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Parametric study and Response Surface of an IGBT Module using finite element method

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ABSTRACT

Power module contains one or more semiconductor switches packaged together for easy connectivity. Power semiconductor modules play a key role in a power electronic system. The module can be used to enclose diodes, FET, IGBT, or similar semiconductor switches. Nowadays, Insulated Gate Bipolar Transistors are widely used because of their good switching performance combined with fairly low conduction losses. A lot of effort has been put to develop the next generation IGBT modules of hybrid vehicles. The trend of power electronics miniaturization, both in consumer and military applications, challenges board assembly design, materials, and processes. PEs must meet strict automobile manufacturers' design criteria like weight, size, reliability, and cost when used in HEVs. Existing designs rely mainly upon over sizing the PEs or by inclusion of large heat sinks, both of which detract from size and cost criteria of automotive design criteria. In this paper, inverter module of Toyota Prius consisting of 12 pairs of IGBT devices and diodes is used. Parametric study is carried out to study the effect of cold plate dimensions, total power on IGBT, TIM and its thickness and convective heat transfer coefficient on the performance of module. Also, response surface tool is used to get the optimized structure.

Keywords— IGBT, miniaturization, optimization, parametric study.

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I. INTRODUCTION

POWER semiconductor devices are an enabling technology to convert energy between different forms. In the last two decades, they are playing an increasingly important role in safety-critical aerospace and automotive applications where stringent reliability constraints are placed on power electronic (PE) systems. As a result, there is a pressing need to improve power electronic systems by optimized design, advanced manufacturing and packaging, as well as system integration. PEs must meet strict automobile manufacturers' design criteria when used in HEVs. The four most important design criteria for the automotive industry are weight, size, reliability, and cost [1]. Insulated-gate bipolar transistor (IGBT) is a typical power electronic device having ability to operate without breakdown at hundreds and thousands of volts and current capacities in tens to thousands of amperes. IGBT power modules find widespread use in various applications including renewable energy, transport and space, industry, utility and home appliances. They have been manufactured in large quantities and have dominated a large portion of the medium- and high-power conversion market for decades. Their failures determine the system downtime and increase the operational cost [2], [3]. Power semiconductor devices were rated as the most fragile component of a power electronic system from a recent industrial survey, followed by capacitors and gate drives [4]. Also, IGBT device generates a lot of heat in normal operation because of its power conversion inefficiency, which is exacerbated when the IGBT devices are used as the high-speed switching devices in power systems operating at high voltage and high current levels [5]. Fig 1 shows a typical multilayered IGBT power module.

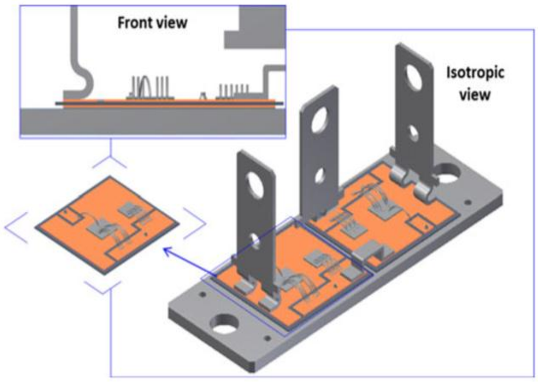


Fig. 1.Typical multilayered IGBT power module. [6]

The heat flux of these devices for hybrid electric vehicles is now at the level of 100–150W/cm2 and is projected to increase to 500W/cm2 in the next generation as the current capacity and switching frequency increase [7–9]. High heat flux leads to high IGBT temperatures and has grown into one of the major barriers to the development of advanced power electronics for electric vehicles. The device and package-related failures account for 35% of the faults in the power electronics system [10]. The constantly growing need for power semiconductor devices coupled with important roles they have played in the system has led to corresponding reliability. In general, an IGBT module is comprised of one or more semiconductor chips and its package, which are equally important in providing high performance service. It is constructed with different materials (e.g., silicon, aluminum, copper, ceramics, and plastics), package designs (e.g., layout, geometry, and size) and properties (e.g., electrical, thermal, and mechanical). These components/layers are mostly bonded together by soldering and bond wires. The assembly is then covered with an insulating gel and enclosed in a polymer housing from which only the metal connectors of the device terminals emerge. The base plate of the assembly is mounted onto a heat sink or other cooling devices with thermal interface material greased between them for improved thermal contact. Today, there is a growing trend toward IGBT. In most cases, this trend is technology driven and for a given application, gain in terms of cost, reliability or manufacturability are often not achieved. So it has become an essential part to study the effect of various parameters on IGBT.

II. OBJECTIVE

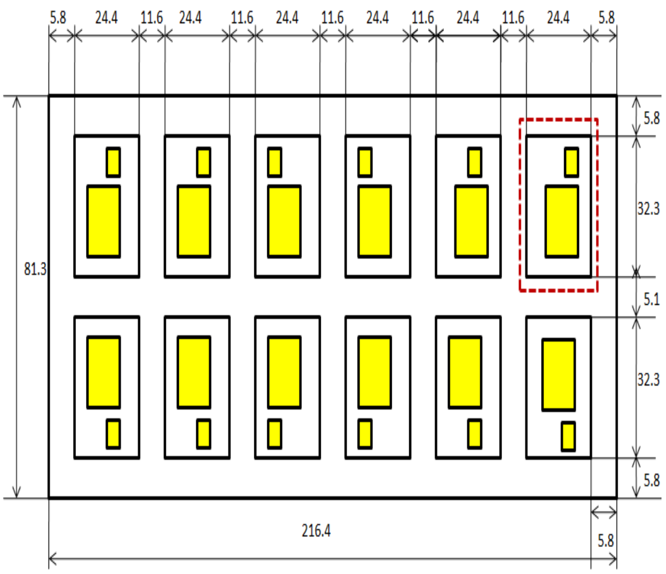
A steady state thermal analysis of a twelve-pack Insulated Gate Bipolar Transistor (IGBT) power module is carried out. Several key design parameters such as coolant, inlet temperature of the coolant, channel height, various TIM materials that can be used, TIM thickness and convective heat transfer coefficient are taken into consideration in the analysis for parametric study. A comparison of variation in these parameters and its effect on IGBT temperature is shown which integrates the response surface methodology and ANSYS.

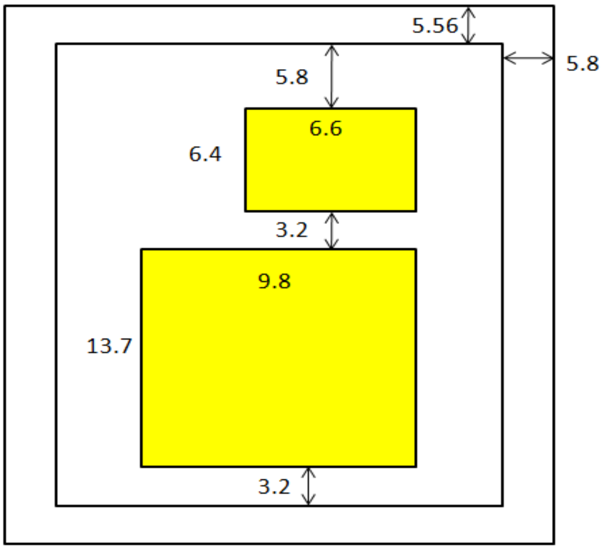
III. FINITE ELEMENT MODEL AND TESTING CONDITIONS

In this study, IGBT module of the well-known Toyota Prius inverter is considered. The Prius IGBT module inverts dc input power from the battery to variable frequency, variable voltage, three-phase ac output to drive the motor. A three dimensional model with: 12 pairs of chip- diode, two solder layers and one DBC layer below each pair mounted on a base plate is generated. The base plate is mounted on the cold plate using TIM, the stacked up layer is as shown in Fig. 2. The cold plate has 80 number of channels with the channel height of 1mm, the channel width of 0.5mm and the wall thickness of 0.5mm. More details on the Prius inverter and motor can be found in reference [11]. Finite element simulation software is used to create the geometry and to carry out the steady state thermal analysis. Material properties are assigned to cold plate, base plate, solder layer, DBC, diode and chip as given in table 1. Finite element model is generated as shown in the Fig. 3 in which the total number of nodes is 3594966 and total number of body elements is 754223. Element type Solid 87 and Solid 90 are used for components while Conta 174 and Targe 170 are used for contact elements. Mesh sensitivity analysis is carried out where maximum IGBT temperature varies in the range of +/- 5%. Fine meshing is used for the analysis. A power dissipation of 40W is applied on each diode and 160W is applied on each chip. This contributes to a total heat flux of 120 W/cm2 on the IGBT device, 95 W/cm2 on the diode, and a total power dissipation of 2400Won the entire motor inverter [12]. The model has been validated with reference [13].

TABLE 1

Material	**Dimensions(mm)**	**Thermal Conductivity (W/mk)**
Aluminum Cold Plate	81.3 x 216.4 x 6	200
TIM	81.3 x 216.4 x 0.1	4
Copper Base Plate	81.3 x 216.4 x 3	393
Solder Layer 1	32.3 x 24.4 x 0.1	50
Copper 1	32.3 x 24.4 x 0.41	393
AlN Substrate	32.3 x 24.4 x 0.64	170
Copper 2	32.3 x 24.4 x 0.41	393
Solder Layer 2	32.3 x 24.4 x 0.1	50
Diode	6.6 x 6.4 x 0.32	120
Chip	13.7 x 9.8 x 0.51	120





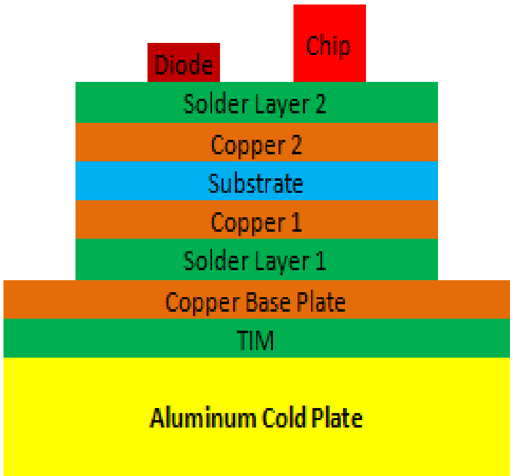
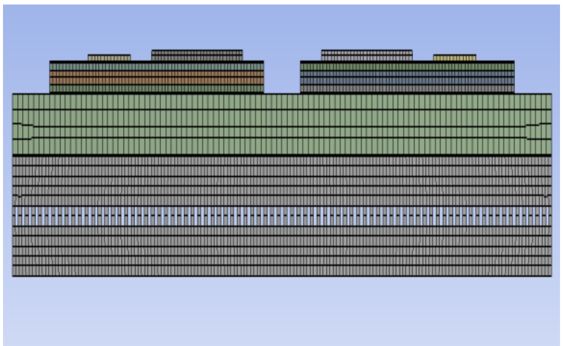
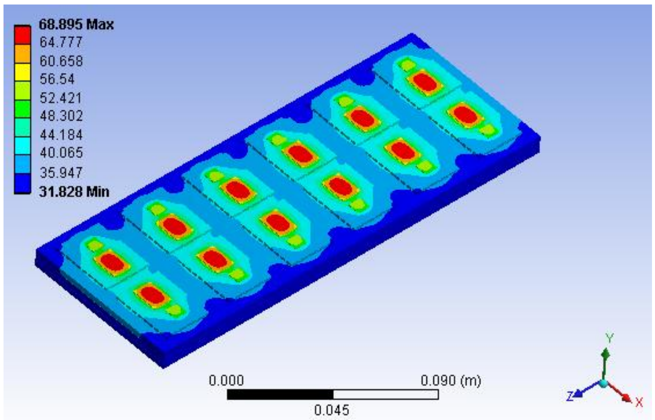
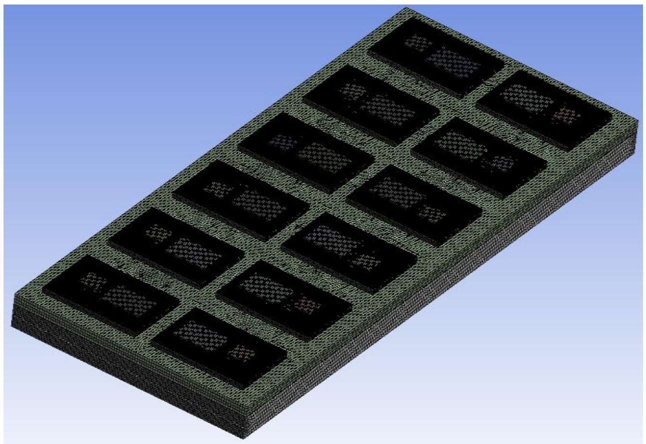


Fig. 2 Single IGBT







R134a is considered as the working fluid. The convective coefficient range for this coolant is generally, 10,000 W/m2K to 22,000 W/m2K. For steady state analysis the average heat transfer coefficient is taken as 11500W/m2K [13].

Fig 3(a) The layout of the IGBT device for Toyota Prius inverter(b) Isometric view finite element IGBT test model (c) Front view of finite element meshed model

IV.RESULT & DISCUSSION

Fig. 4 Temperature plot showing results for Baseline case
Maximum temperature for baseline case is 68.895ºC as shown in fig. 4

Thermal Interface Material	**k (W/mk)**
Wacker Silicone P12	0.8
AavidThermalloyThermalcote 251 G	0.369
Arctic Silver 5	8.7
ThermaxtechXt-flux-GA	7
Dow Corning TC-5022	4
Shinetsu X-23-7762-S	4.4
Multi layerGraphene	14
PCM	3-8

Effect of change in convective coefficient on maximum IGBT temperature:

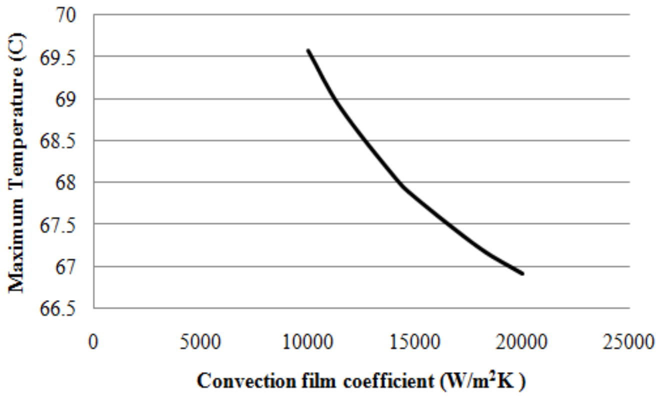


Fig. 5Tmax vs. convection film coefficient (Tinlet=30°C, Pinlet=7.7 bars, Nch =80, Hch=1.0mm)

A parametric study is carried out using coolant R134a, with h varying from 10,000 W/m2K to 20,000 W/m2K.The effect of convection coefficient on maximum IGBT temperature is shown in Fig. 5. The results indicate that with increase in convective coefficient of the refrigerant, maximum temperature decreases.

Effect of Change in Inlet Temperature on maximum IGBT Temperature:

Fig. 6 shows saturation pressure for R134a. The pressure for evaporation at temperatures higher than 60°C is high and difficult to maintain. Also, the condenser is cooled by air. To avoid condensation on the cold plate, the temperature should not be kept too low.

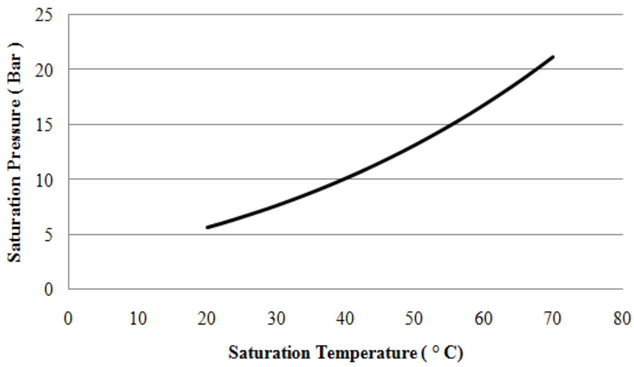


Fig. 6 Saturation pressure vs. Saturation temperature

The inlet temperature is varied from 30ºC to 60ºC to see its effect on maximum temperature. It is found that there is a linear relationship between convection ambient temperature and maximum temperature.

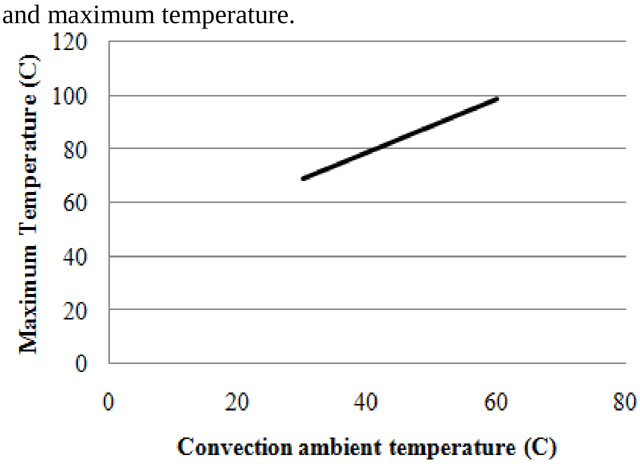


Fig. 7Tmax vs. Convection ambient temperature

Effect of change in Thermal Interface Material:

Thermal interface materials pose a major barrier to heat removal from the IGBT package. This TIM layer can contribute almost 40 to 50% of the total thermal resistance of the different layers in the package. For an ideal TIM, high thermal conductivity and minimum thickness is desirable. Reducing the thermal resistance of the TIM can significantly improve the overall efficiency. TIMs have to be mechanical stable, reliable, non-toxic, low-cost and easy to apply. The following commercially available TIMs shown in table 2, like thermal greases and PCM were considered in our study [14,15].

Thermal greases typically are silicones loaded with thermally conductive fillers. The Shinetsu-X23-7762-S and Dow Corning TC-5022 greases are considered as high-thermal performance materials but expensive, as compared to Wacker Silicone P12 and Thermalcote 251G. The selection of a suitable material to fill the interface is critical to the performance and reliability of the power electronic device. We studied the effect on maximum IGBT temperature by varying the thermal conductivity up to 20 W/mk. Fig. 8 shows the impact of the TIM thermal conductivity on the

maximum temperature. As the TIM thermal conductivity increases, the maximum temperature reduces. Interestingly, with further increase in TIM thermal conductivity, maximum temperature approaches almost a constant value.

Table. 2 Thermal Conductivity for different TIMs

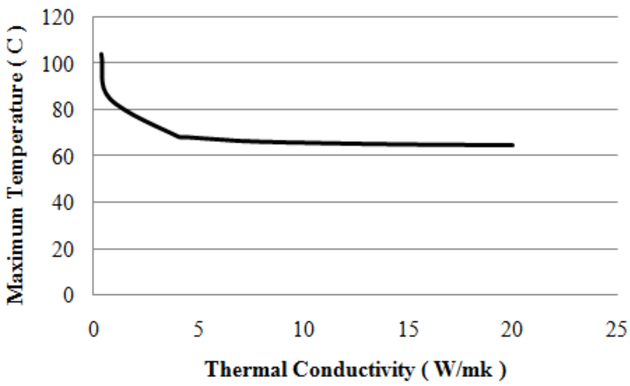


Fig. 8Tmax vs. Thermal conductivity of TIM (Tinlet=30°C, Pinlet=7.7 bars, Nch =80, Hch=1.0mm)

Thus, it does not matter if the conductivity is further increased. Also, we see that if we use TIM with low conductivity, maximum IGBT temperature can be maintained below 125°C, which is desirable.

Effect of change in TIM thickness:

As discussed above, for an ideal TIM minimum thickness of TIM is desirable. TIM thickness has been varied in the range of 25µm to 150µm. The graph shows there is a steady increase in temperature as the thickness is increased. Even if the thickness of TIM is kept 200µm, the temperature can be maintained within limits.

There are many TIMs currently available that perform quite well. Even after the numerous alternatives that have come on in the market in recent years, a low cost thermal paste solution with good performance is still an issue.

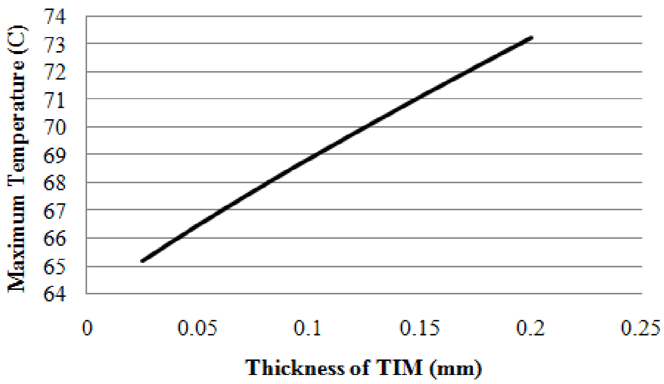


Fig. 9Tmax vs. Thickness of TIM layer (Tinlet=30°C, Pinlet=7.7bars, Nch =80, Hch=1.0mm)

However, even though the final objective function that needs to be optimized is only a single variable, the parameters contributing to the different design sets could be many, if not infinite. In other words parametric design is a “must” in this new age of design optimization of systems. The purpose of RSM is to build response surface function, which is in accordance with the specific rules of sampling parameters and response parameters to build approximate functional relationship between the input parameters and response parameters. An approximate model is used as the alternative

Effect of change in channel height:

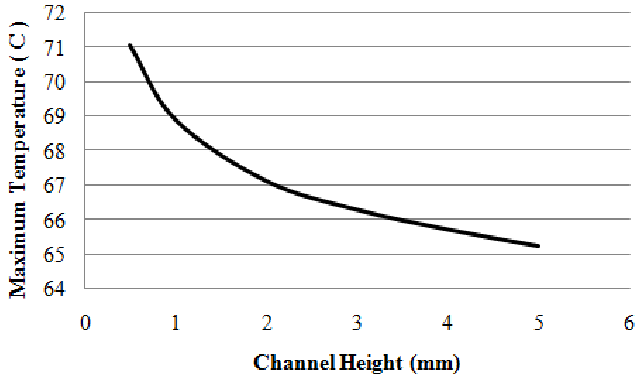


Fig. 10Tmax vs. Channel height of Cold plate (Tinlet=30°C, Pinlet=7.7bars, Nch =80)

Changing the cold plate dimensions affects the convective coefficient directly. For this study we have varied the channel height. As the channel height is increased, it is seen that, the convective coefficient increases which results in decrease in maximum IGBT temperature. It is seen that for 1mm channel height, 11500 W/m2K convective coefficient, the maximum temperature is 68.895°C. Therefore, the coolant required for this channel height is less as compared to 4mm channel height

VI. Response Surface Methodology (RSM) and Optimization

In engineering, design optimization is an advanced level concept because optimization requires tedious mathematical operations. Yet, the need for advanced complex designs requires optimization over multi-valued parameters. The example of these systems could be mechanisms in motion, actuating sensors, heat exchangers, structural configurations, composite lay-ups and other systems which all require optimization for the most efficient design that is cost effective (i.e. angular motion optimization, deflection vs. drive voltage optimization, least number of pipes, minimum beam weight)

model of the exact solution of practical problems when the response surface function is generated. Therefore, the response surface function can be used for further optimized design.

In response surface analysis, we have parameterized input - channel height, TIM thickness, convection film coefficient, convection ambient temperature and output – maximum temperature on IGBT. Design Of Experiments (DOE) is carried out and design points are auto defined by Ansys.

Table of Schematic B2: Design of Experiments (Central Composite Design : Auto Defined)

	A	Clear Generated Data	C	D	E	F
1	Name	P1 - channel_ht	P2 - tim_thck	P4 - Convection Film Coefficient (W mm^-2 C^-1)	P5 - Convection Ambient Temperature (C)	P3 - Temperature Maximum (C)
2	1	1	0.1	0.0115	30	63.96
3	2	0.9	0.1	0.0115	30	64.307
4	3	1.1	0.1	0.0115	30	63.615
5	4	1	0.09	0.0115	30	63.896
6	5	1	0.11	0.0115	30	63.984
7	6	1	0.1	0.011	30	64.177
8	7	1	0.1	0.012	30	63.759
9	8	1	0.1	0.0115	27	60.96
10	9	1	0.1	0.0115	33	66.96
11	10	0.92958	0.092958	0.011148	27.887	62.208
12	11	1.0704	0.092958	0.011148	27.887	61.711
13	12	0.92958	0.10704	0.011148	27.887	62.27
14	13	1.0704	0.10704	0.011148	27.887	61.774
15	14	0.92958	0.092958	0.011852	27.887	61.901
16	15	1.0704	0.092958	0.011852	27.887	61.426
17	16	0.92958	0.10704	0.011852	27.887	61.964
18	17	1.0704	0.10704	0.011852	27.887	61.489
19	18	0.92958	0.092958	0.011148	32.113	66.433
20	19	1.0704	0.092958	0.011148	32.113	65.936
21	20	0.92958	0.10704	0.011148	32.113	66.496
22	21	1.0704	0.10704	0.011148	32.113	65.999
23	22	0.92958	0.092958	0.011852	32.113	66.126
24	23	1.0704	0.092958	0.011852	32.113	65.651
25	24	0.92958	0.10704	0.011852	32.113	66.189
26	25	1.0704	0.10704	0.011852	32.113	65.715

Fig. 11 Table in Ansys showing design of experiments

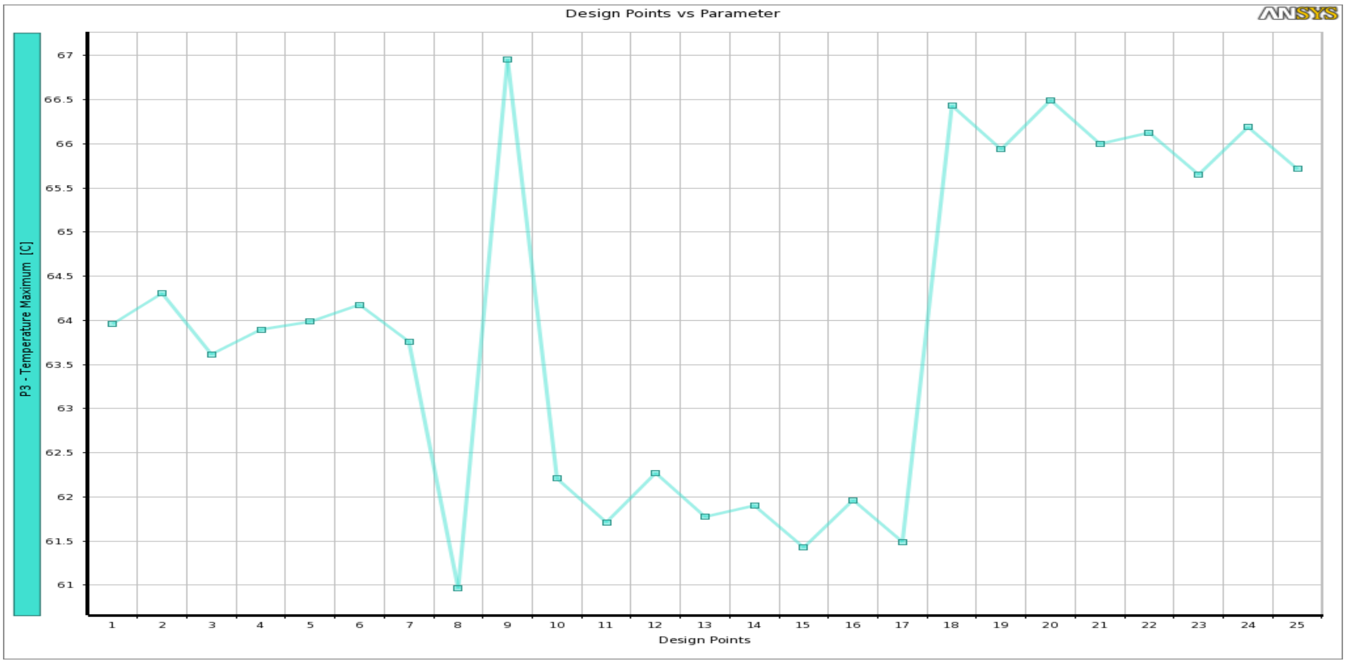


Fig. 12 Design points vs. maximum temperature

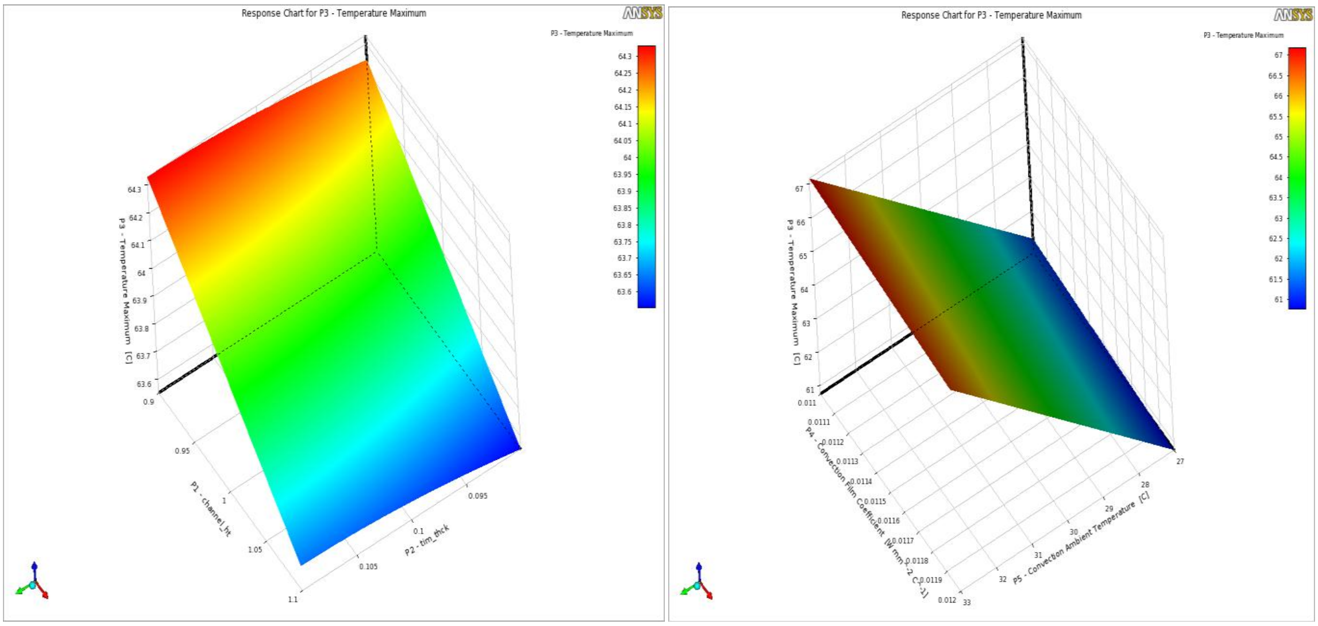


Fig. 13 Response chart for maximum temperature

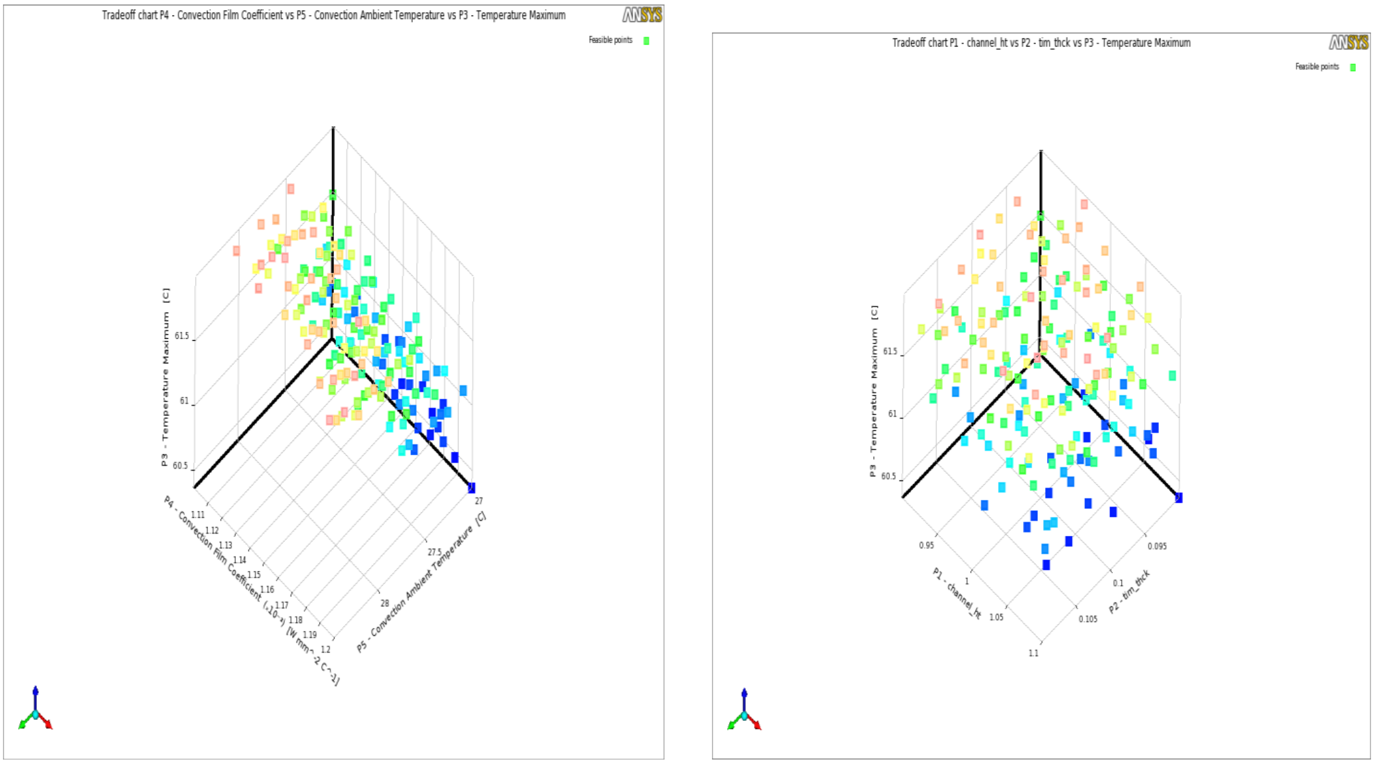


Fig. 14 Tradeoff chart

V.CONCLUSION

In this paper, a generalized parametric study is presented with respect. The results of the analysis illustrate their effect on thermal performance of IGBT, which are in turn crucial to consider during the designing process of two phase cooling system for IGBT. This study provides insights into the system's thermal behaviour and quantitative information about individual factors. Thus, we see the performance of IGBT module mainly depends on proper coolant selection, which is directly responsible for convective coefficient. Moreover, convective coefficient value is dependent on flow rate, heat flux, channel dimension, saturation temperature, etc. Uniform cooling is possible if proper pumping power is selected. The parametric study shows that the inlet coolant temperature for R134a can be in the range of 30°C to 60°C. Also, it is seen that improving the thermal conductivity of TIM layer upto a certain limit i.e. using a better performance TIM results in decrease in overall temperature. Fig 13 and fig 14 shows the result of response surface. Response surface allows you to graphically view the impact that changing each input parameter has on the displayed output parameter. In fig 14, the colors indicate how good the configurations are with respect to the design objectives. Blue color indicate the best suitable design with repect to maximum temperature.

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