Application of Simulation Technology to Thermal Issues

Yumiko SAWAI*, Kiyotaka HIRAHATA, Masao YOKOTA, Akinori OKAYAMA, Masahiko SAWADA and Satoshi HAGIHARA

Electronic equipment has reduced in size and advanced in processing speed. As the heat density of such equipment has increased, conventional thermal designs do not always meet the temperature specification requirements any more. To meet these specifications, SimDesign Techno-Center has been working on the improvement of thermal simulation technology. This paper describes the latest technology in thermal design along with some product design examples particularly in the following four cases: 1) thermal design using copper trace models on a printed circuit board, 2) thermal design concerning solar radiation, 3) thermal design most suitable for electric wire, and 4) manufacturing support by using thermal simulation to determine the temperature profile of the reflow furnace. The cost effectiveness of the thermal simulation is also proved in practice.

Keywords: simulation, thermal design, electronic equipment, solar radiation

1. Introduction

In recent years, due to the rapid advancement of electric equipment, conventional thermal designs using fans, vents, and heatsinks do not always meet the temperature specification requirements. To address this challenge, we need to focus on 1) detailed modeling (e.g. modeling of copper trace for the PCB (printed circuit board)) in addition to the conventional simple modeling technology with equivalent thermal resistance, 2) adaptability to various environmental conditions (e.g. solar radiation), 3) upgraded simulation technology (e.g. transition simulation), 4) the application to fields other than electronic equipment manufacturing, and 5) improved thermal simulation accuracy. To satisfy these requirements, we have worked on the development of various thermal design technologies and improvement of the simulation accuracy. This paper describes the latest simulation technology in thermal design along with some product design examples.

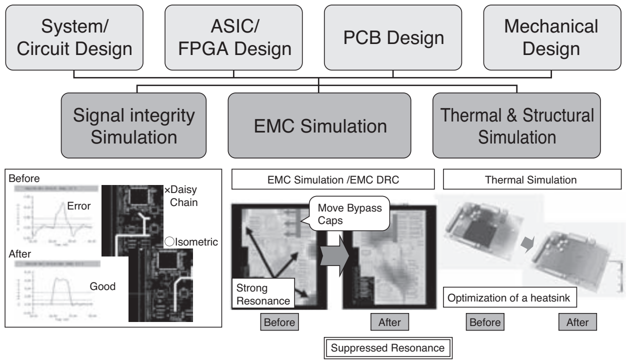


Fig. 1. Simulation-based design method

2. Advantages of the Design Methods

SimDesign Techno-Center, a business unit of Sumitomo Electric System Solutions Co., Ltd., develops and designs electronic equipment. The design process includes concurrent design of systems and circuit design, ASIC/FPGA (application specific integrated circuit/field-programmable gate array) design, PCB design, and case/mechanical design. In each design step, we use the "Simulation-based Design" method to determine signal integrity, EMC (electromagnetic compatibility), temperature, and structure (**Fig. 1**).

In product development, we have used both concurrent design techniques and the simulation-based design methods to shorten design process time, reduce trial product cycles, and improve final design quality. This paper describes our thermal simulation technology, one of the most important factors that affect performance of electronic circuits and the entire system.

3. Our Approach in Thermal Design

Figure 2 shows the thermal design process in SimDesign Techno-center.

In this development process, different thermal simulation tools are used in each design step. In STEP 1 (concept design), a suitable cooling method (forced air cooling with blower, or natural air cooling without blower, etc.) is selected depending on the capacity and gross calorific value calculated by an operator. In STEP 2, simulation tools are used to determine the PCB position in the case. The PCB model is assumed to generate heat from the body uniformly, and the temperature distribution on the PCB is calculated taking account of air flows and the PCB position. Based on the result, we determine a rough layout guideline of the thermally dominant high-power consuming components or low heat-proof components. Then the results of

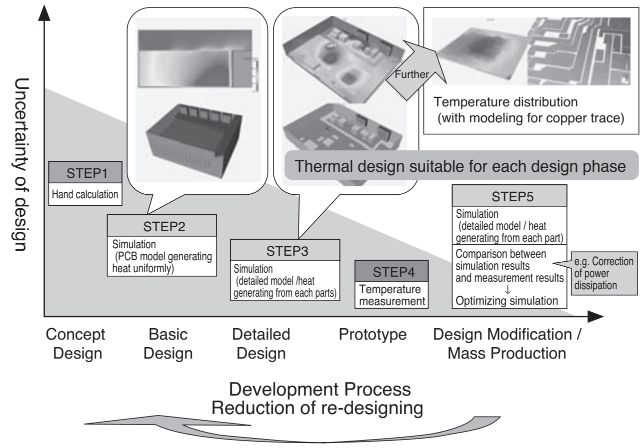


Fig. 2. Thermal design process

the simulation are fed back to each design step. In STEP 3, the layout of components is determined. Electronic parts are mounted on the PCB model of STEP 2 and the temperature is calculated. If the temperature of semiconductor components exceeds the maximum junction temperature, we consider additional measures such as changing the configuration of heatsinks or reducing the number of blowers. In the PCB where a large current flows, layer structures, such as thickness of copper foil, number of layers, usage of outer or inner layers, and width of the traces are optimized. In STEP 4, the temperature distribution of the prototype is measured. Then, the simulation results are compared with the measured values and the difference between them is fed back to the model design. In STEP 5, the thermal design is optimized to reduce design iterations for mass production.

3-1 Flow of a thermal simulation

Figure 3 shows the flow of STEP 2 and STEP 3.

①3D-CAD (3-dimensional computer aided design) data is provided from customers (development sections). ②Modeling and parameter setting (e.g. power dissipation and material property value) are implemented. The computer calculation is executed between ①-③. ③Based on the calculated result, the solutions, such as ventilation and heatsink, are examined. ④Trade-offs between solution ideas and manufacturing costs are discussed with the customers (development sections) to optimize the thermal design.

Here, the most important point for the thermal simulation is modeling. As the 3D-CAD data has detailed information suitable for manufacturing and is not simplified for the simulation, it can take up to several days to finish the computation. Therefore, ingenuity is needed to simplify the model for effective computation. In addition, multiple cases are verified to select optimized solutions at the same time. So, computation time can be too long to implement the design process in a reasonable period of time. For such occasions, thermally equivalent simplified modeling is required for the case, PCB, and electronic components. In SimDesign Techno-Center, we have accumulated experience of design solutions, as we repeated computing calculated results and measured results, after we had implemented thermal simulation tools.

However, the simplification techniques are not always the top priority. What is the most important is to adjust the modeling level according to the target product's requirement. Detailed simulation flow is explained in the next chapter.

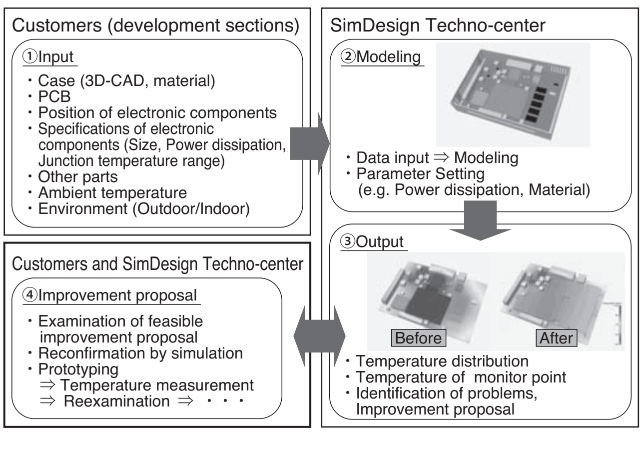


Fig. 3. Thermal design flow

4. Examples of Thermal Design

The latest thermal design examples are described in this chapter.

4-1 Thermal simulation with copper trace model

Generally, PCBs have multilayered structures, and different copper trace patterns are formed on each layer. In general, a PCB is modeled as a material of an equivalent thermal conductivity by synthesizing copper traces and glass-epoxy insulation layers. However, in the case that a large current flows on copper trace, more detailed simulation models are needed. The purpose is to calculate the heat radiation by the conduction of heat from electronic parts mounted on the PCB, and there are three reasons for this attempt. ① In the case that miniaturized electronic equipment cannot accommodate a large heatsink, copper trace of the PCB is an important heat-conducting route. ② As heat generating components tend to be miniaturized, their surface areas decrease and the heat released to the PCB relatively increases. Then the heat radiation to the air decreases. ③ As more electronic equipment has a large current, in many cases joule heat generated on copper trace becomes unignorable. In addition, the design using simulation tools has become common. Therefore, we have provided simulation results improved in accuracy.

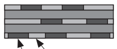
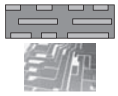
To take a PCB as an example, four types of models are prepared,as shown in **Table 1**, to select a model suitable for each case. The feature of each model is as follows:

I : a model based on the assumption that the PCB is a synthetic thermal conductivity

II : a model with the copper foil ratio set for each layer.

III : a model for which the wiring density of each layer is reproduced

Table 1. PCB simulation model

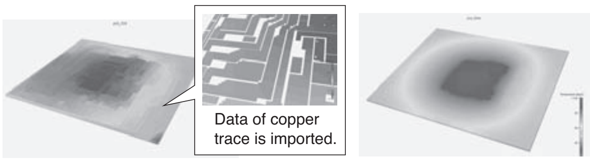
	I	II	III	IV
Model	Uniform thermal conductivity	FR4 + uniform thermal conductivity for each layer	FR4 + high or low thermal conductivity for each layer	FR4 + copper trace
Image				
Lead Time	Short →			Long
Precision	Low →			High
Process	Concept design →			Detailed design

IV : a model for which the copper trace pattern of each layer is considered.

As the design advances, the models shift II→III→IV after model I is used at the initial design stage. The model I has a computable advantage in a short time. However, the error margin factor of the simulation tends to be larger. On the other hand, the model IV requires longer simulation time but the simulation accuracy is higher than the others. These models are selectively used depending on the purpose of the simulation.

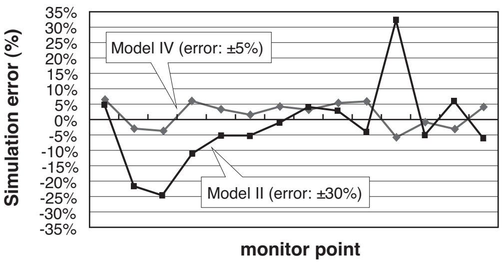
An actual example of the detailed simulation results using a copper trace model is shown in **Fig. 4**. In (a), copper traces are modeled and the joule heat from a large current is considered. On the other hand, in (b), joule heat trace distribution is not considered. Temperature distribution results of (a) and (b) are quite different. As shown in (c), measured temperature distribution is similar in (a) rather than in (b). The result shows a detailed modeling of copper traces brings more accurate simulation results.

Because model IV resembles the actual PCB and the distributed heat source is quite different from those of I-III, the simulation error margin of IV becomes small when a large current flows and joule heat generation is disregarded. For instance, the error margin with the measured result is 5% with model IV, while it is ±30% with model II. Moreover, the best PCB structure is examined by this approach, and it is possible to reflect it to the PCB design. Thus, the improvement of design precision is expected by obtaining a highly accurate calculation result.



(a) Temperature distribution on the model IV (with modeling for copper trace)

(b) Temperature distribution on the model II (without modeling for copper trace)



(c) Simulation error (models II and IV)

Fig. 4. Modeling example of copper trace

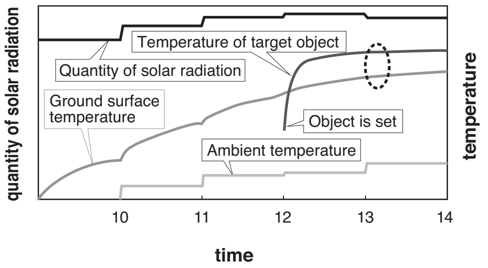
4-2 Transient analysis*3 considering solar radiation effects

In recent years, electronic equipment installed outdoors increases with the development of communication networks and photovoltaic power generation devices. The electronic equipment used indoors can meet specifications through the inspection of a temperature rise caused by the heat of the equipment itself. But, for electronic equipment installed outdoors, solar radiation (sunlight) should also be considered.

In this section, a typical case that the effect of solar radiation cannot be ignored is reported.

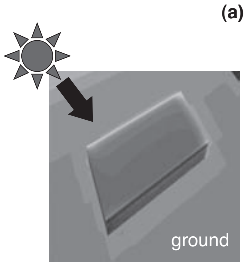
In this case, this product is installed on the ground and left for about one hour. Additionally, it was required to predict the temperature rise in summer using computer simulation, because the temperature evaluation of the prototype was carried out in the season of weak sunlight. At first, we compared the calculated result with the measurement result obtained by using the prototype equipment placed on the ground. We used simulation tools that calculate the quantity of solar radiation by setting latitude and longitude. The measurement result is: (surface temperature of the equipment's top side) > (surface temperature of the equipment's bottom side). The calculated result is: (surface temperature of the equipment's top side) < (surface temperature of the equipment's bottom side). These results show the different tendency. In calculation, the surface temperature of the bottom side of the equipment is higher than that of the top side. Because the prototype is painted with a low solar radiation absorption*4 material, the bottom of the equipment is heated by the ground heat. In the traditional steady analysis, we cannot avoid this phenomenon. We concluded that the calorific capacity of the experimental model is small and it will be in a steady state in about one hour, but the ground, whose calorific capacity is large, has not reached a steady state. Therefore, we decided to apply the transient analysis instead of the traditional steady analysis (**Fig. 5**).

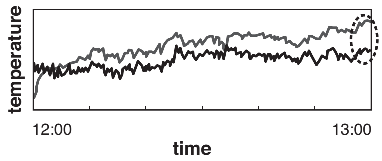
As a result, the simulated temperature rise for the equipment kept outside for one hour after the installation at noon was in agreement with the actual measured result, and the temperature distribution both on top and bottom sides was also identical. We predicted the annual maximum temperature with this simulation method by setting summer temperature and solar radiation. We came to a conclusion that there is no thermal problem in using simulation results for the actual measured value. In fact, we confirmed that there is no problem in the actual temperature rise test conducted in the summer season. This demonstrates that the mass-production sample of this simulation technique is of service. This simulation model enables us to develop products without waiting for test results of summer season and shortens the development process.



Temperature by the solar radiation using transient analysis

(a) Result of simulation





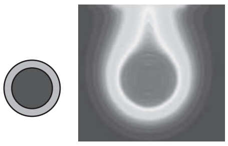
(b) temperature distribution (results of simulation)

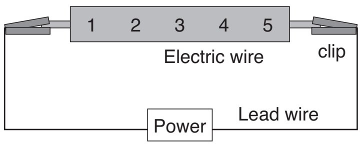
(c) results of temperature measurement

result of simulation ≒ result of temperature measurement

( ) in (a) corresponds the same area in (c)

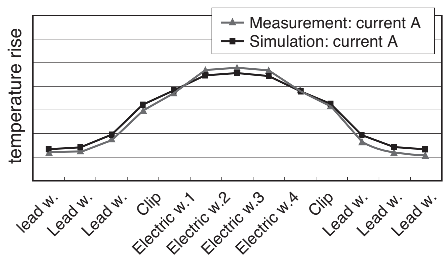
Fig. 5. Example of solar radiation analysis (Transient analysis at each time)



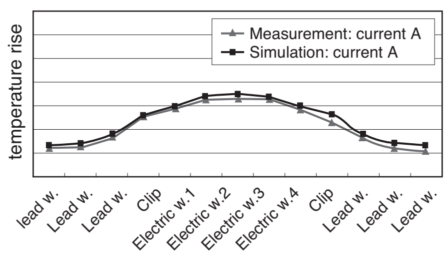


(a) Pattern diagram of round-shaped electric wire and temperature distribution

(b) Pattern diagram of test environment



(c) Temperature of round-shaped wire Comparison between measurement results and simulation results



(d) Temperature of electric wire with the new structure Comparison between measurement results and simulation results

Fig. 6. Optimization of electric wire shape

4-3 The most suitable cross sectional shape of electric wire

In the next two sections, different thermal simulation applications are shown. **Figure 6** shows the case that we studied the cross sectional shape and wire coating material of the electric wire.

Figure 6 (a) shows the simulation results for the traditional round–shaped wire. (b) shows the test and simulation condition. (c) shows the measured and simulated results of the round shaped wire. (d) shows that of the new structured wire, which has the same cross sectional conductor area as that of the round-shaped wire. In (c) and (d), we can confirm simulated results are almost identical to measured one. We also estimated the thermal effect of wire coating material using the simulation technique and fed back the result to the design process.

4-4 Support for manufacturing

Other than the thermal design in product development described so far, we are trying to apply the thermal simulation technique to manufacturing process.

In mounting process, electronic parts on a PCB are heated and soldered in a reflow furnace. In the traditional way, the temperature profile is determined by skilled operators based on past measurement records of similar products. In an ordinary situation, a custom-made test board is used to check the temperature rise and adjust temperature profiles to realize required soldering condition. In this way, we cannot determine the temperature profile easily and have to go through a trial and error process, which can cause a delay in product development. In some cases, the number of test boards is limited because of the high cost of electronic parts. In recent years, lead-free soldering has been generally used. As the melting point of lead-free solder is higher than that of eutectic solder, the operating temperature during the soldering process becomes higher. The operating temperature margin difference between the limiting temperature of each part and the soldering temperature become smaller in ease of lead-free soldering than eutectic soldering (**Table 2**).

Therefore, we developed a method of predicting the temperature of electric parts on the PCB in a reflow furnace. This method has three advantages in quality control: ① shortening the preparation time for soldering settings by optimizing the temperature profile in the design process, ② minimizing the production costs of test boards with precious electric parts, and ③ optimizing the layout of copper traces and large components that have a signifi-

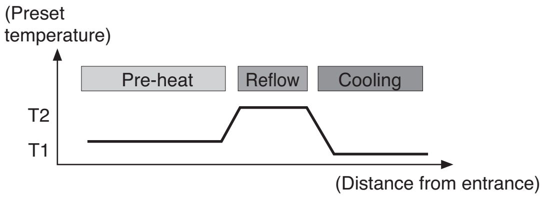
Table 2. Melting points in soldering and thermal limits of parts

	Temp. (˚C)
Melting point of eutectic soldering (Traditional way)	183
Melting point of Pb-free soldering	About 220
Thermal limit of parts in reflow furnace	About 230~260

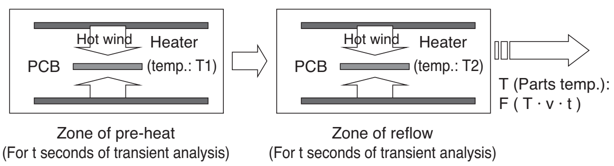
Temperature management in Pb-free soldering
- As the melting point is higher than that in eutectic soldering, temperature management is difficult.
- Temperature must be controlled to be 220-230˚C.
- Temperature destribution must be kept uniform over the board.

cant affection on the temperature distribution on the PCB in the reflow furnace.

At the beginning of this trial, we built a simulation model of a reflow furnace. We employed the transient analysis for this simulation. For the reflow furnace model, conditions of simulation temperature and conveyor belt speed are given as time functions (**Fig. 7**). At the initial simulation, the results of simulation did not match the results of temperature measurement because of the lack of detailed information on the internal structure of the reflow furnace. Therefore, we adjusted the parameter to build the simulation model that matches the actual temperature profile.

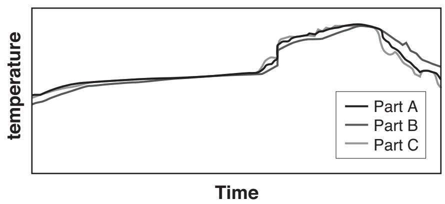


(a) Example of preset temperature in reflow furnace

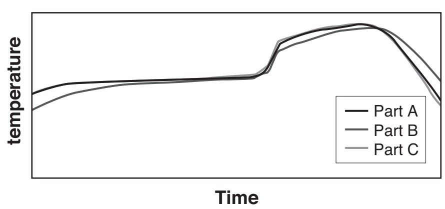


(b) Pattern diagram of simulation model of reflow furnace

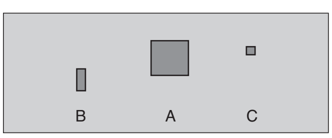
Fig. 7. Outline of reflow model



(a) Results of temperature measurement



(b) Results of simulation



(c) Parts design

Fig. 8. Temperature of parts in reflow furnace

Next, we added the simulation model of the test PCB to verify the furnace model. We compared the simulation results with the measurement results of the test PCB. This test PCB contains three typical parts of different shapes. In this simulation, we studied the shape of parts and the physical property value. The simulation results and measurement results were almost identical (**Fig. 8**).

Our next challenge is simplifying the simulation model as much as possible for actual PCBs with a number of parts densely arrayed.

At present, we are yet in the trial stage, where this method is used on an experimental basis. To put it into practical use, we intend to increase the variety of parts applicable for the simulation model and verify its validity.

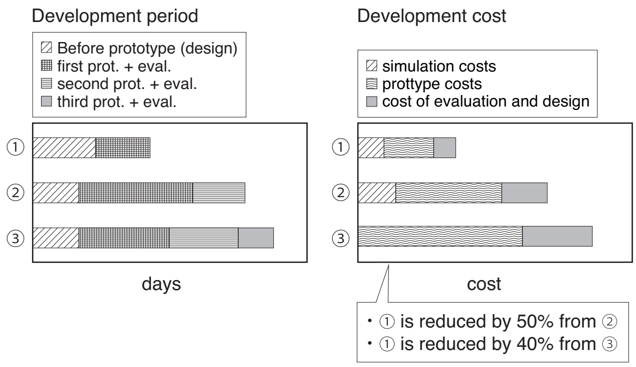
5. Cost Effectiveness of Thermal Simulation

In this section, the cost-effectiveness of the thermal simulation is discussed for the three possible cases (**Fig. 9**).

We calculated the following costs for product development to which the thermal simulation is applied from the early stage of design: ① actual cost, ② estimated cost that would be required when a thermal problem occurs with the first prototype, and then the thermal simulation is applied, ③ estimated cost that would be required when the thermal simulation is NOT applied. ② and ③ are based on assumptions of "design costs of product development before utilizing thermal simulation," and "measures enabled by the thermal simulation before trial product manufacturing."

Although in the case of ①, the primary design period is longer than those in ② and ③. The entire design period is shorter in ①. Also the cost ① is about 50% of ② and about 40% of ③ for the reduction of test product costs and measures.

As a result, ① is most effective method for both shortening the development period and reducing the cost. This demonstrates the effectiveness of our thermal simulation method in the development process.



①	Actual design (simulation is applied before prototyping)
②	When simulation is applied after first prototyping
③	When simulation is not applied

Fig. 9. Cost effectiveness when simulation is applied

6. Conclusion

In this paper, some examples of application of thermal design to Sumitomo Electric's products are reported. Then, the effectiveness of our thermal simulation method is discussed.

As we intend to expand environmental and mobile businesses, which are expected to grow in the future, it is essential for products used in these fields to be able to deal with severer thermal conditions. To meet these thermal requirements, we must improve the thermal design techniques utilizing thermal simulation and build up innovative techniques such as the thermal stress analysis. We will contribute to the development of a variety of products.

Technical Term

*1 Heat density: A unit that indicates the value of generated heat per unit volume
Heat density = total power dissipation/volume of equipment

*2 Transient phenomenon: A phenomenon in which temperature in a stable state changes over time.

*3 Transient analysis: A calculation technique for the temperature change by the transitional phenomenon.

*4 Ratio of solar radiation absorption: A ratio of sunbeam energy absorbed by the housing surface.

Reference

(1) Sawada, Kaneko, et al. "Simulation-based Design of GHz High-speed Interface Boards and Expansion of DMS Business," SEI Technical Review No.168 (2006. 3)

Contributors (The lead author is indicated by an asterisk (*).)

Y. SAWAI*

- Sumitomo Electric System Solutions Co., Ltd.
She is engaged in the thermal design that uses simulation techniques.

K. HIRAHATA

- Sumitomo Electric System Solutions Co., Ltd.

M. YOKOTA

- Manager, SimDesign Techno-Center, Sumitomo Electric System Solutions Co., Ltd.

A. OKAYAMA

- Manager, SimDesign Techno-Center, Sumitomo Electric System Solutions Co., Ltd.

M. SAWADA

- General Manager, Market Development Department, Sumitomo Electric System Solutions Co., Ltd

S. HAGIHARA

- Manager, SimDesign Techno-Center, Sumitomo Electric System Solutions Co., Ltd.