

Figure 2 shows the schematic of the heat sink. Heat sink products are generally consisting of a heat receiving block, which is connected to heating elements, heat pipes, radiation fins and cooling fans. Among them, the heat receiving block and the radiation fins are solid thermal conductivity substances. They can be used as thermal conductivity components without modification in the general thermal analysis software. With respect to the cooling fans, they are applicable as a standard model in a number of software. In many cases, the P-Q (static pressure-air volume) curve gives not only the function of regulating the air volume depending on the pressure loss of the system but also gives the rotational components of the airflow generated by the rotation of the fan blades. Compared to these components, the application of the heat pipe model to the thermal analysis software was limited. However, in recent years, some examples show its application in a form of thermal network components.

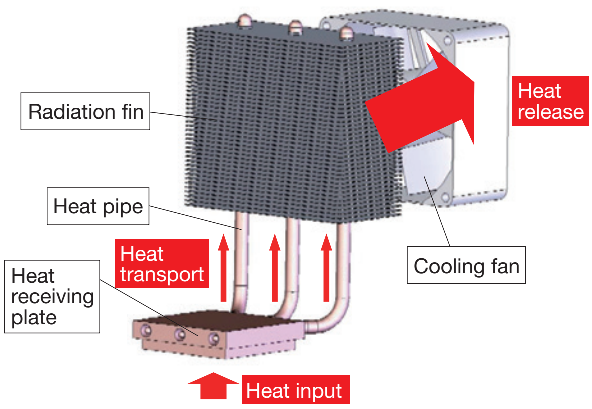


**Figure 2 Schematic of the heat sink.**

Figure 3 shows the inner structure of the heat pipe. The heat pipe has a simple structure where a small amount of working fluid is included under the decompression state in a metal container. While the working fluid circulates by repeating the phase transition of evaporating in the heating section and condensing in the cooling section, the heat is transported with the flow of the vapor[3]. In addition, a mechanism called a wick is set in a heat pipe to reflux the working fluid, which is in the liquid phase of being generated in the condensing section, to the evaporating section. In recent years, from the environmental consciousness, water is used as working fluid and copper is used as a heat pipe container in most cases. Table 1 shows the three major and superior properties of the heat pipe as a heat transport device.

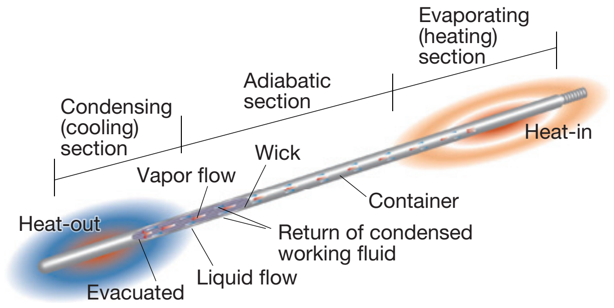


**Figure 3 Schematic of the heat pipe.**

**Table 1 Properties of the heat pipe as a heat transport device.**

| | |
|---|---|
| Long distance heat transportation | The temperature gap does not become large when the heat transport distance becomes longer because the heat resistance of the heat pipe is small dependent on the length. |
| Isothermal property | The temperature in the heat pipe is always stable because the working fluid transports the heat from the high temperature part to the low temperature part autonomously. |
| Heat density conversion | The size of the heating section and that of the cooling section can be different. Heat can be released and retrieved from larger or smaller area. |

Although the structure of the heat pipe is simple, to handle the gas-liquid phase change in the working fluid directly by a simulation becomes a large burden to a computer. In particular, in the scale which targets the whole heat sink, the analysis in a practical period of time is difficult. Therefore, in many cases, it is handled by a simple model in analysis such as in Figure 4. First, in the heat sink analysis, the heat pipes are modeled as a stick which has uniformed solid-state properties. Then, the conditions which are equivalent to the heat resistances between the heat input source and the working fluid and between the working fluid and the heat release component are given by setting coefficients of heat transfer in the space between the heat receiving block and between the fins. In the case where heat pipe components themselves are treated as heat transport components, a sufficiently large thermal conductivity is set to avoid that the heat transport property in the heat pipe element itself has a large impact on the heat resistance between the heat receiving block and the fins. In certain thermal analysis software, the heat pipe components which are built based on the same idea are available. The reproduction of the heat transport property in the heat pipe by a simulation becomes possible by using the software.

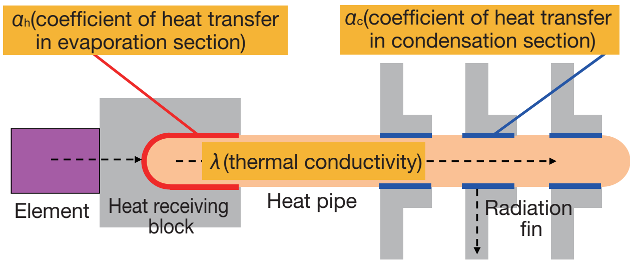


**Figure 4 Example of the analysis model of the heat pipe.**

Figure 5 shows an example of the simulated temperature distribution map of the heat sink for electric devices in which the heat pipes were not used. In this example, the temperature distribution in the base plate was large because the sizes of the heating elements were small and their heat densities were large. In such a simple heat sink, its thermal property can be estimated to some extent without using a simulation but using a simple heat calculation tool[4].

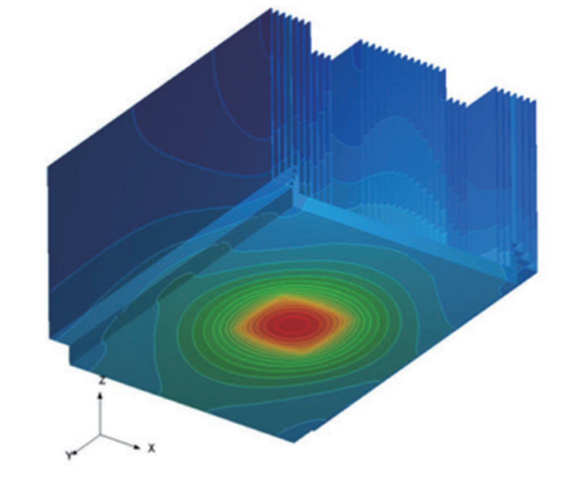

**Figure 5 Example of the temperature distribution of a heat sink obtained by a simulation (without heat pipes).**

Figure 6 shows an analysis example of the heat sink using heat pipes. Six heat pipes were used in this example. The design was that heat was released from the fins with the cooling air from the centrifugal fans located in the center. Assuming the thermal performance of the heat sink with multiple heat transport routes and with complicated flow of the cooling air as in this example is difficult. However, an accurate heat resistance can be obtained by calculation including the airflow using a simulation. At present, the heat designing with simulations is crucial for the heat sink devices using heat pipes.

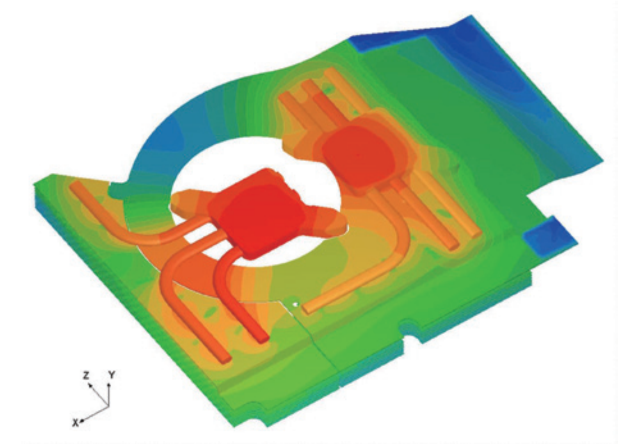

**Figure 6 Example of the temperature distribution of a heat sink obtained by a simulation (with heat pipes).**

## 3. PROBLEMS IN THE ANALYSIS OF LARGE HEAT SINKS AND THEIR SOLUTIONS

The application of the thermal simulation technology to the designing had been difficult in large heat sink products in the energy and in the automotive fields. Table 2 shows its three major causes.

**Table 2 Differences between the large heat sinks in the energy field and the heat sinks in the electronics field in the performance of simulations.**

| | |
|---|---|
| Product size | The heat sinks in the electronics field are comparatively small and the typical size is about 100 mm. The heat sinks for the energy field are large and their maximum size reaches 1000 mm. |
| Airflow | The flow of cooling air is laminar in the small heat sinks. In some cases, it is turbulent in large heat sinks. |
| Cooling condition | The cooling conditions are regulated by the air volume in the small heat sinks. They are regulated by the wind speed in a particular point in the large heat sinks. |

The first cause is the size difference between the analysis models of the heat sink products in the electronics field and of the ones in the energy and in the automotive fields. The typical size of the heat sink products for the electronics field is about 100 mm, which is small. Therefore, the time required for an analysis is 1 – 2 hours, which is short. And the optimal designs can be achieved by repeating the analysis using multiple structural designs and being assigned with designing parameters in a comparatively short period of time. On the other hand, in a POWER KIKER for railway vehicles, which is an example of the large heat sinks, the maximum size of a side reaches about 1000 mm. Because of this, the number of elements reaches several tens of millions when a mesh division is applied with an accuracy of the same level of the heat sinks for PCs. In such a case, the analysis may last for several days, thereby increasing the cost. When the calculating time is long and the calculating cost is large, the advantages can hardly be obtained by the optimization of the designing using a simulation.

The second cause is the difference of the states of the airflow between the fins. In the heat sinks in the electronics field, the airflow is laminar because the intervals between the fins are narrow. On the other hand, in the large heat sinks, the intervals between the fins are generally wide, and the turbulence flow occurs in some cases when the Reynolds number reaches about several thousand due to the large wind speed between the fins. However, in the simulation of the heat sink, there was a problem that the element breakdown for the application of the standard turbulent flow model was difficult.

The third cause is the difference in the thermal design specifications. In general, in the heat sinks in the electronics field, their thermal properties are defined as the heat resistance against the specified air volume in many cases because they are capable of measuring the heat resistance accurately with air channels. Therefore, quantitative evaluations with the result of the simulation are easy. On the other hand, in the large heat sinks, the measurement evaluation with accurately-controlled air channels is difficult because their sizes are large. For this reason, in many cases, their thermal properties are regulated by the relationship between the wind speed and the thermal resistance in a particular point on the front side of the fins when the cooling air is blown with the heat release part covered with the ducts in a thermal evaluation. That caused the difficulty in the quantitative comparison with the analysis result.

To address the problem of having a large number of meshes due to the large size, the shape of the analysis model was simplified. Although a simulation using a design made by a three-dimensional CAD is common at present, the analysis without changing the product shape was difficult and the simplification of the shape of the analysis model was common at the time the capability of computers was incomparably low. For example, in large-sized heat-pipe-based heat sinks, the fixing of the fins by pressing the heat pipes into the fins with burring work is a standard method (Figure 7). However, a fine element breakdown is required to reproduce the shape of the fin burring by a simulation, and it causes the increase in the number of the elements in the whole analysis model. To overcome this, the analysis was conducted with the fin model without the burring. The number of the meshes was reduced by the methods such as correcting with the coefficient of heat transfer to counter the influence of the reduction in the contact areas between the heat pipes and the fins.

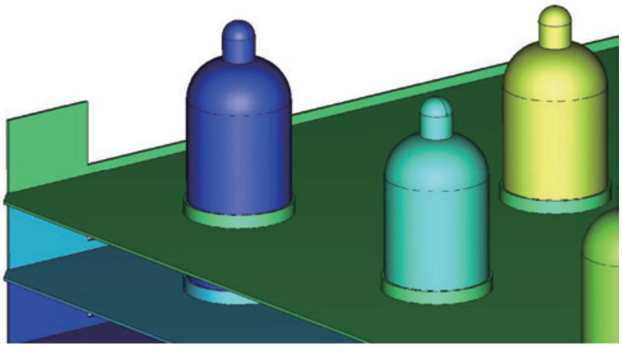

**Figure 7 Schematic of the heat pipe and the fin burring.**

To address the problem of having a larger Reynolds number for the airflow between the fins, a turbulent model of a low Reynolds number type, which is provided for the case in which a standard turbulent model is difficult to be applied, was used. To overcome the problem of “the destabilization of the thermal calculation” which is likely to happen in the model, we mitigated by discussing with the software vendor. We finally prevented the problem by establishing conditions of the element breakdown to avoid the destabilization of the calculation and by standardizing it.

To address the problem where the quantitative comparison between the measured result and the analysis result was difficult, we conducted the analysis with the position of adhering to the measured evaluation state with simulation. A gap was generated between the wind speed which was given as a boundary condition in a simulation and the wind speed at a specific point in the analysis. To overcome this, the condition of the boundary wind speed was controlled by a user subroutine per cycle in an analysis, then, the wing speed at the specific point was converged to the designated value. Thereby, the repetition of the analysis for matching the wind speed with the specific value was avoided.

Figure 8 shows an example of the comparison between the analysis result and the measured result of the heat sink in railway vehicles with the methods introduced above. In this product, when the wind speed is low, the airflow between the fins is between turbulent flow and laminar flow. In the analysis, whether to treat the airflow as turbulent flow or laminar flow needed to be decided, thus the gap between the analysis result and the measured result became large. However, in the region of the large wind speed which was estimated to be in a full turbulent state with a large Reynolds number, the analysis gap of the heat resistances was within 5%.

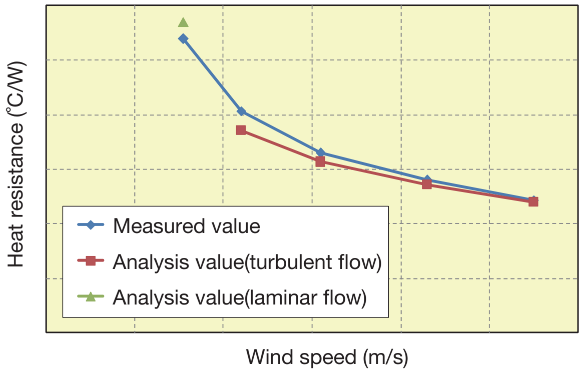


**Figure 8 An example of the comparison between the measured value and the analysis value of the POWER KICKER for railway vehicles.**

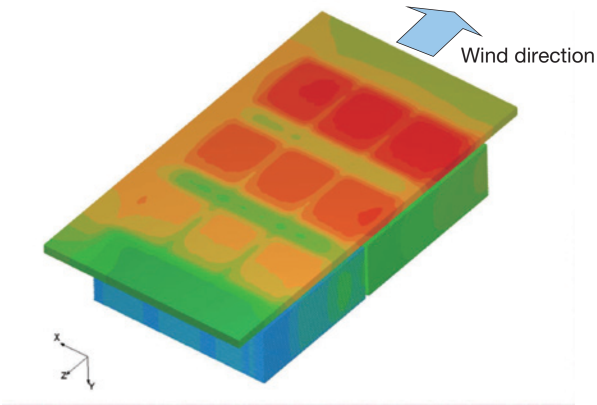


**Figure 10 Temperature distribution of the POWER KICKER for railway vehicles (first trial design).**

## 4. EXAMPLE OF THE DESIGN OPTIMIZATION IN THE HEAT SINK IN RAILWAY VEHICLES

We will explain the actual example of the optimization of the heat sink designing by a simulation. Figure 9 shows the first trial design of the POWER KICKER. We investigated the design problems of this first trial design by a simulation. As the analysis result in Figure 10 shows, although the fin pitches on the leeward side were set narrow and the heat release areas were set wide, the temperature of the heating elements became higher as they were closer to the leeward side. The reason is that the fins on the leeward side were difficult to release heat and the temperatures in the elements gradually rose because the temperature of the air which was flowing between the fins gradually rose with the heat released by the fins as it moved to the leeward side. Also, it was confirmed that the heat load tended to concentrate into a part of the heat sinks caused by the positional relationship between the heating elements and the heat pipes which were used in the heat sinks.

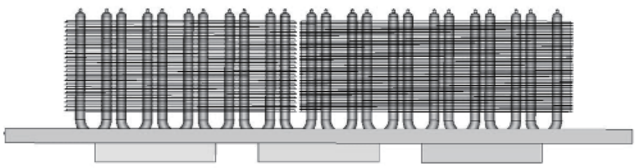

**Figure 9 First trial design of the POWER KICKER for railway vehicles.**

Given this factor, we studied the optimization of the dividing methods of the fins in the windward and in the leeward directions, the ratio of each fin pitch and the two designing elements of the heat pipe arrangement by simulations. The result was that the $\Delta T$ (value of the temperature rise) of the heat sink became smaller when the division number of the fins was increased from two to three. Also, when the ratio of the neighboring fins was 2:1, the airflow became smooth and the $\Delta T$ of the elements on the leeward side became smaller. Although we studied the arrangement of the heat pipes, the improvement in the arrangement did not lead to the enhancement of the thermal performance because it brought the reduction in the number of the heat pipes which could be arranged. Therefore, the arrangement in the first design was adopted.

Figure 11 shows the composition of the final design. It divided the fins into three parts along with the airflow. Restraining the rise in the air temperature by widening the space between the fins on the windward side, the fins on the leeward side became capable of releasing heat effectively. Figure 12 shows the analysis result of the final design. As it shows, the $\Delta T$ of the heat sink was lowered by 6°C and the temperature gap between the heating elements was reduced by 70%.

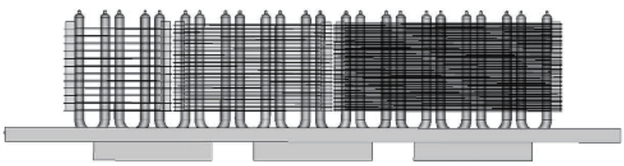

**Figure 11 Final design of the POWER KICKER for railway vehicles.**

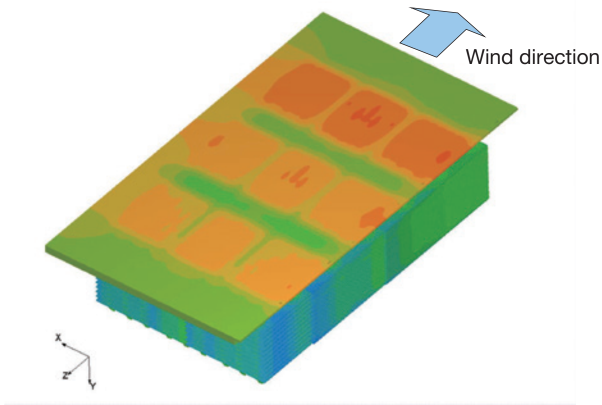


**Figure 12  Temperature distribution of the POWER KICKER for railway vehicles (final design).**

In the case of the large heat sinks for railways, a sufficient design optimization was difficult in many cases time wise and cost wise because each trial evaluation took one to two months. However, this product could achieve the finally targeted heat release performance only with a trial between the first trial design and the final design by running 30 ways of simulations in the process of designing. At present, the simulation method of the large heat sinks for railway vehicles is standardized in the company and is used in almost all designing of the products.

## 5. EXAMPLES OF THE SIMULATION OF THE HEAT SINK DEVICES FOR AUTOMOBILES

In automobiles, a number of semiconductor elements such as integrated circuits (ICs) are becoming mounted in line with the rapid advancement of the electrification and the computerization of automobiles for an accurate control of the drive trains targeting the improvement of the fuel efficiency and the enhancement of the comfort in the living space. In hybrid electric vehicles (HEVs), in electric vehicles (EVs) and in fuel cell vehicles (FCVs), the drive-trains are electrified. When the cooling of the power source or of the electronic control unit (ECUs) in engine vehicles is required, the water-cooling system which is originally mounted on them is commonly used. However, in recent years, the cooling technology of air-cooling which is lightweight and has a lot of flexibility in the layout is becoming the focus in the automotive field.

Figure 13 shows the cooling system of a junction box in which heat pipes were applied. The design of this product is that the heat in the junction is accumulated by the heat pipes and then, it is transported to the chassis. The heat is finally released to the outside from the vehicle body. This design enabled the heat release without using a water-cooling system or cooling fans.

In HEVs and EVs which are increasing recently, the size reduction in the battery packs and a cooling method which prevents the deterioration of the batteries are the problems because these vehicles are mounted with the batteries of a large capacity.

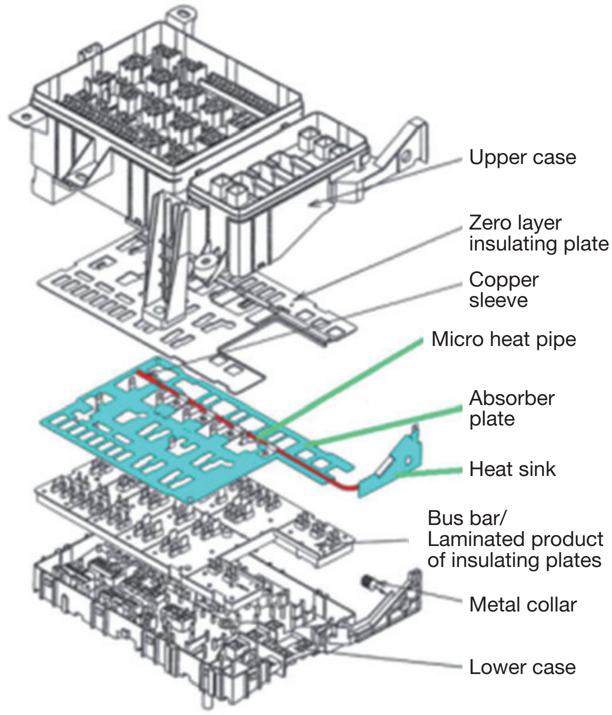


**Figure 13  Heat-pipe-based heat sink for a junction box.**

Figure 14 shows an example of the simulation of a heat sink for the cooling of batteries. In this example, four battery cells are cooled simultaneously in a heat sink. The method is the heat is transported to the heat release part in a distant place by the heat transport function of the heat pipes, and the heat is released by air-cooling. In this design, the temperature fluctuation between the cells could be smaller with the isothermalization effect of the heat pipes and the fluctuation of the time degradation speed could be smaller.

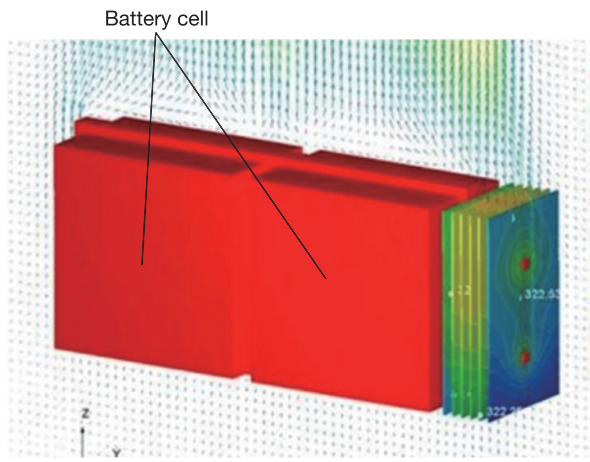


**Figure 14  Analysis example of the heat sink for the cooling of batteries.**

In addition, as the electrification of the automobiles advances, the cooling method of the semiconductors which have large heat values such as inverters and converters became one of the problems, as well as in electric trains. Figure 15 shows an example of the simulation of the heat sink for inverters. The heat values in the inverters change constantly along with the change in the running condition of the vehicle. In the indicated heat-pipe-based heat sink, a rapid change in the temperature along with the change in the heat values in the elements are restrained, and rapid heat release by transporting the heat to the fins with the heat pipes which had a small thermal capacity and had a quick response became possible simultaneously by optimizing the thermal capacity of the receiving block.

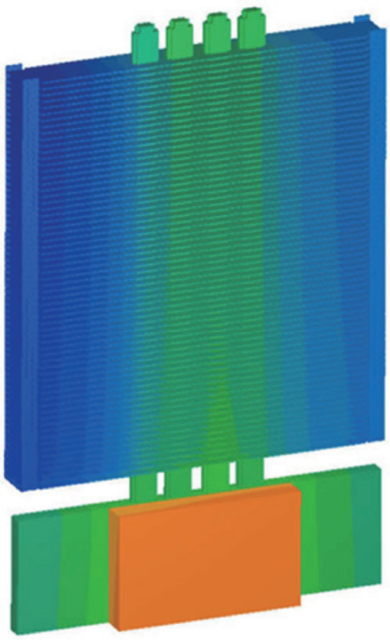

**Figure 15 Analysis example of the heat sink for inverters.**

## 6. CONCLUSION

This paper introduced the expansion of the simulation technology of the designing of heat sink products in the electronics, in the energy and in the automotive fields. Heat sink products in the energy and in the automotive fields have large sizes, and the large sizes caused some problems when simulations were conducted. However, the analysis accuracy of within 5%, which was equivalent to that of the small heat sinks in the electronics field, was achieved by devising an analysis method. As speed is always required in the designing and the development of heat-related products, we will progress in the reduction of the trial times and the designing efficiency to meet the needs by simulations.

In addition, thermal simulation software has been evolving. They can be used as a tool by the product designers with ease because they have been installed with convenient physical models and their user interfaces have been upgraded. However, as the case that various turbulent models are used depending on the purpose shows, the thermo-fluid analysis is comparatively a difficult field. Therefore, it should be used with a confirmation of the accuracy by continuously comparing to the measured data. Given this condition, we will continue the study of enhancing the analysis accuracy and we will make efforts to advance the simulation technology to ultimately achieve the analysis accuracy of within 5% in all products.

### REFERENCES


1) Kunimine (supervision): The newest thermal design technique and electronics cooling technology, CMC Publishing Co., Ltd., (2011) (in Japanese)
2) Takahashi and others: Environment-Friendly Vertical Air-Cooling Heatsink: Heatpipe-Based Heatsink "POWER KICKER", Furukawa Review, No.27 (2005), 30.
3) Edited by Japan Association for Heat Pipes: Heat pipes in actual use, Nikkan Kogyo Shimbun Ltd., (2001). (in Japanese)
4) Kimura and others: Thermal Design Simulation Software "HIEROH", Furukawa Review, No.27 (2005), 52.