Direct Water Cooling Technology for Power Semiconductor Modules for xEVs

TAMAI, Yuta* KOYAMA, Takahiro* INOUE, Daisuke*

ABSTRACT

In the automobile industry, the switchover to electricity-powered electric vehicles (EVs) and hybrid electric vehicles (HEVs) has been accelerating. This has increased the demand for smaller, thinner, and more reliable power modules for xEVs. To meet this demand, Fuji Electric has been developing direct water cooling structures that integrate a heat sink and water jacket. The cooling performance of the structures has improved with each successive generation. Compared with conventional open fin structures, the direct water cooling structure can suppress cooling unit deformation. This characteristics allows the heat sink base to be thinned up to 20% to achieve better heat dissipation performance and increase the temperature cycling capability more than twice, improving overall reliability.

1. Introduction

In order to achieve the Sustainable Development Goals (SDGs) adopted at the United Nations Summit, countries around the world are required to reduce CO_2 emissions and save energy to combat global warming. The automotive industry is going through a period of major change defined by the keywords CASE (Connected, Autonomous, Shared, and Electric). In the field of electrification, the switch to electric vehicles (EVs) and hybrid electric vehicles (HEVs), which run on motors powered by electricity, is accelerating. Since inverter units used to control motors are installed in limited spaces, reduced size, thickness, and weight to achieve low fuel consumption (electricity consumption) are sought in addition to improved efficiency. To meet these requirements, the development of new integrated mechanical and electrical systems that integrate gearboxes in addition to motors and inverters is gaining momentum. In power modules, Fuji Electric is developing compact, thin, and highly reliable products that are ideal for this new system.

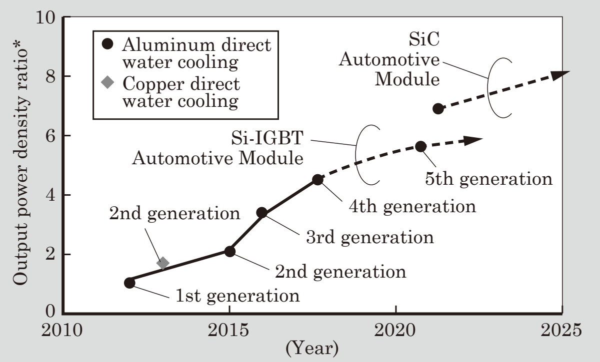
This article describes improved heat dissipation, reduction of size and thickness, and high reliability of a power module with a fin structure (integrated fin) with a water jacket in which the heat sink is integrated with the water jacket for power semiconductor modules for xEVs, as well as the flow visualization technology that plays an important role in conducting computational thermo-fluid simulation.

* Electronic Devices Business Group, Fuji Electric Co., Ltd.

2. Trends and Features of Fuji Electric's Direct Water-Cooled Power Modules for Automotive Applications

Figure 1 shows the power density trend of Fuji Electric's direct water-cooled power modules for automotive applications. Fuji Electric has thus far developed a direct water-cooled power module with an aluminum cooler that is lightweight and easy to process. The power density has improved by approximately 20% with each generation: 1st generation (2012), 2nd generation (2015), 3rd generation (2017), and 4th generation (2019)[1]. The main applied technologies are as follows:

(a) High heat dissipation cooler design technology[1]-[3]
(b) High-reliability soldering technology[1]
(c) Ultrasonic welding technology[2],[3]
(d) Technology that guarantees continuous opera-



* Output power density ratio: Power density ratio of each generation when the 1st-generation aluminum direct water-cooled power module is 1
Power density (kVA/L) = maximum output power (kVA) / module volume (L)

Fig.1 Power density trend of direct water-cooled power modules for automotive applications

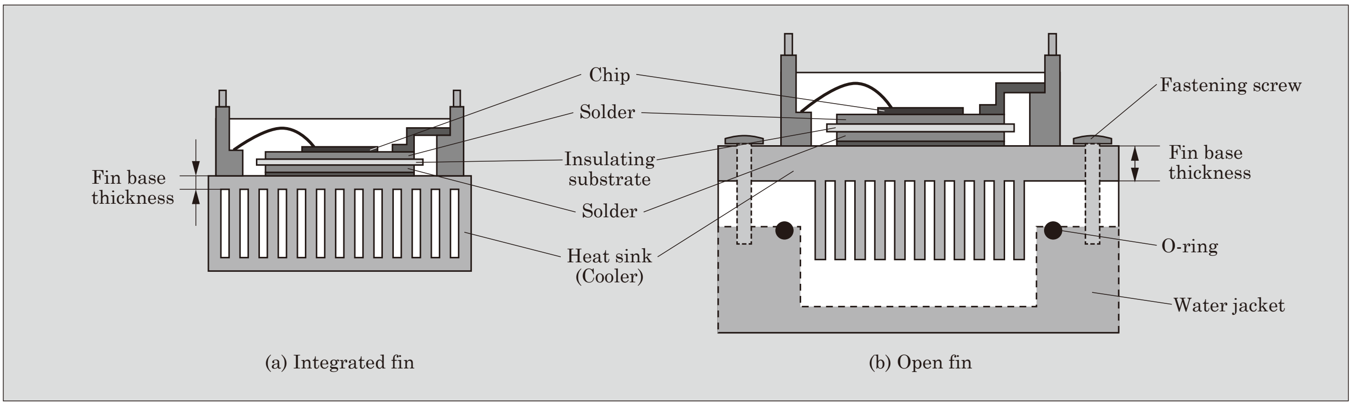


Fig.2 Cross-sectional view of integrated fin and open fin

tion at 175 °C[(2),(3)]

(e) Reverse-conducting insulated gate bipolar transistor (RC-IGBT)[(4)], which combines an IGBT and a free wheeling diode (FWD), which are semiconductor elements (chips) into a single chip.

(f) Lead frame wiring technology[(5)]

In the aforementioned (a) high heat dissipation cooler design technology, the integrated fin shown in Fig. 2 was developed and adopted from the 2nd-generation to improve the cooling performance (heat dissipation) of the cooler. This structure can suppress the deformation of the cooler compared to the non-integrated open fin. Also, the base thickness of the heat sink (thickness of the fin base) can be reduced by 20%, which not only improves the cooling performance, but also has more than twice the thermal cycling capability.

3. Heat Dissipation Improvement Using the Fin with the Water Jacket Integrated Structure

3.1 Challenges to heat dissipation improvement

To improve the heat dissipation of a power module, the rate of the refrigerant flowing on the surface of the fins of the cooler needs to be increased. As shown in Fig. 3, however, there is a trade-off between thermal resistance, which is a characteristic that indicates heat dissipation, and the pressure loss of the cooler. This means that increasing the flow rate increases the pressure loss, which increases the load on the circulation pump. Therefore, with each generation, the fin shape has been redesigned to reduce this trade-off and improve heat dissipation[(6)]. There is a way to adjust the fin height without increasing the pressure loss. However, as clearly indicated in the cross-sectional view of the cooler in Fig. 4, raising the fins increases the volume of the cooler. Therefore, in order to achieve high power density, it is necessary to achieve both high heat dissipation and high reliability within a range of pressure loss and volume that is acceptable to clients.

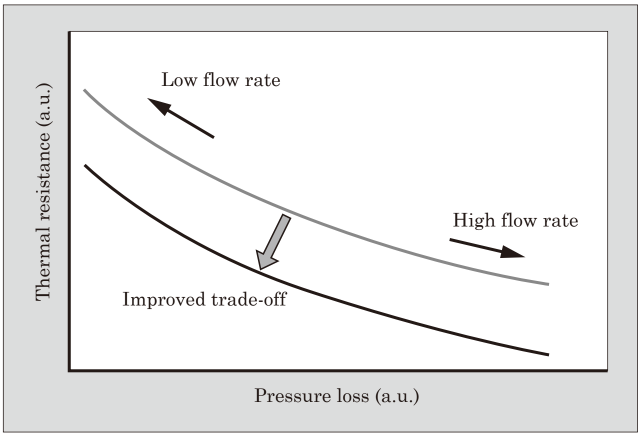


Fig.3 Relationship between thermal resistance and pressure loss

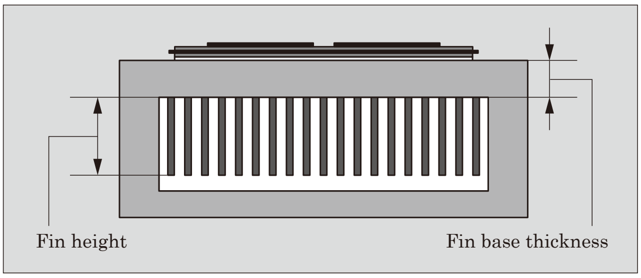


Fig.4 Cross-sectional view of the cooler

3.2 Exothermicity improvement

Figure 5 shows the result of investigating the thermal resistance of the 1st-generation direct water-cooled power module by dismantling it by component. The thermal resistance of the fin base of the cooler accounted for 36% of the total, which was hindering the heat dissipation performance. The thermal resistance of the module can be improved if the fin base thickness is reduced to 20%. In order to control the thermal deformation of the module, however, it was also necessary to ensure the rigidity of the cooler. In the past, the rigidity has been ensured by increasing the thickness of the fin base.

Thus, the integrated fin that integrates the heat sink and water jacket was developed to reduce thermal

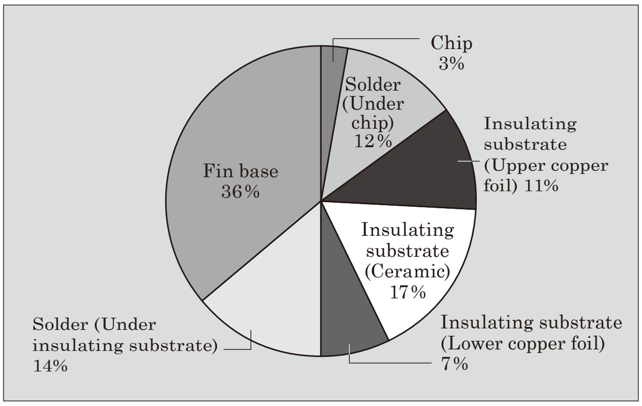


Fig.5 Thermal resistance ratio of the 1st-generation direct water cooling structure

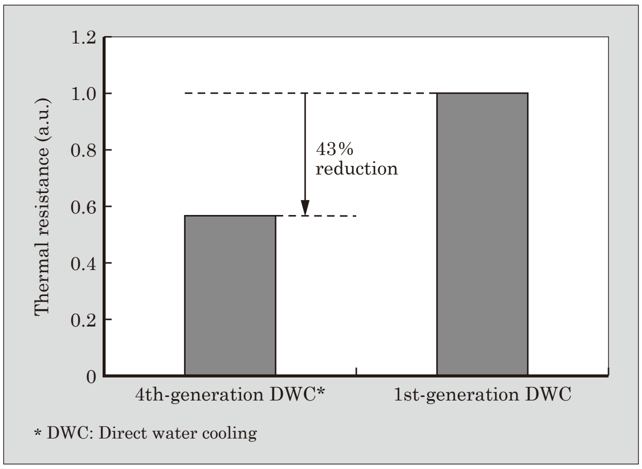


Fig.6 Comparison of the thermal resistance between 1st- and 4th-generation direct water-cooled power modules

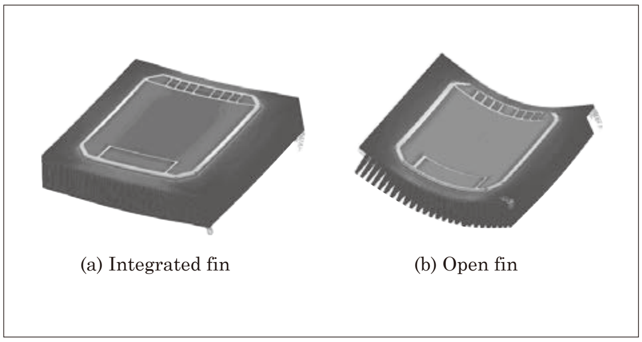


Fig.7 Thermal stress simulation of elemental models of integrated fin and open fin

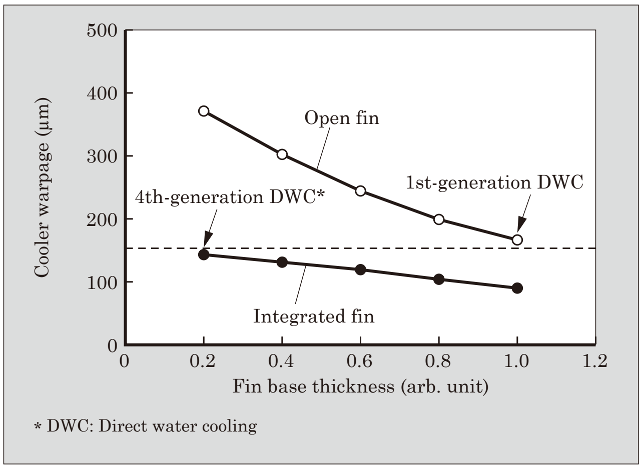


Fig.8 Dependence of cooler warpage on fin base thickness using elemental model

resistance and suppress thermal deformation. Figure 6 shows a comparison of the thermal resistance of the power modules using the 1st-generation direct water cooling (DWC) structure with an open fin and the 4th-generation DWC structure with a integrated fin. The 4th-generation direct water-cooled power module increases the rigidity of the entire cooler by integrating the water jacket, and has a thinner fin base compared to the open fin system. In addition, the thermal resistance was reduced by 43% compared with the 1st-generation by optimizing the fin shape, thinning the solder, and conducting other measures to reduce thermal resistance.

4. Reliability Improvement Using the Integrated Fin

4.1 Warpage reduction using the thermal stress of the cooler

The power module needs to achieve high reliability in addition to high heat dissipation performance. Figure 8 shows the dependence on the fin base thickness with warpage of a cooler obtained by thermal stress simulation (see Fig. 7) conducted using elemental models of open fin and integrated fin.

The smaller the warpage of the cooler, the better, due to the sealability of the cooler and the ease of mounting the cooler on the inverter; thus, it is designed to be approximately 150 μm or less. As shown in Fig. 8, by adopting the structure to increase rigidity, the integrated fin has been able to reduce warpage to less than 150 μm.

4.2 Thermal cycling capability improvement

In temperature cycling, the difference in the thermal expansion coefficients between the cooler and the insulating substrate repeatedly causes strain in the solder joints, and cracks develop in the solder, which lowers the thermal resistance and leads to the destruction of the power module. Figure 9 shows the temperature cycle until failure occurs as the temperature cycle tolerance. The temperature cycle resistance of the fin structure with integrated water jacket is less affected by the thickness of the fin base. In contrast, the open fin is highly dependent on the thickness of the fin base. In the case of an open fin with a thin fin base (0.2 arb. unit), the cooler follows the thermal deformation of the insulating substrate, which reduces the strain generated in the solder and increases the temperature cycle resistance, but as mentioned above, the warpage is

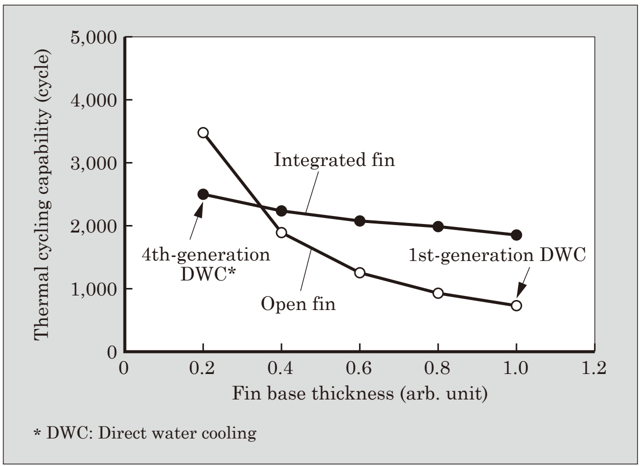


Fig.9 Dependence of temperature cycling resistance on fin base thickness using elemental model

large and not suitable for practical use. In Fig. 9, comparing the temperature cycle resistance of the 1st- and 4th-generation elemental models, where the warpage of the cooler was approximately 150 µm, the integrated fin (fin base thickness: 0.2 a.u.) has more than twice the temperature cycle resistance than the open fin (fin base thickness: 1.0 a.u.) cycle resistance.

The above results indicate that the integrated fin is suitable for both reducing the fin base thickness and improving reliability. Compared with the 1st generation, the 4th-generation direct water cooled module can reduce the thickness of the fin base by 20% and the overall height of the cooler by one-half (50% reduction).

4.3 Reliability improvement of power module

Figure 10 shows the result of evaluating the thermal cycling capability of the 1st- and 4th-generation direct water-cooled power modules. The 4th-generation direct water-cooled module has a 1.4 times higher temperature cycling capacity due to the use of a integrated fin. In addition, one of the measures to improve the thermal cycling capacity of power modules is to increase the strength of the solder material[7]. Fuji Electric developed high-strength Sn-Sb solder by optimizing the Sb content[8],[9]. The application of high-strength solder to the 4th generation of direct water-cooled power modules can further improve reliability in the future.

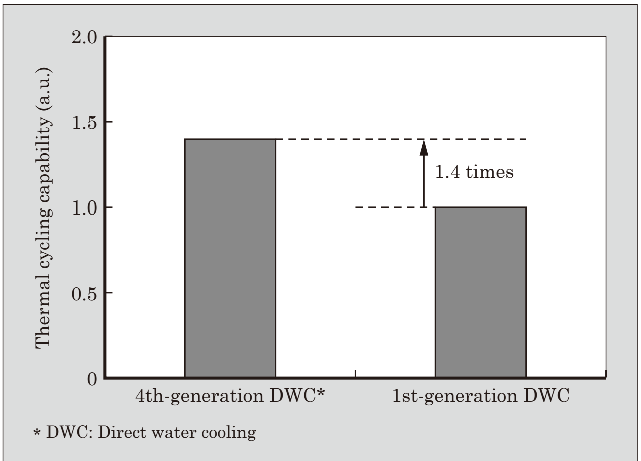


Fig.10 Thermal cycling capability of power module

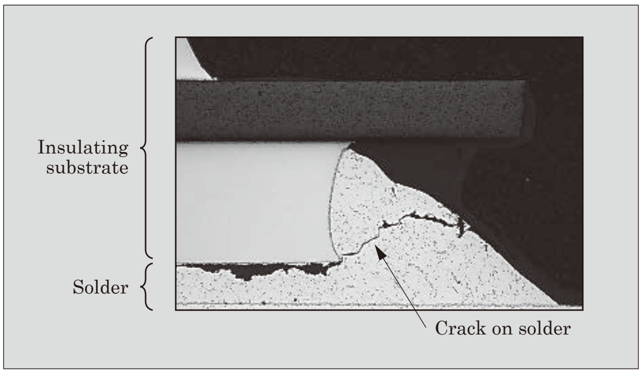


Fig.11 Fracture condition of solder joint under insulating substrate after thermal cycle test

Figure 11 shows the damage initiation pattern at the solder bond of the power module after the evaluation of thermal cycling capacity. The fracture pattern is similar to the 1 st generation with the cracks extending across the substrate and solder interface. Since the deterioration of thermal resistance due to this cracking determines the thermal cycling capability of the product, reliability design is based on the fatigue life curve of the solder material.

5. Visualization Technology for Cooler Design

The analytical accuracy of computational thermo-fluid simulation and the visualization of the actual flow are important in designing a cooler. Figure 12 shows the calculation results of the velocity distribution in the cooler channel obtained through computational thermo-fluid simulation. To verify whether the velocity distribution in the cooler channel calculated by the computational thermo-fluid simulation can be reproduced as intended, particles were dispersed in the refrigerant and channeled into a transparent cooler, and the particle image velocimetry (PIV) was used to visualize the velocity distribution of the refrigerant[10]

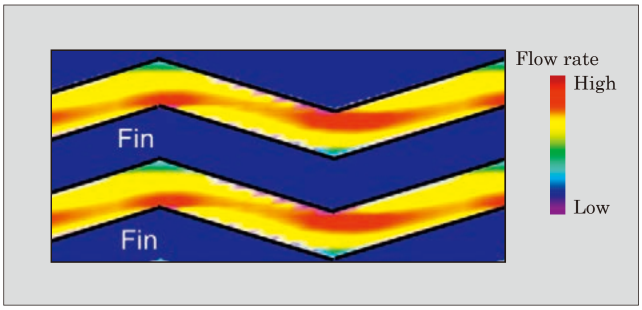


Fig.12 Calculation results of the velocity distribution in the cooler channel obtained through computational thermo-fluid simulation

[11]. Figure 13 shows the result of measuring particle motion in the cooler channel. Based on this measurement, the velocity distribution in the cooler channel was obtained as shown in Fig. 14. As a result, it was confirmed that the flow was faster at the refracted part of the wave fin, meaning the flow was reproduced as intended, which was consistent with the computational thermo-fluid simulation in Fig. 12. Combining thermo-fluid simulation and visualization technologies, the mesh size of the simulation model was optimized to reproduce the actual flow. This enabled us to obtain an analysis accuracy of less than 5% error in thermal resistance, which enabled us to improve the cooling performance and limit design.

6. Postscript

This article described the direct water-cooling technology for power semiconductor modules for xEVs.

Continuous technological development will be continuously promoted based on these technologies to provide products that satisfy customers' requirements in a timely manner, thereby contributing to the reduction of CO_2 emissions to combat global warming and achieve a sustainable energy-saving society.

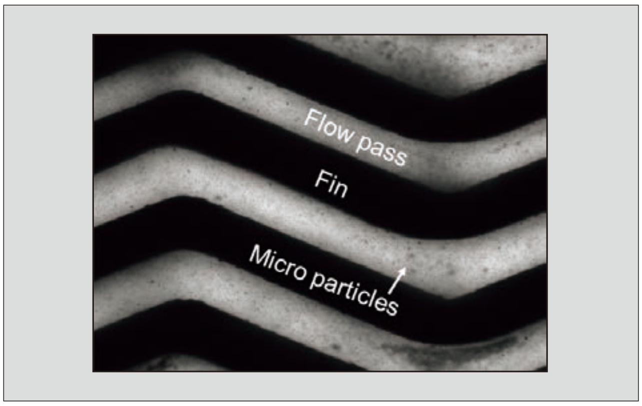


Fig.13 Measurement of particle motion in a cooler channel using PIV

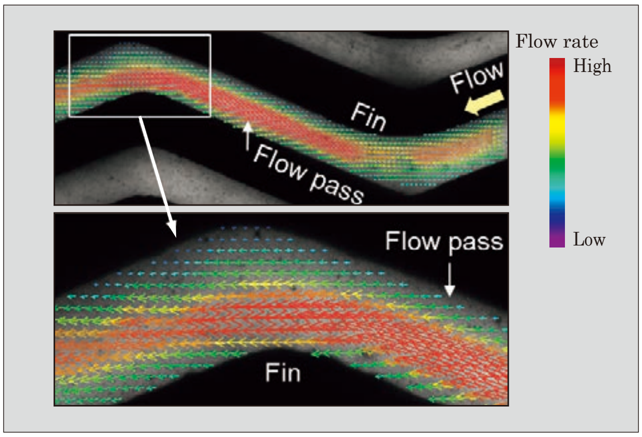


Fig.14 Results of evaluating the velocity distribution in the cooler channel

References

(1) Gohara, H. et al. Packing Technology of IPMs for Hybrid Vehicles. FUJI ELECTRIC REVIEW. 2013, vol.59, no.4, p.235-240.

(2) Gohara, H. et al. Packaging Technology of 2nd-Generation Aluminum Direct Liquid Cooling Module for Hybrid Vehicles. FUJI ELECTRIC REVIEW. 2014, vol.60, no.4, p.228-232.

(3) Gohara, H. et al. Packaging Technology of 3rd-Generation Power Module for Automotive Applications. FUJI ELECTRIC REVIEW. 2015, vol.61, no.4, p.258-262.

(4) Sato, K. et al. Functionality Enhancement of 3rd-Generation Direct Liquid Cooling Power Module for Automotive Applications Equipped with RC-IGBT. FUJI ELECTRIC REVIEW. 2016, vol.62, no.4, p.256-260.

(5) Inoue, D. et al. 4th-Generation Aluminum Direct Liquid Cooling Package Technology for xEV. FUJI ELECTRIC REVIEW. 2019, vol.65, no.4, p.229-234.

(6) Gohara, H. et al. "Next-gen IGBT module structure for hybrid vehicle with high cooling performance and high temperature operation". Proceedings of PCIM Europe 2014, 1187-1194.

(7) Saito, T. et al. "Investigation of New Joint Technology for High Temperature Operation and High Reliability of Power Module". Proceedings of the 20th Symposium on Micro joining and Assembly Technology in Electronics. Yokohama, 2014.

(8) Nishiura, A. et al. "Improved life of IGBT module suitable for electric propulsion system". Proceedings of the 24th EVS, Stavanger, 2009.

(9) Saito, T. et al. "New assembly technologies for Tjmax=175°C continuous operation guaranty of IGBT module". Proceedings of PCIM Europe 2013, 455-461.

(10) McKenna, S.P.; McGlillis, W.R. "Performance of digital image velocimetry processing techniques". Exp. Fluids, 32 (2002), 106-115.

(11) The Visualization Society of Japan. "PIV Handbook". print 2002.