Hints and Tips for Thermal Design for Discrete Semiconductor Devices — Part 3

Outline

This application note demonstrates the effects of chassis, fans, air inlets or outlets (hereinafter, “grills”), and heatsinks on the thermal resistance of discrete MOSFETs using thermal simulation.

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1. Introduction

Semiconductor devices are becoming progressively smaller while board assembly density and power consumption are increasing. This is making thermal design increasingly important for heat-generating components and automotive applications. Under these circumstances, Toshiba has published two application notes: *Hints and Tips for Thermal Design for Discrete Semiconductor Devices* that describes thermal design guidelines for reducing chip temperature based on actual measurement data and *Hints and Tips for Thermal Design for Discrete Semiconductor Devices — Part 2* that provides simulation data for the conditions under which actual measurement data cannot be obtained. These application notes provide data using the models of on-board MOSFETs exposed to ambient air through natural convection without using a chassis.

This application note, *Hints and Tips for Thermal Design for Discrete Semiconductor Devices — Part 3*, provides simulation data using forced-convection models with an enclosed chassis and a cooling fan so as to emulate real applications more closely. Although it is difficult to create evaluation boards with all possible thermal conditions because of time and cost constraints, thermal flow simulation provides useful information on the general tendency under many different conditions. As described in *Hints and Tips for Thermal Design for Discrete Semiconductor Devices — Part 2*, once a basic analysis model is created, it provides great flexibility, making it possible to considerably save time and cost.

Part 3 uses simplified models for leaded MOSFETs that are easily affected by fans and other cooling apparatus. Surface-mount packages do not lend themselves to simulation under forced-convection conditions because they provide a dominant package-to-board heat conduction path. Therefore, surface-mount packages are not modeled herein. Part 3 uses a model of a four-layer board. Since simulation makes it possible to visualize the effects of airflow and other conditions on cooling, it is useful for component placement during thermal design. We hope that this application note will help you understand thermal behavior inside a chassis.

2. Summary of simulation results

Simulations are performed under certain fixed conditions. An actual cooling effect depends on conditions. You can expect, however, that the tendencies of cooling effect that were revealed by simulation also apply to real-world devices. The following table summarizes the simulation results. Detailed conditions and the data are provided in subsequence sections.

Table 1 Summary of simulation results

Item	Conditions	Cooling effect
Placement of a MOSFET	･Heat from a single MOSFET in different sections ･A blower fan and a grill positions are changed.	･Because the fan has the greatest effect on the nearest section, the MOSFET had the lowest thermal resistance when placed there. (The lowest one is less than 60% of the highest one.) ･Because air is sucked in by the fan (inlet) and comes out of the grill (outlet), placing a MOSFET along this path is most effective.
Placement of 25 MOSFETs	･Heat from 25 MOSFETs simultaneously ･A blower or a suction fan and a grill positions are fixed.	･A blower fan produced a faster airflow. The air from a blower fan traveled along the vertical and horizontal sides of the chassis, lowering the thermal resistance of MOSFETs along airflow path. ･Although a suction fan did not produce a strong airflow, it created an almost uniform airflow across the entire chassis. A blower fan is more effective in directly cooling hot devices whereas a suction fan has an advantage in cases where there is a need to cool the entire board.
Realistic model	･A blower or a suction fan and a grill positions are changed.	･A fan and a grill have more cooling effect on nearby MOSFETs. ･A fan had less effect on MOSFETs that are located adjacent to large components, because the air from the fan hit the large components and then spread out.
Effects of grill	･A suction fan ･Change in grill size	MOSFETs near the fan exhibited less change in thermal resistance regardless of the grill size than MOSFETs, which were affected by the grill size because they are farther away from the fan and closer to the grill. Increasing the grill size (opening) is effective in cooling the entire space inside the chassis.
Natural convection vs forced convection	･Natural convection: The entire top surface of the chassis is open. ･Forced convection : A blower fan and grill	･Forced convection creates a much faster air velocity than natural convection and therefore has a greater cooling effect. (Two times in allowable power dissipation. 50% in thermal resistance.)
Distances from a fan	A chassis with relatively wide space or with the same width as for a fan	･Thermal resistance of the MOSFET in a small, airtight chassis was low across the board. ･Thermal resistance of the MOSFET increased regardless of the chassis space as it was moved farther away from the fan.
Fan performance	Change in airflow for a blower or a suction fan	Both fans with a high airflow helps reduce the MOSFET thermal resistance
MOSFET heatsinks	Change in heatsink orientations.	A heatsink works most effectively when it is directly hit by air. The greater the area that is exposed to air, the lower the thermal resistance. (At most 14% reduction)
Chassis heatsinks	MOSFET heatsinks or chassis heatsinks	The thermal resistances of a MOSFET with a chassis heatsink decreased considerably. (More than 50% reduction compared to a MOSFET heatsink.)

3. Chassis simulation models

We used two types of chassis models. The first chassis model, which measures 120 mm in length, 200 mm in width, and 40 mm in height as shown in Figure 1 and Figure 2, represents a relatively small power supply. It has three positions for a fan on the front face and three positions for a grill (i.e., air inlet/outlet) on the back. During simulation, we changed the position of either the fan or the grill according to analysis conditions instead of using all the fans and grills simultaneously. The chassis contains a board slightly smaller than it. For the sake of convenience, the board is divided into 25 sections of a 5x5 array, in each of which one MOSFET is mounted. In order to calculate the chip-to-ambient thermal resistances of these MOSFETs (hereinafter, “MOSFET thermal resistances”), we simulated their chip temperatures while changing the positions of the fan and grill. The purpose of this is to acquire data on the effects of the positions of fans, grills, and electronic devices on heat dissipation. The simulation models are designed to analyze thermal behavior inside the chassis. Because the chassis acts as a thermal boundary, its external environment is beyond the scope of analysis.

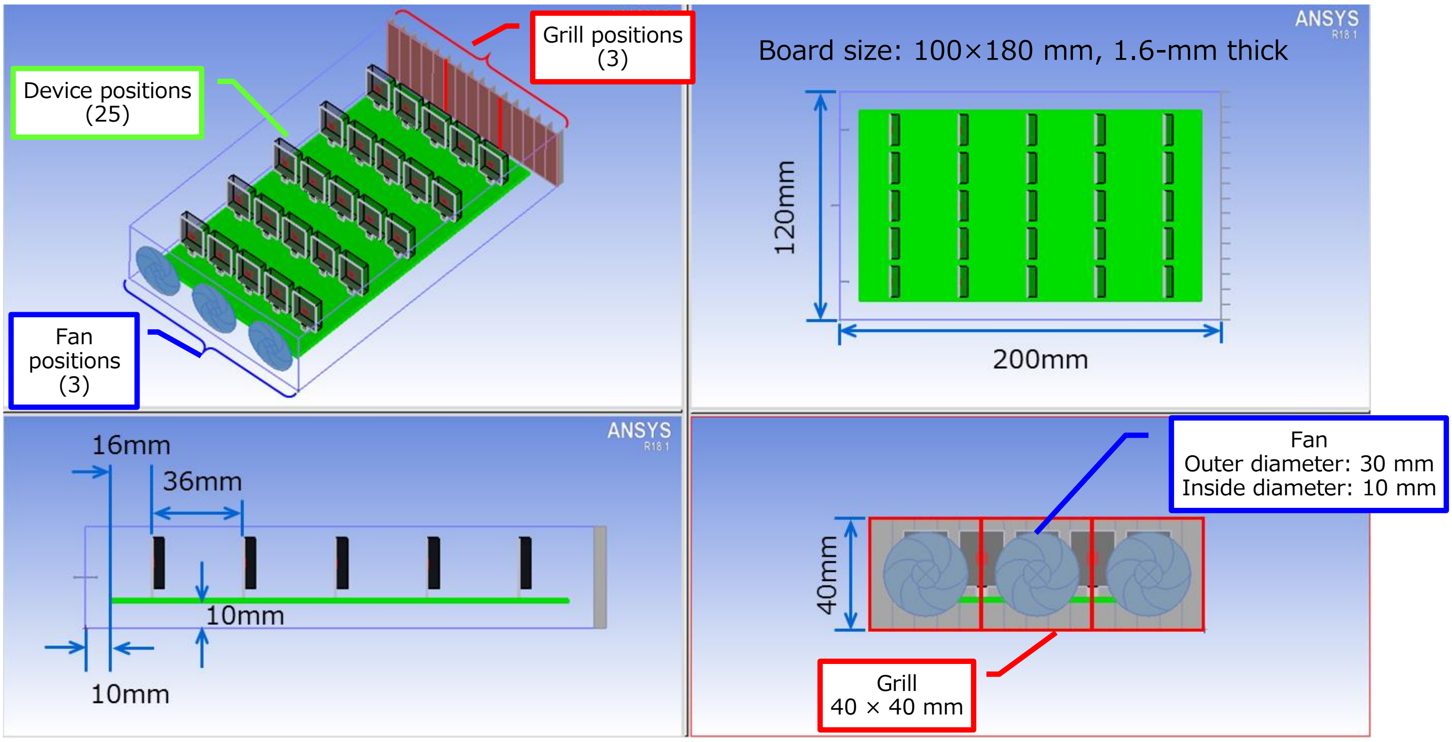
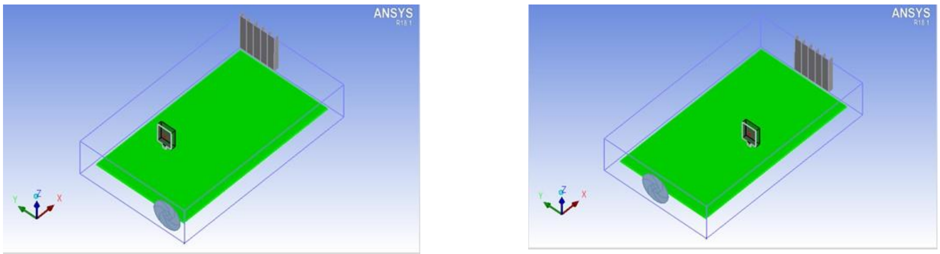


Figure 1 Simulation model 1

Table 2 Component placement (a view from the top of the chassis)

Fan position	MOSFET position					Grill position
Fan C	A5	B5	C5	D5	E5	Grill C
	A4	B4	C4	D4	E4	
Fan B	A3	B3	C3	D3	E3	Grill B
	A2	B2	C2	D2	E2	
Fan A	A1	B1	C1	D1	E1	Grill A



Model with Fan A, Grill C, and MOSFET B4 Model with Fan B, Grill B, and MOSFET C2

Figure 2 Model combination example

The other model represents actual applications more closely. (Figure 3) Whereas Model 1 has only MOSFETs, Model 2 comprises electrolytic capacitors, coils, inductors, ICs, and other types of components. Only the MOSFETs are configured to generate heat, and the other components are intended to change only the airflow. We used Model 2 to analyze the changes in MOSFET temperature under conditions close to actual applications. Unlike Model 1, Model 2 takes account of the external environment of the chassis, making it possible to analyze the model including the chassis. As is the case with Model 1, Model 2 allows the positions of the fan, grill, MOSFETs, and other components to be changed. The chassis size is also variable.

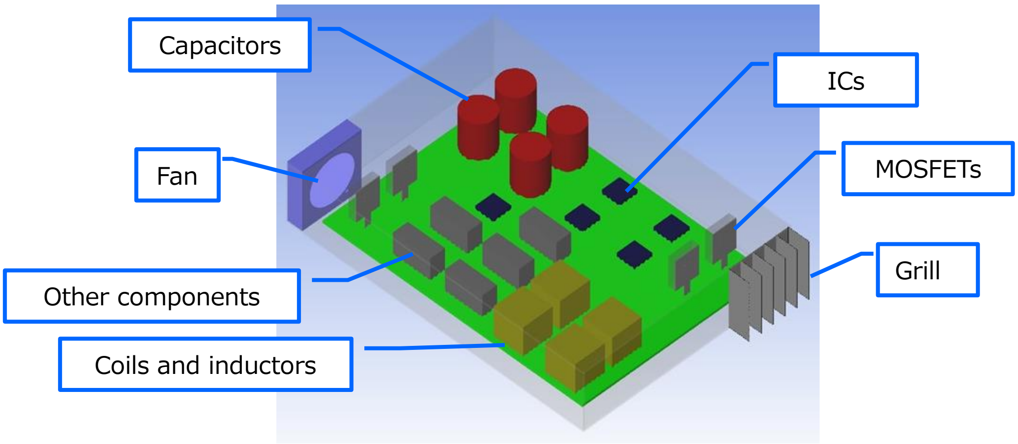


Figure 3 Simulation model 2 (example)

The following describes the simulation models in greater detail.

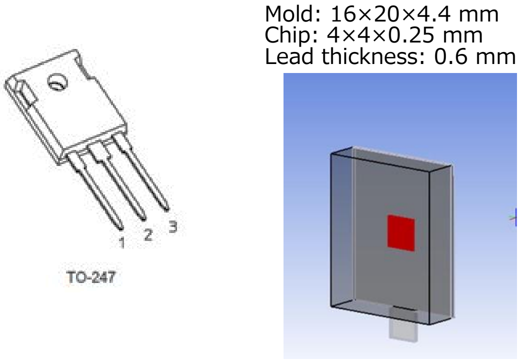
Chassis:

The chassis of Model 1 is a rectangular solid, measuring 120 mm in length, 200 mm in width, and 40 mm in height. In Model 1, all the six sides of the chassis are configured as heat insulators that do not allow heat to pass. Model 2 measures 140 mm in length, 200 mm in width, and 40 mm in height and has aluminum plates in all the six sides of the chassis so as to allow an analysis of the chassis temperature. The aluminum plates are 1-mm thick. The chassis can also act as a heatsink.

MOSFETs:

The MOSFET model is based on the TO-247 package. To reduce the analysis time, the MOSFET is modeled as consisting of three parts (mold, chip, and lead) and as being as close an approximation to a rectangular solid as possible. (Figure 4)

The chip size is 4×4×0.25 mm. Bonding wires and solder for chip mounting are omitted from the model.



Mold: 16×20×4.4 mm
Chip: 4×4×0.25 mm
Lead thickness: 0.6 mm

Figure 4 MOSFET shape (left) and simplified model (right)

PCB:

The board of Model 1 measures 100 mm in length, 180 mm in width, and 1.6 mm in thickness whereas the board of Model 2 measures 125 mm in length, 175 mm in width, and 1.6 mm in thickness. Both of them are four-layer boards. Table 3 shows the detailed settings of the boards. The board material is FR4, and all the four layers have copper (Cu) traces. The copper percentage is set as shown in Table 3. The top and bottom layers of the Model 2 board have thicker traces than those of Model 1. The settings of overall thermal conductivities of the boards are based on the results of calculation using these parameters. The boards do not have a solder resist layer on top. The simulation settings include only emissivity to compensate for the effect of a solder resist layer. The boards do not have any through-holes and thermal vias.

Table 3 Board model specifications

Board specifications for Model 1

Board size (mm)	100×180	Trace thickness (μm)		Copper percentage
Board thickness (mm)	1.6	Top-layer thickness	35	80 (%)
Board material	FR4	Bottom-layer thickness	35	80 (%)
Trace material	Cu	Inner-layer thickness	35	80 (%)
Number of layers	4			

Board specifications for Model 2

Board size (mm)	125×175	Trace thickness (μm)		Copper percentage
Board size (mm)	1.6	Top-layer thickness	70	80 (%)
Board material	FR4	Bottom-layer thickness	70	80 (%)
Trace material	Cu	Inner-layer thickness	35	80 (%)
Number of layers	4			

Other components:

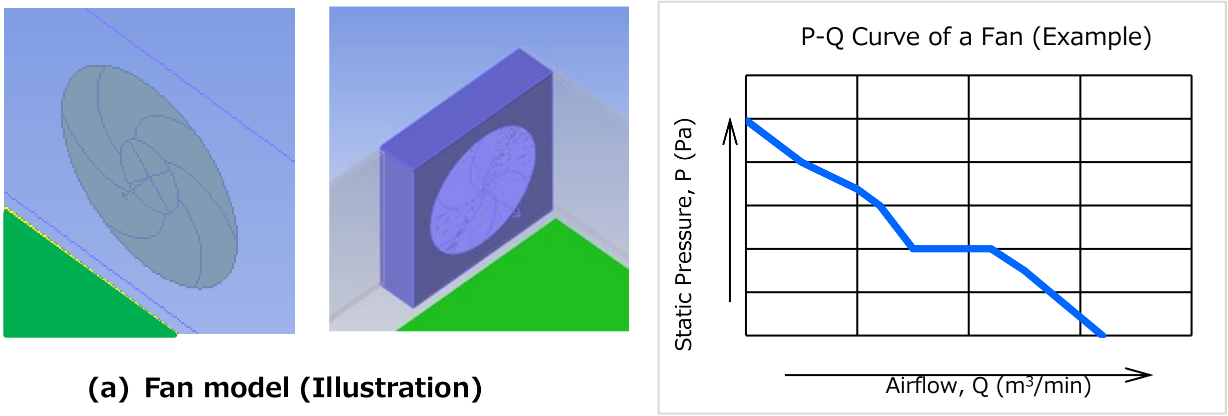
Model 2 has four types of components:

- Electrolytic capacitors
- Inductors such as coils and transformers
- IC devices
- Other components

The simulation settings include the shapes and materials of all these components. Although transformers and IC devices generate heat in reality, they are not modeled as heat-generating devices. These components are intended to act as resistance against airflow.

Fan:

The fan measures 40 mm in length and 40 mm in width. The simulation settings include its static pressure-vs-airflow curve (P-Q curve). (Figure 5(a)) Figure 5(b) shows an example of the P-Q curve of a fan. Fans with different P-Q curves were analyzed during simulation.



(a) Fan model (Illustration)

(b) Example of the P-Q curve of a fan

Figure 5 Fan model and example of the P-Q curve of a fan

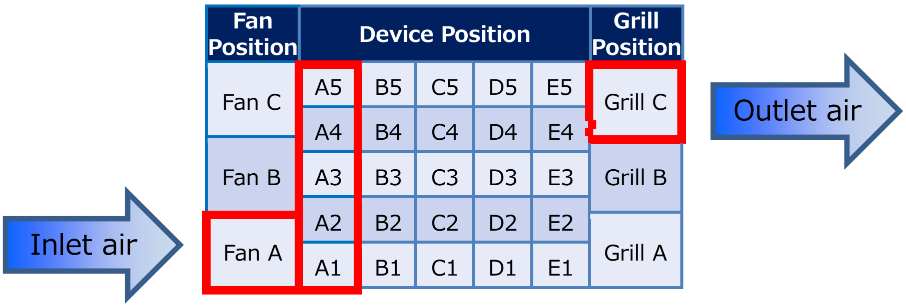
Grill:

A grill is attached on the wall of the chassis to take in or let out air. The grill can be configured to act as either an outlet or an inlet by setting the fan as a blower or a suction fan. The grill has an opening ratio of 1.0 (i.e., 100% airflow).

4. Placement of only MOSFET (Model 1)

First of all, we placed a MOSFET in different sections of Model 1 to simulate changes in chip temperature. The assumption is that the MOSFET has a power dissipation of 2 W. The fan and grill positions were also changed to measure the average MOSFET chip temperature, and thermal resistance was calculated from the MOSFET chip temperature. Figure 6 shows the temperature distribution on the board and the MOSFET as well as the air velocity vectors (with the red color being fast and the blue color being slow) when MOSFETs in A1 to A5 were individually heated.

The inlet air from the fan spreads across the chassis and comes out of the grill. In this simulation, the fan was attached at Position A whereas the grill was attached at Position C. The MOSFET was cooled by the air that comes from the fan. When the MOSFET was placed away from the airflow, it did not cool enough, causing its thermal resistance to increase. Table 4 shows the thermal resistance of the MOSFET, which has a maximum difference of 8.8°C/W depending on its position. Table 5 summarizes the thermal resistance of the MOSFET when it is placed at other positions.



Fan Position	Device Position					Grill Position
Fan C	A5	B5	C5	D5	E5	Grill C
	A4	B4	C4	D4	E4	
Fan B	A3	B3	C3	D3	E3	Grill B
	A2	B2	C2	D2	E2	
Fan A	A1	B1	C1	D1	E1	Grill A

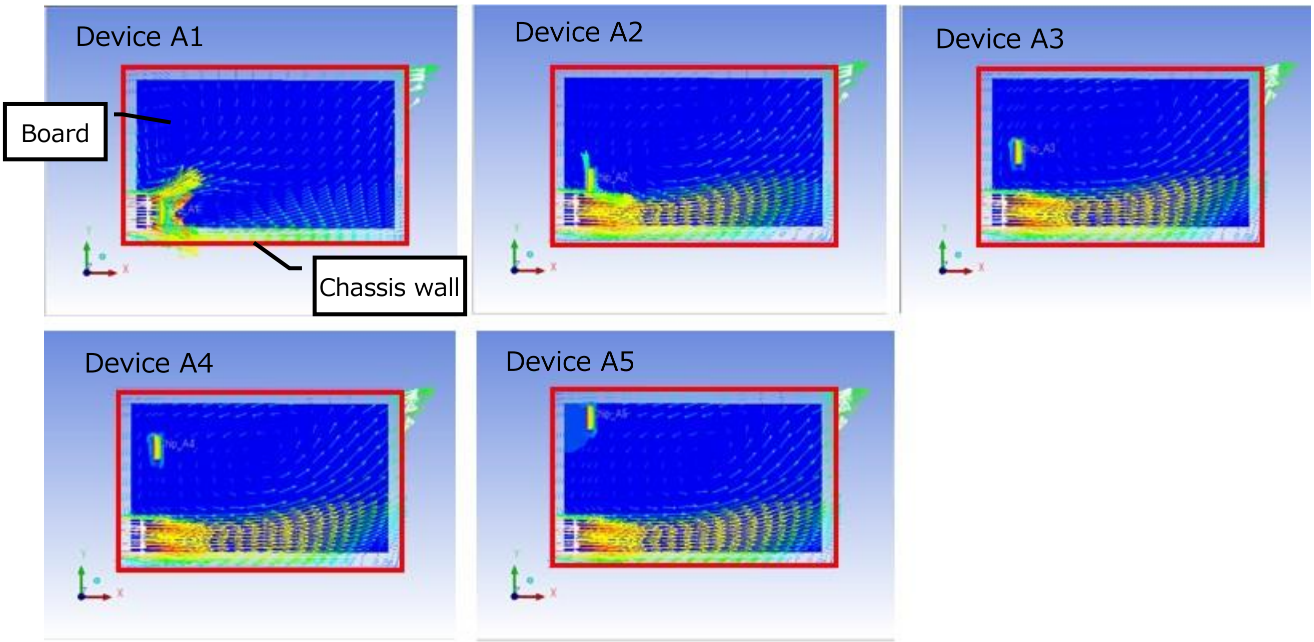


Figure 6 Airflow from Fan A to Grill C

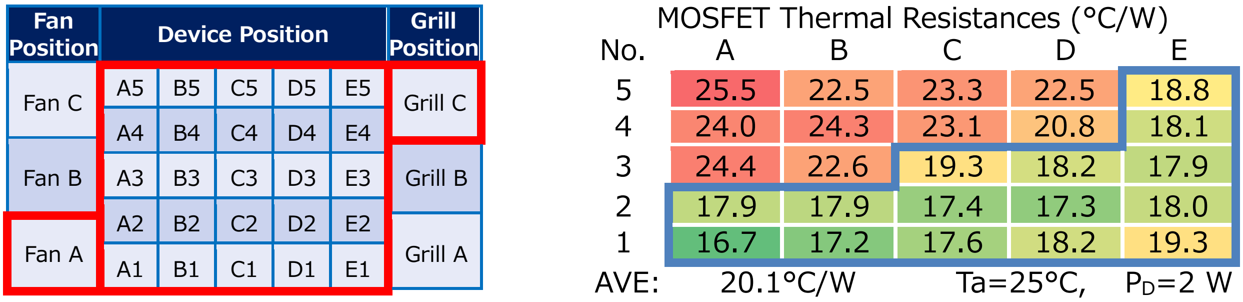
(Only the vector direction is shown for the outside of the chassis.)

Table 4 Thermal resistance of the MOSFET when placed in A1 to A5

Fan	Grill	MOSFET	Thermal Resistance (°C/W)
A	C	A5	25.5
		A4	24.0
		A3	24.4
		A2	17.9
		A1	16.7

Table 5 MOSFET thermal resistances when Fan A and Grill C are used

(A). Fan position: A, grill position: C



Fan Position	Device Position					Grill Position
Fan C	A5	B5	C5	D5	E5	Grill C
	A4	B4	C4	D4	E4	
Fan B	A3	B3	C3	D3	E3	Grill B
Fan A	A2	B2	C2	D2	E2	Grill A
	A1	B1	C1	D1	E1	

MOSFET Thermal Resistances (°C/W)

No.	A	B	C	D	E
5	25.5	22.5	23.3	22.5	18.8
4	24.0	24.3	23.1	20.8	18.1
3	24.4	22.6	19.3	18.2	17.9
2	17.9	17.9	17.4	17.3	18.0
1	16.7	17.2	17.6	18.2	19.3

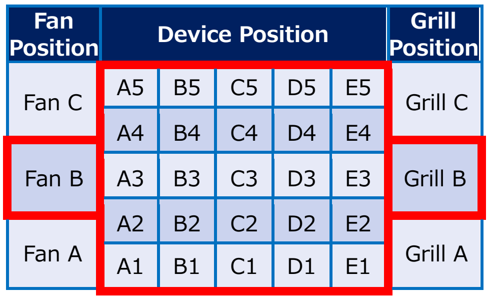
AVE: 20.1°C/W Ta=25°C, P_D=2 W

Note: Thermal resistance is calculated as
((average simulated chip temperature) – (ambient temperature)) / power dissipation.

Because the fan has the greatest effect on the nearest section (A1), the MOSFET had the lowest thermal resistance when placed in A1. Since air moves forward over the board more than spreading horizontally, the MOSFET temperature was lower when placed in front of the fan (B1 to D1). As air traveled far from the fan, it changed direction owing to the effect of the grill and did not reach E1. Therefore, the temperature of the MOSFET became higher when placed in E1. Table 6 shows the MOSFET thermal resistances for different fan and grill positions. The MOSFET has lower thermal resistance than the average when placed in the sections surrounded by blue lines. This indicates that because air is sucked in by the fan (inlet) and comes out of the grill (outlet), placing a MOSFET along this path is most effective.

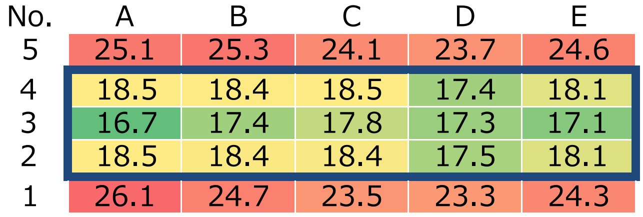
Table 6 MOSFET thermal resistances in the case of a single MOSFET acting as a heating source

(B). Fan position: B, grill position: B



Fan Position	Device Position					Grill Position
Fan C	A5	B5	C5	D5	E5	Grill C
	A4	B4	C4	D4	E4	
Fan B	A3	B3	C3	D3	E3	Grill B
Fan A	A2	B2	C2	D2	E2	Grill A
	A1	B1	C1	D1	E1	

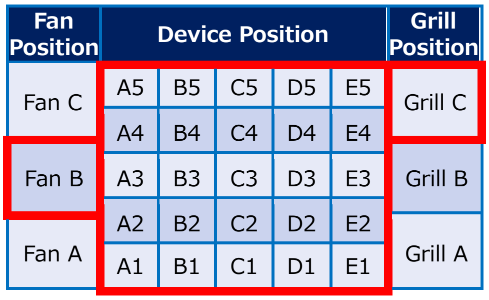
MOSFET Thermal Resistances (°C/W)



No.	A	B	C	D	E
5	25.1	25.3	24.1	23.7	24.6
4	18.5	18.4	18.5	17.4	18.1
3	16.7	17.4	17.8	17.3	17.1
2	18.5	18.4	18.4	17.5	18.1
1	26.1	24.7	23.5	23.3	24.3

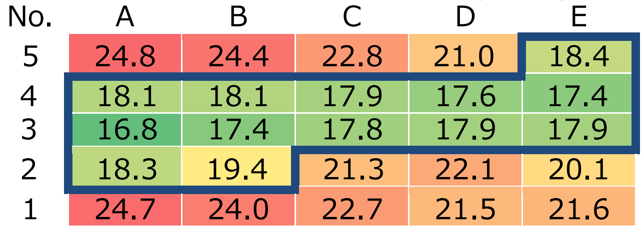
AVE: 20.5°C/W Ta=25°C, P_D=2 W

(C). Fan position: B, grill position: C



Fan Position	Device Position					Grill Position
Fan C	A5	B5	C5	D5	E5	Grill C
	A4	B4	C4	D4	E4	
Fan B	A3	B3	C3	D3	E3	Grill B
Fan A	A2	B2	C2	D2	E2	Grill A
	A1	B1	C1	D1	E1	

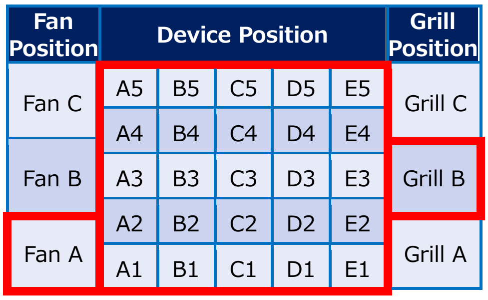
MOSFET Thermal Resistances (°C/W)



No.	A	B	C	D	E
5	24.8	24.4	22.8	21.0	18.4
4	18.1	18.1	17.9	17.6	17.4
3	16.8	17.4	17.8	17.9	17.9
2	18.3	19.4	21.3	22.1	20.1
1	24.7	24.0	22.7	21.5	21.6

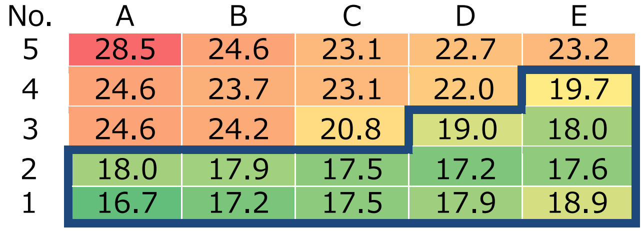
AVE: 20.2°C/W Ta=25°C, P_D=2 W

(D). Fan position: A, grill position: B



Fan Position	Device Position					Grill Position
Fan C	A5	B5	C5	D5	E5	Grill C
	A4	B4	C4	D4	E4	
Fan B	A3	B3	C3	D3	E3	Grill B
Fan A	A2	B2	C2	D2	E2	Grill A
	A1	B1	C1	D1	E1	

MOSFET Thermal Resistances (°C/W)



No.	A	B	C	D	E
5	28.5	24.6	23.1	22.7	23.2
4	24.6	23.7	23.1	22.0	19.7
3	24.6	24.2	20.8	19.0	18.0
2	18.0	17.9	17.5	17.2	17.6
1	16.7	17.2	17.5	17.9	18.9

AVE: 20.7°C/W Ta=25°C, P_D=2 W

Next, the fan and the grill were placed at the lower left and upper right corners of Model 1 respectively, and 25 MOSFETs were heated simultaneously. Figure 7 shows temperature distribution (with colors) as well as air velocity distribution (with vectors). The left figure is the case of using a blower fan whereas the right figure is the case of using a suction fan. The temperature and air velocity distributions shown in Figure 7 are different from those shown in Figure 6. This is because when all the MOSFETs are placed, the resulting airflow differs from that by a single MOSFET.

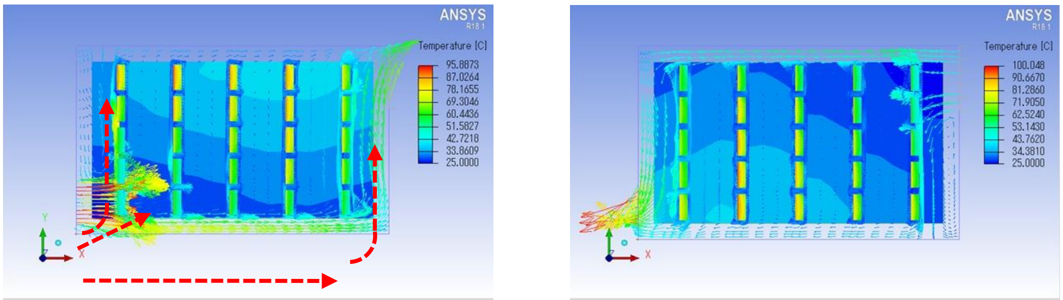
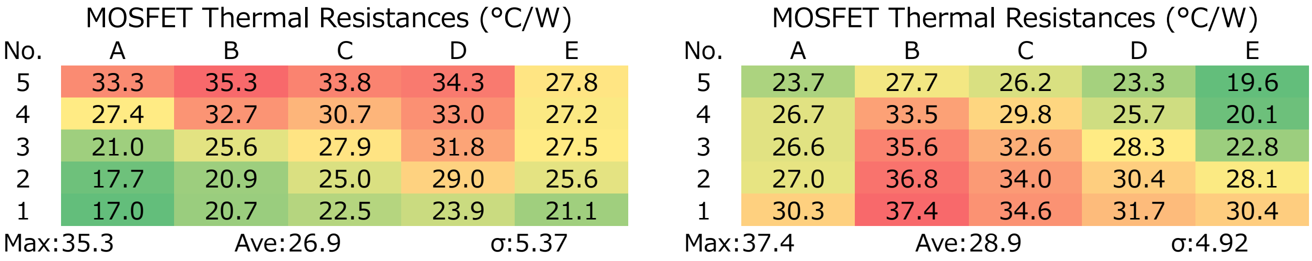


Figure 7 Temperature and air velocity distributions in a model with 25 MOSFETs: Blower fan (left), suction fan (right)

Table 7 MOSFET thermal resistances obtained from a model with 25 MOSFETs: Blower fan (left), suction fan (right)



MOSFET Thermal Resistances (°C/W)

No.	A	B	C	D	E
5	33.3	35.3	33.8	34.3	27.8
4	27.4	32.7	30.7	33.0	27.2
3	21.0	25.6	27.9	31.8	27.5
2	17.7	20.9	25.0	29.0	25.6
1	17.0	20.7	22.5	23.9	21.1

Max:35.3 Ave:26.9 σ:5.37

MOSFET Thermal Resistances (°C/W)

No.	A	B	C	D	E
5	23.7	27.7	26.2	23.3	19.6
4	26.7	33.5	29.8	25.7	20.1
3	26.6	35.6	32.6	28.3	22.8
2	27.0	36.8	34.0	30.4	28.1
1	30.3	37.4	34.6	31.7	30.4

Max:37.4 Ave:28.9 σ:4.92

Table 7 shows MOSFET thermal resistances obtained from a model with 25 MOSFETs for blower fan and suction fan. The air from a blower fan traveled along the vertical and horizontal sides of the chassis, lowering the thermal resistance of MOSFETs in Column A and Row 1. In addition, since the MOSFETs are narrowly spaced, the velocity of air increased as it passed through them. The air from the blower fan eventually reached the opposite wall of the chassis and came out of the grill, as indicated by the red arrows.

The velocity vectors indicate that a suction fan produced a slower airflow than a blower fan with the same performance. (Color vectors represent velocity, with red being fast and blue being slow.) However, a suction fan caused air to move in a different manner. Although a suction fan did not produce a strong airflow, it created an almost uniform airflow across the entire chassis. The average MOSFET thermal resistance was 26.9°C/W in the case of a blower fan and 28.9°C/W in the case of a suction fan. This indicates that a blower fan is more effective in reducing thermal resistance more than a suction fan. On the other hand, the suction fan resulted in lower variations in MOSFET thermal resistance than the blower fan, with σ=4.92 in the case of the suction fan and σ=5.37 in the case of a blower fan. The blower fan is more effective in directly cooling hot devices whereas the suction fan has an advantage in cases where there is a need to cool the entire board. However, the suction fan has less cooling effect because the generated airflow is slower. In addition, the suction fan failed to cool some MOSFETs sufficiently since its cooling effect depends on how air travels across the board.

Next, Figure 8 shows the results of a model in which MOSFETs are more widely spaced. Because of wide spacing, air moved more smoothly between the MOSFETs, causing the average MOSFET thermal resistance to decrease, regardless of whether a blower fan or a suction fan was used. (Table 8) When a fan is used, it is important to allow sufficient device spacing in order for air to pass between devices.

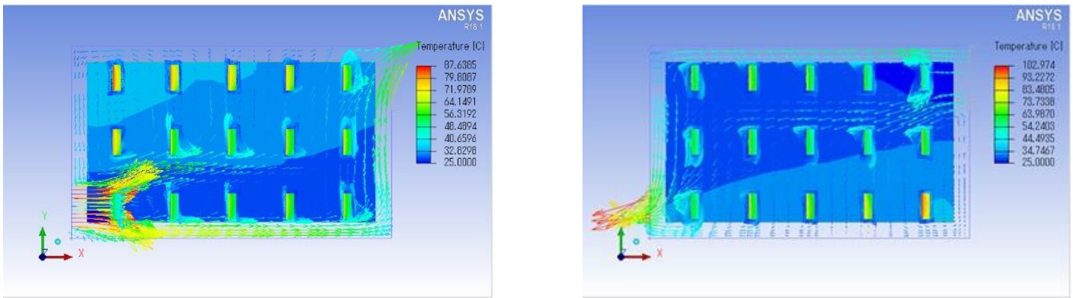


Figure 8 Thermal resistances of widely spaced MOSFETs: Blower fan (left), suction fan (right)

Table 8 Thermal resistances of each of the widely spaced MOSFETs: Blower fan (left), suction fan (right)

MOSFET Thermal Resistances (°C/W)

No.	A	B	C	D	E
5	31.2	29.2	27.9	26.8	23.3
4	–	–	–	–	–
3	28.4	21.8	21.3	22.9	23.4
2	–	–	–	–	–
1	17.0	20.3	21.9	23.5	21.4

Max:31.2 Ave:24.0 σ:3.87

MOSFET Thermal Resistances (°C/W)

No.	A	B	C	D	E
5	23.9	27.7	25.9	23.4	19.1
4	–	–	–	–	–
3	23.2	25.4	23.3	21.9	24.9
2	–	–	–	–	–
1	23.2	27.1	29.2	30.9	38.9

Max:38.9 Ave:25.9 σ:4.65

5. More realistic model (Model 2)

With Model 1, only MOSFETs were heated for analysis. Model 2 allows an analysis of MOSFET thermal resistance in a more realistic environment in which various types of components are mounted on a board.

5.1. Blower fan

Figure 9 shows the basic component placement in Model 2. Figure 10 to 12 show the temperature and air velocity distributions for different combinations of three blower fan positions and three grill positions. Model 2 has four MOSFETs. Table 9 summarizes their thermal resistances.

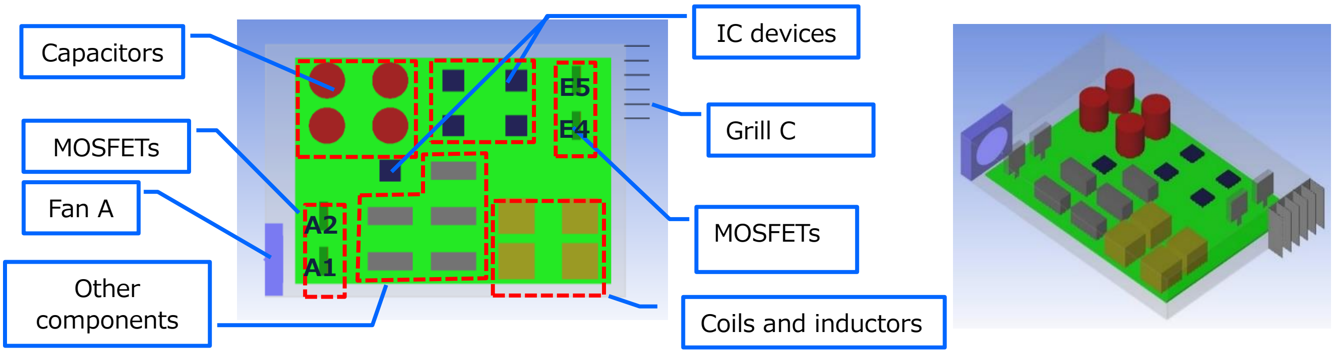
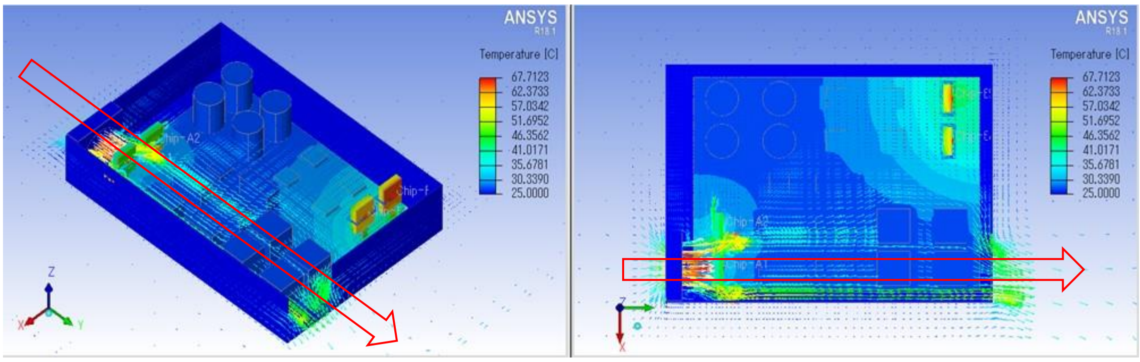
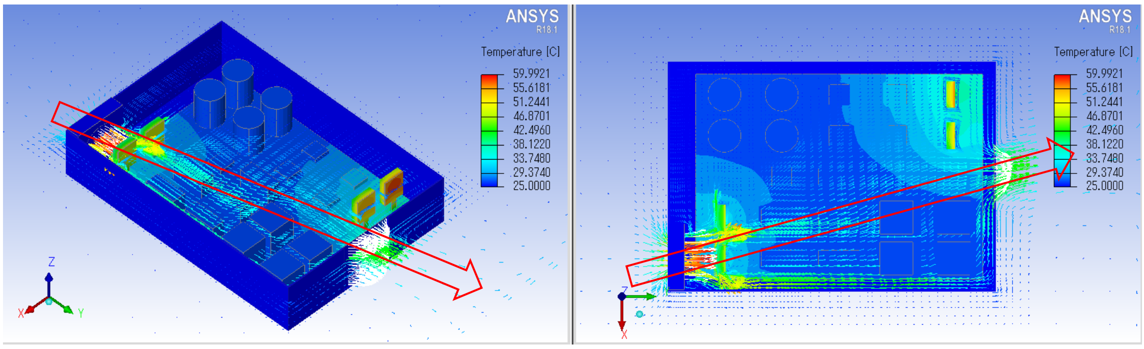


Figure 9 Component placement

From fan A to grill A



From fan A to grill B



From fan A to grill C

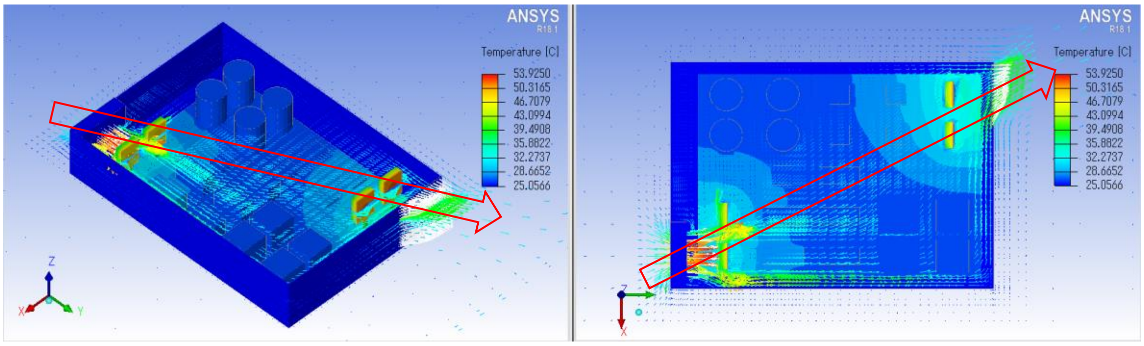
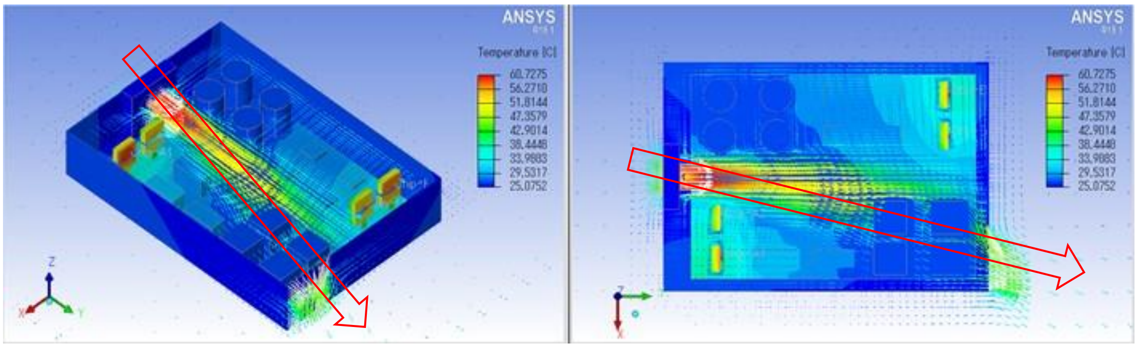
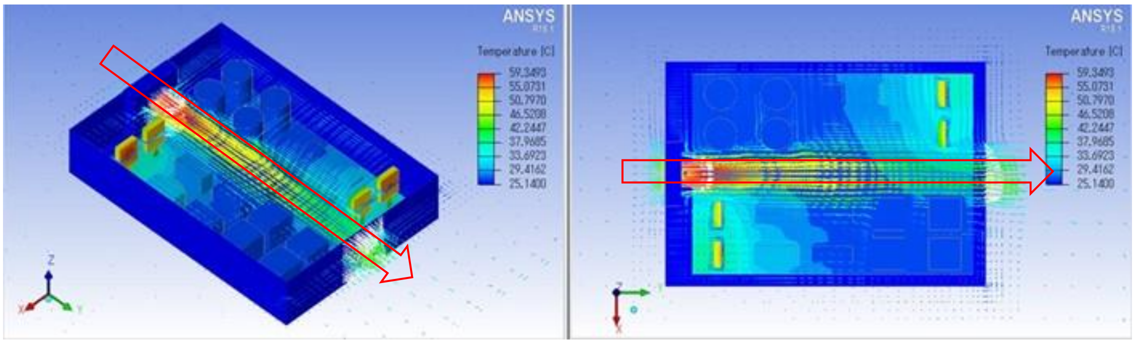


Figure 10 Temperature and air velocity distributions across Model 2 with a blower fan A

From fan B to grill A



From fan B to grill B



From fan B to grill C

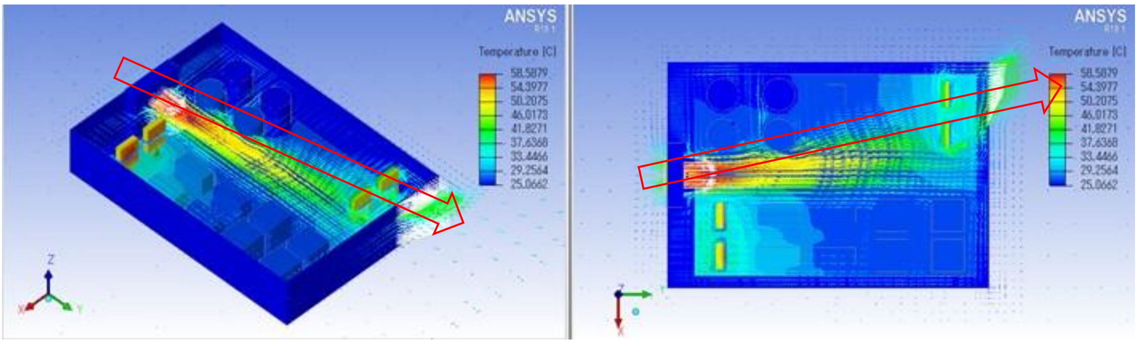
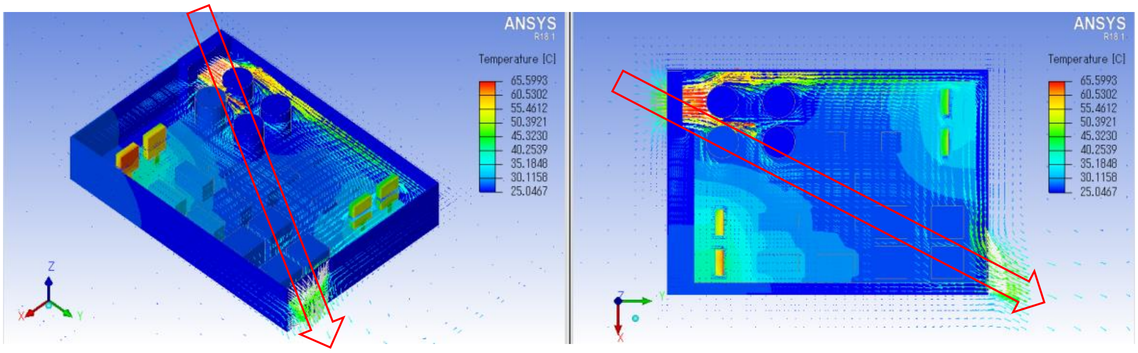
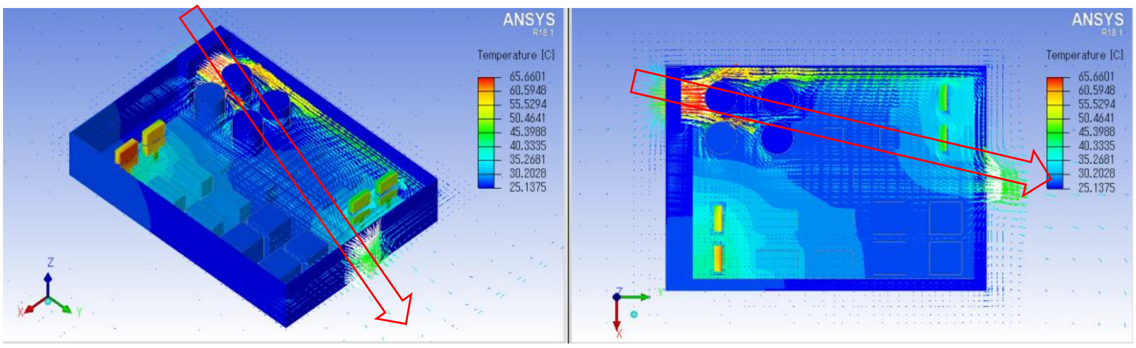


Figure 11 Temperature and air velocity distributions across Model 2 with a blower fan B

From fan C to grill A



From fan C to grill B



From fan C to grill C

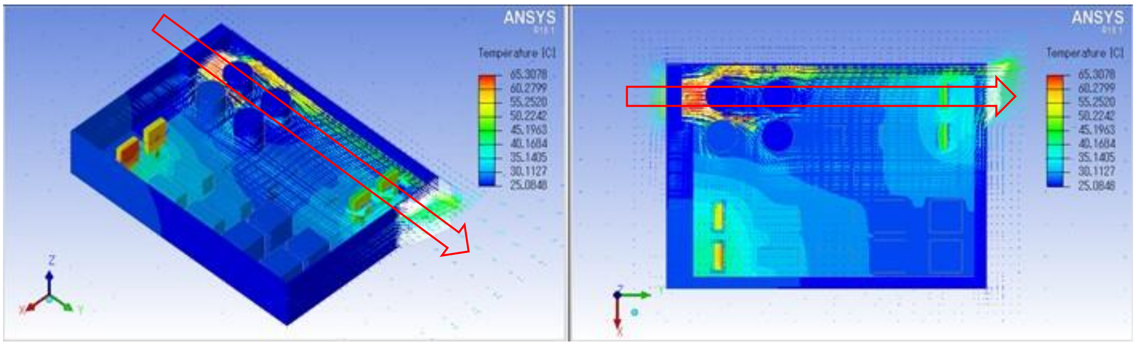


Figure 12 Temperature and air velocity distributions across Model 2 with a blower fan C

Table 9 Thermal resistances of the MOSFETs in Model 2 with a blower fan

Thermal resistances of the MOSFETs in Model 2 with a blower fan (°C/W)									
Fan Position	A			B			C		
Grill Position	A	B	C	A	B	C	A	B	C
Chip A1	12.7	12.7	12.7	17.7	17.0	16.6	20.1	20.2	20.0
Chip A2	13.0	13.0	12.9	15.7	15.6	16.0	18.1	17.9	18.2
Chip E4	19.2	15.5	14.0	15.5	14.8	13.3	14.7	14.3	14.4
Chip E5	21.2	17.3	14.3	16.9	16.5	13.7	14.6	14.3	14.0

A1 and A2, and E4 and E5, are located at almost the same positions. Since A1 and A2 are located in front of a fan, the fan had an equal effect on A1 and A2. Table 9 indicates that the grill position had no effect on these MOSFETs. Next, let's consider E4 and E5. Grill position C is closest to E4 and E5. The thermal resistances of E4 and E5 are lower with grill C because the air comes in from the fan and moves toward the grill. The MOSFETs farther away from the grill exhibited a greater increase in thermal resistance. This indicates that the grill has more cooling effect on nearby MOSFETs.

Next, let consider the case of fan position B. A1 exhibited the highest thermal resistance because it is far away from the direction of air from the fan. The thermal resistance of A2 increased for the same reason. In contrast, E4 and E5 exhibited the lowest thermal resistances because the air from fan B directly hit E4 whereas the air that hit the wall of the chassis had a positive effect on E5. E4 and E5 were cooled by the air that directly reached the back wall of the chassis because there is no component in front of fan B that blocks air.

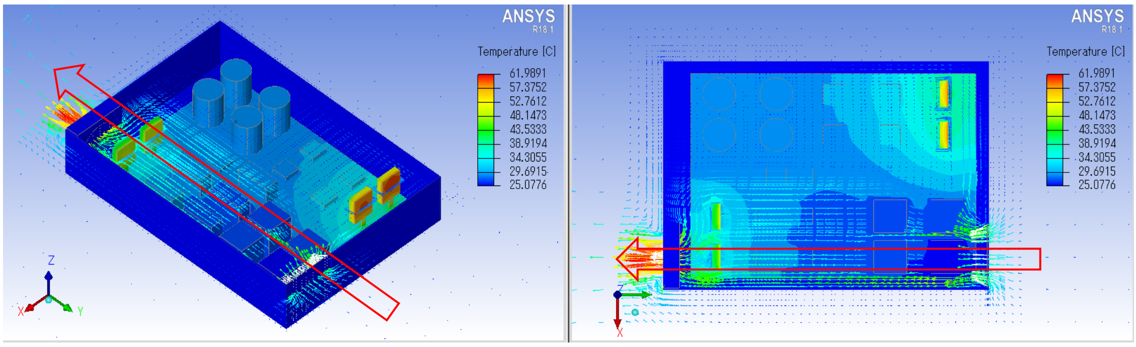
Next, let’s consider the case of fan position C. The fan had less effect on A1 and A2 that are located adjacent to a large electrolytic capacitor in front of the fan. In contrast, the fan had a moderate effect on E4 and E5 because the air from the fan hit the electrolytic capacitor and then spread out as it traveled toward the back of the chassis. Grill C is placed immediately at the back of two MOSFET. Their thermal resistances were lower in cases where air ran to the grill.

A comparison of the three fan positions reveals that fan B provides the most uniform temperature distribution with no extreme hot area. Fan A is effective when there is a need to apply air to directly cool hot devices. If it is difficult to place hot devices near a blower fan, an alternative solution may be to place them near a grill, as demonstrated by the case of fan C.

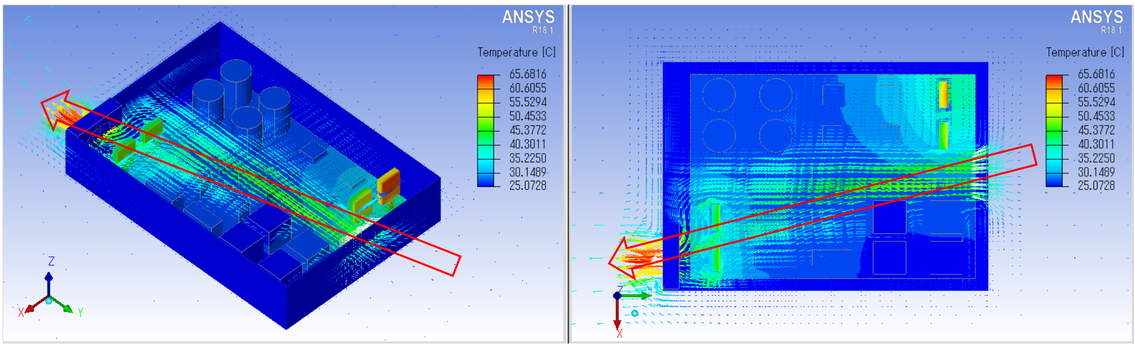
5.2. Suction fan

Next, we used the same model as used in Section 4.1 to analyze a fan that sucks air out of the chassis. Figure 13 to 15 show the temperature and air velocity distributions for different combinations of three suction fan positions and three grill positions.

From grill A to fan A



From grill B to fan A



From grill C to fan A

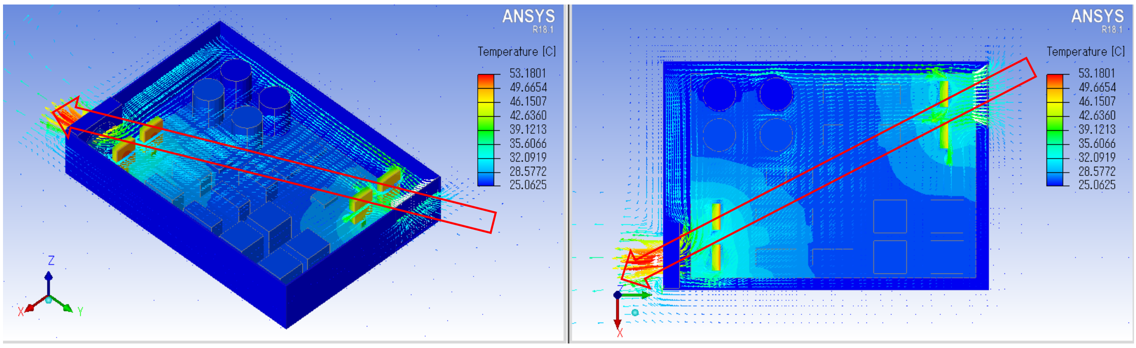
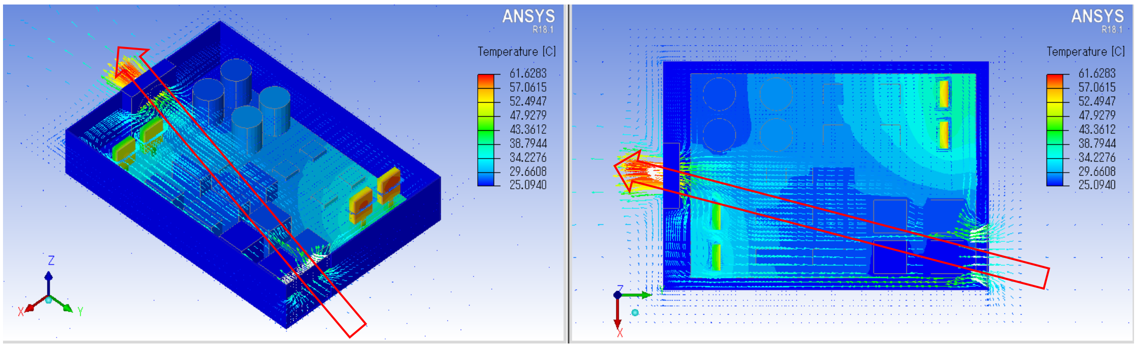
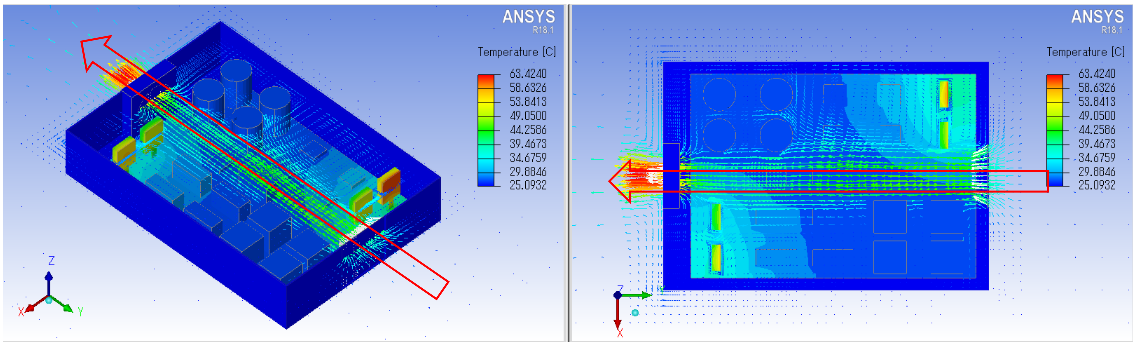


Figure 13 Temperature and air velocity distributions across Model 2 with a suction fan A

From grill A to fan B



From grill B to fan B



From grill C to fan B

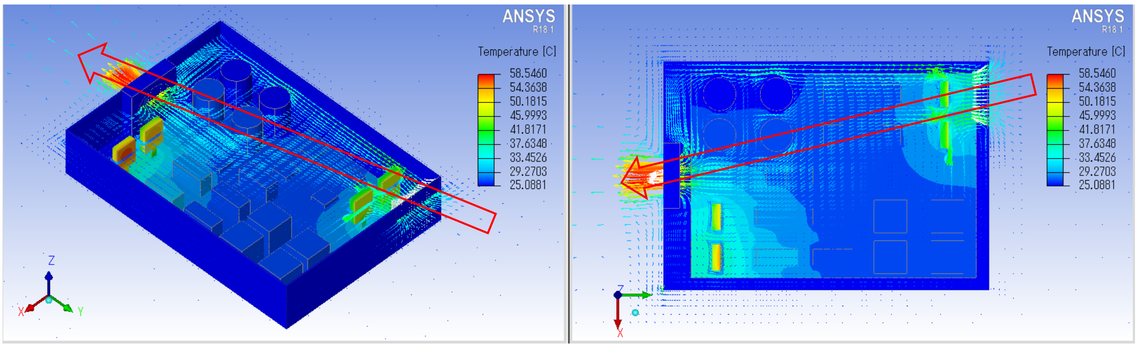
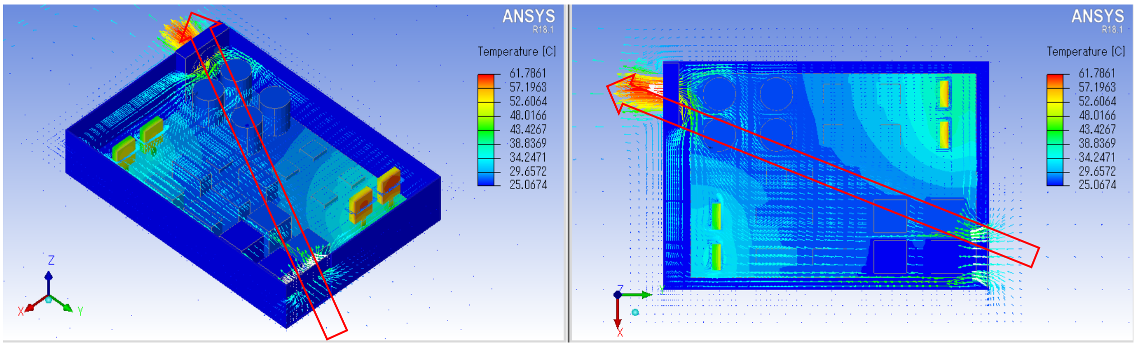
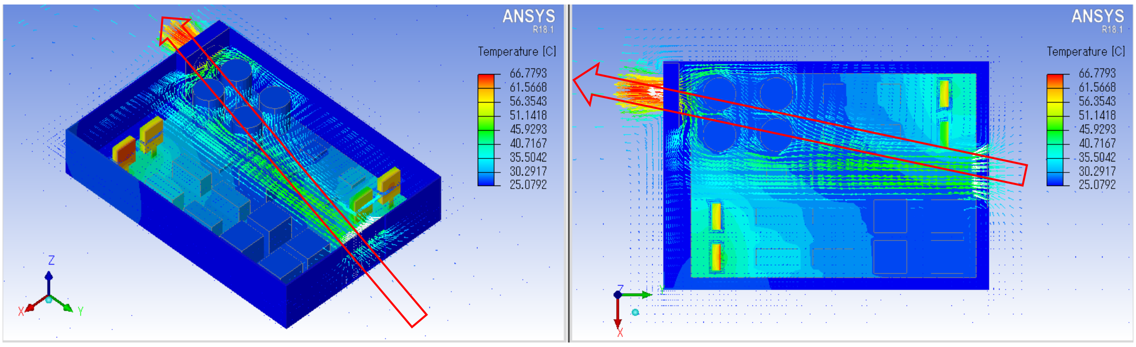


Figure 14 Temperature and air velocity distributions across Model 2 with a suction fan B

From grill A to fan C



From grill B to fan C



From grill C to fan C

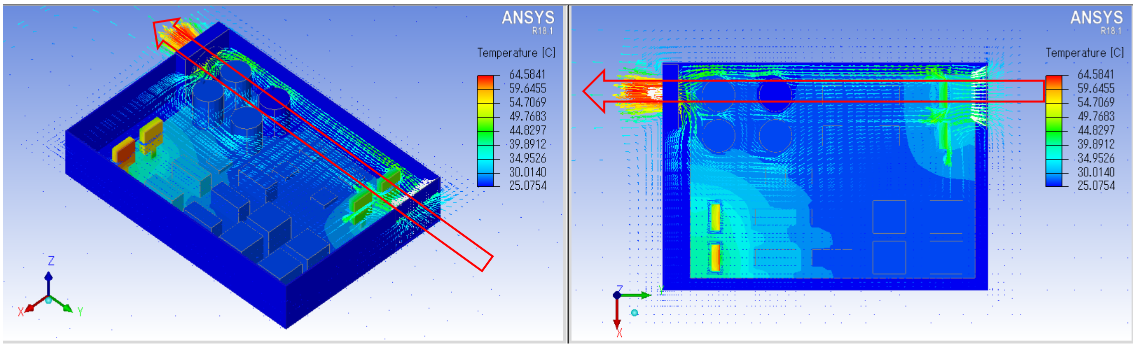


Figure 15 Temperature and air velocity distributions across Model 2 with a suction fan C

Table 10 Thermal resistances of the MOSFETs in Model 2 with a suction fan

Thermal resistances of the MOSFETs in Model 2 with an suction fan (°C/W)									
Fan Position	A			B			C		
Grill Position	A	B	C	A	B	C	A	B	C
Chip A1	13.4	13.2	13.9	13.9	16.6	16.6	14.4	20.7	19.6
Chip A2	13.8	13.0	13.8	13.5	14.0	14.9	14.0	18.5	17.6
Chip E4	18.1	15.5	12.5	18.0	14.8	12.5	18.0	14.7	12.6
Chip E5	18.3	20.2	12.7	18.2	19.0	12.7	18.2	19.2	12.8

As demonstrated with Model 1 having 25 MOSFETs, a suction fan generates airflow with less velocity than a blower fan. It is therefore inferred that a suction fan caused the MOSFETs to exhibit higher thermal resistance. (Table 10) The component placement is also considered to have affected the air velocity. A suction fan is effective for a less densely populated board that allows sufficient airflow and velocity. It is therefore important to grasp how air moves across the board. Since the airflow also varies with the grill opening size, it is also necessary to consider the grill opening size if greater cooling is required (see Section 6).

6. Effects of a grill

This section discusses the effect of the grill size on a model with a suction fan, considering the results of the preceding section. Solid lines in figure 17 plot how the thermal resistances of the MOSFETs at the center of the chassis changed with the grill size. The suction fan was fixed at position B, and a grill (air inlet) was attached to the opposite wall of the chassis as shown in Figure 16. Chips 1, 2, 3, and 4 exhibited less change in thermal resistance regardless of the grill size than Chips 5 and 6, which were affected by the grill size because they are farther away from the fan and closer to the grill. Increasing the grill size (opening) is effective in cooling the entire space inside the chassis.

For the sake of reference, broken lines in figure 17 show the thermal resistances of the MOSFETs when changing to a blower fan from a suction fan. All the chips exhibited less change in thermal resistance regardless of the grill size. Increasing the grill size is not so effective in cooling the entire space inside the chassis.

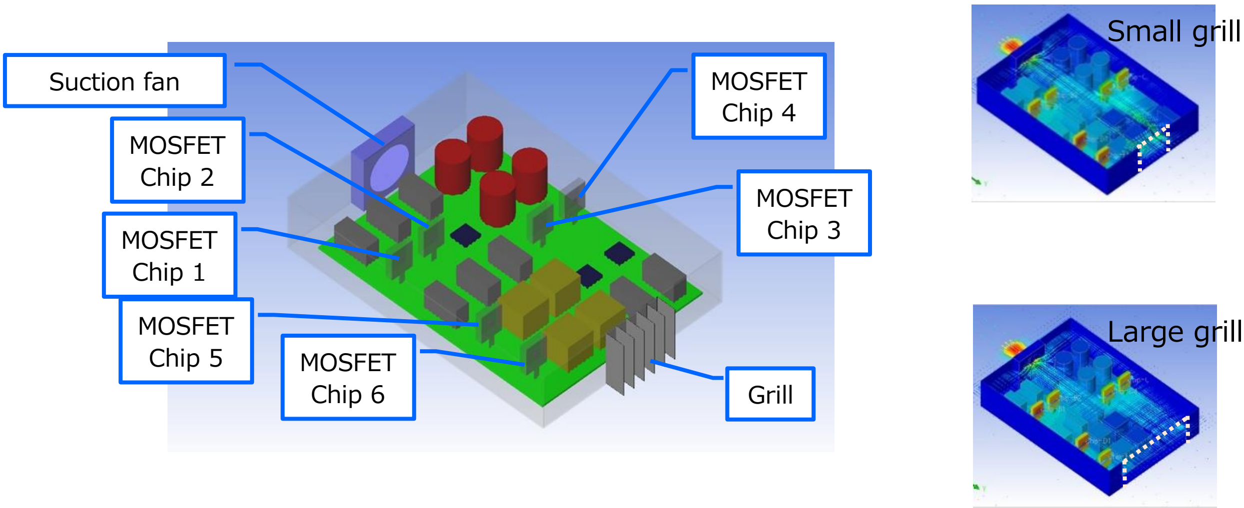


Figure 16 Model for the evaluation of the grill size

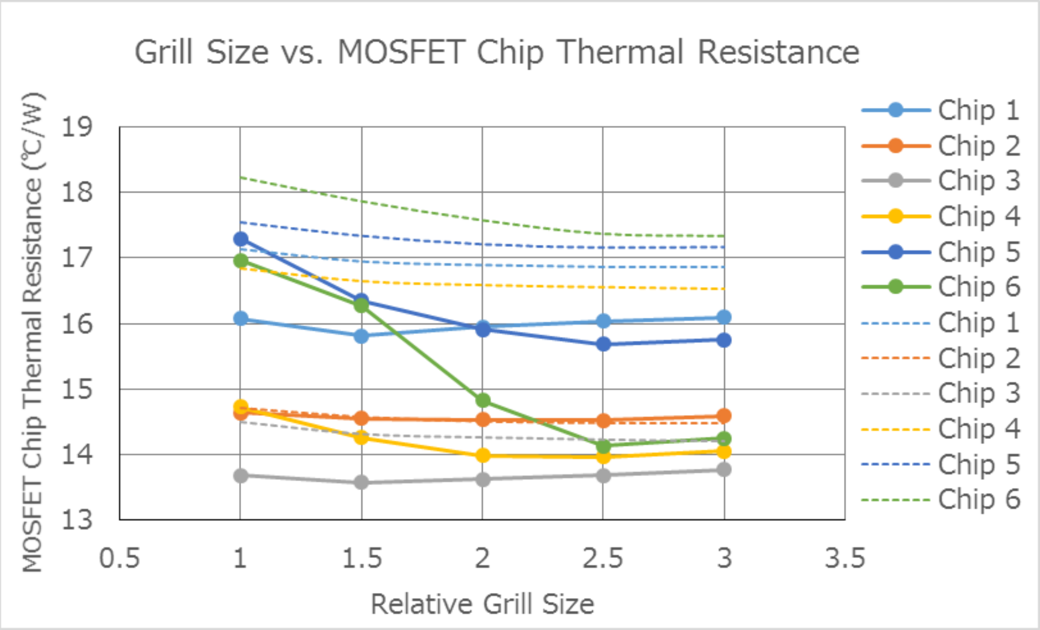


Figure 17 MOSFET thermal resistance vs. grill size

7. Natural convection vs forced convection

This section discusses the differences in the effects of natural and forced convection. Natural convection uses the circulation of warm air produced by the heat dissipated from device packages. In contrast, forced convection uses fans or other devices to pull cool air from outside to cool devices. An airflow due to natural convection rises in the opposite direction of gravity because of buoyant force. As air rises, new air rushes in to fill the space, to which heat transfers from a hot element via convection. The warmed air, in turn, rises again. This process repeats until the hot element becomes stable. Therefore, a chassis that uses natural convection must be fitted with an opening on the top through which air comes out. A chassis that uses forced convection does not need an opening on the top because airflow is controlled using fans and grills. Since air is forced to move with a fan, forced convection creates a much faster air velocity than natural convection and therefore has a greater cooling effect. However, forced convection is more costly as it requires fans as well as mechanical design.

We used two models to simulate differences between forced convection and natural convection. For natural convection, the entire top surface of the chassis was modeled as being open. For forced convection, Model 2 with fan A and grill C was used. Both the models have the same component placement as shown in Figure 18.

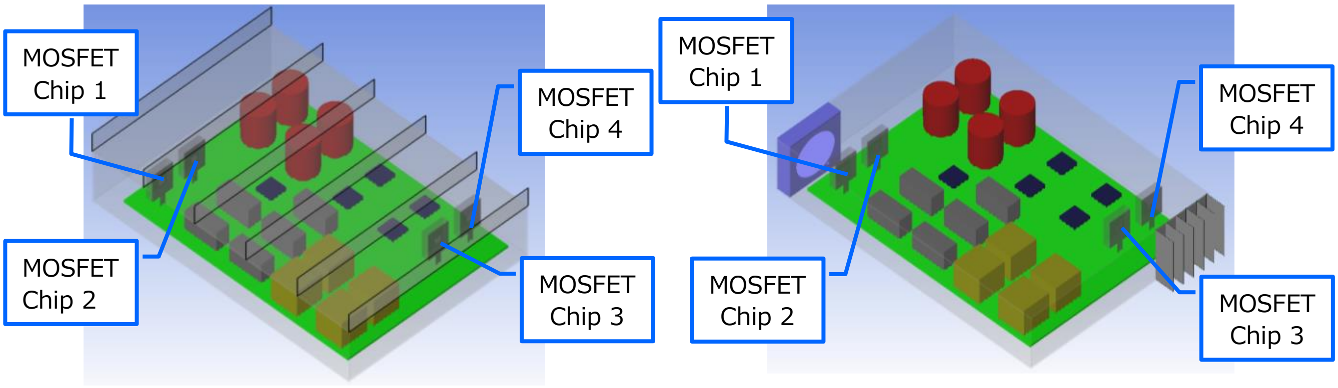


Figure 18 Natural-convection model (left) and forced-convection model (right)

Figure 19 shows the changes in the chip temperature of each MOSFET over a range of power dissipation (for comparison with the absolute maximum ratings). The red and blue lines show the chip temperature changes due to natural and forced convection respectively. The solid lines show the changes in the temperature of Chip 1 and Chip 4 on the periphery of the board (i.e., close to the chassis) whereas the dashed lines show the temperatures of Chip 2 and Chip 3 at an inner area on the board. Figure 19 shows that forced convection helps keep the chip temperature well below the absolute maximum rated temperature of 150°C and is therefore more desirable if only power dissipation is considered. (Thermal resistance is inversely proportional to power dissipation as shown in the note of the table 5.)

There are considerable differences in the MOSFET chip temperature between two models under the same conditions. Apparently, with natural convection, the temperatures of the MOSFETs close the wall of the chassis might decrease because of air convection, but the velocity of natural convection is not so fast. Because MOSFETs cool via solid-to-gas heat transfer, those in the inner area of the board tend to cool more easily as they are exposed to a greater amount of air. In the case of forced convection, MOSFET chip temperatures differed, depending on their positions relative to the fan and the grill.

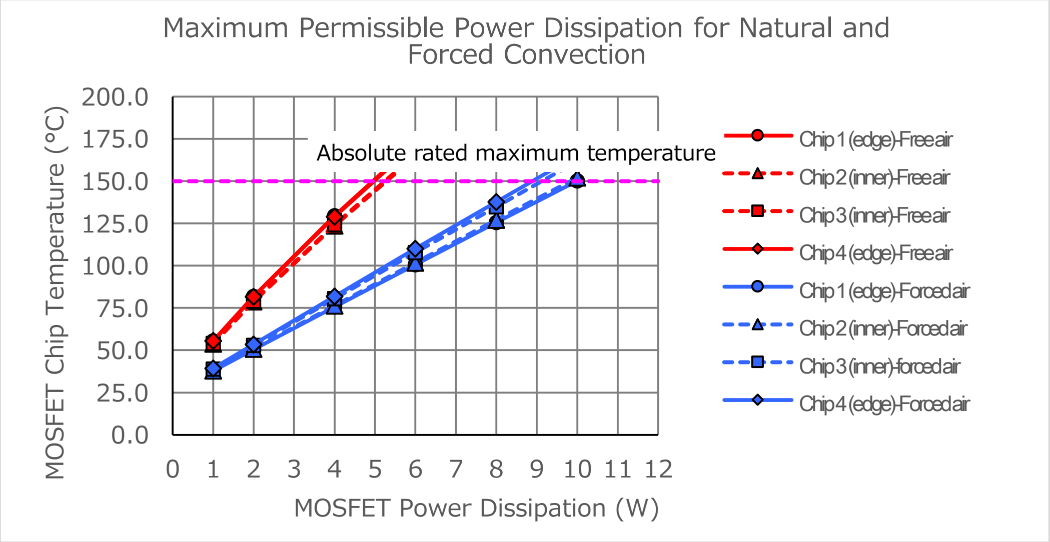


Figure 19 MOSFET chip temperatures in the case of natural and forced convection

8. Distances from a fan

In the case of forced convection, the distances from a fan to the devices to be cooled are also important. We used two models shown in Figure 20 to compare the effects of a fan: a model with relatively wide space (left) and a model with the same width as for a fan (right). We compared the thermal resistance of a MOSFET in these models while changing its position as indicated by the red arrow.

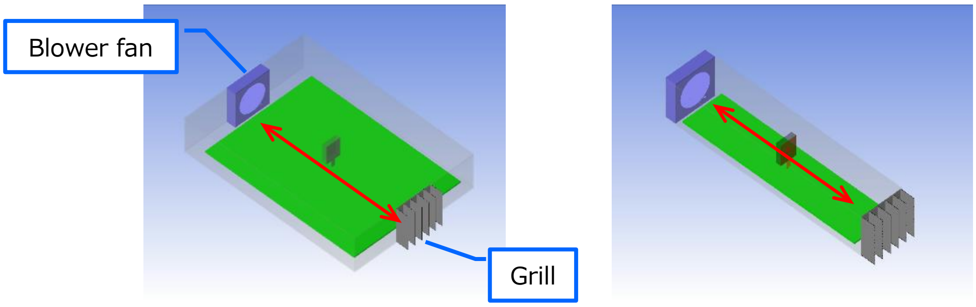


Figure 20 Simulation models used to evaluate the effects of the fan-to-MOSFET distances (with fixed fan and grill sizes)

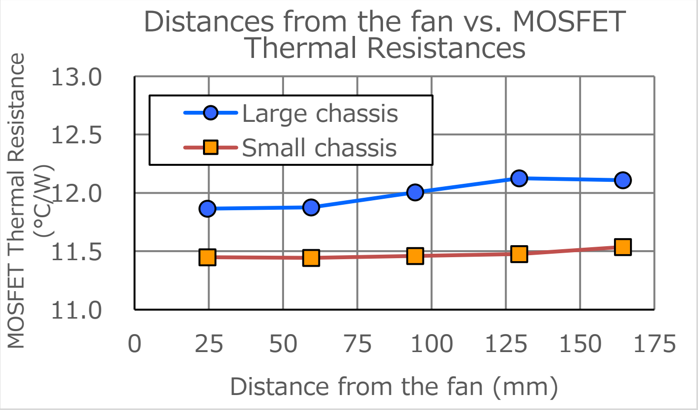


Figure 21 MOSFET thermal resistances vs. fan-to-MOSFET distances

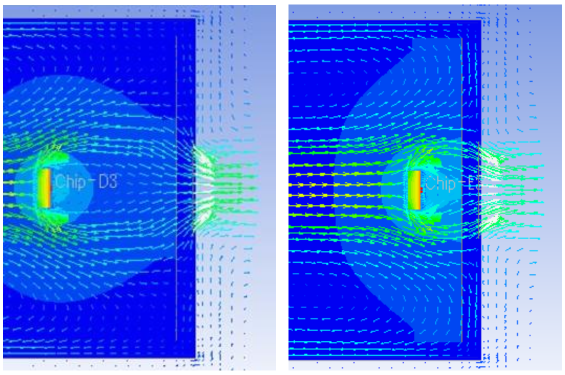


Figure 22 Airflow at the back of the MOSFET

The thermal resistance of the MOSFET in a small, airtight chassis was low and did not change much as it was moved farther away from the fan. In contrast, air from the blower fan spread wider in the large chassis as it traveled farther from the fan, causing the air velocity to decrease with the distance from the fan. Therefore, the thermal resistance of the MOSFET increased as it was moved farther away from the fan (Figure 21). However, the thermal resistance of the MOSFET decreased as it was moved to the farthest point from the fan. This is considered to have occurred because the air that spread from the fan converged as it approached the grill (Figure 22).

9. Fan performance

The P-Q curve is commonly used to represent the fan performance. P represents static pressure whereas Q denotes the airflow. (Figure 23) Since the P-Q curve is an important factor that determines the fan characteristics, it serves as a guide for selecting a fan according to the chassis size. Therefore, we compared the cooling effects of three fans with different P-Q curves (Figure 24).

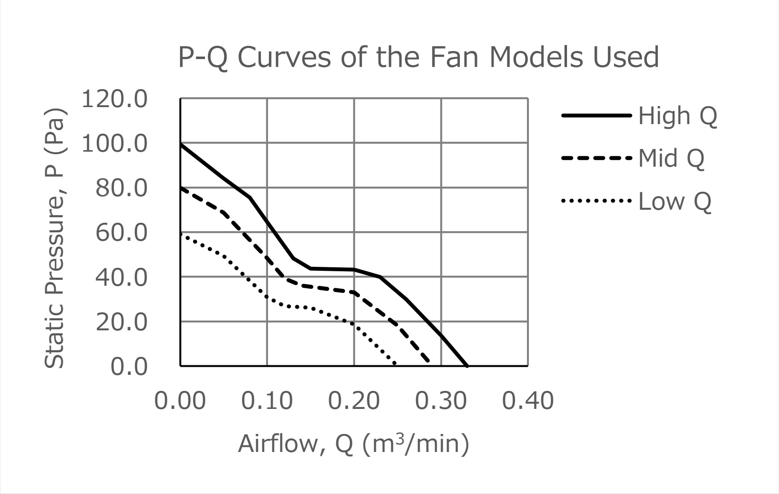


Figure 23 P-Q curves of the fan model

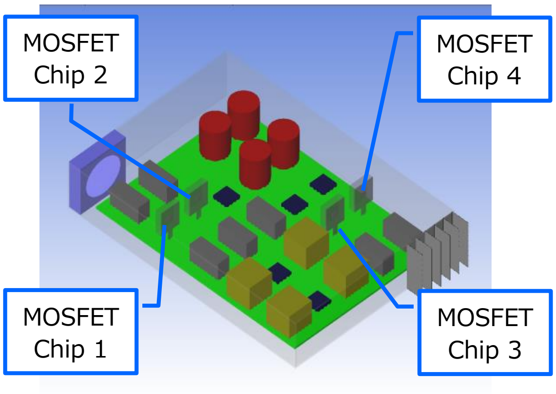


Figure 24 Analysis model

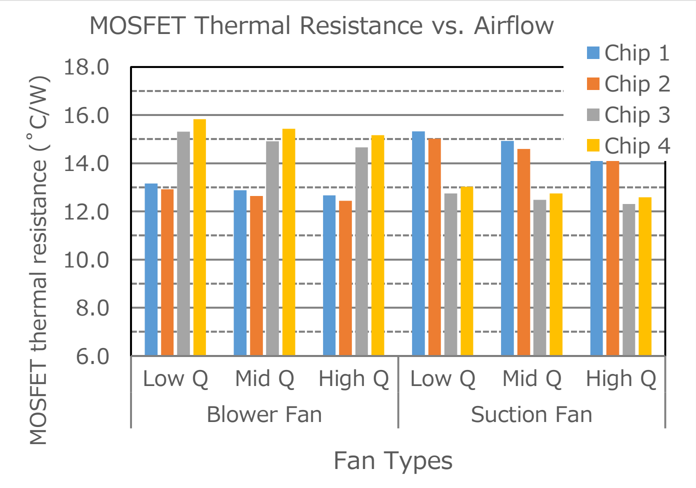


Figure 25 Comparison of the effects of fan performance on the MOSFET thermal resistance

Table 11 MOSFET thermal resistances (°C/W) when fans with different performance are used

Fan Performance	Blower Fan			Suction Fan		
	Low Airflow	Medium Airflow	High Airflow	Low Airflow	Medium Airflow	High Airflow
Chip 1	13.2	12.9	12.7	15.3	14.9	14.7
Chip 2	12.9	12.6	12.4	15	14.6	14.3
Chip 3	15.3	14.9	14.7	12.7	12.5	12.3
Chip 4	15.8	15.4	15.2	13	12.7	12.6

Figure 25 and table 11 shows that fans with a high airflow rate helps reduce the MOSFET thermal resistance. In the case of a blower fan, the MOSFET closest to the fan had the lowest thermal resistance whereas, in the case of a suction fan, the MOSFET closest to the grill had the lowest thermal resistance. This is due to the airflow along the line between the fan and the grill as demonstrated in the preceding section.

It is true that increasing airflow increases the cooling effect, but fans with a high airflow are costly and generate acoustic noise. It is therefore necessary to select an appropriate fan.

10. MOSFET heatsinks

Heatsinks are attached to the devices that generate lots of heat. We performed a simulation to evaluate the effects of heatsink orientations. For the sake of simplicity, the simulation models have a MOSFET with a heatsink at the center of a small chassis as shown in Figure 26.

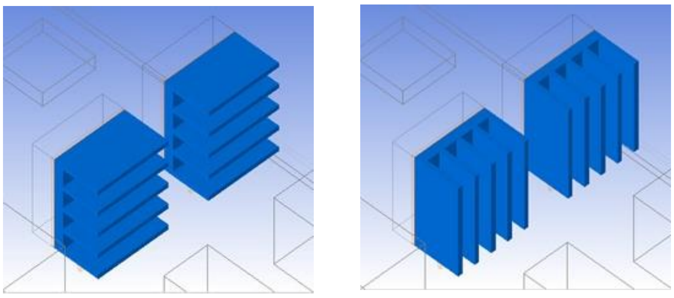


Figure 26 Heatsink orientations: Horizontal (left), vertical (right)

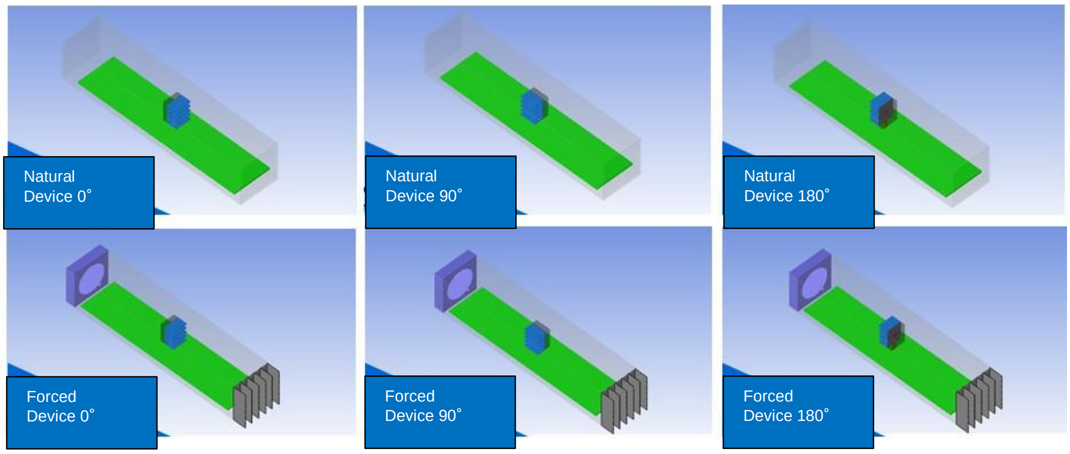


Figure 27 Simulation models used to evaluate the effects of heatsink orientations

The upper three models have natural convection whereas the lower three models have forced convection. A MOSFET was placed at a 0 degrees (with the front side facing the fan), 90 degrees, and 180 degrees (with the back side facing the fan) as shown in Figure 27.

Table 12 Effects of heatsink orientations on the MOSFET thermal resistance

Cooling Method	Heatsink		MOSFET Thermal Resistance (°C/W)		
			Device Orientation		
	With or Without	Orientation	0°	90°	180°
Natural	w/o	–	23.2	23.2	23.2
Natural	with	Horizontal	19.6	19.6	19.6
Natural	with	Vertical	18.9	19	18.9
Forced	w/o	–	11.5	11.4	11.3
Forced	with	Horizontal	7.4	6.4	6.5
Forced	with	Vertical	7.1	7.2	6.1

Table 12 shows effects of heatsink orientations on the MOSFET thermal resistance. In the case of natural convection, placing heatsinks vertically in a chassis is obviously most effective regardless of their orientations. In the case of forced convection, the MOSFET that receives air on the hot side (i.e., the metal exposed on the back side of the mold of the MOSFET model) had the lowest thermal resistance when no heatsink is attached to it. However, a heatsink affects the thermal resistance, depending on its orientation and the direction of airflow. A heatsink works most effectively when it is directly hit by air. The greater the area that is exposed to air, the lower the thermal resistance.

Figure 28 shows the airflow around the heatsink when it was placed vertically. In all cases shown in Figure 28, air comes in from the left side. When the heatsink was oriented at 0 degrees, the MOSFET was cooled by the air that moved around the edges of the heatsink. When the heatsink was oriented at 90 degrees, only the leftmost fin of the heatsink was hit by a sufficient amount of air. When the heatsink was oriented at 180 degrees, air also traveled between the fins of the heatsink, causing the heatsink to exert a significant cooling effect and reduce the MOSFET thermal resistance. In fact, a simulation shows that the MOSFET had the highest thermal resistance when a heatsink was attached at 90 degrees and the lowest thermal resistance when a heatsink was attached at 180 degrees.

When a heatsink is placed horizontally at 90 degrees, its fins are oriented in the same direction as airflow. Therefore, the heatsink provides a significant cooling effect as a large area of the heatsink is exposed to air. In this case, the heatsink causes the MOSFET thermal resistance to be lower than the case in which the heatsink is oriented at 0 degrees at which lots of air do not hit its fins. As described above, the effect of a heatsink varies depending on its placement and orientation (horizontal vs. vertical). It is advisable to evaluate its effect through experiments or simulation.

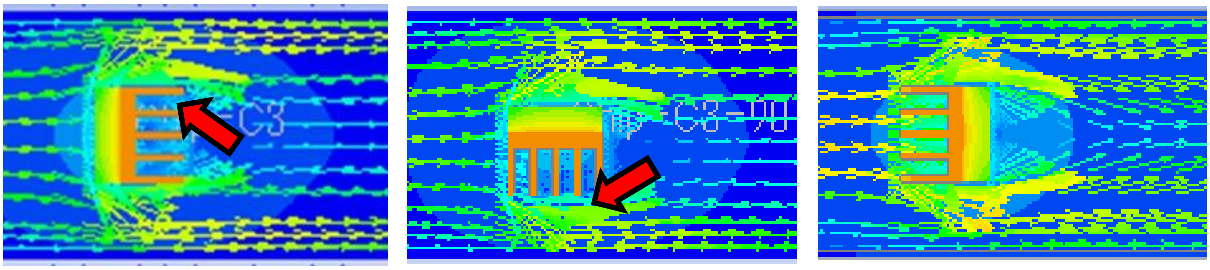
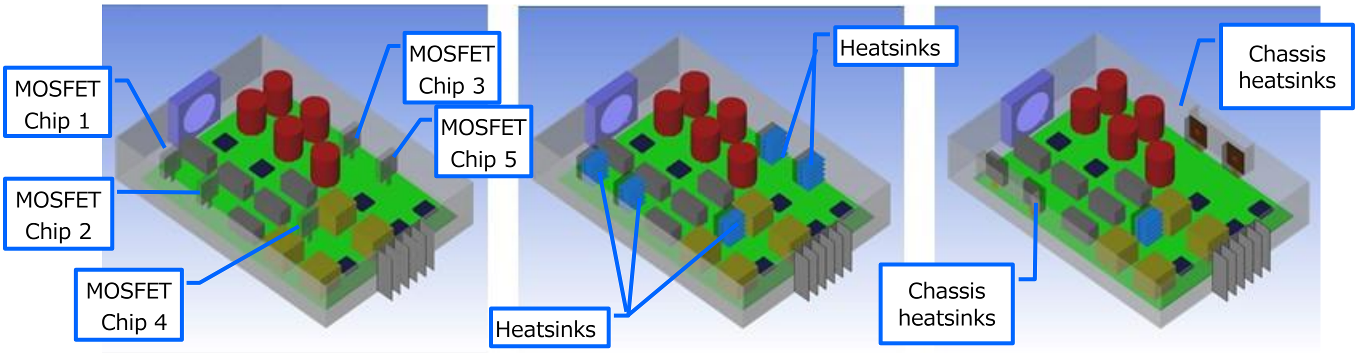


Figure 28 Air velocity distribution around the heatsink

(Inner fins have less cooling effects as highlighted by red arrows because of low airflow.)

11. Chassis heatsinks

It is sometimes difficult to attach heatsinks to MOSFETs in limited chassis space as described above. Depending on the board layout, it is also sometimes necessary to attach heatsinks close to the wall of a chassis where a sufficient amount of air does not pass. In such cases, chip temperature can be decreased by using a chassis as a heatsink. Figure 29 shows three models. The leftmost model has only a fan and no heatsink. The rightmost model shows chassis heatsinks connected to the chassis with aluminum plates. For the sake of comparison, we also analyzed a model in which heatsinks are attached to each MOSFET. A thermal interface material (TIM) was inserted between the chassis heatsinks and the MOSFET in order to provide electrical insulation between them. Therefore, the TIM was also modeled in addition to the chassis heatsink. The TIM was also modeled for each MOSFET heatsink.



(a) No heatsink (b) Attach heatsink to MOSFETs (c) Use a chassis as a heatsink

Figure 29 Simulation models:

Table 13 and figure 30 show the simulation results. The thermal resistances of four MOSFETs with a chassis heatsink decreased considerably. A chassis heatsink was not attached MOSFET Chip 4 because it is placed at the center of the board. Its thermal resistance slightly decreased probably because of a change in airflow resulting from the changes made to the orientations of the other MOSFETs.

Chassis heatsinks use thermal conduction, which is advantageous in terms of heat dissipation. However, using chassis heatsinks makes chassis design more complicated. This simulation assumed the use of an aluminum chassis. Chassis heatsinks might not provide expected results, depending on the chassis material. Great care is required for applications that come in direct contact with human beings because chassis heatsinks cause the chassis temperature to increase.

Table 13 MOSFET thermal resistances when chassis heatsinks are attached

MOSFET Thermal Resistance (°C/W)				Remarks
Heatsink	(a)	(b)	(c)	
Chip 1	18.1	12.8	5.8	-
Chip 2	16.5	11.3	5.7	-
Chip 3	16.6	12.4	5.5	-
Chip 4	13.6	10	9.6	No chassis heatsink
Chip 5	17	13	5.5	-

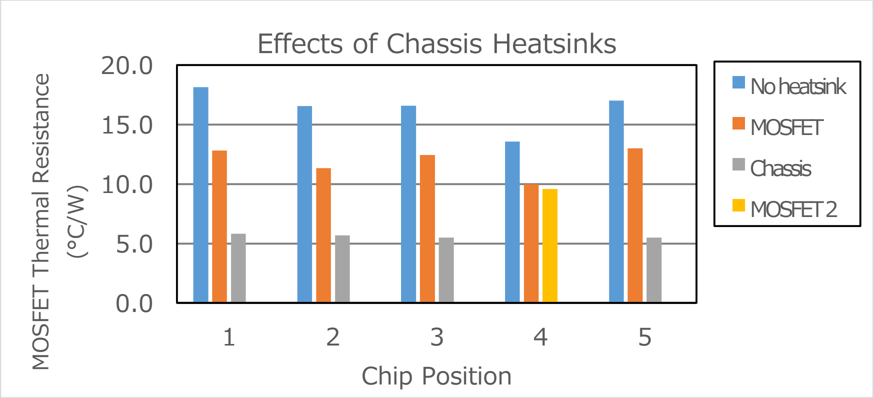


Figure 30 Effects of chassis heatsinks

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