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Modeling and Cooling Analysis of Electronic Critical Components Fitted to A PCB with Natural Convection and Radiation using CFD-POST(ANSYS)

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ABSTRACT

The analytical study of cooling with natural convection and radiation from a heat source located at the bottom of a PCB is presented. The flow of fluid was assumed to be laminar, steady and of constant physical properties. The process was described by the continuity and energy partial differential equations, which were expressed in Cartesian coordinates system. The modeling and analysis of the PCB was done by using a finite element packages FLUENT, Design Modeler (DM), CFD-POST under ANSYS workbench. First cooling of PCB with natural convection is analyzed with some boundary conditions, later with the help of S2S radiation model and ray tracing method radiation cooling analysis also done. In both convection and radiation cooling temperature differences are notable. Numerical simulations carried out in this paper clearly demonstrate superiority of coupled convection and radiation cooling of the PCB over the popularly used natural air convection cooling of electronics. This is achieved by comparing with comparison factor in CFD-Post.

KEYWORDS : Electronics cooling, PCB, heat sink, heat source element, natural convection, radiation, S2S radiation model, view factors.

INTRODUCTION

Electronic equipment has made its way into practically every aspect of modern life, from toys and appliances to high-power computers. From sophisticated satellites, rockets and aircrafts to simple appliances for everyday use like TV, personal computer and cellphone depend on electronic devices for proper functioning. The reliability of the electronics of a system is a major factor in the overall reliability of the system.

The continued making on a greatly reduced scale of electronic components has resulted in medium scale integration (MSI) in the 1960s with 50 to 1000 components per chip, large-scale integration (LSI) in the1970s with 1000 to 100,000 components per chip, and very large-scale integration (VLSI) in the 1980s with 100,000 to 10,000,000 components per chip. Starting in 1960 with 50-1000 components per chip, it increased step by step to more than 10^9 components in a chip of 3 cm × 3 cm size. The development of the microprocessor in the early 1970s by the Intel Corporation marked yet another beginning in the electronics industry. The current flow through a resistance is always accompanied by heat generation in the amount of I^2R, where I is the electric current and R is the resistance. When we are considering a single element of electronics, like a transistor that "produces no heat." But when thousands or even millions of such components are packed in a small volume, the heat generated increases to such high levels that its removal becomes an undoubtable task and a major concern for the safety and reliability of the electronic devices. The result is the increase of heat output from 0.1 W/cm^2 to 100 W/cm^2, which is comparable in magnitude with those encountered in nuclear reactors and the surface of the sun.

The temperature of the component will continue rising until the component is destroyed unless heat is transferred away from it. The temperature of the component will remain constant when the rate of heat removal from it equals the rate of heat generation. But electronic components are observed to fail under prolonged use at high temperature, the possible cause being diffusion, chemical reaction and creep of bonding material.

All electronic devices generate heat due to the current flow through them. Unless the heat is removed constantly the temperature of the devices will continuously increase leading to failure. But the developments from transistors, integrated circuits and microprocessor have resulted in millions devices being packed into a chip of millimeter size. Also, the high thermal stresses in the solder joints of electronic components mounted on circuit boards resulting from temperature variations are major causes of failure. Therefore, thermal control has become increasingly important in the design and operation of electronic equipment.

Printed Circuit Boards (PCB)

A printed circuit board (PCB) is a properly wired plane board made of polymers and glass epoxy materials on which various electronic components such as the ICs, diodes, transistors, resistors, and capacitors are mounted to perform a certain task.

Generally three types of PCBs are available. These are single sided, double sided and multilayer boards. Each type has its own strengths and weaknesses. Single-sided PCBs have circuitry lines on one side of the board only and are suitable for low-density electronic devices (10 to 20 components). Double-sided PCBs have circuits on both sides and are best suited for intermediate-density devices. Multilayer PCBs contain several layers of circuitry and are suitable for high-density devices.

In critical applications, the electronic components are placed on boards attached to a conductive metal, called the heat source, that serves as a conduction path to the edge of the circuit board and thus to the cold plate for the heat generated in the components. Such boards are said to be conduction-cooled. The temperature of the components in this case will depend on the location of the components on the boards: it will be highest for the components in the middle and lowest for those near the edge, as shown in Fig. 1. The heat generated first passes through the PCB and then the heat frame. Heat source provides a low resistance path from the PCB to the heat sink. Thicker the heat source lower will be the resistance to heat flow. As heat flow is through the thickness instead of the length, the resistance across the PCB is very much reduced. The devices at the center of the PCB will operate at a higher temperature compared to those at the edges.

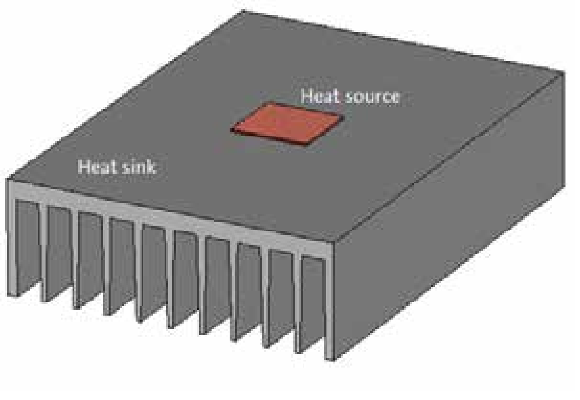

Figure 1: Image of Heat source and Finned Heat sink

Sources: www.googleimages .com/ heat sink

METHODOLOGY / PROBLEM DEFINITION

The aim of the present paper is to gain experience in cooling of a PCB with critical components like IC's resistors, heat sink. The cooling techniques used in the cooling of electronic equipment vary widely, depending on the particular application. Depending upon the load the cooling method is generally chosen. The methods are:

1. Natural convection cooling.
2. Forced convection cooling with air.
3. Immersion cooling with natural convection.
4. Immersion cooling with boiling.
5. Forced circulation of water.
6. Heat Pipe.

The method adopted, to a great extent, depends on the heat generation by the equipment and the maximum heat transfer capacity of the method. Natural convection can be used where the heat dissipation is low. For very high loads like in super computers, immersion cooling becomes necessary. Even in forced convection when air is used as the fluid, the heat dissipation capacity is lower than when water is used for cooling. The choice of the cooling method can be decided by using the chart if we know the heat flux. When the power rating of a device or component is given, the heat flux is determined by dividing the power rating by the exposed surface area of the device or component.

Since there is no moving parts in our design of PCB, we selected Natural convection and radiation cooling technique for cooling of critical components (heat sink and heat source). The Finite element package ANSYS workbench is specially designed to do such analysis. Therefore this package has been chose in this paper to carry out the proposed analysis.

Natural convection and radiation

Low-power electronic systems are conveniently cooled by natural convection and radiation. Natural convection cooling is very desirable, since it does not involve any fans that may break down. Natural convection is based on the fluid motion caused by the density differences in a fluid due to a temperature difference. A fluid expands when heated and becomes less dense. Natural convection cooling is most effective when the path of the fluid is relatively free of obstacles, which tend to slow down the fluid, and is least effective when the fluid has to pass through narrow flow passages and over many obstacles.

Electronic components or PCBs placed in enclosures such as a TV or DVD player are cooled by natural convection by providing a sufficient number of vents on the case to enable the cool air to enter and the heated air to leave the case freely. In our case PCB with critical components fitted in enclosure having open top and bottom is subjected to initially only the heat transfer via convection and conduction will be calculated. The effect of thermal radiation will then be included as a later stage.

Problem definition

A PCB of size 1000 mm x 360 mm is made of a multi-layer material fitted into an enclosure which is open at the top and bottom with thickness of 72 mm for bottom layers and 128 mm for top layers, it has a single heat source element mounted on the bottom surface below to heat sink as shown in Fig.2.

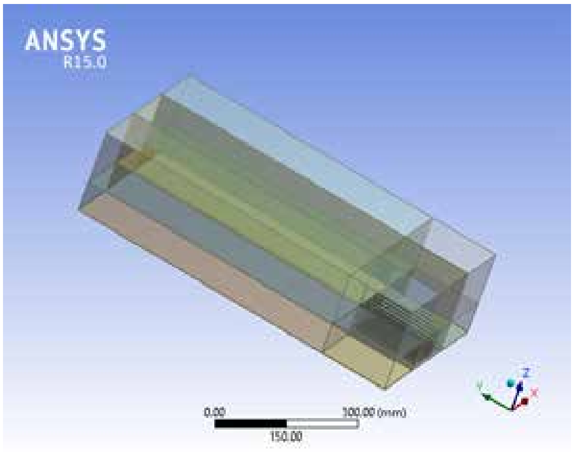

Figure 2: Model of multilayer PCB

It is required to subject this PCB for a cooling analysis with coupled cooling technique (Natural convection and Radiation). Most printed circuit boards are manufactured using glass-reinforced epoxy as the substrate. While there are wide variety of laminate materials are available in the market, we preferred to select FR-4 as a standard material for PCB. FR-4 is a composite material composed of woven fiberglass cloth with an epoxy resin binder that is flame resistant. FR-4 functions well as an electric insulator and has a good strength-to-weight ratio, and is flame resistant. The other critical components materials and their important data like properties for the problem are listed below Table 1.

TABLE – 1
MATERIAL PROPERTIES

Property	Fluid Flow (Air)	PCB (FR-4)	Heat Sink (Copper)	Heat Source (Component)
Density, ρ (Kg/m^3)	constant	1250	8978	1900
Specific heat, C_p (J/Kg-K)	1006.43	1300	381	795
Thermal conductivity, k (W/m-K)	0.242	0.35	387.6	10
Viscosity, μ (Kg-m/s)	1.7894×10^{-5}	-	-	-

Modeling of critical components with their geometrical dimensions are shown in the Fig. 3 and corresponding dimension values are shown in Table 2

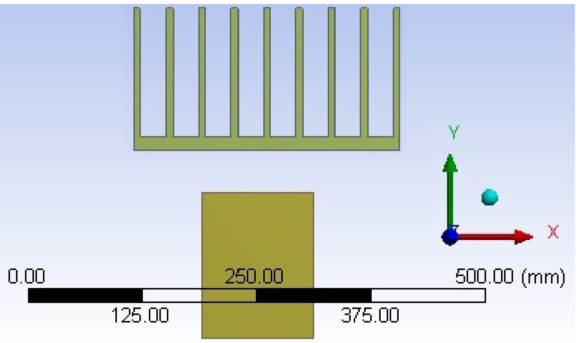

Figure 3: Model of Heat sink (top), Heat source

TABLE – 2
MATERIAL PROPERTIES

Details	Finned Heat sink	Heat Source Element
Length X, mm	123	123
Length Y, mm	160	160
Length Z, mm	60	6
Body Area, mm^2	2.188×10^5	42756
Body Volume, mm^3	3.7728×10^5	1.1808×10^5

First fine element workbench ANSYS does the discretization of the PCB and the critical components into elements. The finite element mesh model is shown in Fig. 4.

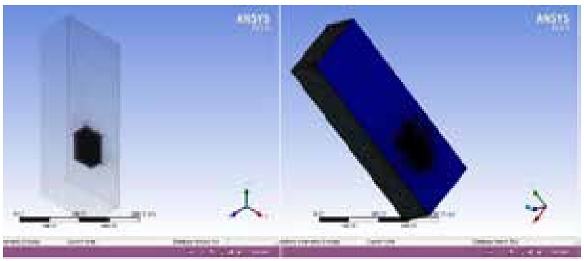

Figure 4: Finite element meshing Model of PCB mounted with critical components

The PCB, heat element and the heat sink is modeled using 1478567 nodal elements. The mesh information shown in below Table 3.

TABLE – 3
MESHING REPORT OF MODEL

Domain	Nodes	Elements
fluid	217944	203576
solid_PCB board	13764	6716
solid_heatsink	6300	2980
solid_heatsource	2646	1640
All Domains	240654	214912

Nomenclature

L	= length of conduction medium, m
T_s	= surface temperature, ^{0}C
T	= fluid temperature, ^{0}C
T_{surr}	= surrounding temperature, ^{0}C
ΔT	= temperature difference in medium, ^{0}C
A_s	= heat transfer surface area, m^2
k	= conductivity of the material, W/m. K
H	= heat source per unit volume
h_{conv}	= heat transfer coefficient, W/m^2.^{0}C
ε	= emissivity of the surface
σ	= Stefan-Boltzmann constant
Q	= conduction heat transfer, W
Q_{conv}	= convection heat transfer, W
Q_{rad}	= radiation heat transfer, W
u,v,w	= the velocity components in x, y, z directions respectively.

Mathematical model
In the present mathematical model, Cartesian coordinate system (*x, y, z)* is used to express the fluid flow governing equations. The governing equations consist of the continuity equation, energy equation, and three modes of heat transfer equations, which can be written for steady state condition. The first model is based on conduction to the PCB base or the casing. Steady one-dimensional heat conduction through a plane medium of thickness *L*, heat transfer surface area *A*, and thermal conductivity *k* is given

$$Q = kA\frac{\Delta T}{L} \quad \text{... (1)}$$

The heat transfer from a surface at temperature T_s to a fluid at temperature T fluid by convection is given by

$$Q = h_{conv}\, A_s(T_s - T) \quad \text{... (2)}$$

Radiation heat transfer between a surfaces at temperature T_s completely surrounded by a much larger surface at temperature T_{surr} can be expressed as

$$Q = \varepsilon\, A_s\sigma(T_s^4 - T_{surr}^4) \quad \text{... (3)}$$

The continuity equation for the three dimensional flow and energy equations are written below as equation 4 and equation 5 respectively

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad \text{... (4)}$$

$$\rho C_p\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}\right) = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + H \quad \text{... (5)}$$

S2S Radiation model
Layers of low-power PCBs are cooled by natural convection by mounting them within a chassis with adequate openings at the top and at the bottom to facilitate airflow. The air between the PCBs rises when heated by the electronic components and is replaced by the cooler air entering from below. This initiates the natural convection flow through the parallel flow passages formed by the PCBs.

Radiation heat transfer between surfaces depends on the orientation of the surfaces relative to each other as well as their radiation properties and temperatures, as illustrated in Figure 5. To account for the effects of orientation on radiation between two surfaces, we selected a new parameter called the view factor which is a purely geometric quantity and it is independent of the temperature.

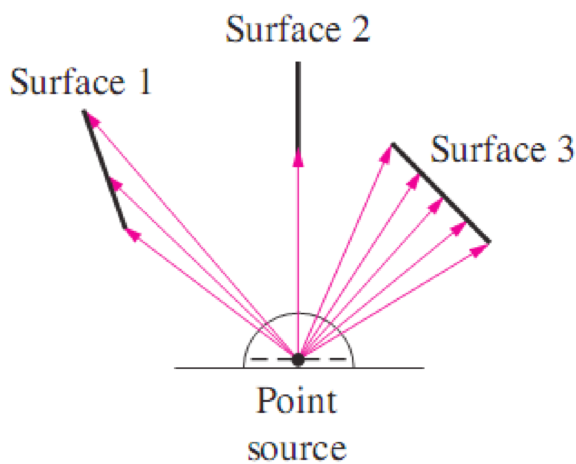

Figure 5: Radiation between surfaces
Sources: Heat transfer book by Cengel

For radiation analysis we prefer to use this surface to surface (S2S radiation model) radiation with some view factor.

Heat dissipation through the heat element (heat source) to be 75 W, hence volumetric heat source is $\frac{75}{V} = \frac{75}{0.00011808} = 635160$ W/m^3

Where V = Volume of heat source

= 0.123 × 0.160 × 0.006 = 0.00011808 m^3

RESULTS AND DISCUSSION

The PCB, heat sink and heat element modeling mainly involves four bodies as fluid, solid PCB board, solid heat sin, and solid heat source are created by using ANSYS workbench modeler (DM). The materials and their properties applied for all the above bodies as shown in table 1. As natural convection is gravity driven, we enabled earth gravity of -9.81 m/s^2 in cell zone conditions. After setting the inlet and outlet temperature to 45^0C and pressure to 0 Pa, An analysis run is made using FLUENT for the convection and radiation heat transfer analysis. The output function obtained by the PCB for the convection heat transfer is shown in Fig. 6,

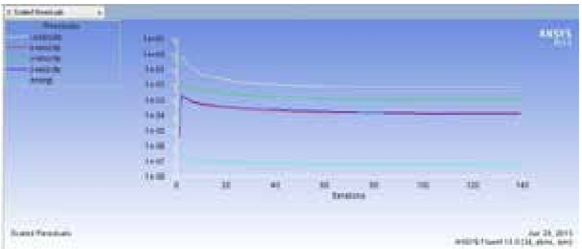

Figure 6: Output function for PCB (with convection and conduction)

Fig. 6 show the plots of the velocity components in X-direction velocity *u*, Y-direction velocity *v*, Z-direction velocity *w* for the convection and heat transfer cooling. The maximum value of X-velocity is about 3.85e-04 m/s and occurs along the width of the PCB. The maximum value of Y-velocity is about 3.59e-03 m/s and occurs along the length of the PCB. The maximum value of Z-velocity is about 4.72e-04 m/s and occurs along the thickness of the PCB. We can also notice a gradual variation of the velocity over the PCB.

Later the result obtained from Eq. 1-5 must be multiplied by a view factor, which is the fraction of the view of the hot surface blocked by the cooler surface. The value of the view factor ranges from 0 (the hot surface has no direct view of the cooler surface) to 1 (the hot surface is completely surrounded by the cooler surface). By using ray tracing method with a view factor of 0.3 we performed radiation analysis with 500 iterations by enabling S2S radiation model. The boundary conditions of the model is changed by keeping internal emissivity of 0.9 to PCB wall left boundary, wall right boundary, wall top boundary, and air flow boundaries inlet and outlet to an internal emissivity value of 1. This time we analyzed the flow fields (radiation enabled) with 500 iterations. After 295 iteration we came across that the solution has been converged. The output function obtained by the PCB for the radiation heat transfer is shown in Fig. 7

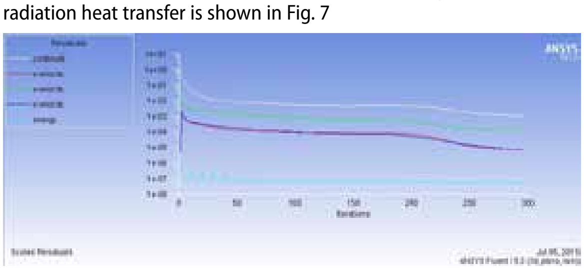

Figure 7: Output function for PCB (with Radiation enabled)

Fig. 7 show the plots of the velocity components *u*, *v*, and *w* for radiation transfer cooling. The maximum value of *u* is about 3.23e-04 m/s and occurs along the width of the PCB. The maximum value of *v* is about 4.25e-03 m/s and occurs along the length of the PCB. The maximum value of *w* is about 3.66e-04 m/s and occurs along the thickness of the PCB.

Post processing of the two results was done in ANSYS CFD-Post to compare the convection (labeled as FLU in left) and radiation enabled heat transfer values (labeled as flntgz 50967 in right) shown in Fig.8. A special comparison tool was available in CFD analysis, which helps us to compare these two cases.

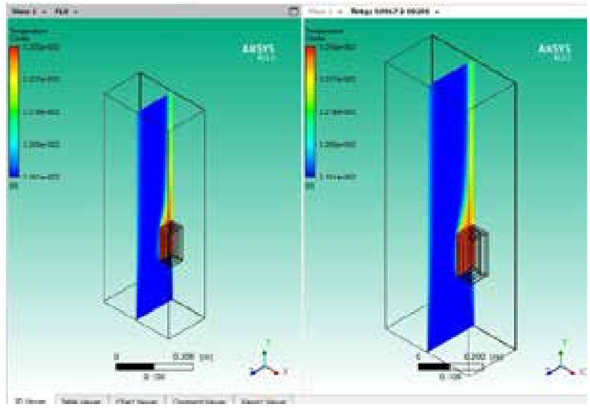

Figure 8: Temperature distribution plot along the length of PCB

As shown in Fig. 8, the temperature will be a key variable for any electronics cooling application so it will be displayed in several locations, displayed such as within the flow along the YZ plane by making X at center (x = 0). Similarly the contour plots of flow field along the vertical PCB is shown in Fig. 9.

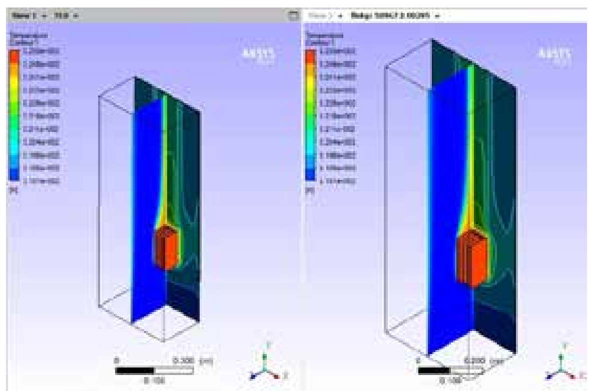

Figure 9: Contour plot of temperature distribution along the length of PCB

Hence from the results we noticed that the maximum temperature in both the cases have slight difference. The maximum temperature of 325.57 (K) is occurred at the critical component (location heat source in both cases) of PCB in convection case, whereas the maximum temperature attained in Radiation case is 311.01 (K). Results shows the significance of cooling effect of electronics with radiation and without radiation.

SUMMARY AND CONCLUSION

In this paper cooling analysis of PCB with critical components has been carried out using FLUENT/CFD-POST (ANSYS). Three velocity modes of the PCB with its components have been computed, as well as the temperature difference of the PCB and its critical components due to natural convection and radiation have been obtained. The three velocity modes show qualitative differences among themselves and the response of the PCB to cooling with radiation and without radiation also was found to be interesting. Giving clear indication that the results obtained by the proposed cooling of PCB with radiation and no radiation with same materials shows minimization of the temperature along the fluid flow region. By using the proposed cooling effect the maximum temperature of PCB reduced on an average of 4.47% (14.56 K) in radiation enabled case. The results demonstrate the effectiveness of the proposed methodology for the cooling of electronics. The proposed method can be extended to solve other electronics devices such as ICs, Chips made up of composite materials, etc.

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