4th-Generation Aluminum Direct Liquid Cooling Package Technology for xEV

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ABSTRACT

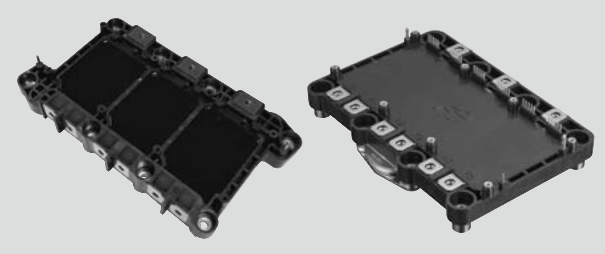
In recent years, the automotive industry has accelerated the development and spread of hybrid electric vehicles (HEVs) and electric vehicles (EVs). As a result, power modules need to be more compact and lightweight while achieving lower loss and higher output in order to improve fuel efficiency. Fuji Electric has developed a design technology for heat-dissipating cooling units, as well as a technology for replacing the aluminum wires in the main circuits of semiconductor devices with lead frames. 4th-generation direct liquid cooling modules for automotive applications use the lead frame wiring technology, as well as the enhanced design technology for heat-dissipating cooling units. They also reduce the footprint and height, thus improving power density per volume by 36% compared with 3rd-generation direct liquid cooling modules.

1. Introduction

Reducing CO_2 emissions and conserving energy to mitigate global warming are becoming increasingly important around the world as initiatives to achieve the United Nation's Sustainable Development Goals (SDGs). The spread of electric vehicles (xEVs), such as hybrid electric vehicles (HEVs) and electric vehicles (EVs), which run on electric motors is accelerating. Inverter units used to control these motors must be mounted in a location with limited space, and they need to be compact, have a high degree of mounting flexibility and be lightweight and highly efficient in order to facilitate low fuel and power consumption. We have been developing compact, high-output power modules to meet these needs.

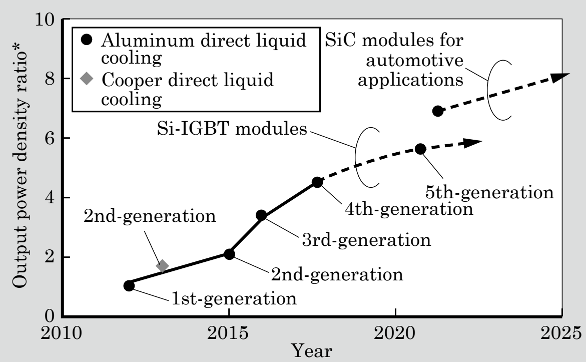
2. Development History of Fuji Electric's Direct Liquid Cooling Modules for automotive applications

Figure 1 shows the 3rd- and 4th-generation aluminum direct liquid cooling modules for automotive applications, and Fig. 2 shows the power density trend in direct liquid cooling modules for automotive applications. Fuji Electric has developed an aluminum direct liquid cooling module for automotive applications, equipped with a lightweight, corrosion-resistant aluminum cooling unit. Power density has improved at least 20% with each generation starting with the 1st-generation in 2012, 2nd-generation in 2015 and 3rd-generation in 2017.[1] To achieve this, we have been developing semiconductor chips, such as a reverse-conducting insulated gate bipolar transistor (RC-IGBT)[4] that integrate an IGBT and free wheeling diode (FWD). We have also developed various technologies, such as high heat-dissipating cooling design technology[(1)-(3)], high reliability solder technology[1], ultrasonic



(a) 4th-generation (b) 3rd-generation

Fig.1 Aluminum direct liquid cooling modules for automotive applications



* Output power density ratio: Power density ratio for each generation when the 1st-generation aluminum direct liquid cooling module is set to 1 as the reference point.
Power density (kVA/L) = Maximum output power (kVA) / module volume (L)

Fig.2 Power density trend in direct liquid cooling module for automotive applications

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bonding technology[(2),(3)] and 175 °C continuous operation guarantee technology[(2),(3)].

In order to achieve a higher power density and output, the 4th-generation not only improved the high heat-dissipating cooling unit design technology, but also changed the chip's main circuit wiring from aluminum wires to a lead frame. As a result of these enhancements, the power density of the 4th-generation module is 36% higher than that of the 3rd-generation.

3. Challenges Surrounding Direct Liquid Cooling Package Technology

High power density requires both high output and compactness. In order to achieve both, it is necessary to reduce the size of components, starting with the chip, and achieve high-density mounting. Figure 3 shows the analysis results of the effect of the chip size on the chip junction temperature T_{vj} when using a direct liquid cooling module under constant current conditions. As the chip area decreases, the chip temperature rises. When the chip area is reduced by 25%, T_{vj} increases by 8 °C. In order to reduce the size of the chip, either of the following is required.

(a) Improve heat dissipation performance and reduce chip temperature.

(b) Raise the guaranteed operating temperature by improving the heat resistance (improve reliability).

Therefore, we have developed an aluminum direct liquid cooling package as a cooling technology that improves heat dissipation performance.

4. Development of an Aluminum Direct Liquid Cooling Package

The heat dissipation performance of the power module depends on the thermal conductive performance, which expresses the performance of heat generated by the chip to the cooling fins (thermal conductivity/heat transfer distance), and the heat transmissibility, which expresses the heat transfer performance between the cooling fins and refrigerant (heat transfer coefficient × surface area/module heat transfer area). In other words, to improve cooling performance, it is important to increase heat dissipation, focusing on the heat conductivity of the cooling unit itself and the heat transfer performance of the refrigerant.

4.1 Low thermal resistance

By changing the material of the cooling unit from copper to aluminum, the mass was reduced to approximately one-third. In regard to the thermal conductive performance of the cooling unit, the thermal conductivity of aluminum (170 to 210 W/mK) is lower than copper (393 W/mK). Therefore, it is essential to thin the base that joins the device to the cooling unit to improve the performance of the aluminum cooling unit. Thermo-fluid analysis was performed to analyze this effect. Figure 4 shows the analysis model of direct liquid cooling when the insulating substrate and simple cooling unit are joined together with solder. The cooling fins were 1 mm thick, spaced 1 mm apart, and 10 mm high. The refrigerant was set to flow evenly to the refrigerant inlet and the flow velocity at the central part of the cooling fin cross section was adopted as the representative flow velocity.

Figure 5 shows the results of the analysis. Ther-

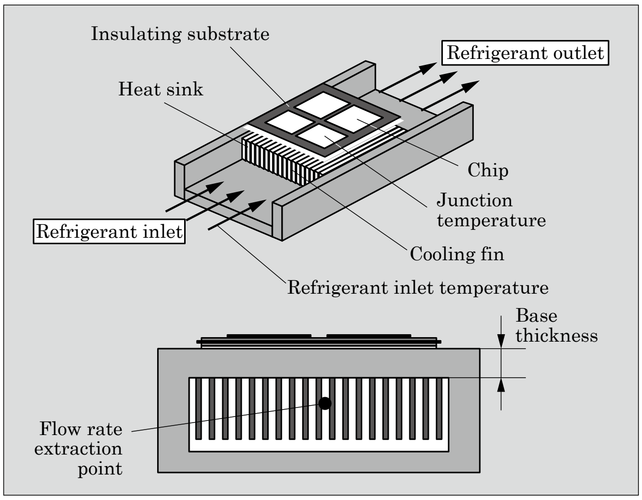

Fig.4 Thermo-fluid analysis module

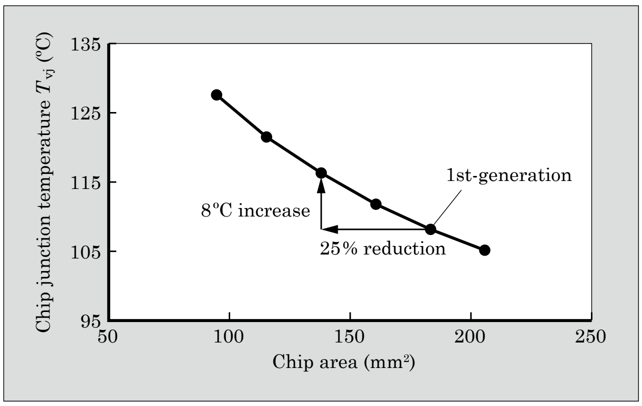

Fig.3 Effect of chip size on junction temperature

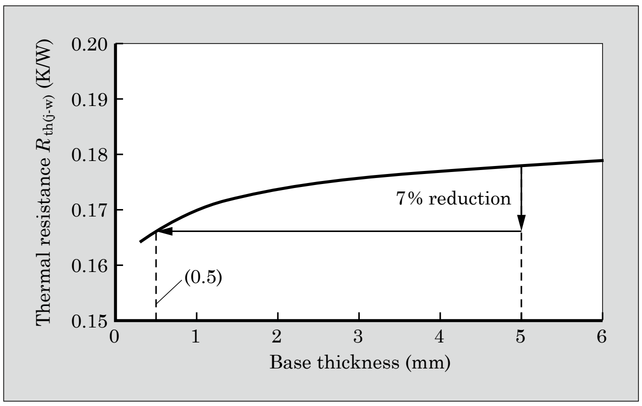

Fig.5 Dependence of base thickness on thermal resistance

mal resistance R_{th} is an indicator of the heat dissipation performance of the power module. It is the value obtained by dividing the temperature difference generated between T_{vj} and the location of comparison by the power dissipation. As the base becomes thinner, the thermal resistance $R_{th(j\text{-}w)}$ between T_{vj} and the refrigerant temperature T_w at the representative flow velocity extraction point decreases and the heat dissipation performance increases. When thinning from 5 mm to 0.5 mm, it is expected that $R_{th(j\text{-}w)}$ can be improved by 7%.

4.2 Improvement in heat transfer coefficient

As a second parameter that influences the performance of the cooling unit, we will consider heat transfer coefficient that expresses the heat exchange performance between the cooling fins and the refrigerant. As the refrigerant circulates in the cooling unit, the heat generated by the power module is dissipated from the radiator to the outside through the refrigerant. At such a time, the heat exchange performance between the cooling unit and the refrigerant determines the heat dissipation capacity.

In particular, heat dissipation capacity (heat transfer) is determined by the refrigerant flow rate and the shape of the cooling fins.

The effect of the refrigerant flow rate on heat transfer coefficient can be determined from Equations (1) and (2).[5] The heat transfer coefficient h is expressed by Equation 1 using the surface area A of the surface in contact with the refrigerant and the thermal resistance value R_{th}.

$$h = \frac{1}{R_{th} A} \qquad (1)$$

h : Heat transfer coefficient
R_{th}: Thermal resistance
A : Surface area of the surface in contact with the refrigerant

Furthermore, heat transfer coefficient can be expressed by Equation (2) using the characteristics of the refrigerant, length L of the surface in contact with the refrigerant, the Nusselt number N_u and the thermal conductivity λ of the structural components.

$$h = \frac{N_u \lambda}{L} \qquad (2)$$

L : Length of the surface in contact with the refrigerant
N_u: Nusselt number
λ : Thermal conductivity

The Nusselt number can be calculated by Equation (3) from the Reynolds number R_e and Prandtl number P_r using the shape parameters. At such a time, the Reynolds number is expressed by Equation (4) using the refrigerant density ρ, speed v and viscosity η. The Prandtl number is expressed by Equation (5) using the specific heat C_p and the thermal conductivity λ of the refrigerant.

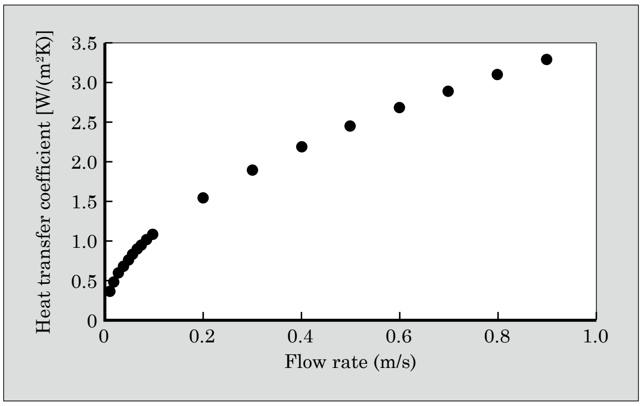

Fig.6 Relationship between thermal conductivity and refrigerant flow rate

$$N_u = 0.664 R_e^{1/2} P_r^{1/3} \qquad (3)$$

R_e : Reynolds number
P_r : Prandtl number

$$R_e = \frac{\rho v L}{\eta} \qquad (4)$$

ρ : Density of refrigerant
v : Speed
η : Viscosity

$$P_r = \frac{\eta C_p}{\lambda} \qquad (5)$$

C_p: Specific heat

By combining these equations, the relationship between the thermal conductivity h and flow velocity v can be obtained as shown in Equation (6). It can be seen that the thermal conductivity is proportional to the square root of the flow velocity.

$$h = 0.664 \left(\frac{\rho^3 \lambda^4 C_p^2}{\eta L^3} \right)^{\frac{1}{6}} v^{\frac{1}{2}} \qquad (6)$$

Figure 6 shows the results of estimating the heat transfer coefficient for the velocity using this equation. This graph shows that the faster the refrigerant flow velocity is, the greater the thermal conductivity will be. With respect to the heat exchange from the cooling fins to the refrigerant, the faster the refrigerant flow velocity on the surface of the cooling fins is, the more effective the improvement in heat dissipation performance will be.

4.3 Refrigerant flow between cooling fins

The flow of the refrigerant flowing inside the cooling unit changes depending on the friction, surface shape and viscosity of the refrigerant when it flows. As cooling performance improves inside limited spaces, cooling fins inevitably become more complex. Figure 7

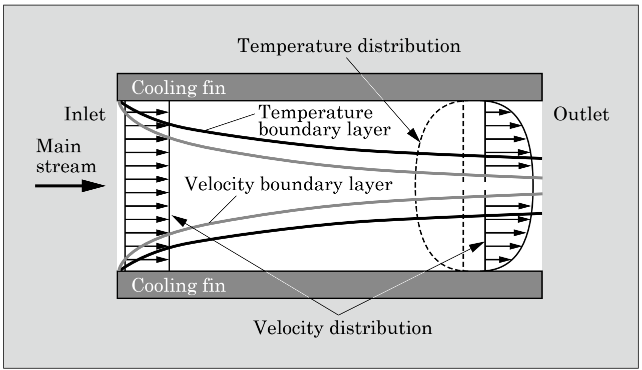

Fig.7 Relationship between flow path length and velocity boundary layer

shows the refrigerant flowing inside the closed space. If we assume that the flow velocity of the refrigerant inside the parallel flat plate between the cooling fins is uniform upstream, then the flow velocity distribution will be faster in the central part and slower on the surface of the flat plate as it moves downstream. This is due to the friction of the surface of the flat plate and the viscosity of the refrigerant and because of the development of the velocity boundary layer[(6)].

When comparing the flow velocity on the surface of the cooling fins with that of the central part of the flow path, the flow velocity on the surface of the cooling fins significantly reduces as the flow moves from upstream to downstream, while the difference of the flow velocity at the central part increases. Since the heat dissipation performance depends on the flow velocity on the surface of the refrigerant's cooling fins, heat dissipation performance can decrease downstream where differences in the flow velocity distribution increase.

When considering heat exchange performance, it is important to determine how much the flow velocity on the surface of the cooling fins can be maintained, while also suppressing the development of the boundary layer in order to improve cooling performance.

Fuji Electric has developed straight and wave-shaped fin shapes as shown in Fig. 8 to achieve optimal cooling fin shapes in consideration of the above mentioned matters. As a result, we have improved heat dissipation performance of each generation by approximately 10%.

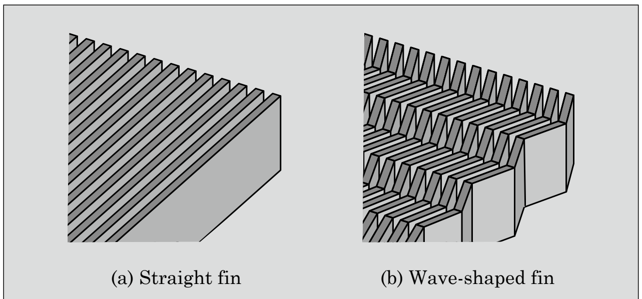

Fig.8 Cooling fin shape for aluminum direct liquid cooling structure

4.4 4th-generation direct liquid cooling package

We designed the 4th-generation aluminum direct water cooling package on the basis of the results described from sections 4.1 to 4.3. In particular, we optimized the base thickness on the basis of the cooling structure that integrates a heat sink and jacket, which had been used since the 2nd-generation. Furthermore, the 3rd-generation had a two-dimensional cooling fin shape, but the 4th-generation has a three-dimensional one. By forcibly refracting the refrigerant flow in three dimensions and generating a flow toward the cooling fin surface, we have improved the refrigerant flow rate on the surface of the cooling fins to reduce the thickness of the boundary layer.

Figure 9 shows the thermal resistance of each structure. In the new structure, the thermal resistance is reduced by 15% compared to conventional structures by improving the thermal conductive performance of the base and heat transfer performance of the cooling fins.

Furthermore, the cooling unit in the direct liquid cooling package needs to secure not only heat dissipation performance but also airtightness when mounting the inverter. The cooling unit has a high coefficient of thermal expansion (23 ppm) relative to other structural parts, making it necessary to devise a method for suppressing deformation. The direct liquid cooling structure used in the 2nd- and 3rd-generations is ca-

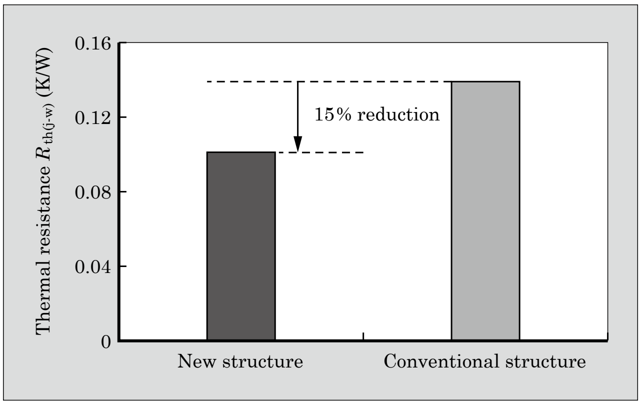

Fig.9 Thermal resistance comparison results

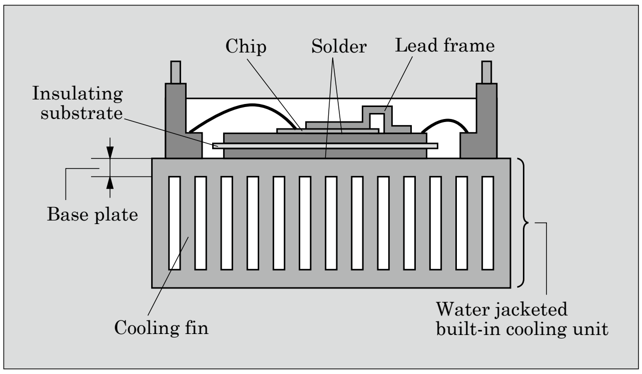

Fig.10 4th-generation aluminum direct liquid cooling structure pable of limiting and reducing the area that ensures airtightness by integrating a water jacket for forming the flow path. This has simplified the airtightness design.[3]

By treating the cooling fins as a stress relief layer, this integrated structure can suppress thermal deformation even when thinning the base plate, thereby ensuring heat dissipation performance and airtightness (see Fig. 10).

5. Lead Frame Wiring Structure

Aluminum direct liquid cooling packages up to the 3rd-generation have used aluminum wires for the internal chip's main circuit wiring. When using aluminum wires, it is necessary to ensure the bonding area needed to route the optimal number of wires corresponding to the current capacity. In order to increase the density (make it more compact and lightweight), the 4th-generation module uses lead frame wiring for the internal main circuit wiring.

5.1 Thermal diffusion effect

Lead frame wiring has a broad bonding area with the chip and uses highly-conductive copper material. The reduction in chip temperature due to the heat-diffusion effect from the lead frame bonding surface enables the lead frame wiring structure to secure a uniform chip temperature, as shown in Fig. 11. As a result, the maximum chip temperature has been reduced by approximately 16 °C compared with the aluminum wiring structure (see Fig. 12).[7]

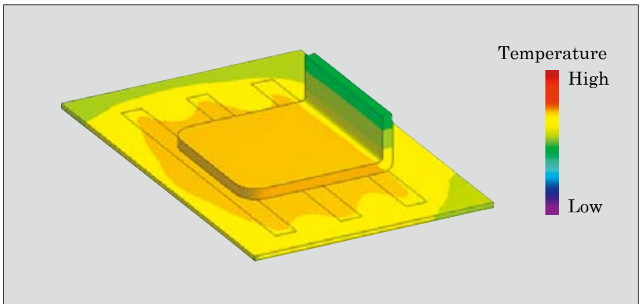

Fig.11 Chip temperature distribution for lead frame wiring structure

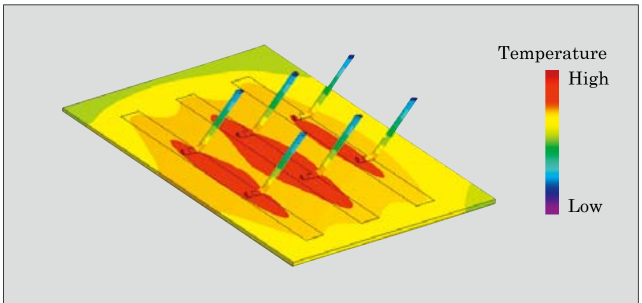

Fig.12 Chip temperature distribution for aluminum wiring structure

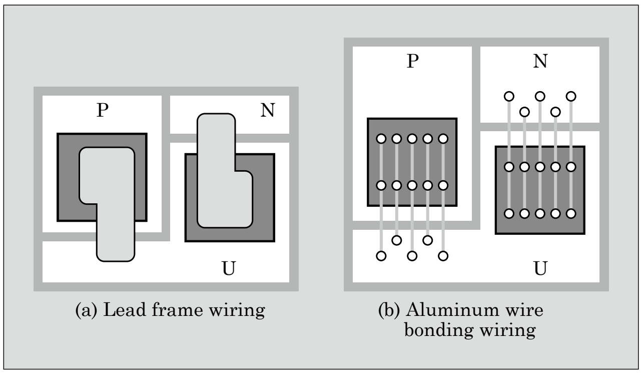

Fig.13 Internal layout

5.2 High-density mounting with lead frame wiring

Figure 13 shows the internal layout of aluminum wiring and lead frame wiring. In lead frame wiring structures, copper terminals and insulating substrate copper circuits are joined by solder in the same way as the bonding between the chip and the copper circuit. This simplifies manufacturing and ensures robust bonding.

By solder bonding the highly conductive copper terminals, the lead frame wiring structure has reduced the footprint area by 15% compared with aluminum wire bonded wiring structures. This can reduce the module size and increase the power density.

In addition to improving the heat dissipation performance of direct liquid cooling packages, the adoption of lead frame wiring technology has enabled 4th-generation aluminum direct liquid cooling modules to achieve a reduced footprint and lower profile than 3rd-generation modules. This has increased power density by 36% per unit volume.

6. Postscript

In this paper, we discussed our 4th-generation aluminum direct liquid cooling package technology for xEV.

We will continue to pursue technological development based on these technologies to provide products with high customer satisfaction and contribute in efforts to reduce CO_2 emissions and achieve energy conservation as measures for mitigating global warming.

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