3-D Numerical and Experimental Analysis of an Integrated Liquid-Cooled IGBT Power Module

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Abstract

This research uses numerically and experimentally methods to design the liquid-cooled module of the driver of an 80kW motor. The configuration of the flow channels of the liquid-cooled module is designed and simulated via computational fluid dynamics (CFD). The designed module is experimentally verified via a simulated heat source of the inverter. The experimental results show that the designed module is capable of releasing the dissipated heat of the inverter 862W. The designed liquid-cooled is water cooling, with copper fin and aluminium base. The flow rate of this module is 10 L/min. The set up mathematical model is able to design follow-up different types of drivers, which have different heat generated. So that the develop schedule can be shortened and cost down the mock-up set up as well.

Keywords: Heat transfer, CFD, IGBT

1 Introduction

For electric vehicle application, the driving motor is no need for doubt the key component. And the driving motor is with high power and is controlled by a driver. The main heat source of the driver of the high-power motor is from the IGBT (insulated gate bipolar transistor). To let the drive efficiency will not be depressed by the temperature rise; we design a liquid-cooled base to remove the dissipation heat generated from the IGBT. The layout of the driver integrated with the cooling module is as figure 1, in which the IGBT is cooled by a bottom liquid-cooled copper base.

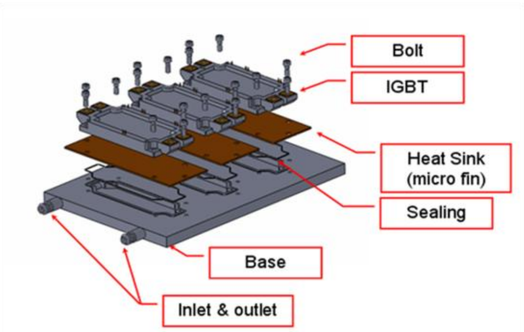

Figure 1: The physical model of the high-power driver with the cooling module

As the cooling system concerned, is meant to measure the rising temperature situation when IGBT is working. Thus, heat transfer should be taken into consideration in cooling base. In the beginning of the design, thermal resistance of system can be estimated by Thermal Network Method (TNM) [1].

2 Design and mathematical model

Governing equations

Normally, fluid motion is described by Navier-Stokes equation. The following assumptions were made to simplify the analysis:

- Flow field is the model of 3-D turbulence
- The properties of fluid are assumed as constants
- The fluid is considered to be incompressible with constant physical properties
- All modules are uniform-heated

Then, for the fluid region, the dimensionless time averaged equations for continuity, momentum (i.e. Reynolds-averaged Navier-Stokes equation) and energy can be expressed in tensor form as:

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial}{\partial x_j}\rho(\overline{u_i}\,\overline{u_j}) = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}[\mu_{eff}(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}) - \rho\overline{u_i'u_j'}] \tag{2}$$

$$\frac{\partial}{\partial x_j}\rho c_p(\overline{u_j}\,\overline{T}) = \overline{u_j}\frac{\partial \overline{p}}{\partial x_j} + \overline{u_j'}\frac{\partial \overline{p'}}{\partial x_j} + \frac{\partial}{\partial x_j}(k\frac{\partial \overline{T}}{\partial x_j} - \rho c_p\overline{u_j'T'}) \tag{3}$$

$$\frac{\partial}{\partial x_j}\left(\rho\overline{u_j}k\right) = \frac{\partial}{\partial x_j}(\frac{\mu_{eff}}{\sigma_k}\frac{\partial k}{\partial x_j}) + \rho(P_r - \varepsilon) \tag{4}$$

$$\frac{\partial}{\partial x_j}\left(\rho\overline{u_j}\varepsilon\right) = \frac{\partial}{\partial x_j}(\frac{\mu_{eff}}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}) + \rho\frac{\varepsilon}{k}[(c_1 + c_3\frac{P_r}{\varepsilon})P_r - c_2\varepsilon] \tag{5}$$

where

$$P_r = \frac{\mu_t}{\rho}[2(\frac{\partial u_i}{\partial x_i})^2 + (\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i})^2 - \frac{2}{3}(\nabla u_i)^2]$$

$$\mu_{eff} = \mu + \mu_t$$

$$\mu_t = \rho c_\mu \frac{k^2}{\varepsilon}$$

where $c_\mu = 0.09$, $c_1 = 1.15$, $c_2 = 1.90$, $c_3 = 0.25$, $\sigma_k = 0.75$, and $\sigma_\varepsilon = 1.15$

Equation (2) contains Reynolds stresses that are set by the k-ε turbulence model proposed by Wang and Chen [2], where the k is the turbulent kinetic energy and ε is the dissipation rate. As to the velocity distribution in the near-wall region ($y^+ \leqq 11.63$), the following law of the wall given by Liakopoulos [3] is applied:

$$u^+ = \ln\left[\frac{(y^+ + 11)^{4.02}}{(y^{+2} - 7.37y^+ + 83.3)^{0.79}}\right] + 5.63\tan^{-1}(0.12y^+ - 0.441) - 3.81 \tag{6}$$

The heat conduction equation for the solid region is expressed by:

$$\frac{\partial^2 T_s}{\partial x_j^2} = 0 \tag{7}$$

Boundary conditions

The inlet is a uniform flow with flow rate 10L/min and temperature (Tin= 20^{o}C) are assumed.

$$k = (I \times u_{in})^2$$

$$\varepsilon = \frac{C_\mu k^{3/2}}{0.05d} \tag{8}$$

where $I = u'/\overline{u}$

At the outlet,

$$\frac{\partial \Phi}{\partial x} = 0 \tag{9}$$

where Φ may be u，v，w，T，p，k，ε

Solid surface boundary condition:

$$\frac{\partial T}{\partial n} = 0 \tag{10}$$

The plane that the IGBT and heat sink contact is the boundary condition of heat source. Total heat source of system is 862W, which is calculated from the rate/maximum deliver power, switching frequency of the IGBT, current waveform, and temperature. Equation (12) and equation (13) represents the condition of continuity of temperature and heat flux on the solid-fluid interface surface.

$$- K \frac{\partial T}{\partial n} = q \quad (11)$$

In addition, at the solid-fluid interface,

$$- k_{fluid} \frac{\partial T_{fluid}}{\partial n} = -k_{solid} \frac{\partial T_{solid}}{\partial n} \quad (12)$$

$$T_{fluid} = T_{solid} \quad (13)$$

Figures 2 is the schematic diagram of the assemble chart of the driver with the cooling base (IGBT module), in which the discrete IGBT is shown in figure 3. The research is to provide the cooling solution of different types of IGBT, in which the generated heat is different.

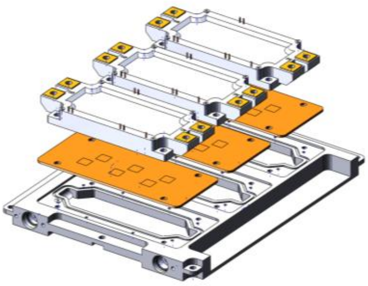

Figure 2: The assemble chart of the driver with the cooling base (IGBT module)

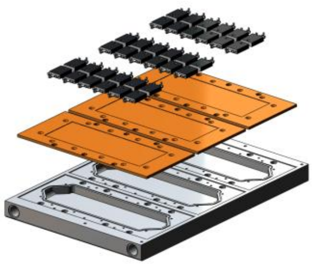

Figure 3: The structure of drive cooling base (IGBT discrete)

The structures of the cooling base of IGBT discrete I, IGBT discrete II, IGBT discrete III, and IGBT discrete IV, are shown in figures 4, 5, 6, and 7, individually.

Figure 4: The structure of the driver's cooling base (IGBT discrete I)

Figure 5: The structure of the drive's cooling base (IGBT discrete II)

Figure 6: The structure of the drive's cooling base (IGBT discrete III)

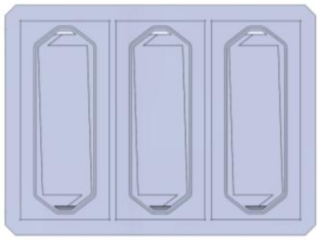

Figure 7: The structure of the drive's cooling base (IGBT discrete IV)

3 Numerical and experimental results

As the cooling system concerned, is meant to Figures 8, 9 and 10 present the numerical results of temperature, pressure, and velocity, respectively, with heat source q= 862W, cooling water volume flow rate Fr = 10 L/min, and inlet temperature = 20^{o}C. In these conditions, the highest temperature of the heat sink side is about 29^{o}C, and the pressure drop is about 8.9kPa. By the heat sink temperature and heat flux, that can be calculate thermal resistance of the cooling base is about 0.009°C/W.

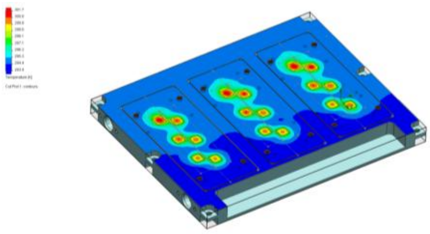

Figure 8: The temperature distribution of base with heat source 862W and flow rate Fr= 10 L/min

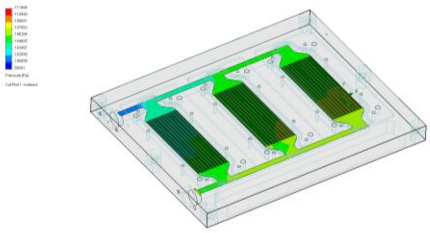

Figure 9: The Pressure distribution of water with heat source 862W and flow rate Fr= 10 L/min

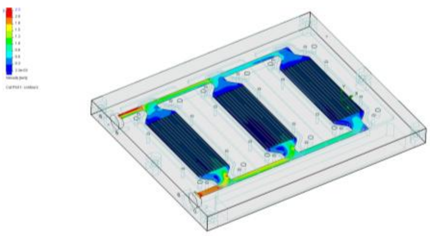

Figure 10: The Velocity distribution of water with heat source 862W and flow rate Fr= 10 L/min

A schematic diagram of the experimental measurement system is shown in figure 11. In discrete design, when IGBT exchanges module for discrete mode. The inside cooling base will be affected by heat sink. There are four types in discrete designs. The results are provided in Table 1. The derived flow rate of the cooling system is 10L/min, and the thermal resistance is about 0.098°C/W. In the discrete, the research offers four types cooling base for the cooling system for consideration. As a result, the thermal resistances of the four models are derived 0.0556, 0.0565, 0.0543, 0.0565°C/W, respectively. The maximum temperature different is defined as the temperature different of the inlet temperature of the water and the point of simulated IGBT. The pressure drop and the maximum temperature different of the mode 1 are both the minimum, so that its design would be the best choice.

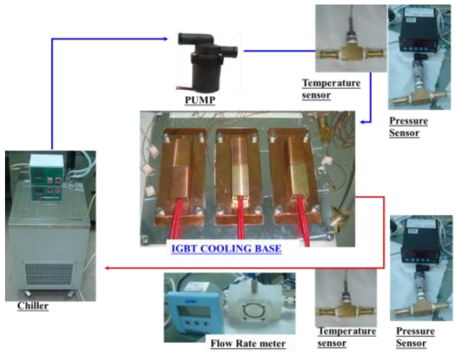

Figure 11: Schematic diagram of the experimental measurement system

Table1: Cooling base design

	Module	Discrete I (mode1)	Discrete II (mode2)	Discrete III (mode3)	Discrete IV (mode4)
Pressure Drop (kPa)	9.5	9	19	12	17
Max Temp. different (℃)	8.3	4.8	5.6	3.7	4.7
Thermal Resistive (℃/W)	0.098	0.0556	0.0565	0.0543	0.0565

4 Conclusions

For the driver with heat loss of 862W, the liquid-cooled module is successfully designed, manufactured, and verified via the numerical and experimental methods. The flow rate of this water-cooled module is 10 L/min. And the cooling layout of multi-drivers is also achieved. The set up mathematical model is able to design follow-up different types of drivers, which have different heat generated.

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