Development of Water-Cooled Heat Sink for High-Power IGBT Inverter

Minsub Han
Department of Mechanical Engineering
University of Incheon
177 Dohwa-dong, Nam-gu, Incheon, Korea 402-749
Email: mhan@incheon.ac.kr

Su-Dong Lee† , Chanook Hong, Chun-Suk Yang
and Kyung-Seo Kim
CENTRAL R&D CENTER, LS INDUSTRIAL SYSTEMS CO., LTD.
533 Hogye-dong, Dongan-gu, Anyang-si
Gyeonggi-do, Korea 431-080
† Email: sdlee1@lsis.biz

Abstract— We present the development of a water-cooled heat sink that provides reliable thermal performance for high-power IGBT inverter. The development process comprises three stages. In the concept design, the thermal performances of two design proposals are considered. The thermal system of each design is particularly analyzed using the compact model. In the detailed design stage, specific dimensions of the heat sink are determined considering the design options under given external restrictions and the results from three-dimensional heat transfer analysis. The prototype of the resultant design is made and tested on the rig for final confirmation. We emphasize the relevant use of the thermal analysis on each stage and also discuss various practical issues involved.

I. INTRODUCTION

Inverter is the device that converts the magnitude and frequency of electric voltage, and it is one of the essential elements in driving electric motors of various purposes by controlling the speed of the motor. The power module in the inverter is increasingly based on IGBT (Insulated Gate Bipolar Transistor) and FWD (Free Wheeling Diode). IGBT inverter usually generates significant amount of heat due to the operational power loss and requires immediate release of the heat to insure good performance. Then, the IGBT inverter needs an additional system that transfers the heat efficiently into environment. Heat sink is commonly found in any electrical device that needs cooling and does the efficient job of transferring the energy from the electric circuits to coolant. The high-power inverters of several Megavolts or those for electric vehicles, which also need miniaturization, require the cooling system of high efficiency and reliability and often introduce the water-cooled heat sink system.

The primary goal in the design of the cooling system of inverter is to maintain the temperature of the transistor junction in the power module below the maximum allowable temperature for normal operation. In the purpose, the heat sink and coolant system need to have enough capacity to exit the heat quickly. The heat pathways from the power module to the coolant also need to be optimized. The relevant issues are, for example, the optimum packaging of modules, minimization of the contact resistance and special arrangement for locally over-heating region.

The optimized cooling system does not only enhance the reliability of inverter. It also minimizes the capacity of heat sink and coolant and, therefore, makes the inverter design more compact. The design reduced in size and weight can significantly contribute, for example, to the performance or the packaging in engine room of electric vehicle.

We here present the development of a water-cooled heat sink that can provide a reliable thermal performance for high-power IGBT inverter. The development process is composed of three stages. In concept design, the thermal performances of the competing designs of inverter are comparatively analyzed by using the compact thermal model. We then develop a detailed design of heat sink by assessing various design parameters using the three-dimensional heat transfer models. The prototype of the final design is made and tested.

II. GENERAL DEVELOPEMNT PROCEDURE

The design process of cooling system may roughly be divided into three stages: concept design, detailed design and test. In the stage of concept design, some fundamental decision on the heat sink design is made according to the requirement of a target inverter. In this stage, it is useful to have some information on performance of the system in consideration even though the system details are not available. It may be provided by so-called compact model that focuses more on the overall performance of the system using simplified thermal models. For example, the three dimensional features like lateral distribution of thermal properties or local thermal pathways are not considered. The compact model makes it possible to analyze overall characteristics of the cooling system quickly with a reasonable accuracy before detailed design decisions are made in the concept stage.

After major design concept on the power module inside the inverter are decided such as the module specifications, operating condition and module arrangement, the detailed dimensions of heat sink are determined. Above all, the dimensions and distribution of fins in the heat sink are determined according to the system requirement and the restrictions imposed by packaging and manufacturing issues. The three dimensional modeling process usually proceeds simultaneously. 3-D CAD (Computer Aided Design) model is produced for the uses of drawing, thermal modeling and prototype production. Also, 3-D thermal modeling is performed that includes three dimensional shape and arrangement of almost all the parts participating in the heat transfer. The 3-D model provides a more accurate picture on the thermal performance of a heat sink design that can be used in decision of the final draft for prototype production.

Finally, the prototype is produced and the test for thermal reliability is performed. Some minor modification of the design is made if necessary according to the test results. However, a major change in design would cost significantly on this stage and, therefore, relevant decisions should be made in development stage as early as possible.

TABLE 1
Two Cases for Compact Model Analysis

	Power Loss per Module: steady state (kW)	Power Loss per Module: excess state (kW)	No. of Module per Inverter	Total area of modules (m^2)
Case I	0.83	1.68	2	0.040
Case II	0.35	0.71	3	0.027

III. RESULT

A. *Concept Design*

One of the primary design decisions to be made at the concept stage was on the power module configuration. We considered inverter systems of two different configurations. One consists of two IGBT modules of a certain type and the other consists of three modules of a different type (See Table 1). While there were other important issues regarding the decision such as inverter design and packaging, we were also interested in thermal performances of the two competing systems. Since it was an early stage of the development, the basic data for accurate analysis was not available. Also, later stages in the development, especially prototype production, usually take up a large portion of the total development period, and a comprehensive modeling of the thermal system is not practical. We instead built a compact thermal model that can be rapidly modeled and is suitable for relative comparison of the systems (Fig. 1a).

The amount of power loss is obtained that is based on the rated current of inverter using the computational tool supplied by the module manufacturer (See Table 1 & 2). The compact model consists of thermal impedances of the power module, thermal grease and heat sink. The data on the power module and thermal grease are provided by the manufacturers. The heat transfer model of the heat sink is based on the theoretical correlations of Sparrow et al [1]. The typical values for the model system are supplied in Table 2.

TABLE 2
Comparison of Model Properties of the Two Thermal Systems

		Case I		**Case II**		**Case II /Case I (IGBT)**
		IGBT	**diode**	**IGBT**	**diode**	
1. Power Module Spec.	**Power loss of each unit (W)**	**96.7**	**42.1**	**42.5**	**16.1**	**0.4**
	R junciton to case (K/W)	**6.0E-02**	**1.0E-01**	**1.3E-01**	**2.4E-01**	**2.2**
	R case to heatsink (K/W)	**4.8E-02**	**8.0E-02**	**1.0E-01**	**1.8E-01**	**2.1**
2. Inverter Configuration	**Number of modules**	**2**		**3**		
	Unit number per module	**6**	**6**	**6**	**6**	
	Module power loss per unit area (kW/m^2)	**42.1**		**38.4**		**0.9**
	Total power loss	**1.7**		**1.1**		
	Total area of modules (m^2)	**4.0E-02**		**2.7E-02**		**0.7**
3. Thermal grease	**R grease (K/W)**	**8.0E-03**		**1.7E-02**		**2.2**
4. Heat sink	**R heatsink to coolant (K/W)**	**4.1E-02**		**8.9E-02**		**2.2**

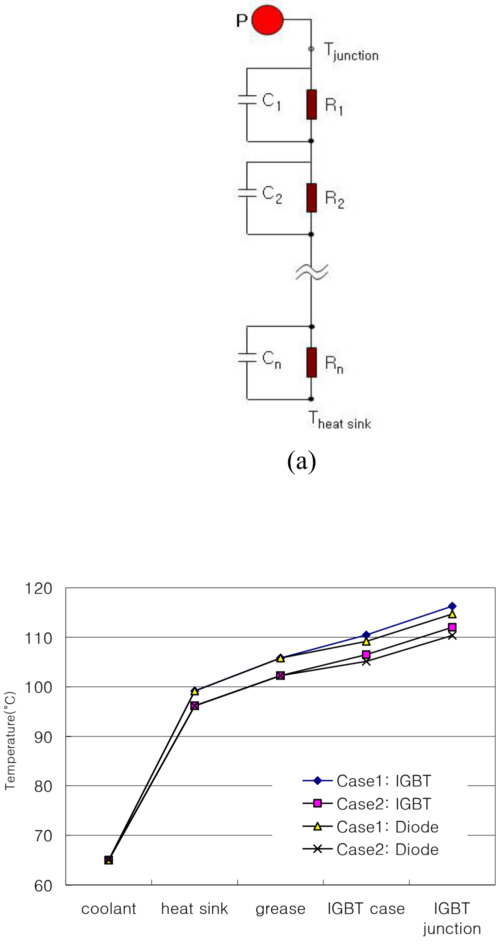
The temperature distribution results from the compact model analysis are compared in Fig. 1b. According to the results, the IGBT junction temperatures are given as 116.3 and 112ºC for Case I and II, respectively. The temperatures are all far less than those of malfunction of the transistors in IGBT even though their accuracy are dependent on the accuracy of thermal impedances of power module and heat sink. On the other hand, the relative comparison of the two cases is more meaningful. The results indicate that Case II does a better thermal performance of the two. Or the performances of the two systems are at least comparable. The two systems are different from each other only in the configurations of power module, which is therefore the direct source of the difference. It is noted in the figures of Table 2 that the module power loss per unit area of Case II is about 10 per cent lower than that of Case I. This indicates that the system of Case II is required to transfer about 10 per cent less amount of energy into the unit area of heat sink and therefore results in a less thermal load.

The thermal performance results from the compact model analysis along with other related issues like inverter system configuration were considered in the inverter design. The results were also used in the initial phase of heat sink design, for example, when the thermal load and fin dimensions of the heat sink are to be determined tentatively.

B. Detailed Design

The detailed design of the heat sink was developed first by considering the design options available under the given restrictions. We built 3-D CAD model based on the considerations. 3-D heat transfer analysis was also performed for checking the overall thermal performance with a more realistic model of heat sink and some local 3-D effects unresolved in the compact model.

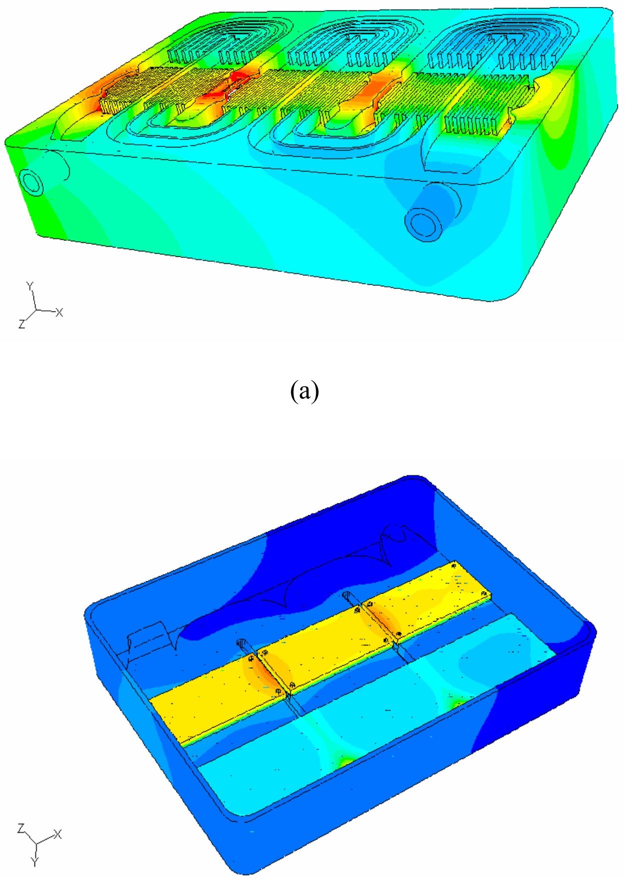
Figure 2 shows a heat-sink design. The heat sink is located on the outer face of the case of inverter (Fig. 2a). The IGBT modules are attached to the inner face of the case (Fig. 2b). The coolant flow path is determined to supply sufficient amount of coolant to the strongly heated locations considering the restrictions, which are imposed by, for example, the positions of the inlet and outlet of coolant and the bolting locations for gasket and cover that are dependent on the packaging condition. The narrow fins are densely



(a)

(b)

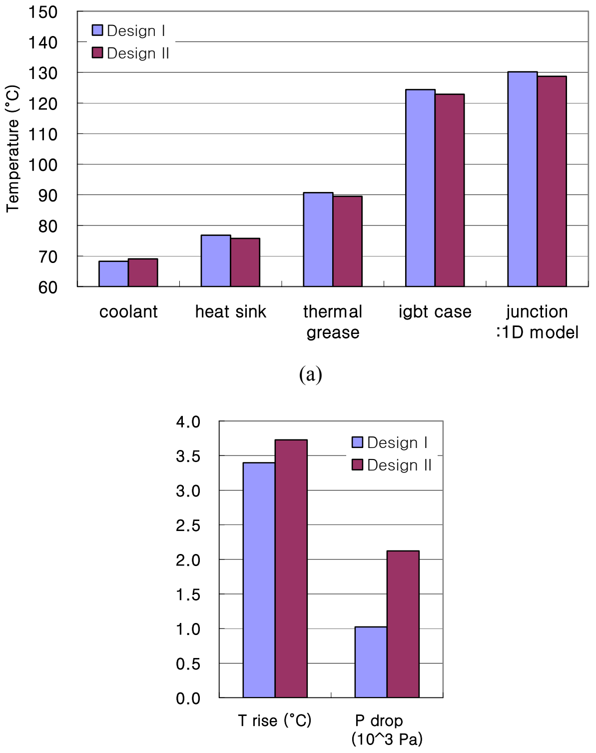
Fig. 1: (a) Compact Thermal Model and (b) Analysis Result



(a)

(b)

Fig. 2: 3D thermal analysis result (a) heat sink outside the inverter case (b) IGBT locations inside the case



(a)

(b)

Fig. 3: 3D thermal analysis result (a) temperature distribution, (b) coolant temperature rise and pressure drop

populated in the middle where three IGBT modules are located. The rest of the flow paths do not have fins except when the flow needs to be guided. The pitch and thickness of fins are decided to maximize the heat transfer under the restriction imposed by the manufacturing issues.

The 3-D heat transfer model resolves the three dimensional heat flow from the IGBT case to heat sink by solving the energy equation and Navier-Stokes equation using a commercial package for computational fluid dynamics (CFD) [2, 3]. The convective heat transfer inside the pathways of coolant is explicitly solved while a typical value of heat transfer coefficient in natural convection is applied on the faces in contact with air. The conductive heat transfer in the heat sink and thermal grease are explicitly solved. The conduction inside IGBT module is not modeled with three-dimensional details and the compact model is used instead. The detailed thermal model of IGBT may be critical in the design of IGBT but less so in the heat sink design. It is pointed out that the thermal resistance values in the compact model provided by manufacturers are obtained by the standardized experimental methods, the results from which are usually relevant only when the cooling capacity of the heat sink is sufficient.

Figure 3a and 3b show the results of 3-D heat transfer analysis for two different designs. There is little difference between the two regarding the overall design of heat sink except for fin density. Design II has smaller fin pitch and thickness than Design I in the region of IGBT. The case in consideration is the excess state where the maximum power loss is sustained steadily (See Table 1). The temperature distributions indicate that the coolant is sufficiently supplied to the entire region of strongly-heated area. The transistor junction temperatures are all below that of the operational failure (150℃) with large margin. Design II has a temperature 0.8℃ less than Design I at the junction. The variations between the three IGBT modules are less than 5℃.

TABLE 3
Comparison between the test result and the thermal analysis

	Coolant	Heat Sink pt #1.	Heat Sink pt #2.	IGBT Case
Test (°C)	30	35.8	35.9	41.4 (NTC Thermister)
3D model (°C)	30	34	34.6	37.2

C. Test

The prototype of the heat sink based on Design II in the section *B* was produced. It is made of aluminum using CAM machining by Machining Center.

Next, the test rig was set up for inverter performance testing. The test configuration for thermal measurement is shown in Fig 4. The inverter is run with constant voltage/frequency ratio, and a passive RL load is applied. The coolant is supplied at constant flow-rate and temperature. Temperatures were measured at more than dozen locations around the heat sink with T-type thermocouple, and the temperature of the NTC thermocouple embedded in IGBT is also monitored. A typical run takes about 30 minutes before all the monitored data are stabilized.

The measured data in the case of coolant temperature of 30℃ are provided in Table 3. While those at the heat sink and thermal grease are relatively easy to collect, the temperatures inside the IGBT module are tricky to evaluate. The thermister embedded in the module may closely represent the temperature of the module case. The measured data are also compared with the 3D simulation results in Table 3. More results on the test will be provided in future publication.

IV. CONCLUSION

A water-cooled heat sink for high-power IGBT inverter is developed that shows a reliable thermal performance. We have presented the development process underscoring various practical issues involved. Careful considerations on the typical design conditions like main requirement, design options and engineering restrictions were made. At each stage of the development, we performed the thermal analysis resorting to the methods that reasonably satisfy the balance between the development schedule and cost and the model accuracy. More work is under way to reliably predict or estimate the temperature of the transistor junction of IGBT along with the optimization of the developed design.

ACKNOWLEDGMENT

M.H. gratefully acknowledges that this research is supported by LS Industrial Systems, Co., Ltd.

REFERENCES

[1] E.M. Sparrow, B.R. Baliga and S.V. Patankar, “Force Convection Heat Transfer from a Shrouded Fin Array with and without Tip Clearance,” 1978, Journal of Heat Transfer, Vol. 100, pp. 572-579.
[2] F. P. Incropera and D.P. DeWitt, Fundamentals of Heat and Mass Transfer, 1996 John Wiley & Sons, New York.
[3] Fluent Inc., FLUENT 6.1 User’s Guide, Lebanon, New Hampshire, 2003.

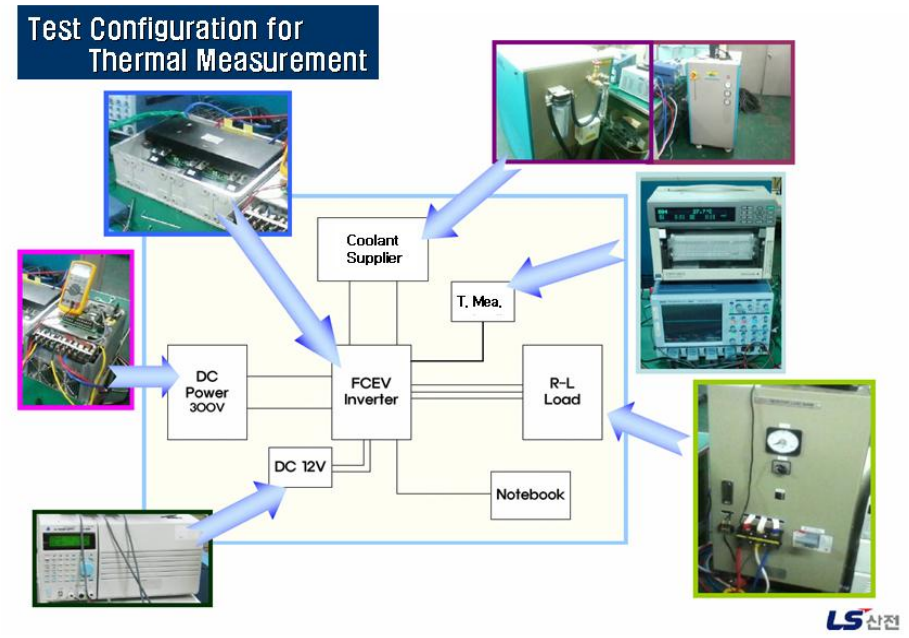


Fig. 4: Test Configuration for Thermal Measurement