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Analysis and Control of Heat Flow of Switching Devices in Heat Sink Environment: A Consideration of Heat Sink Structures

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ABSTRACT: *The issues of overheating of electronic components especially switching devices and the inability for heat sink to adequately contain this thermal effect has posed a lot of problems in most electrical design. Design of electronic components can be achieved by proper design of heat sink environments. This study has considered various heat sink structures, its composition and also analyzed the effects of rectifier diode resistance on heat generation. Matlab/Simulink was used as an analysis tool to design as well as structure most heat sink type based on their structure shape and composition, a steady and transient model was described using Matlab/Simulink. The result of this study revealed that the circular cylindrical plate with insulation has the highest heat absorption of 500 Joules whereas thin plate with and without insulation recorded the lowest value of 200 Joules. The heat absorption capacity decreases and the highest zones of the heat sinks are less cooled. The result presented in this study showed that heat absorption can be increased in any material by deciding on the type of heat sink structure needed. According to the steady and transient analysis conducted, the surface temperature will always be an inconvenient since it is not a constant value. It changes along the plate surface and along the fin surfaces. Long heat sinks tend to have a great variance in their surface temperature.*

KEYWORDS*:* *Heat sinks, switching devices, heat flow, transient model, steady model.*

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I. INTRODUCTION

Electronics are a need in today's culture for people, businesses, and government agencies. The working components are typically enclosed in a tiny volume to suit the demands of greater work efficiency, less occupied space, and more compact shape. Moore's law states that a dense integrated circuit (IC)'s transistor count doubles roughly every two years (Sarkar and Issac, 2016). However, during operation, the high-power density circuits were unable to fully utilize the electricity energy, and some of the input energy was converted into additional heat. The power density (heat flux) of electronics increases with their compactness. Overheating will consequently happen, resulting in a reduction in normal working efficiency, a shorter lifespan, and irreparable damage, (Li, 2023).

As electronic devices continue to undergo intensifying miniaturization, power densities persist in being on a rising trend. Heat fluxes over 10^2 W/cm ^{2} are currently generated by microprocessors. Moreover, hot spots in chips involve localized heat fluxes of 1 kW/cm^2 or more, leading to excessive local temperatures. Rising user demand for augmented computational performance and functionalities has been fueling the development of high-power microprocessors. Apart from IC devices, power semiconductor devices such as insulated gate bipolar transistors (IGBTs) and laser diode arrays also generate heat fluxes above 1 kW/cm^2. Operation at excessive temperatures impairs device performance and reliability and ultimately causes their failure. The different failure modes of microelectronic devices, namely mechanical, electrical, and corrosion, are linked to high operating temperatures, (John and Shankar, 2022).

Heat management in small electronic packages has become a serious problem in microelectronics industries. This is as a result of the excessive heat generated by power packed devices. Consumers keep demanding efficient and portable devices which in turn increase the heat dissipation of the devices, (Ekpu, 2018).

There are technologies with domains particularly developed for electronics such as material science, electromagnetism, system dynamics and also heat transfer. The relation to heat transfer is because of the heat generation of electronics devices. Commonly, these devices need additional cooling in order to avoid extreme temperatures inside it. Heat sinks allow this supplementary cooling, so they are omnipresent in electronic assemblies. Heat sink can work by forced convection, natural convection or liquid cooling. Normally in electronic assemblies they are made of materials with good thermal conduction such as aluminum or copper. The heat transfer in sinks is especially by convection, but also by radiation. Heat transfer by radiation can represent up to 30% of heat rate in natural convection heat sinks, (Joaquim, 2011).

Single-phase liquid convective cooling is one of the most popular methods for thermal management because of its straightforward, compact design, user-safe operation, and effectiveness. A heat sink is a device used for single-phase liquid convective cooling. It has one or more inlets, a centrally situated main design area where heat convection occurs most frequently, and one or more outlets, (Li, 2023).

A. Related works

The development of highly efficient power switches has been made possible by broad bandgap power semiconductors, according to (Balachandranand VijayaKumari, 2019). To take use of the SiC power device's advantages in terms of greater thermal and power handling capability, a thorough understanding of its thermal characteristics is required. This author’s main goal was to develop an accurate thermal model by putting forth and contrasting several approaches to thermal analysis of commercially available SiC devices, which will help choose the best cooling methods for greater system efficiency.

According to (Seshasayee, 2011), who studied thermal dissipation in heat sinks, it is crucial to fully comprehend power dissipation performance before integrating devices on a printed-circuit board (PCB) in order to guarantee that each device is operated within its specified temperature range. A running device uses electrical energy, which is converted into heat. Switching components like MOSFETs, ICs, etc. often produce the majority of the heat.

In a similar vein, (Gess, 2019) argued that advances in heat sink design are now constrained by traditional manufacturing methods that can only manufacture simple fin forms with uniform surface structure.

Based on analysis by (Jung et al., 2022), to improve a power semiconductor's switching and heat dissipation capabilities, a leadless surface mount package was created. A multilayer circuit substrate with embedded cavities made of low-temperature co-fired ceramic (LTCC) was used to implement the package. The cavity in the LTCC substrate was filled with a SiCSchottky barrier diode (SBD) bare die.

In the work of (Ekpu et al., 2022), the miniaturization of the LED and its integration into lightweight, compact gadgets have generated excessive heat, and ineffective heat management could cause the system as a whole to malfunction. In order to increase performance, heat is dispersed from the system to the environment using passive and/or active heat sinks.

We have identified the knowledge gaps existing from the various literatures and we have carried out a research work on the analysis and control of heat flow of switching devices in heat sink environment with a consideration of heat sink structures.

II. MATERIALS AND METHODS

The materials needed for this research work include heat data for switching devices, that is rectifier diodes, heat distribution module for thin plate, heat distribution module for circular cylinder rod, Matlab/Simulink and Hp laptop/windows 10

A. Methodology

To carry out a proper analysis of heat sinks in heat sink environments, consideration was given to the major types of heat sink distribution pattern, a thin plate structure using nonlinear analysis and a circular cylindrical rod. Also, consideration was given to thermal dissipations in heat sink models and heating structure of switching devices like rectifier diodes. The block diagram in Fig. 1 shows the methods to be applied in achieving this research work.

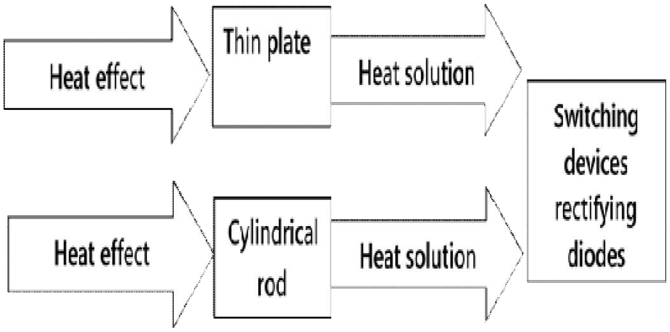


Fig. 1: System block diagram of the study

a. Thermal Dissipation

The maximum allowable junction temperature T_{JMAX} is one of the key factors that limit the powerdissipation capability of a device. T_{JMAX} is defined by the manufacturer and usually depends on the reliability of the die used in the manufacturing process. The typical equation used for calculation of the dissipation is shown in Equation 1:

$$\theta_{JA} = \frac{T_J - T_A}{P_D} \qquad (1)$$

where:
θ_{JA} = thermal resistance
T_J = junction temperature
T_A = ambient temperature
P_D = power dissipation
The maximum power that the device can dissipate is given as

$$P_{DMAX} = \frac{T_{JMAX} - T_A}{\theta_{JA}} \qquad (2)$$

With the help of θ_{JA} and T_{JMAX}, which are determined and listed in the TPS54325 data sheet (SLVS932). At different ambient temperatures of 25°C and 85°C, one can arrive at the values of 2.25 W and 0.9 W, respectively which are listed in the data sheet. From this, the derating factor parameter can be calculated. The power dissipation rating must be reduced by 2250/100 = 22.50 mW/°C if the dissipation is 2250 mW for a 100°C rise (from 25°C to 125°C). This is because the derating factor is linear. When the power dissipation values are not known, this parameter is occasionally employed in calculations. A 2.5 W is given to the load in a specific synchronous buck converter application where the input is 5 V and the output is 2.5 V at 1 A. Remember that this power is not the amount of power the device is losing. An efficiency assumption (90%) must be used to calculate the input power when there are no accurate efficiency curves specified in a data sheet for the application. In this case, the input power is roughly 2.5/0.9 = 2.75 W and the power dissipation in the converter is therefore approximately 2.75 - 2.5 = 0.25 W. Some of this power is lost at the diode, which is independent of the chipset. Since the DCR can be found on the diode data sheet, the diode power is calculated as:

$$P_{diode} = I_{out2}DCR = 1^2 \times 100 \times 10^{-3} = 100mW$$

The formula used to determine the junction temperature rise above ambient and the device power dissipation is given as:

$$\left(\theta_{JA} \times P_D\right) + T_A = T_J \qquad (3)$$

b. Nonlinear Heat Transfer in Thin Plate

The temperature is fixed at the bottom border of the square plate. The other three corners are insulated and do not transmit any heat. Convection and radiation move heat from the plate's top and bottom faces, respectively. A steady state analysis and a transient analysis are both carried out. In a steady state analysis, the final temperature at various locations on the plate after it has attained equilibrium in a transitory analysis would be considered and temperature in the plate as a function of time also would be considered.

c. Heat Transfer Equations for the Plate

The plate is 1 cm thick and has planar dimensions of 1 x 1 m. The temperature can be assumed to be constant in the thickness direction because the plate is thin in comparison to the planar dimensions; this leads to a 2D problem. Between the two plate faces and a predetermined ambient temperature, convection and radiation heat transfer are supposed to occur.

The definition of the amount of heat that is convectively transmitted from each plate face per unit area is

$$Q_C = h_C(T-T_A) \qquad (4)$$

where T_A is the ambient temperature, T is the temperature at a particular x and y location on the plate surface, andh_C is a specified convection coefficient.

The amount of heat transferred from each plate face per unit area due to radiation is defined as

$$Q_r = \epsilon\sigma(T^4 - T_a^4)\ (5)$$

where ϵ is the emissivity of the face and σ is the Stefan-Boltzmann constant. Because the heat transferred due to radiation is proportional to the fourth power of the surface temperature, the problem is nonlinear.

The PDE describing the temperature in this thin plate is given as

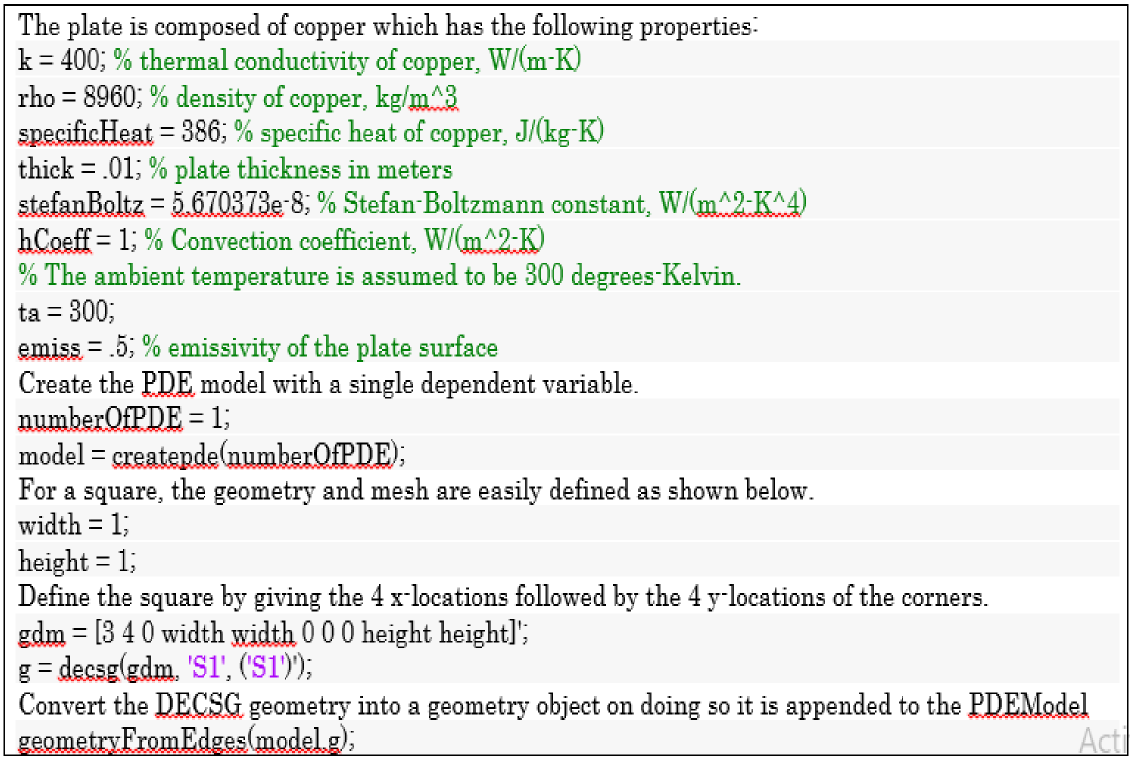
$$\rho C_p t_z \frac{\partial T}{\partial t} - k t_z \nabla^2 T + 2Q_c + 2Q_r = 0(6)$$

where ρ is the material density, C_p is the specific heat, t_z is the plate thickness, and the factors of two account for the heat transfer from both plate faces.

It is convenient to rewrite this equation in the form expected by PDE Toolbox

$$\rho C_p t_z \frac{\partial T}{\partial t} - k t_z \nabla^2 T + 2h_c T + 2\epsilon\sigma T^4 = 2h_c T_a + 2\epsilon\sigma T_a^4(7)$$

The problem set up proportional derivative equation (PDE) for the thin plate is written using Matlab program as follows



```
The plate is composed of copper which has the following properties:
k = 400; % thermal conductivity of copper, W/(m-K)
rho = 8960; % density of copper, kg/m^3
specificHeat = 386; % specific heat of copper, J/(kg-K)
thick = .01; % plate thickness in meters
stefanBoltz = 5.670373e-8; % Stefan-Boltzmann constant, W/(m^2-K^4)
hCoeff = 1; % Convection coefficient, W/(m^2-K)
% The ambient temperature is assumed to be 300 degrees-Kelvin.
ta = 300;
emiss = .5; % emissivity of the plate surface
Create the PDE model with a single dependent variable.
numberOfPDE = 1;
model = createpde(numberOfPDE);
For a square, the geometry and mesh are easily defined as shown below.
width = 1;
height = 1;
Define the square by giving the 4 x-locations followed by the 4 y-locations of the corners.
gdm = [3 4 0 width width 0 0 0 height height]';
g = decsg(gdm, 'S1', ('S1')');
Convert the DECSG geometry into a geometry object on doing so it is appended to the PDEModel
geometryFromEdges(model,g);
```

d. Steady State Solution

Because the a and f coefficients are functions of temperature (due to the radiation boundary conditions), solve pde automatically picks the nonlinear solver to obtain the solution.

```
R = solvepde(model);
u = R.NodalSolution;
figure;
pdeplot(model,'XYData',u,'Contour','on','ColorMap','jet');
title 'Temperature In The Plate, Steady State Solution'
xlabel 'X-coordinate, meters'
ylabel 'Y-coordinate, meters'
axis equal
```

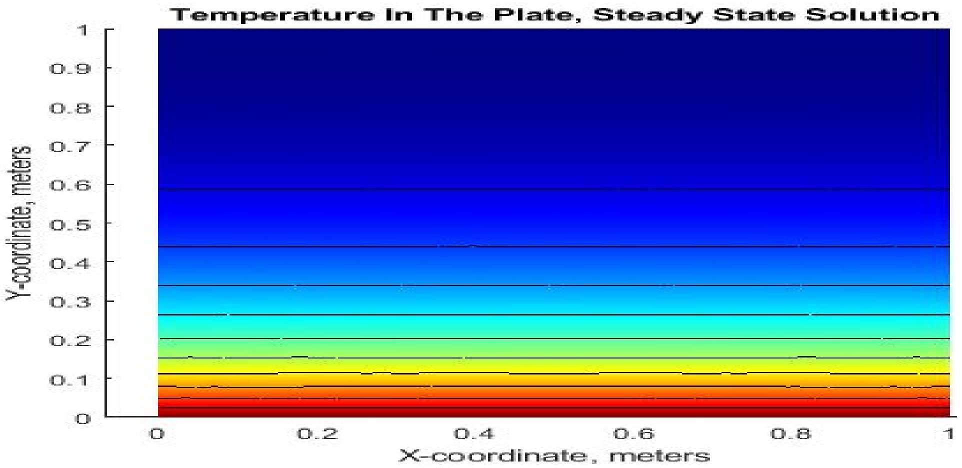
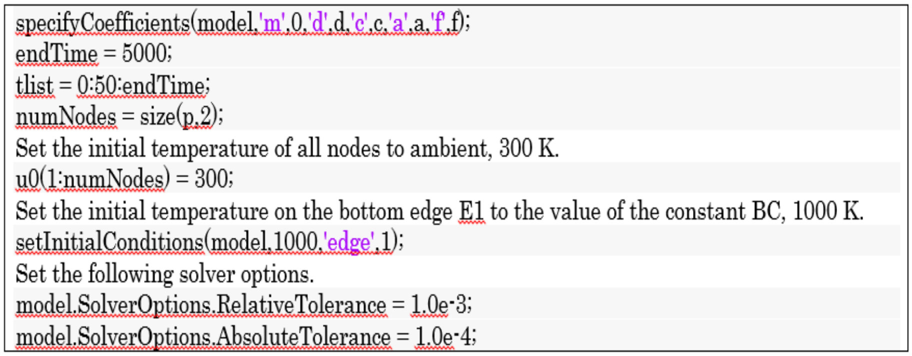


Fig. 2: Temperature in plate at steady state solution

e. Transient Solution

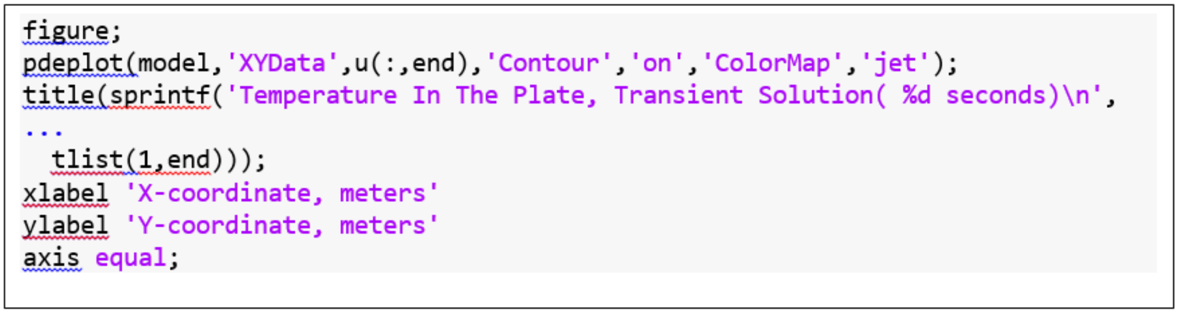
Include the d coefficient.



```
specifyCoefficients(model,'m',0,'d',d,'c',c,'a',a,'f',f);
endTime = 5000;
tlist = 0:50:endTime;
numNodes = size(p,2);
Set the initial temperature of all nodes to ambient, 300 K.
u0(1:numNodes) = 300;
Set the initial temperature on the bottom edge E1 to the value of the constant BC, 1000 K.
setInitialConditions(model,1000,'edge',1);
Set the following solver options.
model.SolverOptions.RelativeTolerance = 1.0e-3;
model.SolverOptions.AbsoluteTolerance = 1.0e-4;
```

Solve the problem by using *solvepde*. The solver automatically picks the parabolic solver to obtain the solution.

```
R = solvepde(model,tlist);
u = R.NodalSolution;
figure;
plot(tlist,u(3, :));
grid on
title 'Temperature Along the Top Edge of the Plate as a Function of Time'
xlabel 'Time, seconds'
ylabel 'Temperature, degrees-Kelvin'
```



```
figure;
pdeplot(model,'XYData',u(:,end),'Contour','on','ColorMap','jet');
title(sprintf('Temperature In The Plate, Transient Solution( %d seconds)\n',
...
  tlist(1,end)));
xlabel 'X-coordinate, meters'
ylabel 'Y-coordinate, meters'
axis equal;
```

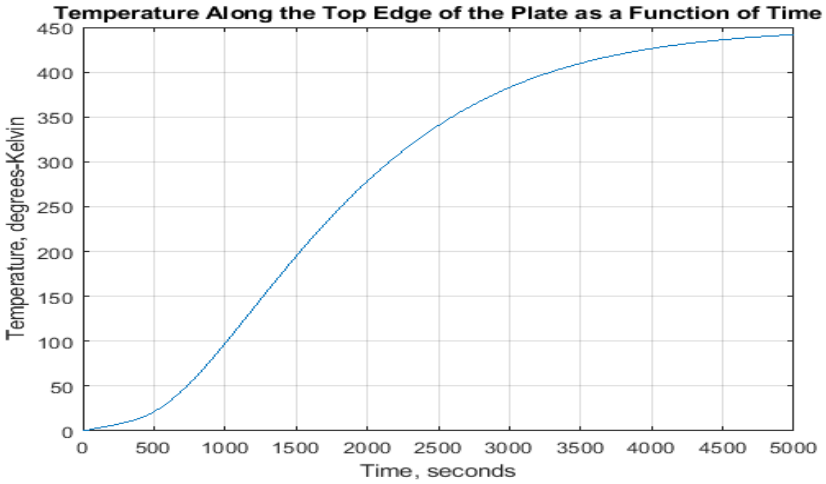


Fig. 3: Temperature along the top edge of the plate

It is seen from Fig. 3 that temperature along the top of the edge of the plate increases almost linearly as time is increasing.

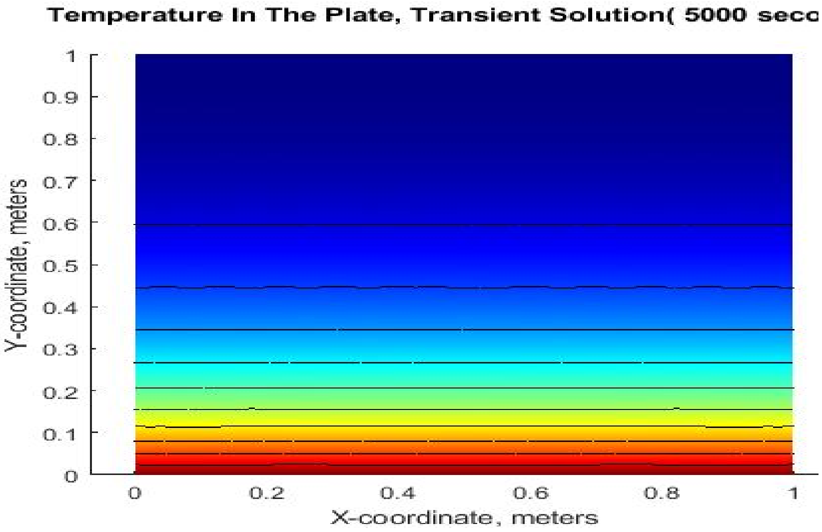


Fig. 4: Temperature in plate at steady state solution (t=5000.0 Secs)=441.8 degrees-K

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III. RESULTS AND DISCUSSIONS

A. Analysis of the heat generated by switching devices

Comparison of the diode heating behaviour depending on the diode resistance was carried out in this study. Diode 1 to diode 5 used for the heat testing analysis is shown in Table 1. The diode resistance quickly shows the opposition of the diode material to the flow of current that leads to the production of thermal effects in heat sink environments. The diode resistance values are shown in Table 1.

Table 1: Diode resistance table

Diode	Diode resistance (Ohms)
Diode 1	5
Diode 2	7
Diode 3	9
Diode 4	11
Diode 5	13

The heat produced as a result of resistance to current through the diodes was investigated for about 10 seconds of simulation at 2 different heating conditions in the heat sink environment. The heating conditions considered are temperatures at 200°C and 300°C. Figs. 5 and 6 describe these heating conditions for the tested diodes.

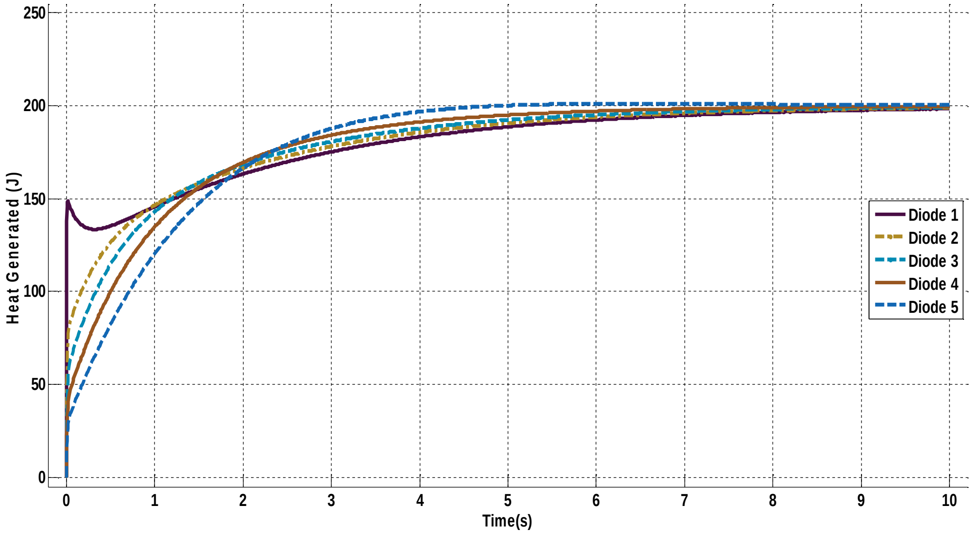

Fig.5: Graph of heat generated by diodes at heating condition 1(temperature at 200°C)

It was observed that diode 5 dissipated heat last at a resistance value of 13 ohms, while diode 1 initially dissipated heat at resistance of 5 ohms, but as simulation proceeds, diode 5 is seen to generate the overall highest amount of heat in the sink environment, with diode 1 generating the least overall amount of heat in the sink environs.

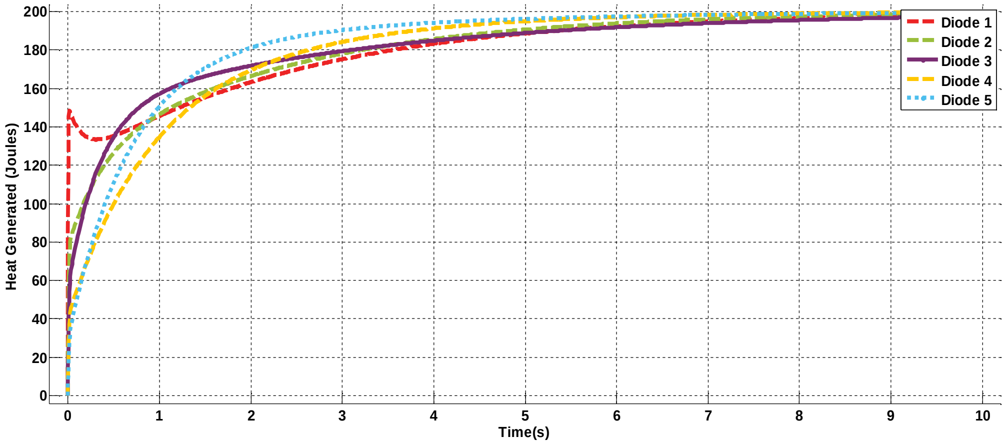

Fig.6: Graph of heat generated by diodes at heating condition 2 (temperature at 300°C)

Fig.6 shows the graph of heat generated by diodes at heating condition 2. From the graph, diode 1 is the last seen to dissipate heat at a resistance value if 13 ohms, while diode 1 is this time is not the least to dissipate heat energy, but produces the highest amount of heat to the system at the end of the simulation. The large amount of heat generated by diode 5 is as a result of its large resistance value, but from the plot the heat generated by the diodes are seen to conform to a particular steady value, this is as a result of the heat sink environment distributing the highest amount of energy to the system.

B. Comparison of heat absorption dynamics of heat sink types

The results compares the heat absorption ability of the heat sinks at different temperatures, the factors considered here are listed in table 2, also the developed heat sink structure consisting of the AL/CU composition ratio is seen to absorb heat generated in the heat sink environment in a good dynamic way.

Table 2: Heating structure of different heat sink material type.

Sink structure	Thermal conductivity W/(m°C)	Density Kg/m^3	Heat capacity Ws/(kg°C)	Composition ratio
Thin plate without insulation	40	7800	500	---
Thin plate with insulation	40	6000	560	-----
Circular cylindrical plate without insulation	40	7000	732	----
Circular cylindrical plate with insulation	40	450	1000	----
Thin plate with improved composition ratio	35	1000	950	0.652

Figs. 7 to 8 show the plots of the heat absorption dynamics for the compared heat sinks at 200 and 300 Joules of energy generated by switching devices.

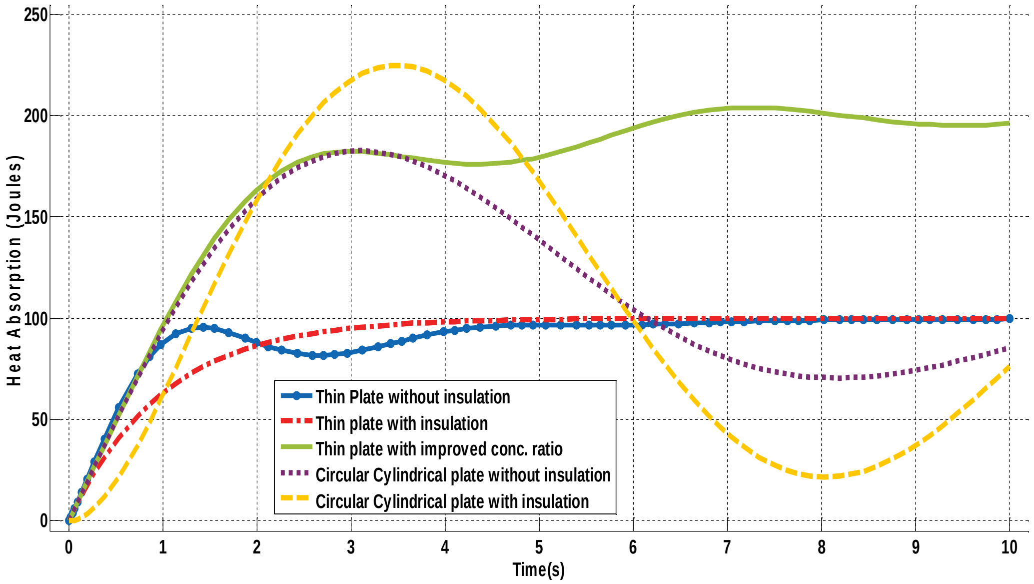

Fig. 7: Heat absorption dynamics of heat sinks at 200°C

At 200°C, the thin plate with improved concentration ratio is seen to absorb heat steadily up to a heat value of 200 J unlike the circular cylindrical plate with insulation that absorbed heat to a high amount of 225 J and later dropped to about 25 J absorption capacity, thin plates with and without insulation are seen to absorb only at a maximum dynamic heat of 100 J.

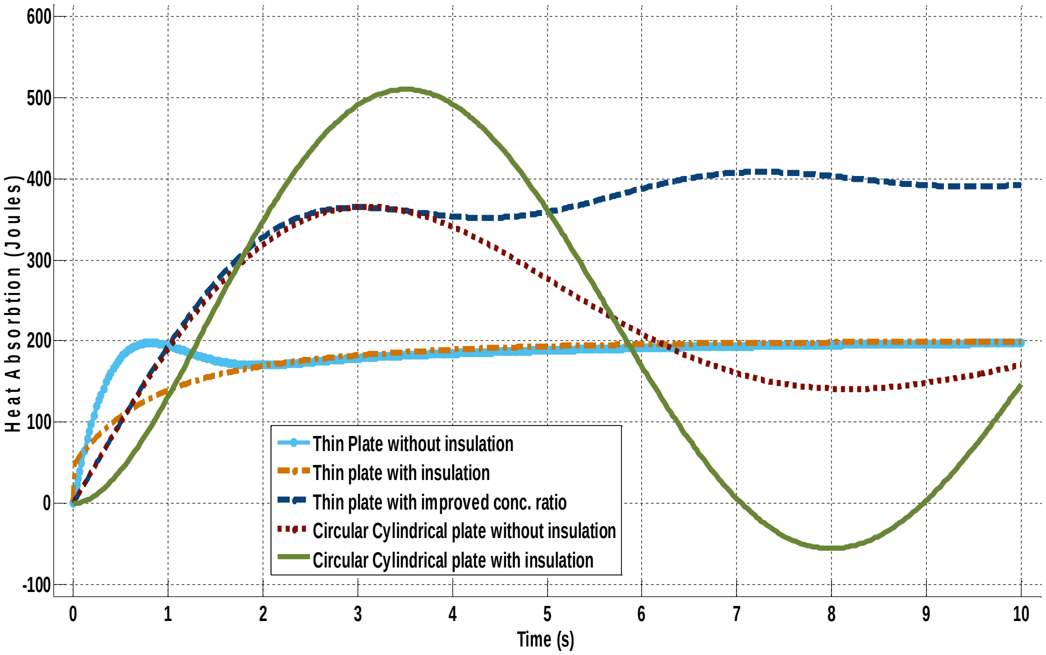

Fig. 8: Heat absorption dynamics of heat sinks at 300°C

Fig. 8 shows the heat absorption dynamics of heat sinks at 300°C. It is seen that the circular cylindrical plate with insulation has the highest heat absorption of 500 Joules whereas thin plate with and without insulation recorded the lowest value of 200 Joules. This implies that the heat absorption dynamics of the heat sink goes higher at a temperature of 300^{o}C, but still maintain the same heat absorption dynamics at 200^{o}C.Therefore, improving the concentration/composition ratio of the AL/CU heat sink, one could improve the heat absorption dynamics of the heat sink.

IV. CONCLUSION

Design of electronic components will be achieved by proper design of heat sink environments. This study has considered various heat sink structures, composition and has also analyzed the effects of rectifier diode resistance on heat generation. According to the steady and transient analysis conducted, the surface temperature will always be an inconvenient since it is not a constant value. It changes along the plate surface and along the fin surfaces. Long heat sinks tend to have a great variance in their surface temperature. The result of this study revealed that the circular cylindrical plate with insulation has the highest heat absorption of 500 Joules whereas thin plate with and without insulation recorded the lowest value of 200 Joules. The heat absorption capacity decreases and the highest zones of the heat sinks are less cooled. The result presented in this study showed that heat absorption can be increased in any material by deciding on the type of heat sink structure needed.

References

Balachandran, R and VijayaKumari, A.(2019). Thermal analysis for optimized selection of cooling techniques for SiC devices in high frequency switching applications Thermal analysis for optimized selection of cooling techniques for SiC devices in high frequency switching applications. https://doi.org/10.1088/1757-899X/577/1/012143

Ka, M and Frede, B. (2012).The Impact of Power Switching Devices on the Thermal Performance of a 10 MW Wind NPC Converter. Energies, 5, 2559 – 2577; https://doi.org/10.3390/en5072559

Dolente, A. (2007). Analysis of the Heatsink Influence on Conducted and Radiated Electromagnetic Interference in Power Electronic Converters, in 2018 17th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm).

Ekpu, M. (2018).Effect of Fins Arrangement on Thermal Performance in Microelectronics Devices. J. Appl. Sci. Environ. Manage., Vol. 22 (11) 1797–1800. DOI:https://dx.doi.org/10.4314/jasem.v22i11.14

Ekpu, M., Ogbodo, E. A., Ngobigha, F., and Njoku, J. E. (2022).Thermal Effect of Cylindrical Heat Sink on Heat Management in LED Applications.1–13.

Gess, J. (2019). An abstract of the thesis of thermal control of heat sink, International Journal of Heat and Mass Transfer, vol. 52, pp. 4592-4603.

Joaquim G. C. (2011). Heat Sink Analytical Modeling.Master thesis.

John, M. and Shankar, K. (2022).A Review on Transient Thermal Management of Electronic Devices. Journal of Electronic Packaging, Vol. 144 / 010801-1

Jung, D., Jang, H., Won, J., Cho, D., and Kwon, S. (2022). Switching and Heat-dissipation Performance Analysis of an LTCC-based Leadless Surface Mount Package. 22(1), 1–9.

Künzi, R. (2008.). "Thermal Design of Power Electronic Circuits", International Journal of Heat and Mass Transfer, vol. 51, pp. 4788-4796.

Li, Y. (2023). Design and topology optimization of heat sinks for the cooling of electronic devices with multiple heat sources, Applied Thermal Engineering, vol. 138, pp. 254-263.

Sarkar, A., and Issac, B. (2016). Importance of thermal radiation from heat sink in cooling of three phase PWM inverter kept inside an evacuated chamber.Engineering Science and Technology, an International Journal. https://doi.org/10.1016/j.jestch.2016.06.004

Seshasayee, N. (2011) .Understanding Thermal Dissipation and Design of a Heatsink, Journal of Mechanical Design, vol. 137, no. 11.