Numerical study of Laminar Forced Convection Cooling of Circuit Board mounted Heat Source Array

Shankar Durgam, S. P. Venkateshan and T. Sundararajan

Indian Institute of Technology Madras, Chennai - India

*Corresponding author: spv@iitm.ac.in

Abstract:
This paper deals with the numerical study of optimal distribution of rectangular heat sources populated on a substrate board for electronic cooling. The simulations are performed for laminar forced convection conjugate heat transfer with vertical orientation of substrate board. The laminar forced convection conjugate heat transfer simulations using COMSOL MULTIPHYSICS® 4.3b software are carried out with heat fluxes of 1500, 2000 and 2500 W/m^2 and at different air velocities and ambient temperatures. The simulations are carried out for various positions of heat sources so as to determine the optimal configuration. Out of the possible 168 million configurations, random sampling is performed to select three hundred possible random configurations to decide the optimal configuration.

Keywords: Conjugate heat transfer, Laminar forced convection, Optimal configuration, Electronic cooling.

1. Introduction

Forced Convection cooling with surface mounted protruding discrete heat sources in a flow channel is one of the most preferred methods of electronic equipment for moderate rate of heat dissipation. Miniaturization of electronic devices posed to dissipate large amount of heat from the small volumes. Thermal management is crucial and challenging in maintaining safe operating temperature limit for better performance and to increase life of electronic equipment. Kim and Anand numerically studied and compared results for laminar developing and periodically fully developed flow and heat transfer between a series of parallel substrates with surface mounted discrete heat sources. They found that thermal entry length decreased with an increase in substrate conductivity and thermal resistance decreased with an increase in Reynolds number, block spacing and substrate conductivity [1]. Sugavanam et al. studied numerically conjugate heat transfer from a flush heat source on a conductive board in laminar channel flow and presented results to show effect of substrate conductivity to fluid conductivity ratio, Reynolds number, air velocity [2]. Cheng et al. simulated numerically conjugate heat transfer in electronic cooling to investigate thermal performance due to the influence of openings on the substrate, height of heat source, and their distribution along the substrate on the maximum temperature and overall Nusselt number [3]. Hajmohammadi et al. presented analytical solution of optimal placement of two unequal heat sources using constructal theory and reported enhancement in heat transfer [4]. Tye-Gingras et al. optimized numerically laminar fully developed forced convection heat transfer and indicated that the phase lag position of each heat source can decrease overall thermal resistance [5]. In the literature, numerical study of laminar forced convection air cooling of electronic equipment in flow channel on rate of heat dissipation and comparison of effect of heat transfer with different substrate material was not studied in great details. The main objective of present work is to study numerically 3D laminar forced convection cooling of circuit board mounted fifteen discrete heat sources in a rectangular flow channel. The effects of circuit board material thermal conductivity on heat transfer and size

Excerpt from the Proceedings of the 2015 COMSOL Conference in Pune

and optimal configuration that maintain minimum excess temperature also investigated.

2. Substrate Board and Heat Sources

Two substrate board materials namely bakelite and FR4 of dimensions 175 x 175 x5, mm are considered in this study. Bakelite and FR4 both are having low thermal conductivities (k = 1.5 and k = 0.3 W/m-K) respectively. Fifteen number of equal slots of size 19 x 44 x 5 mm are crated in such a way that fifteen aluminum (k = 280 W/m-K) protruding heat sources that mimic electronic chips can be mounted on the surface of substrate board. The twelve various configurations for bakelite and FR4 are considered to find the best out of 24 cases that give the highest rate of heat dissipation from the substrate board mounted heat sources to study the effect of heat transfer and excess temperature of each heat source. The design of substrate board is shown in Figure 1. The fifteen aluminum heat sources manufactured in the laboratory and are as shown in Figure 2. The sizes of aluminum heat sources are given in Table1.

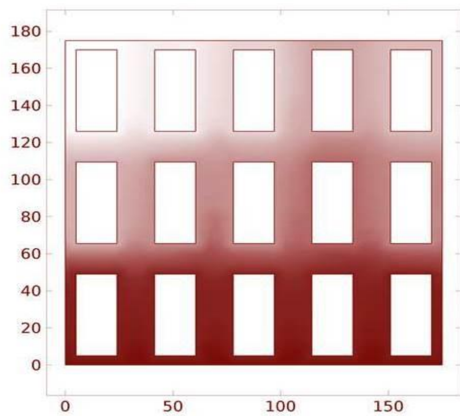

Figure 1. Bakelite Substrate board

Figure 2. Aluminum heat sources

Table 1. Heat source details

Sr. no.	Heat source number	Size in mm W x D x H
1	1, 6, 11	15 x 42 x 5
2	2, 7, 12	15 x 30 x 5
3	3, 8, 13	15 x 20 x 5
4	4, 9, 14	15 x 15 x 5
5	5, 10, 15	15 x 10 x 5

3. Computational Domain

Three dimensional modeling for convection air cooling of substrate board mounted heat sources. The simulation models laminar forced convection conjugate heat transfer air cooling of heat sources is considered to solve the Naiver-stokes equations using Comsol Multiphysics. The computational domain is shown in figure 3. It comprises of substrate board made of bakelite and FR4, fifteen rectangular discrete aluminum heat sources and air flow direction from bottom to top i.e. along Z-axis. The dimensions of the geometry are:
Substrate board: Length 175mm, width 175 mm, thickness is 5mm.
Heat sources: specifications of fifteen heat sources are as shown in Table1.
The thickness of air layer moving upward above the substrate board is 10 mm.

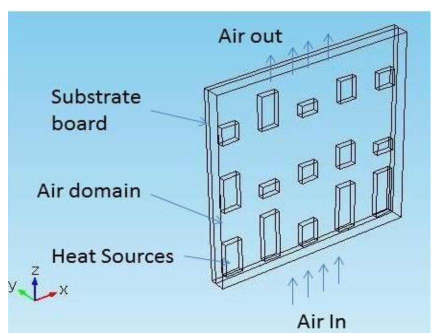

Figure 3 Computational domain

4. Results and discussions

From the 300 number of random sampling that performed by permutation twelve configurations each for bakelite and FR4 are considered to decide the optimal configuration.

The twelve random configurations found by permutation considered in this study are:

1) 12-13-10-2-1-9-5-11-7-4-6-8-3-14-15
2) 8-11-15-9-14-10-5-12-6-13-1-4-7-2-3
3) 9-4-3-11-1-10-13-12-14-5-8-15-6-7-2
4) 8-11-7-15-14-4-12-1-6-5-10-13-3-2-9
5) 4-6-7-15-2 -12-10-1-9-14-5-3-8-13-11
6) 4-13-7-6-11-14-5-12-8-10-2-15-9-3-1
7) 6-4-8-1-9-13-12-5-15-11-3-10-7-2-14
8) 12-6-8-1-11-2-5-14-13-10-4-7-15-3-9
9) 5-2-12-4-8-3-14-10-7-1-15-13-9-6-11
10) 7-4-11-2-10-5-6-1-14-12-13-9-8-15-3
11) 12-3-1-2-8-15-4-9-5-13-11-14-6-10-7
12) 5-10-15-4-9-14-3-8-13-2-7-12-1-6-11

These configurations show the heat source numbers given to each heat source are specified as per the heat source numbers given in Figure 2. The simulations are carried out for bakelite and FR4 substrate board for heat flux of 1500 W/m^2, at velocity of moving air layer v = 1 m/s, the ambient air temperature of 30°C and at air pressure of 1 atmosphere. The total surface area due to all heat sources that is exposed to the moving air layer is 0.011025 m^2 and the total power input to all heat sources is 16.5375 W. The numerical results are shown in table 2. The comsol default velocity and temperature plots for bakelite as a substrate board material are shown in Figure 4 and 5. These plots correspond to configuration number 8. The default velocity plot shows the velocity profile as arrow volume in the flow channel. The default temperature plot shows the temperature exists at each heat source, the streamlines and plums of heat in the direction of air flow.It is found that the maximum velocity at the exit is 1.5379 m/s and the maximum excess temperature is 58.88°C that is lowest among all cases for the same heat flux, air velocity, ambient air temperature and pressure.

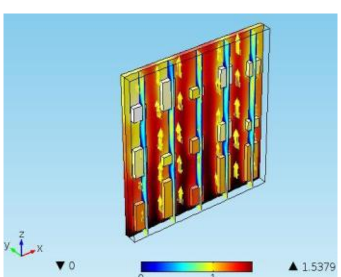

Figure 4. Velocity plot

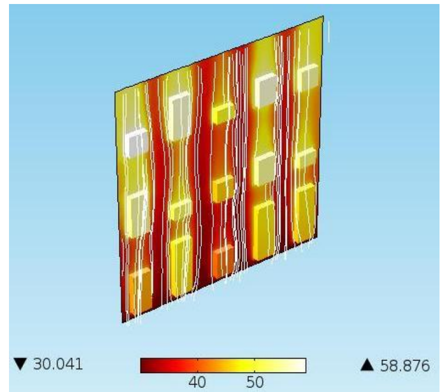

Figure 5. Temperature plot

Simulation results for the same configuration with same input parameters with FR4 as a substrate material shows that the maximum exit velocity is 1.533 m/s and maximum excess temperature is 59.6°C. It is also found that, this value of maximum excess temperature is lowest among all configuration considered for this study but higher as compare with bakelite as a substrate material for the same configuration. Simulation results show that for the same configuration and input parameters with substrate materials of different thermal conductivity gives different temperature excess. The effect of conjugate heat transfer due to entering air layer on the top surface of the substrate board is shown in the surface temperature plot in Figure 6.

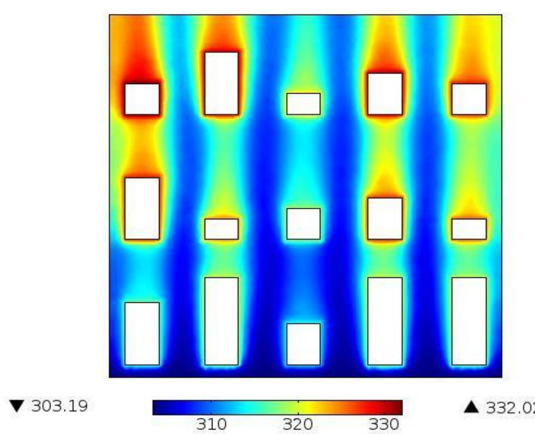

Figure 6. Surface temperature plot

It is observed from the surface temperature plot that because of the laminar forced convection heat is transferred from heat sources to the moving air. Thus upward moving air stream is heated up by gaining heat from heat sources it is becoming warmer and warmer and the surface temperature is increasing in the direction of air flow. The numerical data obtained from the simulation results is used to draw temperature contour graph, Surface temperature lines and labels, 3d-Surface colourmap plot using origin Pro 9.0 plotting software and are shown in Figure 7-9. The temperature contour graph shows that the maximum temperature excess is available at heat source number 12 whereas the minimum temperature excess corresponds to heat source number 15. The temperature is increasing in the direction of air flow. The temperature at the heat sources mounted in the lower row is low that in the middle row is slightly more. The temperature in the topmost or upper row is highest that follows the trend indicated in the literature [6-9].

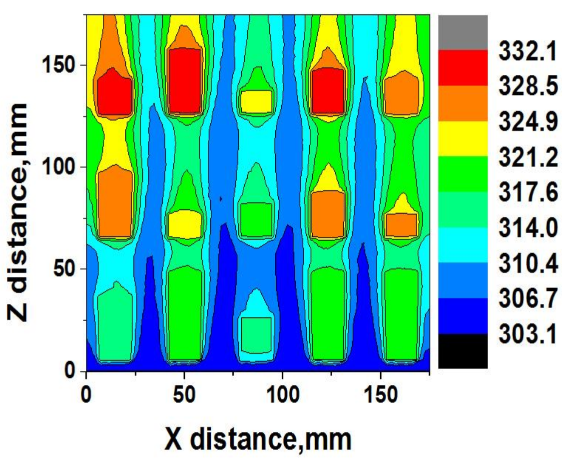

Figure 7. Temperature contour graph

Figure 8 shows surface temperature lines and labels that is quantitative representation of temperature distribution at the upper surface of the substrate board. The 3-dimensional surface color map plot is shown in Figure 9. That indicates the picturesque 3d view of temperature distribution among all heat sources mounted on a substrate board that are dissipating heat by three dimensional laminar forced convection. The heat sources mounted in lower, middle and upper rows indicates gradual increment in temperature.

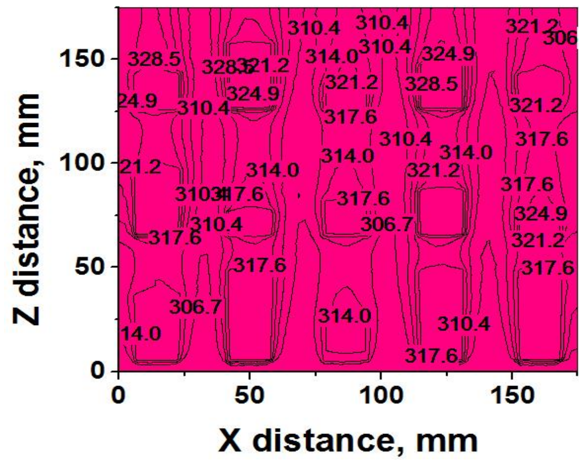

Figure 8. Surface temperature lines and labels

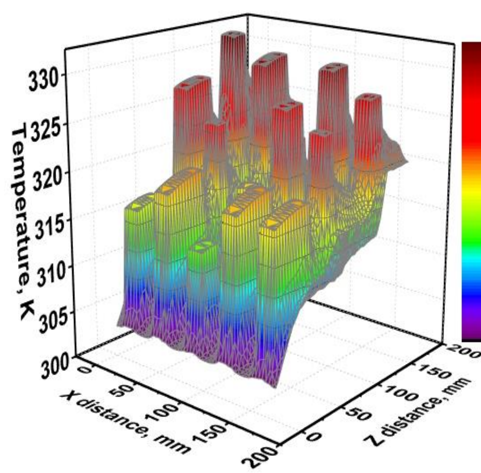

Figure 9. 3d-Surface plot

5. Conclusions

Numerical simulations of 3D steady state laminar forced convection conjugate heat transfer for cooling of circuit board mounted heat sources was investigated in this study. Heat transfer module of Comsol Multiphysics was used to provides some useful guidelines for the thermal management of electronic equipments. Simulation results show that configuration number 8, with bakelite as a substrate material that gives minimum of maximum temperature excess among all configurations. Hence this configuration is optimal among all configurations considered in this study. It is also reported from the simulation result that for the same configuration and input parameters with bakelite as substrate material gives minimum temperature excess it is an indication of maximum heat dissipation from the heat sources. By using optimal configuration and the substrate board material of specific thermal conductivity it is possible to enhance the rate of heat transfer.

6. Acknowledgements

The authors acknowledge P. G. Senapathy computing center for providing high performance computing facilities to complete this work.

10. References

2. Kim S. H., and Anand N. K., Laminar developing flow and heat transfer between a series of parallel plates with surface mounted discrete heat sources, Int. J. Heat Mass Transfer, 37,2231-2244 (1994).

3. Sugavanam R., Ortega A., Choi C.Y., A numerical investigation of conjugate heat transfer from a flush heat source on a conductive board in laminar channel flow, Int. J. Heat Mass Transfer, 38, 2969-2984, (1995).

4. Cheng Y. P., Lee T.S., Low H. T., Numerical simulation of conjugate heat transfer in electronic cooling and analysis based on field synergy principle, Applied Thermal Engineering, 28, 1826-1833 (2008).

1. Tye-Gingres M., Gosselin L., da Silva A. K., Synchronizing time-varying discrete heating elements in forced convection for minimal thermal resistance, Int. J Heat Mass Transfer, 53, 4917-4926 (2010).

5. Hajmahammadi M. R., Shirani E., Salimpour M. R., Campo A., Constructal placement of unequal heat sources on a plate cooled by laminar forced convection, Int. J. Thermal Sciences, 60, 13-22, (2012).

6. Hotta, T. K., and Venkateshan, S., "Natural and mixed convection heat transfer cooling of discrete heat sources placed near the bottom on a pcb". Proc. World Acad. Sci. Eng. Technol, 6,pp. 266–273, (2012).

7. Durgam, S. O., Ramanjaneyulu, G., Venkateshan, S. P., and Sundararajan, T., 2015. "A numerical and experimental study of optimal distribution of discrete heat source array cooled by natural and forced convection",In Proceedings of First TFESC-12696, Begell House, (2015).

8. Durgam S., Venkateshan S. P., Sundararajan T., A Numerical and Experimental Study of Optimal Distribution of Rectangular Discrete Heat Sources Under Laminar Forced Convection, ihmtc-astfe conference, (2015).

9. Hotta T., Muvvala P., Venkateshan S. P., Effect of surface radiation heat transfer on the optimal distribution of discrete heat sources under natural convection, Heat and Mass Transfer, 49(2), 201-207 (2013).

Table 2. Comparative results for configuration 12-6-8-1-11-2-5-14-13-10-4-7-15-3-9, q =1500 W/m^2

V=1m/s T_{amb}=30° C	Temp °C	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15
Bakelite	T_{excess}	14	17	11	17	16.2	25	15.4	16	23	29	26.6	26.4	18.9	27.1	24.7
FR4	T_{excess}	14	17	12	18	17	26	22	16	26	24	29.6	17.7	19.5	28.1	25.4