Direct Liquid Cooling IGBT Module for Automotive Applications

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ABSTRACT

A compact insulated gate bipolar transistor (IGBT) module with low thermal resistance and direct liquid cooling, system has been developed to contribute to reducing the size of user systems. Thermal fluid simulations were used to optimize the liquid cooling fin shape. Square pin fins were selected because of their overall outstanding performance, including heat dissipation performance, cooling liquid flow velocity, and pressure loss. Under optimized liquid flow conditions, measured values of chip temperature were within 2% of simulation values, confirming the accuracy of the simulations. From these results, this IGBT module for direct liquid cooling realizes a 30% reduction in thermal resistance and allow a 40% reduction in size compared to the conventional configuration.

1. Introduction

Hybrid electric vehicles (HEVs), currently the most prevalent type of fuel-efficient cars, have the dual power sources of a internal combustion engine and an electric motor. During acceleration, the motor assists the engine, while during deceleration, regenerative braking acts to charge the battery to improve the fuel efficiency. Because a gasoline engine is used, HEVs can be operated without reliance on quick charger or other infrastructure, and their further popularization in the future is anticipated.

This paper introduces an automotive insulated gate bipolar transistor (IGBT) module suitable for use in drive system inverters in HEVs and electric vehicles (EVs). In order to meet many diverse needs, Fuji Electric plans to create a series of products having specific output power classes, suitable for motor output ratings of up to about 100 kW, and to contribute to the development of fuel-efficient systems for customers such as automobile manufacturers and electric equipment manufacturers.

2. Background

Types of hybrid systems include a 2-motor type equipped with both a drive motor and a generator motor, and a 1-motor type that assists the engine and performs regenerative braking. The 2-motor type is installed mainly in mid-size or large passenger cars and results in a relatively large improvement in fuel efficiency. The 1-motor type is installed mainly in compact cars and although a dramatic improvement in fuel efficiency is not expected, is a small lightweight and relatively low-cost system. In a 2-motor type hybrid system, motors having a relatively large output of 50 kW or greater are used, while for the 1-motor type, motors with output power of 20 kW or less are often used.

Electric vehicles have a battery and a motor as their power source, and do not generate harmful exhaust gas since they do not use fossil fuels when being driven. Additionally, because they have a high well-to-wheel efficiency (efficiency from the primary energy source to actual driving of the vehicle), electric vehicles exhibit a large energy-saving effect and are thought to be the ultimate fuel-efficient car. Motors installed in electric vehicles range from 50 kW to 100 kW according to the body size. A significant reduction in the cost of their batteries, however, is needed in order for electric vehicles to achieve wide-spread adoption. In the meantime, plug-in hybrid electric vehicles (PHEVs) that have been developed to realize higher fuel efficiency performance are being commercialized. Batteries can be charged from household AC power sockets, and through using electric vehicles for short-distance travel and hybrid vehicles that combine an electric motor with engine output for long-distance travel, a dramatic reduction in CO_2 emissions and an increase in cruising distance are anticipated.

In this way, many types of systems are equipped with a motor to save energy, and their output capacities vary from small to large. Accordingly, IGBT modules of various current capacities and voltage classes are used in the inverters in these systems.

A hybrid system is configured from such components as a power control unit (PCU) that controls the power converting function, a motor, a battery and so on. Inside the PCU, IGBTs play a major role in acting as the main switch of an inverter that outputs three-phase alternating current.

Many varieties of IGBT modules have been devel-

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oped for industrial and consumer applications, and their product lineup is also diverse in terms of current capacity. Because the specifications concerning durability of these IGBT modules were not entirely suitable for automotive applications, however, they could not be used as-is, and instead, custom products were often developed and installed. In the future, as electric drive technology becomes indispensible for reducing fuel consumption and various customer requirements for IGBT modules are received, their use is expected to increase further.

3. Product Concept and Specifications

3.1 Product concept

While meeting diverse customer requirements, We have also considered products that incorporate ideas of its own. With the goal of “contributing to miniaturization of the customer’s system,” Fuji Electric has significantly improved the heat dissipation performance of IGBT modules while maintaining the required basic performance in order to enhance the power density.

To reduce the size of the module, a direct liquid-cooling structure was adopted and thermal fluid simulations were carried out in order to optimize the fin shape and the liquid flow. A 30% reduction in thermal resistance, compared to a module with a conventional structure, was confirmed. Additionally, reducing the active area of the power chip (die shrink) was also studied. As a result, We determined that a module size 40% smaller than that of a module with a conventional structure could be realized, and began product development. Use of the latest version “V-series” chip, which has already begun to be mass-produced for industrial applications, as the power chip provides an even greater effect.(1)

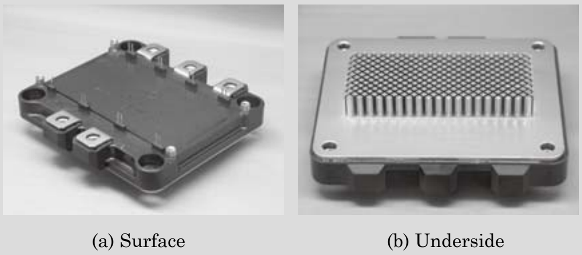

(a) Surface (b) Underside

Fig.1 Appearance of M651 (650 V/400 A) module

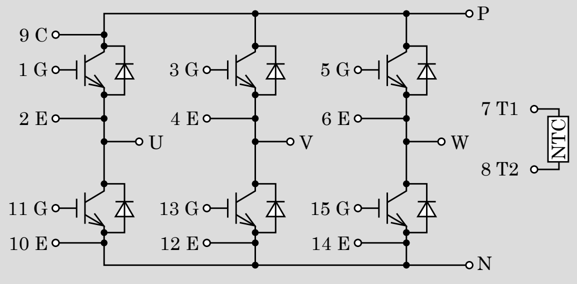


Fig.2 Equivalent circuit of the module

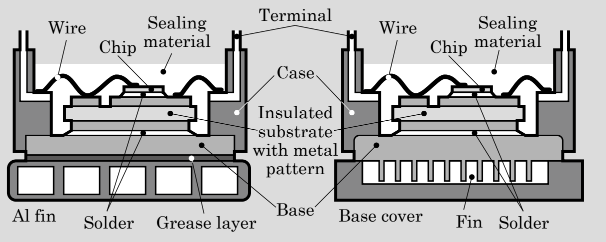
Next, the design of a module that conforms to the usage conditions (battery voltage: 300 V, max. current (RMS value): 200 A, carrier frequency: 10 kHz) actually requested by customers was examined, and the results of evaluation of prototypes will be described below.

3.2 Product specification

Figure 1 shows the appearance of the IGBT module and Fig. 2 shows its equivalent circuit diagram.

This product is characterized by low thermal resistance as a result of a direct liquid cooling structure, and the high current density has enabled the package size to be reduced significantly. The module has external dimensions of 105×108 (mm), which is approximately 40% smaller than our previous comparable product having a conventional structure. Figure 3 compares cross-sections of the conventional structure and the liquid cooling structure, and Fig. 4 compares their thermal resistances.

In the conventional structure, thermal grease is used to reduce the contact thermal resistance between a copper base and the cooling fin surface. Thermal grease has a large thermal resistance even at thick-



(a) Conventional structure (b) Direct liquid cooling structure

Fig.3 Cross-sectional comparison of conventional structure and direct liquid cooling structure

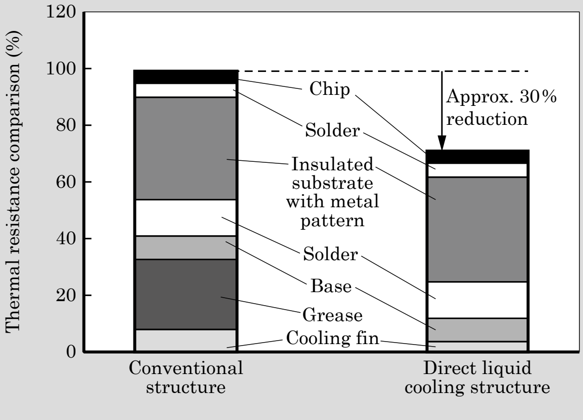


Fig.4 Thermal resistance comparison of conventional structure and direct liquid cooling structure

nesses of several tens of μm, and was unable to conduct waste heat efficiently from the module to the cooling fins. Additionally, an adequate cooling effect could not be obtained since the fluid flow path of the cooling fins did not match the distribution of heat generated by the mounted device. With the newly developed direct liquid cooling structure, the cooling effect was improved by integrating the copper base and the cooling fins so as to eliminate the thermal grease layer. Moreover, by arranging the fins in a high density configuration directly beneath the power chip, which is a heat-generating body, the capacity for heat dissipation between the fins and the cooling liquid is increased. The result is that the thermal resistance between the power chip and the cooling liquid was reduced by approximately 30% compared to that of the conventional structure. By improving the cooling efficiency, the device can be made with higher current density so that more current can flow through a single chip (see Fig.5).

4. Direct Liquid Cooling Technology

4.1 Investigation of heat dissipation performance

With the direct liquid cooling structure, the heat dissipation performance changes according to such factors as the fin shape and the flow direction of the cooling liquid. Fluid simulations were performed for various fin shapes and flow paths in order to optimize the cooling system, and details are presented below.(2)

The IGBT module in an inverter system fulfills the function together with connected smoothing capacitor, circuit board, harness, current sensor and the like. So as to accommodate different system designs from many customers, the fin shape was selected to be a pin-type fin through which cooling fluid could flow in either the width or depth direction. (see Fig.6) Selection of the pin fin cross-sectional shape necessitated a comprehensive examination of the heat dissipating performance, cooling liquid flow velocity and pressure loss, and Fuji Electric investigated the cross-sections of typical round and square pin fins.

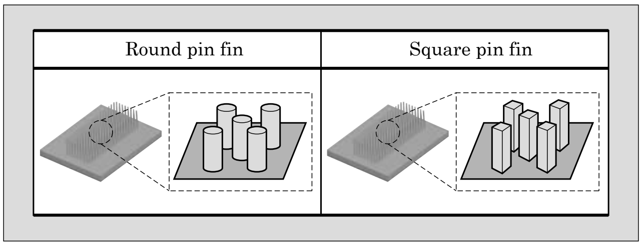


Fig.5 Cooling fin shape

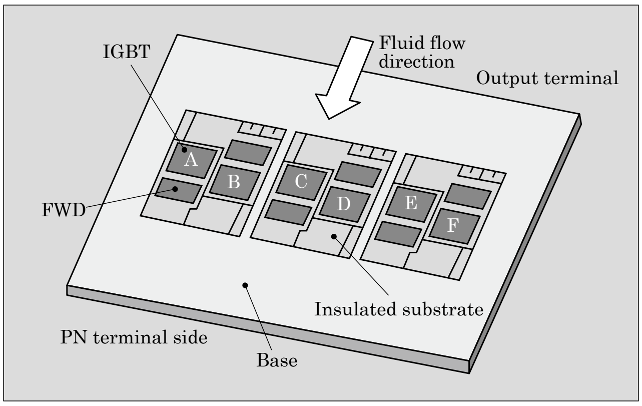


Fig.6 Thermal fluid simulator model

4.2 Optimization of flow path

The flow path was investigated using a thermal fluid simulator (Icepak*1), and the junction temperature, flow velocity of the cooling liquid and pressure loss were computed and compared. Class 2 antifreeze coolant (LLC) 50% is used as the cooling liquid, and the model of the IGBT module shown in Fig. 6 is used as the analysis model. The fins are formed on the underside of the insulated substrate where the heat-generating chip is located. One IGBT chip and one FWD chip are provided in each arm. A single output phase (half bridge) is provided on each insulated substrate. In consideration of the inverter system commonly used and so that the cooling liquid will flow evenly to the fin area, the depth direction shown in Fig. 6 was selected as the direction of fluid flow. Figure 7 shows the structure of a cooling liquid jacket that compares the flow velocities of the cooling liquid.

With the fluid flow direction shown in Fig. 6, the flow of cooling liquid in the fin area becomes nearly constant and uniform. A flow velocity distribution that is uniform, from the liquid inlet to below the insulated substrate, is obtained for each phase, and the cooling performance in each phase is predicted to be equal. Moreover, in order to reduce the pressure loss, because

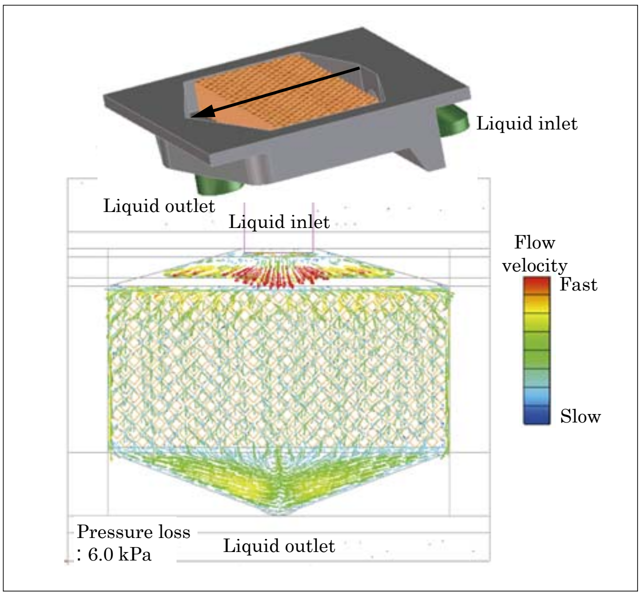


Fig.7 Fluid flow velocity distribution in cooling liquid jacket

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*1: Icepak is a trademark or registered trademark of US-based ANSYS, Inc. and its subsidiaries.

the cooling liquid traverses a short distance in passing through the fin area, and the flow velocity of the cooling liquid must be constant in the fin area, the flow path of Fig. 7 is found to enable efficient cooling.

4.3 Selection of the fin shape

Using the cooling liquid jacket of Fig. 7, thermal fluid simulations were performed to select the fin shape in consideration of its effect on junction temperature and pressure loss. The analysis conditions assumed loss at the time of inverter operation, heat generation of 258 W by the IGBT and 31 W by the FWD, a cooling liquid of LLC 50%, a cooling liquid flow rate of 10 L/min, and a cooling liquid temperature of 65 °C.

Figure 8 shows the simulation results of the rise in junction temperature. The junction temperature was verified and compared for each fin shape. The maximum junction temperature was 141.6 °C for round pin fins and 136.0 °C for square pin fins, while the pressure loss was 4.8 kPa for round pin fins and 6.0 kPa for square pin fins. Figure 9 compares the IGBT junction temperature and pressure loss for round pin fins and square pin fins. The round pin fins have a smaller fin volume density, and therefore the pressure loss is less. On the other hand, because the square pin fins have a larger surface area, the junction temperature decreases, but the fin volume density increases and the pressure loss becomes greater. The difference in pressure loss was determined to be about 1 kPa, which is not considered to be a significant difference, and therefore square pin fins were selected so as to fully utilize the cooling performance of direct liquid cooling.

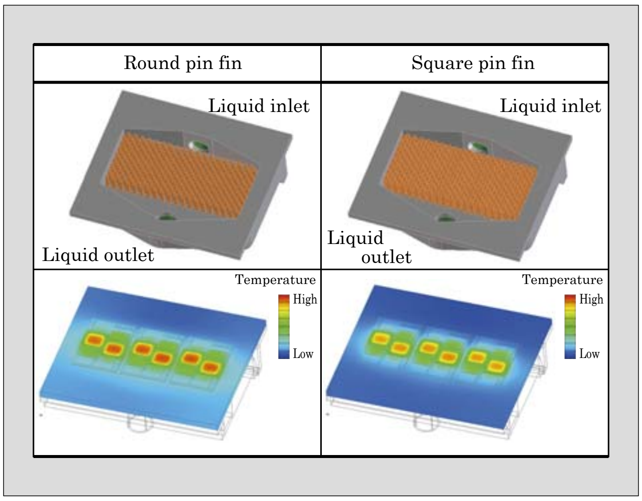

Fig.8 Simulation results of junction temperature rise

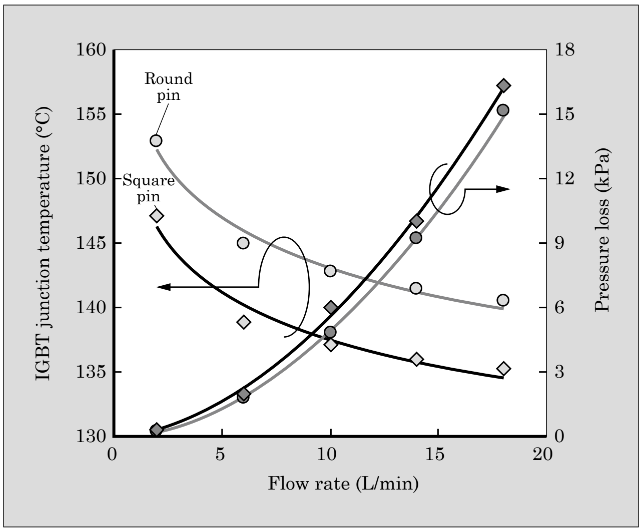

Fig.9 Flow rate dependence of round pin fin and square pin fin IGBT junction temperature and pressure loss (simulation)

4.4 Actual measurement results of junction heat generation

To confirm the validity of the simulation of the cooling performance, the rise in junction temperature of an actual sample was verified. So that the measurement conditions matched those of the simulation, the following conditions were used.

○ Loss: IGBT 258 W, FWD 31 W
○ Cooling liquid: LLC 50%
○ Flow rate: 5 to 15 L/min
○ Cooling liquid temperature: 65 °C

In consideration of the aforementioned results, the water jacket used for the measurements was fabricated based on the model of Fig. 7. (see Fig. 10)

A comparison of the square pin fin simulation and measurement results in the case of a flow rate of 10 L/min is shown in Table 1. Columns A through F in Table 1 show the junction temperatures of each

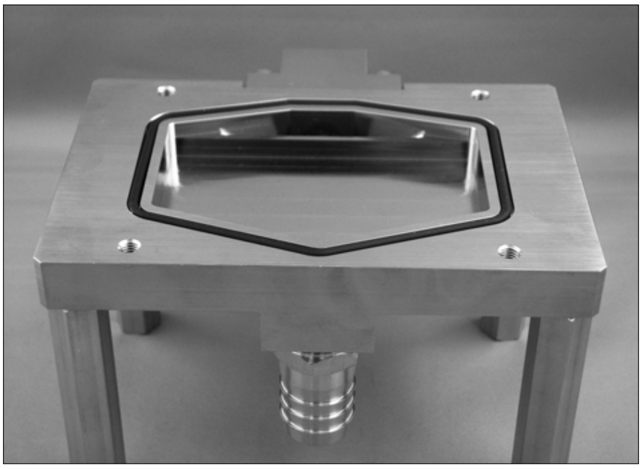

Fig.10 Prototype of cooling liquid jacket

Table 1 Comparison of junction heat generation by simulation and actual measurement (IGBT)

(Units: °C)

	A	B	C	D	E	F
Actual measurement	133.6	137.6	138.4	139.1	136.6	137.7
Simulation	136.7	137.4	137.1	137.6	136.9	136.9
Difference	2.3%	0.1%	0.9%	1.1%	0.2%	0.6%

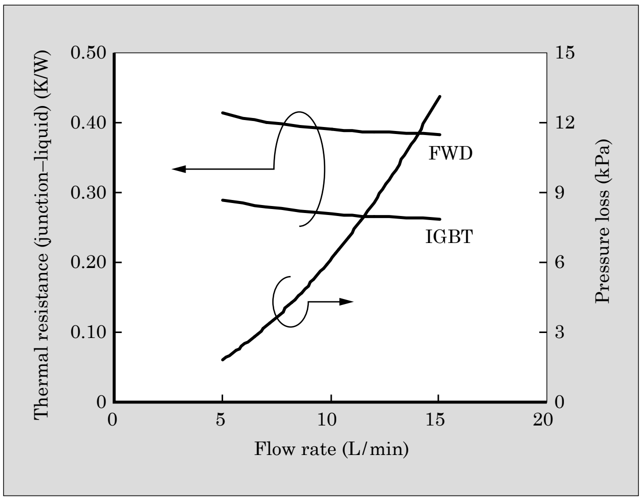

Fig.11 Flow rate dependence of thermal resistance and pressure loss (actual measured values)

chip in Fig. 6. The difference for each phase is at most about 2%, which confirms the equivalence of the simulation and the measurement results. From the measured results, the thermal resistance was calculated to be 0.27 K/W (IGBT average value). While taking the measurements, the flow rate was varied in order to confirm the flow rate dependence of thermal resistance. Figure 11 shows the flow rate dependence (actual measured values) of thermal resistance and pressure loss for flow rates of 5 to 15 L/min.

Comparing the 5 L/min and 15 L/min flow rates, it can be seen that the IGBT and the FWD both exhibited a decrease in thermal resistance by about 10% at 15 L/min, and that by increasing the flow rate, the heat dissipation performance was found to improve. Increasing the flow rate, however, results in a greater loss of pressure, and therefore optimization of the pump performance during use and of the flow path design are needed.

5. Postscript

A direct liquid cooling-type IGBT module for automotive applications has been introduced. The 400 A rated product introduced in this paper will serve as a stepping stone for Fuji Electric's planned development of high-current rated 600 A and 900 A products in the future. We intends to develop a series of products that are widely applicable to inverter systems for motor outputs up to about 100 kW.

We will continue to develop highly reliable, high-performance modules that facilitate system design for an increasing number of users, and to reduce the environmental impact of automobiles.

References

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(2) Nagaune, F. et al. Small Size and High Thermal Conductivity IGBT Module for Automotive Applications. PCIM Europe 2011, p.785-790.

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