NATURAL CONVECTION HEAT TRANSFER AND OPTIMIZATION STUDY FROM FIVE PROTRUDING IC CHIPS MOUNTED ON A PCB –A NUMERICAL APPROACH*

BY

[1]NAVEEN G PATIL♣, [2]MATHEW V. KARVINKOPPA, [2]ARCHANA CHANDAK,
[2]ANURAG NEMA, [3]TAPANO KUMAR HOTTA

[1]Assistant Professor, Ajeenkya DY Patil Innovation University, Pune-412105, India
[2]Assistant professor, MIT-ADT University, Loni Pune-412201, India
[3]School of Mechanical Engineering, Vellore Institute of Technology (VIT), Vellore, Tamilnadu

ABSTRACT

*The manuscript compares the heat transfer enactment from five identical and symmetric protruding discrete IC chips positioned on a three-dimensional vertical substrate board under natural convection. 3D, steady-state numerical analysis are carried out using COMSOL v 4.2 for different heat source configurations subjected to variable volumetric heat generation rate. The various designs of heat sources are identified by proposing the distance, λ. It is observed that temperature excess decreases with increase of λ. The study is carried out for uniform and non-uniform spacing (following Golden Mean Ratio, GMR) of IC chips on the substrate board. The configuration of heat sources following GMR leads to a temperature drop of 10% as compared to their uniform spacing. An empirical correlation is put forward for the (θexcess) in terms of dimensionless distance parameter (λ), non-dimensional position parameter (z), and non-dimensional volumetric heat generation (q*v).*

KEYWORDS

COMSOL Multi-physics; Discrete heat source (IC chip); Golden mean ratio.

NOMENCLATURE

A	heat sources area (IC chip), m2
g	gravitational acceleration, 9.81 m/s2
h	heat transfer coefficient, W/m2K
k	thermal conductivity, W/m K
L	IC chip length, m
q	heat flux, W/m2

---

[*] Received 22 September 2021, Accepted 09 October 2021, Published 24 October 2021

♣ Corresponding Author

T	temperature, K
Tmax	maximum temperature of IC
∆Tref	reference temperature (∆Tref=qL/k)

INTRODUCTION

Technological advancements in semiconductor industries have led to miniaturization in the overall dimensions of the electronic components, and hence the area available for heat dissipation continues to become smaller. This has resulted in excess of high heat flux at the chip level. Furthermore, for reliable operation of electronic components, their operating temperature should not exceed around 80ºC. Thus, it is necessary to determine the optimal arrangement of heat sources mounted on a substrate board to dissipate heat efficiently and improve their reliability.

Da Silva et al. [1] carried out numerical simulations to maximize the global conductance between the heat source wall and the fluid using the constructal method. They found that the optimal arrangement is not uniform. Furthermore, they reported that the IC chips are mandatorily placed near the boundary to consider the increase in Rayleigh number (Ra). Hotta and Venkateshan [2-3] investigated experimentally steady, 3D, conjugate natural convection cooling of five non-identical heat sources mounted on a substrate board. They have proposed an empirical correlation for the dimensionless maximum (θ) in terms of λ and found that θ decreases with increasing λ. They also determined the global optimum configuration of heat sources using hybrid optimization (ANN+GA) technique. Diaz and Milanez [4] studied the numerical optimization of non-uniform heat sources using a genetic algorithm (GA). They found that only 2% of the numerical simulation data are enough for optimization using the GA technique. [Sudhakar et al. 5, Patil and Hotta 13] performed the numerical and experimental studies for optimal arrangement of three identical heat sources mounted on a wall under conjugate laminar mixed convection. They have developed a correlation between the (θexcess), and the dimensionless geometric distance parameter (λ). Liu and [Phan-thein 6, Patil and Hotta 14] studied numerically to seeking the optimal arrangement of the discrete IC chips using the different algorithms. They concluded that the optimal thermal performance is achieved when the distance between the heat sources follows a GMR of 1.618. They also suggested that 10% significant drop in a temperature. Kadilaya and Chattopadhyay [7] performed the optimization of heat source placed in square enclosure under free convection by combining hybridization of (ANN+GA) .They found that, at high Rayleigh number the spacing between the heat sources should be the minimum for optimum heat transfer. Chen and Liu [8] determined the optimum spacing ratio experimentally among the heated elements and found the highest temperature drop of 8.24% and reduction in a relative temperature difference of 27.62% when heat sources are arranged in geometric series. Chadwick et al. [9] have investigated the effect of natural convection experimentally in a discrete heated enclosure using Mach-Zehnder interferometry and reported that for a single heat source near to bottom wall shoots higher HTC with Grashof number range. [Yang et al.10, Patil and Hotta 12] experimental study rectifying the optimal arrangement of five IC chips placed on a conductive substrate. They found a maximum temperature drop of 20% when center to center distance between the heat sources follows a geometric series with a common ratio equal to 1.618. Tou et al. [11] carried out a 3D numerical investigation of natural convection cooling from a 3 x 3 array of discrete heat sources in a liquid-filled enclosure and found that Nusselt number increases with Rayleigh number.

Several studies have been carried out for the identical discrete heat sources mounted on a substrate board with uniform spacing. However, the heat transfer characteristics from non-identical heat sources and non-uniform spacing are rarely studied in the literature. Again, the analysis using COMSOL Multiphysics is an area to explore. Hence, the present study compares identical and non-identical heat sources when they are arranged uniformly and non-uniformly on a substrate board using COMSOL Multiphysics.

NUMERICAL MODELLING

3-D conjugate laminar free convection in a vertical column has been considered in the present study. The numerical models have been made for both five identical and non-identical size finite heat sources, each generating heat at a uniform rate. Figure 1 shows the similar size heat sources arranged in a central configuration. In contrast, figure 2 shows the arrangement of non-identical size heat sources placed in geometric series having a common ratio equal to golden mean (1.618). There are 120 possible configurations for the arrangement of non-identical heat sources in a geometric series configuration. The configuration shown in figure 2 is denoted as B-A-C-E-D, where the heat sources are given alphabetical notations according to the decreasing order of their hydraulic diameter (A>B>C>D>E). Five different values of volumetric heat generation (8.5 x 105≤ qv≤ 12.5 x 105 W/m3) are considered for the present numerical simulation.

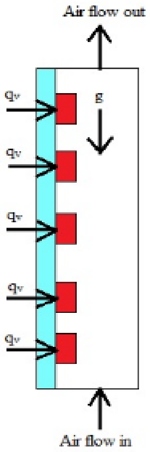

Figure 1. Computational domain of identical heat sources

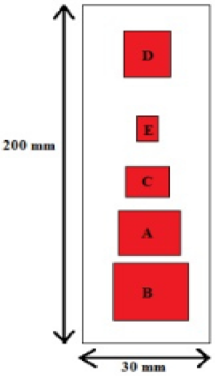

Figure 2. A typical non- identical heat source configuration

The thermos-physical properties and dimensions of different components of the computational domain are given in Table 1 and 2, respectively.

Table 1 Thermo-physical properties of the heat source and substrate board

Material	Heat	Substrate
Density (kg/m^3)	2330	1900
Specific heat (J/kg K)	703	1369
Thermal conductivity	163	0.3

Table 2 Dimensions of different components of the computational domain

Components	Dimensions (mm)
Substrate board	200 x 30 x 6
Vertical air cavity	200 x 30 x 15
Heat source A	16 x 16 x 5

Heat source B	20 x 20 x 2
Heat source C	12 x 12 x 5
Heat source D	20 x 15 x 2
Heat source E	10 x 5 x 2

GOVERNING EQUATIONS

Air is taken as the fluid medium and is considered to be steady, incompressible, and laminar flow having constant fluid properties excluding density. Domain are expressed as follows.

Fluid domain:

Continuity equation

$$\frac{\partial \mathrm{u}}{\partial \mathrm{x}} + \frac{\partial \mathrm{v}}{\partial \mathrm{y}} + \frac{\partial \mathrm{w}}{\partial \mathrm{z}}$$

(1)

Momentum equation (Fluid Domain)

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + v\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right)$$

$$\frac{\partial \mathrm{v}}{\partial \mathrm{t}} + \mathrm{u}\frac{\partial \mathrm{v}}{\partial \mathrm{x}} + \mathrm{v}\frac{\partial \mathrm{v}}{\partial \mathrm{y}} + \mathrm{w}\frac{\partial \mathrm{v}}{\partial \mathrm{z}} = -\frac{1}{\rho}\frac{\partial \mathrm{p}}{\partial \mathrm{y}} + \mathrm{v}(\frac{\partial^2 \mathrm{v}}{\partial \mathrm{x}^2} + \frac{\partial^2 \mathrm{v}}{\partial \mathrm{y}^2} + \frac{\partial^2 \mathrm{v}}{\partial \mathrm{z}^2}) + \rho\beta(\mathrm{Tmax} - \mathrm{Tamb})$$

$$\frac{\partial \mathrm{v}}{\partial \mathrm{t}} + \mathrm{u}\frac{\partial \mathrm{v}}{\partial \mathrm{x}} + \mathrm{v}\frac{\partial \mathrm{v}}{\partial \mathrm{y}} + \mathrm{w}\frac{\partial \mathrm{v}}{\partial \mathrm{z}} = -\frac{1}{\rho}\frac{\partial \mathrm{p}}{\partial \mathrm{y}} + \mathrm{v}(\frac{\partial^2 \mathrm{v}}{\partial \mathrm{x}^2} + \frac{\partial^2 \mathrm{v}}{\partial \mathrm{y}^2} + \frac{\partial^2 \mathrm{v}}{\partial \mathrm{z}^2})$$

(2)

Energy equation (Solid heat sources and board)

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} = \frac{k}{\rho C}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + Q_g$$

(3)

For steady (state condition)

$$\frac{\partial \rho}{\partial t} = \frac{\partial u}{\partial t} = \frac{\partial v}{\partial t} = \frac{\partial w}{\partial t} 0$$

(4)

BOUNDARY CONDITIONS

For the complete formulation of the problem, the following boundary conditions are considered.

Thermal insulation condition

$\mathbf{n}.(-\mathbf{k}\nabla \mathrm{T}) = 0$ (5)

No slip condition (6)

$\mathbf{u} = 0$

Symmetry condition (on side walls of vertical air cavity)

$$\mathbf{u}.\mathbf{n} = 0 \tag{7}$$

$$\mathbf{k} - (\mathbf{k}.\mathbf{n})\mathbf{n} = 0 \tag{8}$$

$$\boldsymbol{k} = [\mu(\nabla\mathbf{u} + (\nabla\mathbf{u})^{\boldsymbol{T}}].\mathbf{n} \tag{9}$$

Open boundary condition (on inlet and outlet walls)

$$\left[-p\mathbf{I} + \mu(\nabla\mathbf{u} + (\nabla\mathbf{u})^{\boldsymbol{T}}) - \left(\frac{2}{3}\right)\mu(\nabla.\mathbf{u})\mathbf{I}\right].\mathbf{n} = -\mathrm{f}\mathbf{n} \tag{10}$$

, if $\mathrm{T} = \mathrm{T0}$, if $\mathbf{n}.\mathbf{u} < 0$

, if $\nabla\mathrm{T}.\mathbf{n} = 0$, if $\mathbf{n}.\mathbf{u} \geq 0$

Periodic heat flow condition (on the substrate board left the wall and vertical air column right wall)

Tsrc=Tdst (11)

Jsrc=Jdst (12)

NUMERICAL SCHEME AND SOLUTIONS

Numerical scheme

Three-dimensional governing equations (1) - (4) for natural convection along with the boundary conditions (5) - (12) form a set of coupled non-linear partial differential equations, which are solved using COMSOL Multiphysics v 4.2. The stationary fully coupled solver is used for the numerical scheme, and linearized equations are solved using the right preconditioned GMRES (generalized minimum residual) iterative solver. The value of relative tolerance 0.001 is adopted as the convergence criteria. The relative error on the estimate of 10-5 and close residual of 10-6 is observed upon convergence.

Solution

The temperature and velocity profile for identical size heat sources in equidistance configuration is shown in figure 3 and figure 5, respectively. It is observed that the highest temperature is attained by the fifth heat source positioned at the bottom of the board, and the temperature increases with distance from the bottom of the board. Figure 3 shows that the air velocity is the maximum above the most heated element and is almost zero close to the walls. Figure 4 shows a similar trend in the velocity profile of non-identical size heat sources. But it is seen from figure 6 that the highest temperature among the non-identical size heat sources is attained by the third chip positioned at the substrate bottom. About 52 simulations are carried out for different positions of heat sources on the substrate board, and 22 simulations are carried out with five different volumetric heat generation values (qv).

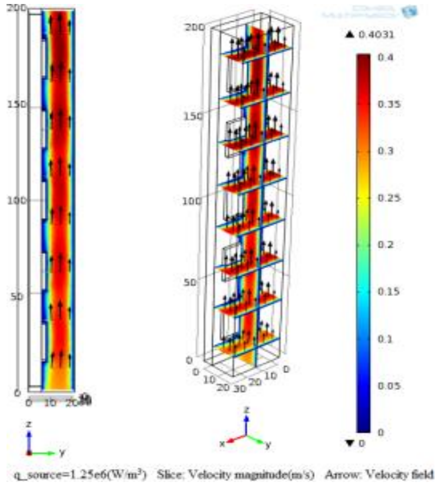

Figure.3.Velocity profile for identical heat sources (Equi-distance arrangement)

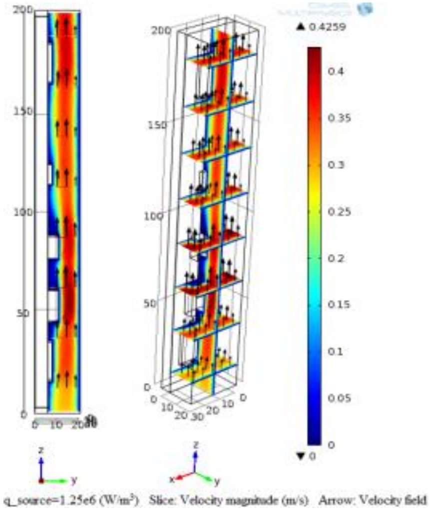

Figure 4. Velocity profile for non-identical heat sources (Geometric series arrangement)

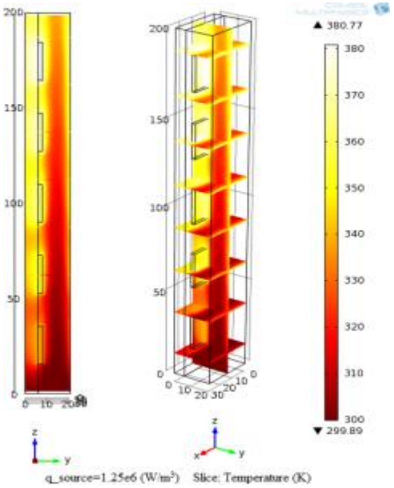

Figure 5. Temperature profile for an identical heat source

(Equi-distance arrangement)

RESULTS AND DISCUSSION

Figure 7 shows the variation of (t)excess of identical heat sources in equidistance and geometric series configuration concerning qv. It is observed from the figure that, (t)excess for geometric series configuration is lower than that of the equidistance configuration by around 10% for all the five different qv values. Also, the maximum (t)excess increase as the qv value is increased for both equidistance and geometric series configuration. Figure 8 shows the variation of leading (hconv) of identical size heat sources in equidistance and geometric series configuration with qv. Figure 8 depicts the variation of maximum (hconv) increases with an increase in qv value. Similar trends have been observed for non-identical heat sources.

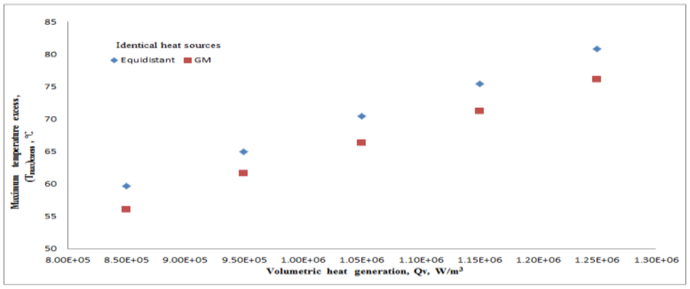

Figure 7. Variation of (θexcess) of identical heat sources with qv

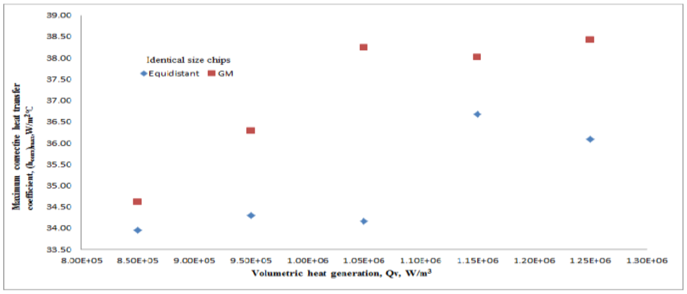

Figure 8. Variation of (hconv) coefficient of identical heat sources with qv

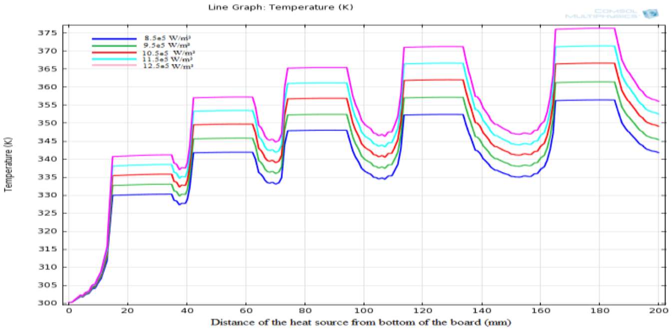

Figure 9. Temperature variation of identical size heat sources in geometric series with their distance from substrate bottom

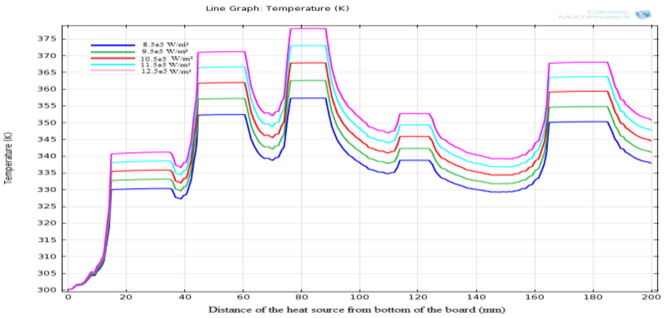

Figure 10. Temperature variation of non-identical heat sources in geometric series with their distance from substrate bottom

The changes in temperature for of identical heat sources in a geometric series configuration with their distance from the bottom of the substrate board is shown in figure 9. It is seen that each heat source temperature is increases with an increase in qv value. It is clear from figure 9 that, the maximum temperature is achieved by the heat source which is farthest from the substrate bottom, while in case of non-identical size heat sources in B-A-C-E-D configuration, as shown in figure 10, the maximum temperature is attained by heat source C, which is positioned at third from the substrate bottom. Also, the temperature of each heat source also increases with an increase in qv in the case of non-identical heat sources. Hence, it has been observed that the geometric series configuration is better than the equidistant configuration both in the case of the identical and non-identical size heat source. Also, the maximum temperature excess and temperature profile in the case of non-identical size heat sources depend radically upon the configuration in which heat sources are positioned.

Correlation

The IC chip temperature depends on a particular configuration, distance from the substrate bottom, and volumetric heat generation, so an empirical correlation is proposed between the dimensionless temperature (θ) and dimensionless distance parameter (λ), dimensionless position parameter (z) and non-dimensional volumetric heat generation (q*v) using regression analysis, and is given in Eq 13. Eq. 13 is valid for 625 data points. The R2 value is 0.81, with a standard error on the estimate is 0.024.

$$\theta = 0.82 * \lambda-0.028 * (1+z)2 * (q*v)1.06 \qquad (13)$$

This equation is valid for the following range of parameters:

$0.595 \leq \lambda \leq 1.103$

$0.075 \leq z \leq 0.875$

$0.012 \leq q*v \leq 0.123$

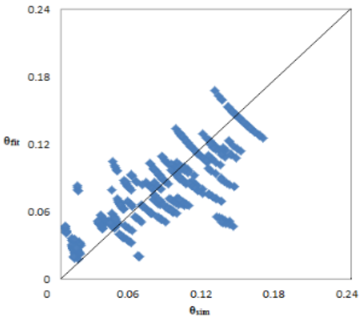

Figure 11. Parity plot between θsim vs θfit

A parity plot, shown in figure 11 is plotted between the dimensionless (θsim) and dimensionless fit (θfit), which shows the goodness of the curve fitting between simulation data and data obtained using Eq. 13.

Another correlation for the Nusselt number (Nu) is given in terms of Rayleigh number (Ra), non-dimensional distance parameter (λ), and non-dimensional position parameter (z). This relation is shown in Eq. 14.

$$Nu = 7267 * Ra-0.65 * \lambda-2.26 * (1+z)-1.35 \qquad (14)$$

Eq. 14 is valid for the following range of parameters.

$2000 \leq Ra \leq 40000$

$0.595 \leq \lambda \leq 1.103$

$0.075 \leq z \leq 0.875$

The parity plot is shown in Fig. 12 shows good agreement between Nusselt number simulation (Nusim) and Nusselt number fit (Nufit).

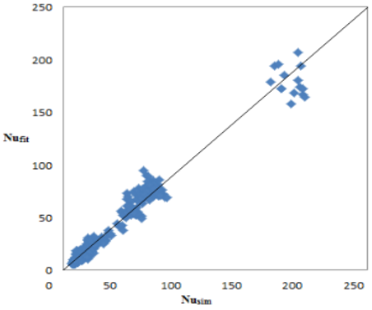

Figure 12. Parity plot between Nusim vs Nufit

Conclusions

3D, steady-state numerical analysis has been carried out from five symmetric, and asymmetric protruding IC chips mounted on a three-dimensional vertical substrate board under natural convection using COMSOL v 4.2. The different configurations of heat sources are subjected to variable volumetric heat generation rates, and these are identified using a non-dimensional geometric distance parameter, λ. The changes in the (t)excess of IC chips with respect to λ is carried out and it is observed that the (t)excess decreases with the increase of λ. A comparison is made between the identical and non-identical heat sources mounted at a uniform (equidistant) and non-uniform (geometric series) distance on the substrate board. There is a reduction of the maximum temperature by 10% geometric series configuration as compared to the equidistance one. The maximum temperature is achieved by the heat source, which is farthest from the substrate bottom board for the equidistance arrangement. In contrast, in the case of non-identical size heat sources, the maximum temperature is attained by heat source C, which is positioned at a third from the substrate bottom. The maximum temperature excess and temperature profile in non-identical size heat sources depend radically upon the configuration in which heat sources are positioned. An empirical correlation is also put forward for the dimensionless temperature (θexcess) in terms of non-dimensional distance parameter (λ), non-dimensional position parameter (z), and non-dimensional volumetric heat generation (q*v).

References

1. Da Silva, A. K., S. Lorente, and A. Bejan. 2004. “Optimal distribution of discrete heat sources on a wall with natural convection”. International Journal of Heat and Mass Transfer 47(2). 203-214.
doi: 10.1016/j.ijheatmasstransfer.2003.07.007
2. Hotta, T.K. and S. P. Venkateshan. 2014. “Optimal distribution of discrete heat sources under natural convection using ANN-GA based technique”. Heat Transfer Engineering, 36(2). 200-211.
doi: 10.1080/01457632.2014.909222.
3. Hotta, T.K., P. Muvvala, and S. P. Venkateshan. 2013. “Effect of surface radiation heat transfer on the optimal distribution of discrete heat sources under natural convection”. Heat and Mass Transfer 49 (2). 207-217.
doi: 10.1007/s00231-012-1072-0
4. Dias, T. and L.F. Milanez. 2006. “Optimal location of heat sources on a vertical wall with natural convection through genetic algorithms”. International Journal of Heat and Mass Transfer 49 (13-14). 2090-2096.
doi: 10.1016/j.ijheatmasstransfer.2005.11.031
5. Sudhakar, T., C. Balaji, and S. P. Venkateshan. 2010. “A heuristic approach to optimal arrangement of multiple heat sources under conjugate natural convection”. International Journal of Heat and Mass Transfer 53 (1-3). 431-444.

doi: 10.1016/j.ijheatmasstransfer.2009.09.013

6. Liu, N. and N. Phan-Thien. 2000. “An optimum spacing program for three chips mounted on a vertical substrate in an enclosure”. Numerical Heat Transfer, Part A 37 (6). 613-630. doi: 0.1080/104077800274118

7. Kadiyala P. and H. Chattopadhyay. 2011. “Optimal location of three heat sources on the wall of a square cavity using genetic algorithms integrated with artificial neural networks”. International Communications in Heat and Mass Transfer 38 (5). 620-624.
doi: 10.1016/j.icheatmasstransfer.2011.03.018

8. Chen S. and Y. Liu. 2002. “An optimum spacing problem for three-by-three heated elements mounted on a substrate” Heat and Mass Transfer 39 (1). 3-9.
doi: 10.1007/s00231-001-0286-3

9. Chadwick M., B. Webb, and H. Heaton. 1991. “Natural convection from two-dimensional discrete heat sources in a rectangular enclosure”. International Journal of Heat Mass Transfer 34 (7). 1679-1693.
doi: 10.1016/0017-9310(91)90145-5

10. Yang L., C. Leung, T. Chang, and N. Phan-Thuen. 2000. “An optimal spacing problem for five chips on a horizontal substrate in an enclosure–natural convection”. International Journal of Computational Engineering and Science 1(1). 1671-186. doi: 10.1142/S1465876300000094

11. Bhowmik H. and K. Tou. 2005. “Experimental study of transient natural convection heat transfer from simulated electronic chips”. Experimental Thermal Fluid Science 29 (4). 485-492.
doi: 10.1016/j.expthermflusci.2004.06.003

12. Patil. N. G. and Hotta. T. K. (2018) “Role of working fluids on the cooling of discrete heated modules: a numerical approach”, SADHANA - Indian Academy of Sciences, 43, 187.

13. Patil. N. G. and Hotta. T. K. (2020) “Heat transfer characteristics of high heat generating IC chips cooled using liquid cold plate - a combined numerical and experimental study”, ASME Journal of Thermal Science and Engineering Applications. 13(1), 011019

14. Patil. N. G. and Hotta. T. K. (2020) “A combined numerical simulation and optimization model for the cooling of IC chips under forced convection”, International Journal of Modern Physics – C.31, (6) 2050081.

15. Mathew, V.K., and T.K. Hotta. 2018. “Numerical Investigation on Optimal Arrangement of IC Chips Mounted on a SMPS Board Cooled under Mixed Convection.” Thermal Science and Engineering Progress 7. doi:10.1016/j.tsep.2018.06.010.