Optimization of Heat Sink Embedded with Heat Pipes Design Parameters using Design of Experiments Technique by Taguchi Method

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***Abstract*— The reliability, life and efficiency of electronic components is determined by amount of current passing through them to perform their duties. This has made electronic components to be potential sites for excessive heat generation. Apart from this fact, technological development has also resulted in miniaturization of electrical and electronic components which has also shown its impact on life of electronic components by reducing their reliability further. Thus need of the hour is to increase reliability and life of these components by removing this excess heat generated. A common method used for this purpose is use of active cooled heat sinks that have an advantage of lesser weight as compared to active cooled heat sinks and are capable of removing more amount of heat for same surface area of active cooled heat sink. An up gradation of this technique is to embed heat sinks with heat pipes that are capable of removing more heat for same surface area as compared to that without heat pipe. This heat sink embedded with heat pipe has to be effectively deigned to improve its thermal performance. Thus this paper represents a methodology to optimize the temperature of insulated gate bipolar transistor (IGBT) by optimizing the dimensions of heat sink embedded with heat pipe by using design of experiments method with L12 orthogonal array combination (8 factors with 2 levels). The simulation results were performed using ANSYS CFX and compared with experiments results for validation. The optimized parameters of heat sink embedded with heat pipes was determined by plotting of main effects and S/N ratio response plot using minitab software. The rank of factors that influence temperature on IGBT was also identified using the same. Further the interaction plot was also plotted to study the interaction between different factors and how they affect the temperature on the IGBT.**

Keywords—Air channel,ANSYS CFX, electrical enclosure, heat sink embedded with heat pipes, IGBT,optimization,tagcuchi method.

I. Introduction

With electronic components being the potential sites for heat generation due to their continuous miniaturization, it was identified that their life decreases by half for every 10 degree Celsius rise in temperature. This large amount of heat can be removed by use of different cooling methods available such as use of fans, blowers, heat exchangers and the list goes on. Although all these methods provide a solution to remove heat none are effective from thermal performance and cost stand points of view. To remove such large amounts of heat, either large amount of cost has to be expended or thermal performance of the system is very poor. Thus there occurs a need make a compromise between thermal performance and cost of system. This has led to development of many new technologies with heat sink embedded in heat pipe being one among them. This technique not only increases surface area available for heat transfer thereby improving thermal performance of system but at same time does not have moving parts as well which helps in cutting down maintenance costs. Thus with this as an objective the existing heat sink is modified by incorporating it with straight heat pipes. However this technology can be slightly expensive from its fabrication point of view. With continuous research going on for use of different materials on heat pipe and heat sink design modifications, the cost is expected to come down in coming years.

II. HEAT SINK EMBEDDED WITH HEAT PIPES

Heat sink is a device which has a base plate with fins attached to it. The base plate has holes and mounting pins to which the component whose heat is to be removed is mounted. Different designs of fins are available in market such as rectangular fins, trapezoidal fins, pin fins etc. Based on method of fabrication of heat sinks they may be classified as extruded heat sinks, die cast heat sinks, compound heat sinks etc. The heat sink used for this study is extruded type with rectangular fins. A heat pipe is a device that uses phase change material to absorb and release heat. The device consists of outer copper tube that encloses vapor filled cavity and a wick filled with water. The liquid in wick structure absorbs heat and is converted into vapor that moves to other end of heat pipe due to difference in pressure. This vapor releases heat and flows back as liquid through wick structure due to capillary pressure. This study uses a combination of these two devices where in a specific number of heat pipes are embedded onto the base plate of heat sink based on location of hot spot or high heat generating area on component. The region is specifically aligned and placed on top of heat pipes in such a manner that it contacts with evaporator section of heat pipe. The other end of heat pipe is placed closer to the edge of base plate of heat sink as much as possible to enable the vapor section of heat pipe to release heat through fins via base plate.

III. LITERATURE REVIEW

S.Manivannan et al [1] presented an approach for minimizing the radiation from heat sink by using numerical simulation software Ansoft HSS and validated the results thus obtained by using experimental results and found that length of heat sink plays a significant factor in determining the amount of radiation emitted from heat sink accounting for 44%.

Chang –Woo Han et al [2] examined the performance of different types of air cooled heat sinks using numerical simulation technique by use of a simplified model by taking only single channel of fluid domain and determined that perforated heat sinks have better thermal performance resulting in an operating temperature of about only 68 degree Celsius on IGBT.

Jung Chang Wang [3] performed the analysis of heat sink embedded with heat pipes using thermal resistance network and identified that thermal resistance of heat sink embedded with four heat pipes is minimum (0.24ºC/W) when compared with thermal resistance of heat sink embedded with two heat pipes (0.27ºC/W) which indicates that heat sinks with more number of heat pipes embedded have a better thermal performance as compared to that with lesser number of heat pipes embedded.

Jeevaraj [4] examined the performance of heat sink for different air velocities at the inlet and effects of atmosphere and identified the appropriate capacity of fan required to cool the heat sink. The required velocity of fan to cool heat sink was identified as 4m/s for an ambient temperature of 45ºC using parametric study.

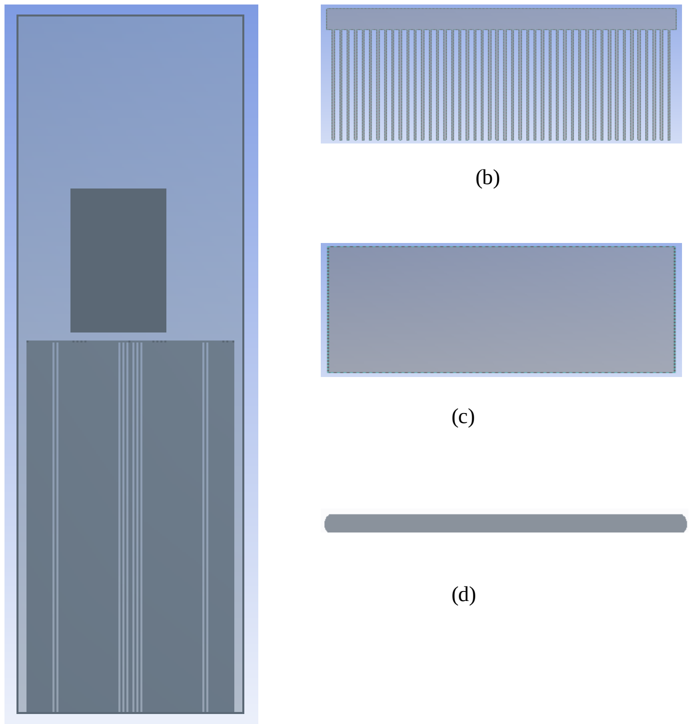
Pawar et al [5] performed thermal analysis of heat sink for different orientations of fan and validated the same using experimental results. The optimized fin spacing and fin thickness was identified as 5 mm and 1.5 mm respectively.

IV. GEOMETRIC MODELLING OF AIR CHANNEL,HEAT SINKS AND HEAT PIPES

All the geometric models required for performing the numerical analysis using CFX were modeled using PTC CREO parametric V3.0 design software. The models required for analysis were simplified my making suitable assumptions and by modeling only the required fluid domains that are of interest to be studied rather than modeling the entire solid and fluid domains. For example, in this study only the air channel of electrical enclosure is modeled as this region is the required region of interest where the heat sinks are located to remove high heat generated by IGBT. For the case of IGBT geometric model, only its base plate is modeled so as to reduce complexity and solving time. The final geometric models after assembly operations are exported in IGES format into design modeler of ANSYS. The assumptions made in order to simplify the geometric models are listed below.

- The properties of materials used remain constant with respect to change in temperature.
- Turbulent flow intensity is assumed to be in medium level range.
- Heat load given on IGBT is assumed as surface load while in real time, it is a hotspot.
- Heat transfer due to radiation is assumed to be minimum and hence can be neglected.
- The fluid is assumed to be incompressible in nature.
- The problem is assumed to be steady state problem so as to reduce complexity and solving time.
- There is no thermal interface material such as air between IGBT and base plate of heat sink
- Heat load given on IGBT is directly transmitted to heat sink and heat pipes as percentage of total heat load shared by heat sink and heat pipes is not known.

The air channel is modeled with dimensions 524.009 mm x 106.9 mm x 1800 mm. The models of air channels, heat sinks, IGBT and heat pipe assembly are shown below in fig. 1.(a), fig. 1.(b), fig. 1.(c) and fig. 1.(d) respectively. For heat pipes, the copper tube, vapor phase and wick phase are modeled separately and assembled together. The different components of heat pipe are not shown below and instead the entire assembly of heat pipe model is shown below. The nomenclature if heat sink is shown in figure 2 and entire assembly model is shown in figure 3. All geometric models given below represent only a general case. A similar procedure is adopted for modeling of different geometric models based on different dimensions of heat sink according to design of experiments L12 orthogonal array table.



(a)

Fig. 1.(a) Air channel (b) Heat Sink (c) IGBT (d) Heat pipe assembly

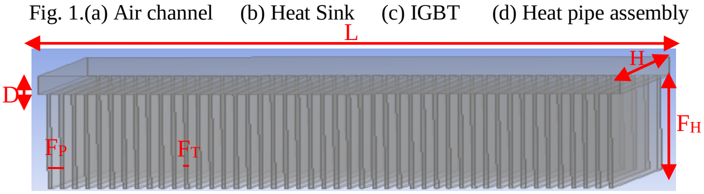


Fig. 2.Heat sink nomenclature

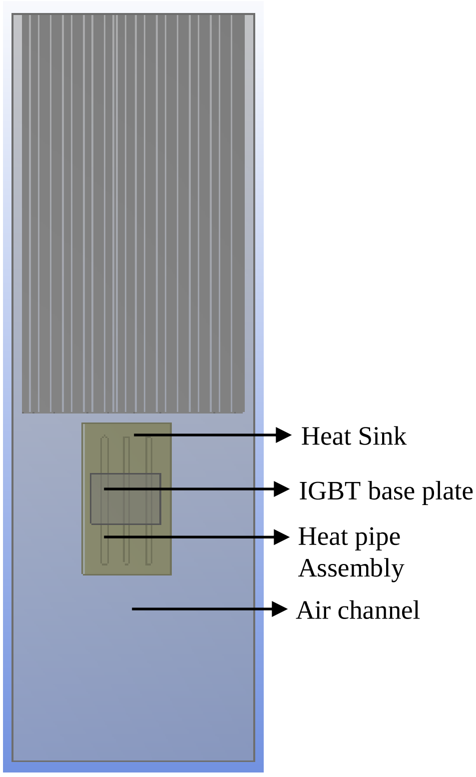


Fig. 3.Final assembly model

V. MESHING,SETUP AND BOUNDARY CONDITIONS

The meshing was performed using ANSYS mesh module on 4 GB RAM Core i5 2450M processor windows 7 64 bit PC. The mesh size was set as fine to get an average orthogonal quality of 0.6 for all cases. The meshing method was chosen as quadrilateral type for all cases. For slender models such as wick phase and vapor phase of heat pipe, separate body size having an element size of 0.5 mm was used to obtain better quality mesh on these elements. The meshing obtained on final assembly is shown below for one of the cases.

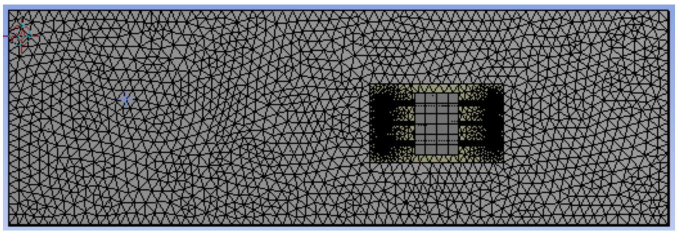


Fig. 4.Meshing of final assembly

The model obtained after meshing is exported to setup module where necessary boundary conditions, interfaces and other setup conditions required are defined by user. The materials and domains of respective geometric models are given in table 1. The materials and boundary conditions on air channel and heat sink used for this study are given below in table 2, table 3 respectively. Similarly respective boundary conditions are also defined on heat pipes.

Table 1: Domain and materials of corresponding geometric models

Geometric model	Domain	Material
Air channel	Fluid	Air
Heat sink	Solid	Aluminium
IGBT	Solid	Copper
Outer heat pipe	Solid	Copper
Inner heat pipe	Fluid	Water
Innermost heat pipe	Fluid	Vapor

Table 2: Material properties

Materials	Properties		
	Density (kg/m^3)	Thermal Conductivity (W/m K)	Specific Heat (kJ/kg K)
Copper	8960	385	0.9
Aluminium	2700	205	0.38
Vapour	0.02308	9.8626E-06	1.9116
Air	1.185	1.831E-05	1.004

Table 3: Boundary conditions on air channel and heat sink

Boundary Conditions	Value
Heat loss	2400 / 3600 Watts
Inlet: Mass flow rate	0.4046 kg/s
Outlet: Pressure	1 atm
Ambient temperature	303 K

VI. DESIGN OF EXPERIMENTS BY TAGUCHI METHOD

Among other available techniques for optimization, design of experiments by taguchi method was chosen to reduce costs and time as this study was conducted in an industry. Taguchi design helps to save time by reducing the number of trials to be performed .Based on literature survey 8 factors namely base plate length, base plate height, base plate depth, fin height, fin length, distance between fins (fin pitch),heat load and heat pipe were considered as factors. The temperature on IGBT was considered as response variable. In this study, absence of heat pipe is taken as -1 and presence of heat pipe is taken as +1.As per requirements of Danfoss Industries Pvt Ltd and based on available designs the factors and their levels used in design of experiment array is given in table 4. Based on design of experiment by taguchi design, for 8 factors with 2 levels, an L12 orthogonal array consisting of 12 trials is obtained.

Table 4: Design of experiment factors and levels

Factors	Levels	
Base plate length (mm) (L)	212	241.8
Base plate height (mm) (H)	181.5	365
Base plate depth (mm) (D)	15	18.01
Fin height (mm) (F_H)	93.8	62
Fin thickness (mm) (F_T)	1.96	1.5
Distance between fins (mm) (F_P)	2.05	3.66
Heat load (W) (HL)	2400	3600
Heat pipe (HP)	-1	+1

VII. NUMERICAL SIMULATION RESULTS

Numerical simulation was performed for all 12 trials and the results thus obtained are shown in table below. These results are then analyzed by using minitab software to optimize their values. The results obtained from numerical simulation correspond to average of temperatures corresponding to the respective contours on IGBT. The average temperature over IGBT is denoted as Avg T due to space constraints.

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Table 5: Simulation results

S.No	L (mm)	H (mm)	D (mm)	F_H (mm)	F_T (mm)	F_P (mm)	HL (W)	HP	Avg T (K)
1	212	181.5	15.00	93.8	1.96	2.05	2400	-1	448.00
2	212	181.5	15.00	93.8	1.50	3.66	3600	-1	448.33
3	212	365	18.01	62	1.96	2.05	2400	-1	376.00
4	241.8	181.5	18.01	62	1.96	3.66	3600	-1	404.67
5	241.8	365	15.00	62	1.50	2.05	3600	-1	396.25
6	241.8	365	18.01	93.8	1.50	3.66	2400	-1	366.00
7	212	365	18.01	93.8	1.96	3.66	3600	+1	403.00
8	212	365	15.00	62	1.50	3.66	2400	+1	376.33
9	212	181.5	18.01	62	1.50	2.05	3600	+1	424.67
10	241.8	365	15.00	93.8	1.96	2.05	3600	+1	347.25
11	241.8	181.5	18.01	93.8	1.50	2.05	2400	+1	381.25
12	241.8	181.5	15.00	62	1.96	3.66	2400	+1	383.50

The temperature pattern obtained for respective trials are shown in figures below from figure 5 to figure 16.

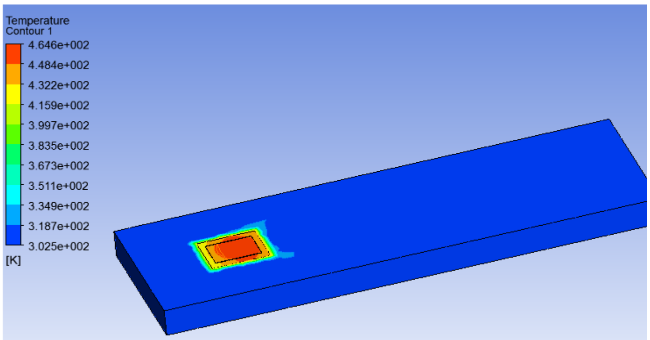

Fig. 5.Temperature pattern obtained on assembly for first trial

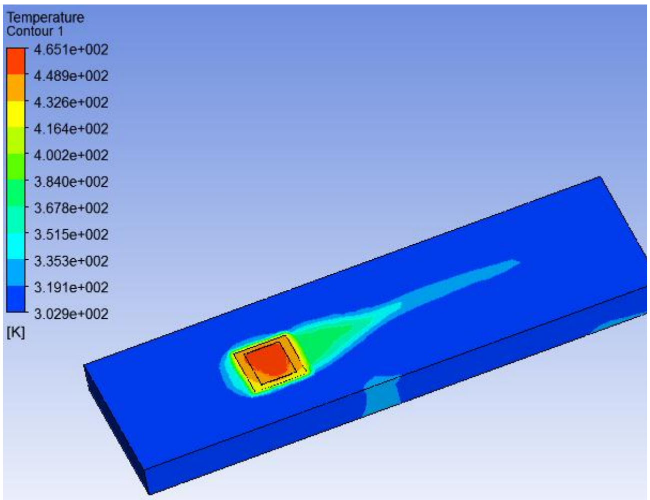

Fig. 6.Temperature pattern obtained on assembly for second trial

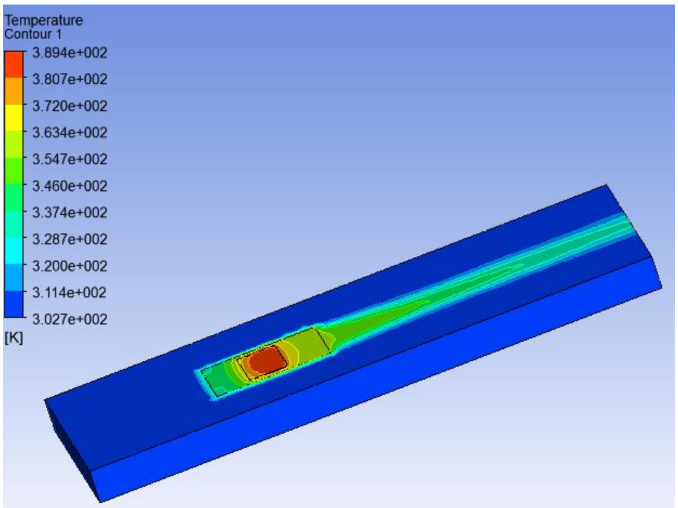

Fig. 7.Temperature pattern obtained on assembly for third trial

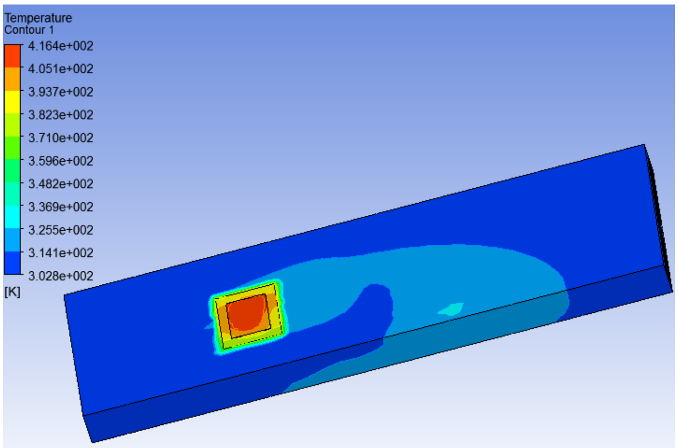

Fig. 8.Temperature pattern obtained on assembly for fourth trial

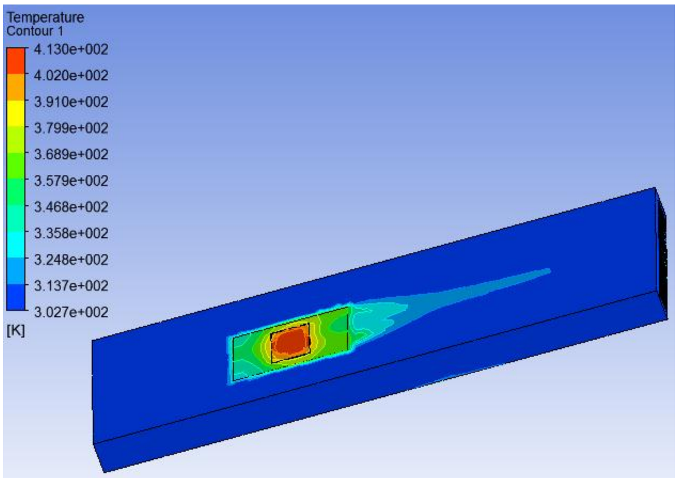

Fig. 9.Temperature pattern obtained on assembly for fifth trial

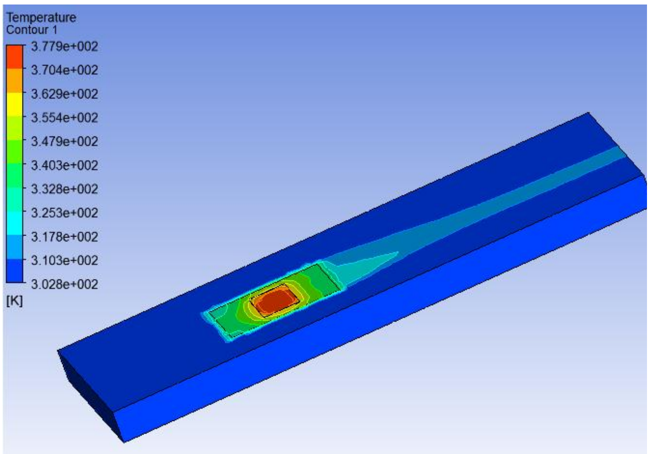

Fig. 10.Temperature pattern obtained on assembly for sixth trial

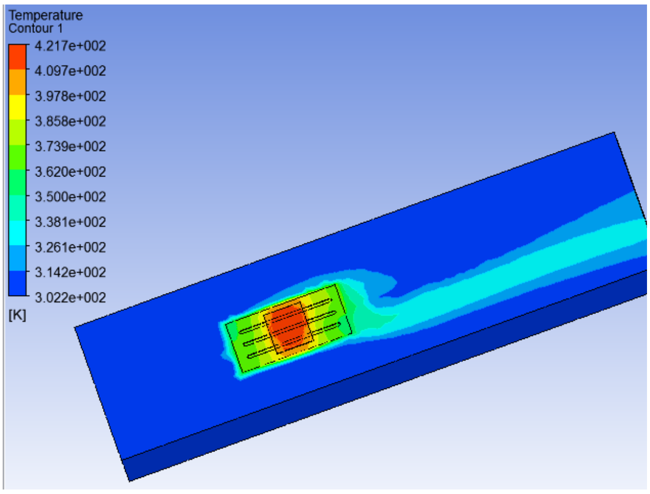

Fig. 11.Temperature pattern obtained on assembly for seventh trial

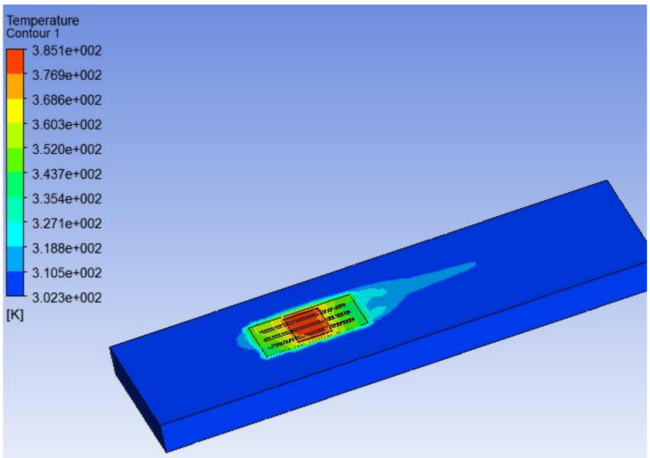

Fig. 12.Temperature pattern obtained on assembly for eighth trial

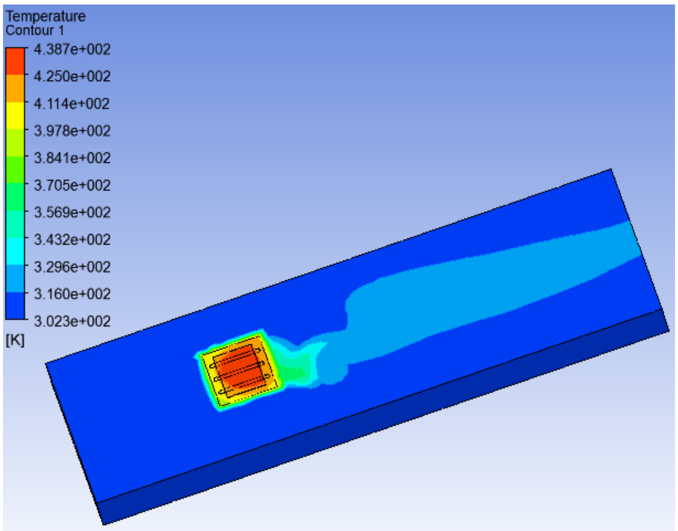

Fig. 13.Temperature pattern obtained on assembly for ninth trial

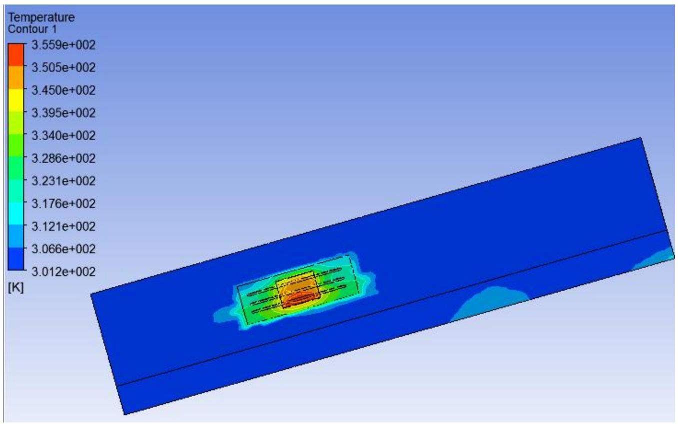

Fig. 14.Temperature pattern obtained on assembly for tenth trial

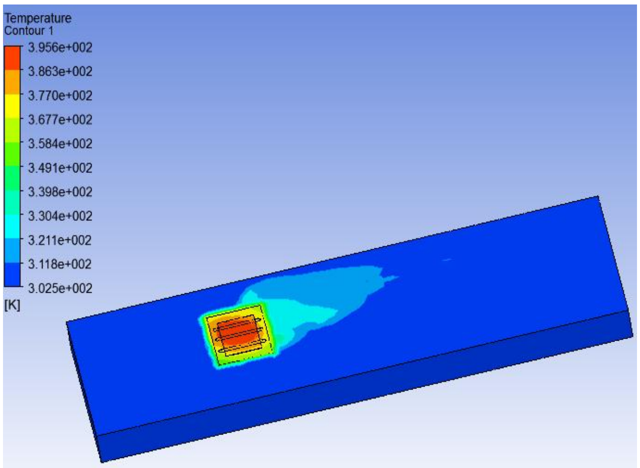

Fig. 15.Temperature pattern obtained on assembly for eleventh trial

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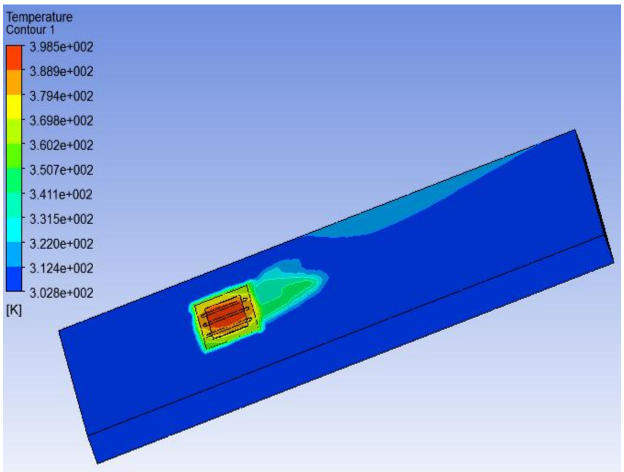

Fig. 16.Temperature pattern obtained on assembly for twelfth trial

VIII. VALIDATION OF NUMERICAL RESULTS

To validate the numerical simulation results obtained for first six trials, experiment is conducted to measure actual junction temperature of IGBT and theoretical calculations are also used. For measuring junction temperature of IGBT, J type thermocouple is used and based on heating load, appropriate voltage and current are supplied to the electrical enclosure (drive).For experimental validation, junction temperature obtained from experiment and simulation results are compared while for theoretical validation, base plate temperature of heat sink obtained by numerical simulation and theoretical calculation using nusselt number correlations and heat transfer correlations in [6] and [7] are compared. The deviation obtained between experiment and simulated values and theoretical and simulated values are found to be within 10% which is in an acceptable range. These deviations can be attributed due to difficulty of defining exact boundary conditions on heat pipes due to their complex process, meshing errors and other human errors. For remaining six trials with heat pipes validation of simulation results is carried out with only experimental values only due to unavailability of proper models to calculate heat transfer for heat sinks embedded in heat pipes. The schematic of experimental setup is shown in figure 17.

Table 5: Validation of numerical results for first six trials

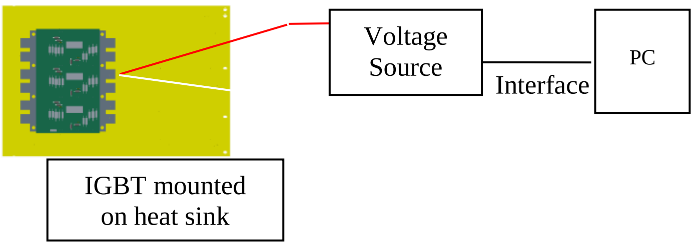

Fig. 17.Experimental setup schematic diagram

J type thermocouple
terminals

Table 6: Validation of numerical results for other trails with heat pipes embedded in heat sink

S.No	Experimental results Temperature (K)	Simulation results Temperature (K)
7	373	403.00
8	355	376.33
9	391	424.67
10	327	347.25
11	361	381.25
12	365	383.50

The section below gives model calculation of how the base temperature of heat sink is obtained using theoretical formulas. A similar procedure was adopted to calculate base temperature of heat sinks for first six trials.

As in [6] the Nusselt number correlation is given by

$$Nu = \left(\frac{1}{\left(\frac{Re\,Pr}{2}\right)^3} + \frac{1}{\left(0.664\sqrt{Re}\sqrt{1+\frac{3.65}{\sqrt{Re}}}\,Pr^{0.33}\right)^3} \right)^{-0.33}$$

Where Re is Reynolds number determined using [6] and Pr is Prandtl number determined from properties using [7]. The properties of air were obtained at temperature of 303K using table properties of air given in [7] and are listed below in table 7 below.

Table 7: Properties of air

Density (ρ)	1.165 kg/m^3
Prandtl number (Pr)	0.701
Viscosity (μ)	$18.63x10^{-6}Nm^2/s$
Specific heat (C_P)	1.005J/kgmolK
Thermal conductivity (k)	0.02675W/m^2K

For trial 1

S.No	Numerical results Base plate temperature of heat sink (K)	Theoretical results Base plate temperature of heat sink (K)	Num results Average Junction temperature (K)	Exp results Average Junction temperture (K)
1	439	400	448	423
2	442	480	448.33	425
3	354	355	376	340
4	388	405	404.67	385
5	368	366	396.25	370
6	349	347	366	350

$$Re = \frac{1.165x5.3x2.05x10^{-3}}{18.63x10^{-6}}\,\frac{2.05x10^{-3}}{181.5x10^{-3}} = 7.67$$

Where velocity of air was determined using flow rate equation.

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$$\left(\frac{1}{\left(\frac{\mathrm{Re}\,\mathrm{Pr}}{2}\right)^3}\right)=\left(\frac{1}{\left(\frac{7.67\mathrm{x}0.701}{2}\right)^3}\right)=0.0514$$

$$\frac{1}{\left(0.664\sqrt{\mathrm{Re}}\sqrt{1+\frac{3.65}{\sqrt{\mathrm{Re}}}}\,\mathrm{Pr}^{0.33}\right)^3}=0.064$$

$$\mathrm{Nu}=\left(0.0514+0.064\right)^{-0.33}=2.07\cong 2.$$

Using Nusselt number correlation convection coefficient of air was determined as26W/mK.

$Q_{HEAT\ TRANSFER} = \eta \times N \times h \times A_b \times (T_{base} - T_{surrounding})$

Where efficiency of fin is determined using fin efficiency graph in [7] and base area is calculated using known dimensions as per equation given in [7].Knowing the number of fins, the base temperature of heat sink is calculated as

$2400 = 0.6 \times 40 \times 212 \times 181.5 \times 10^{-6} \times (T_{base} - 303)$

T_{base}= 400K.

IX. TAGUCHI ANALYSIS AND OPTIMIZATION

The results obtained from numerical simulation are subjected to a optimization study using minitab software and main effects plot and interaction plots are plotted which are shown in figures 18 and 19 respectively. The main effects plot show the level and effect of factor on the response while interaction plots show nature of the interaction between different factors considered on the response. In interaction plot, two lines are said not to interact with each other when they are exactly parallel to each other. For other cases, where lines are not exactly parallel to each other, the greater the slope of 2 lines intersecting greater is their interaction on the response. Regression plot is obtained which shows the fit of results obtained on regression line and this is shown in figure 20. The factors are analyzed also using S/N ratio response plot and their contribution in affecting the response is shown in form of ranks in table 8.

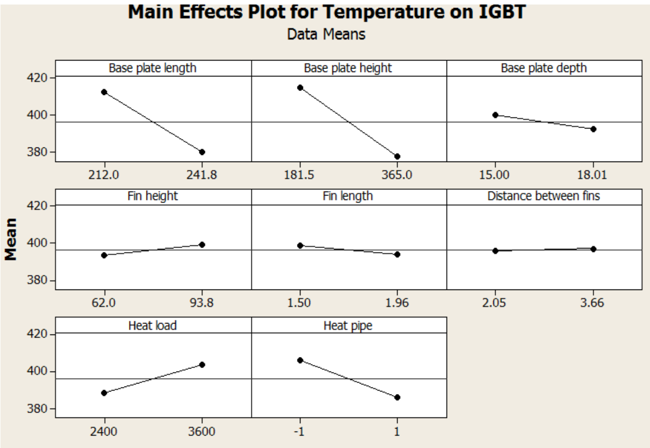

Fig. 18.Main effects plot for temperature on IGBT

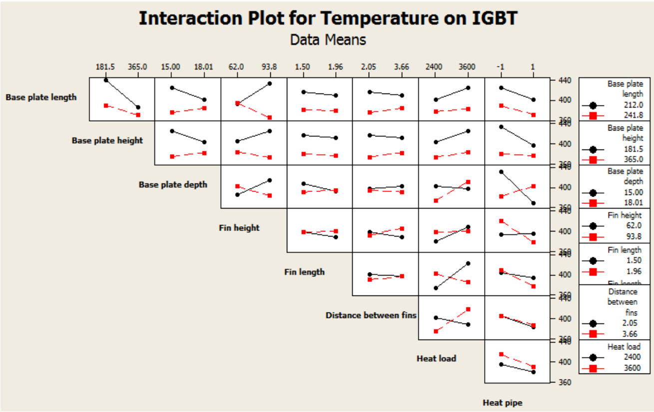

Fig. 19.Interactions plot for temperature on IGBT

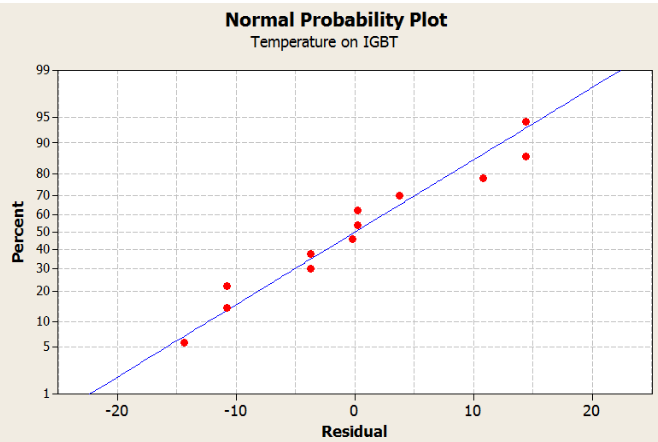

Fig. 20.Residuals plot for temperature on IGBT

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The regression equation thus obtained for the line plotted is given by

Temperature on IGBT = 707.606 - 1.10408 Base plate width - 0.204896 Base plate height - 2.4402 Base plate depth + 0.169864 Fin height - 11.0181 Fin length + 0.8706 Distance between fins + 0.0129292 Heat load - 10.2708 Heat pipe.

This equation can be used to obtain the temperature on IGBT for any given dimensions of heat sink, heat load and heat pipe.

Table 8: Rank of factors using S/N ratio response

Factors	Levels		Delta	Rank	%
Base plate length (mm) (L)	212	241.8	32.9	2	29.99
Base plate height (mm) (H)	181.5	365	37.6	1	39.17
Base plate depth (mm) (D)	15.00	18.01	7.3	5	1.49
Fin height (mm) (F_H)	93.8	62	5.4	6	0.80
Fin thickness (mm) (F_T)	1.96	1.5	5.1	7	0.71
Distance between fins (mm) (F_P)	2.05	3.66	1.4	8	0.05
Heat load (W) (HL)	2400	3600	15.5	4	6.67
Heat pipe (HP)	-1	+1	20.5	3	11.68

X. RESULTS AND DISCUSSIONS

From optimization study obtained using taguchi design of experiment, it is identified that height of heat sink plays a significant role in determining temperature on IGBT followed by base plate length. The presence of heat pipe also plays a role in removal of heat from IGBT as expected. This is followed by factors such as heat load, base plate depth, fin height, fin thickness. The pitch of fins plays a minor role in minimizing the temperature on IGBT. The values obtained from these parametric studies agree well with that obtained by previous research works. The percentage of influence for different factors is shown in pie chart in figure 21.

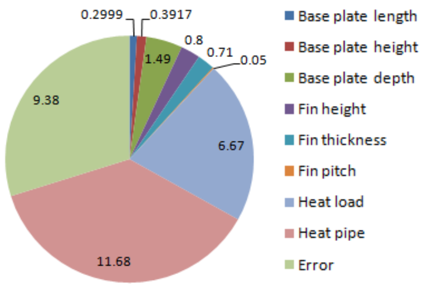

Fig. 21.Percentage influence of different factors for temperature on IGBT

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NOMENCLATURE

L (m)	Base plate length
H (m)	Base plate height
D (m)	Base plate depth
F_H (m)	Fin height
F_P (m)	Distance between fins (fin pitch)
F_T (m)	Fin thickness
HL (W)	Heat load
HP	Heat pipe
ρ (kg/m^3)	Density
μ (Nm^2/s)	Dynamic viscosity
C_P (J/kgmolK)	Specific heat
K (W/m^{2}K)	Thermal conductivity
Re	Reynolds number
Pr	Prandtl number
Nu	Nusselt number
$Q_{HEAT\ TRANSFER}$ (W)	Heat transferred by heat sink
h (W/mK)	Convection coefficient
N	Number of fins
η (%)	Efficiency of fins
A_b (m^2)	Base plate area of heat sink
T_{base} (K)	Base plate temperature of heat sink
$T_{surrounding}$ (K)	Surrounding temperature

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