Thermal aspect of material selection for substrate board equipped with high heat flux IC chips

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Abstract. This paper investigates the material selection for substrate board equipped with nine silicon heaters that mimic IC chips. This includes computational research on laminar forced convection air cooling of silicon IC chips in electronic components mounted on substrate boards subjected to high uniform heat fluxes in a horizontal channel. Copper clad boards with single and multilayer having thermal conductivities of 8.8, 40.5, and 61.5 W/m K are the substrate materials used in this study. Three-dimensional steady-state conjugate heat transfer with laminar non-isothermal fluid flow module is used from COMSOL Multiphysics 5.4 to study fluid flow and heat transfer. Simulations performed with flowing air velocities of 1.5, 2.5, and 3.5 m/s with very high heat fluxes of 10000, 12500, and 15000 W/m². It showed that the temperature on substrate board strongly depends upon placement of heaters, Reynolds number, substrate thermal conductivity. It also found that higher thermal conductivity substrate materials results in heat transfer enhancement and decrease chances of failures of electronic devices. A non-dimensional temperature based correlation is also devised in terms of non-dimensional heat flux, thermal conductivity, Nusselt number, and Reynolds number.

Keywords: Material Selection, Forced convection, Computational heat transfer, Heat sources, High heat flux, Conductive substrates, Thermal control.

1. Introduction
Due to continual miniaturization of electronic equipments proper heat dissipation has become challenging due to high heat fluxes. Forced convection is receiving increasing attention in recent times for dissipating high heat density. Along with forced convection material selection for high heat dissipation electronic devices is required. The current work is applicable for electronic devices like gaming laptops, desktop personal computers, and digital cameras which uses air cooling for guiding material selection. They uses customised PCB designs of about 3”× 3” subjected to high heat fluxes. Huang et al. [1] numerically investigated that change in incoming parabolic velocity and vortices zones significantly enhances heat transfer. Nemati [2] performed the fin heat sink’s optimization using the effect of dimensionless parameters on entropy generation. Ismail et al. [3] found that 30% ethylene glycol is suitable cooling fluid for microchannel heat sink. Baris and Nagulapally [4] determined that power dissipation of PCB on trace correlates with the square of electric current. Heindel et al. [5] found that fully developed nucleate boiling is a preferred condition for electronic cooling. Choi et al. [6] studied loop heat pipe for high power electronics. Maghrabie et al. [7] numerically determined that third-row obstacles is best position for cooling of heated obstacles. Das et al. [8] studied conjugate
mixed convection from vertical non-isothermal heat sink and found that overall Nusselt number is a function of conductance, fin spacing, clearance. Anuwarullah et al. [9] experimentally investigated enhanced heat transfer from electronic equipment cooled by air jet impingement and presented the correlation of Nusselt number in terms of flow parameters and aspect ratio. Talukdar et al. [10] found 7-10% heat transfer enhancement by geometric modifications in natural convection cooling of heat sources. Tsay et al. [11] numerically studied heat sources with slots for enhancement of heat transfer and found an 81% increment in Nusselt number for front blocks. Wang et al. [12] numerically conducted a parametric study for phase change material (PCM) based heat sink and found an increase in thermal performance under natural convection. Hotta et al. [13] introduced a geometric parameter for heat source configurations and found an optimal placement using an experimentally trained genetic algorithm. Bhowmik and Tou [14] experimentally studied transient forced convection from simulated electronic chips and developed correlation for Nusselt number in terms of Peclet number and Fourier number. Chen and Liu [15] carried out air cooling of nine identical heat sources with a wide range of velocities, there was a drop in the substrate board’s temperature when the spacing between heat sources follows geometric ratio. Deng and Liu [16] performed liquid metal cooling for high-heater dissipation of CPUs and found energy saving compared with heat pipe and water cooling. Wang et al. [17] numerically studied the cooling of a chip with a flow-disturbing obstruction block and found enhanced heat transfer. Rosas et al. [18] performed experiments to investigate convective heat transfer in an electronic module using a curved deflector and found heat transfer enhancement. Hung and Fu [19] numerically studied the passive enhancement of electronic cooling through geometric modifications. Mathew and Hotta [20] numerically and experimentally studied forced convection cooling of IC chips in optimal configuration with different orientations of substrates and found 3 - 5°C reduction in temperature. Durgam et al. [21] studied SVR technique for heat source temperature prediction. Moumni et al. [22] used nanofluid for enhancing heat transfer for heated blocks.

The literature shows that much of research based on laminar conjugate heat transfer under natural, forced, or mixed convection cooling is available. The studies mainly focusing on material selection of substrate board equipped with ICs is very limited in previous studies. Furthermore, forced convection air cooling of IC chips dissipating very high heat flux density is scarce. This work aims to select the material for substrate board by thermal aspect with study of nine silicon heaters subjected to very high flux densities. The present study is a unique work useful for a variety of heat transfer applications in the fields like military, biomedical, aircraft, space, and all kinds of consumer electronic devices subjected to high heat fluxes.

2. Numerical modeling and data reduction

The numerical model consists of a substrate board embedded with nine silicon heaters fixed on bottom walls of horizontal channel. The heat source material considered is silicon that mimics the IC chips on PCB. Substrate boards of different materials viz. single layer CCB (copper clad board), multilayer CCB (CCBML - 1), and multilayer CCB (CCBML 2) having thermal conductivities of 8.8, 40.5 and 61.5 W/m K, respectively have been considered. The different flowing air velocities of 1.5, 2.5, 3.5 m/s with very high uniform heat fluxes 10000 W/m², 12500 W/m², and 15000 W/m² are reviewed in the simulation study. This model, including the geometry and heat dissipation values, replicate an actual design. Thermal management techniques mainly heat spreaders and heat pipes are used for high heat fluxes, but for given heat flux values, air cooling systems are suitable. For methodology and necessary assumptions we have followed steps given by Durgam et al. [21]. Three dimensional steady state conjugate transfer with non-isothermal fluid flow module were selected from COMSOL Multiphysics 5.4 for finding numerical solution of present problem [23, 24]. The computational domain consists of a horizontal channel with heaters fixed on substrate board having specific arrangement of placement, coordinate axes, and the airflow direction have shown in Fig. 1(a).
Optimal placement of heaters used in the study for all simulations is shown in Fig. 1(b). This configuration was obtained from the simulation study of 100 random configurations for 1.5 m/s air velocity and 10000 W/m$^2$ heat flux. The configuration presented in Fig. 1(b) results in lowest maximum temperature of heat sources for the same input parameters; hence it is considered as optimal configuration but is limited to the 100 cases discussed in this study. This configuration is used to select material of substrate board according to thermal aspects. Length, width, and thickness of substrates board are 75×75×1.6 mm. The thickness of air above the board is assumed to be 6 mm. The heat source details and sizes are described in Table 1. The heat source sizes selected are used in practical application. The thickness of all heat sources is 3 mm.

| Heat source | Size, mm |
|-------------|----------|
| A1, A2      | 5×5×3    |
| B1, B2, B3  | 5×10×3   |
| C1, C2, C3  | 5×15×3   |
| D           | 10×15×3  |

2.1. Governing equations and boundary conditions
The governing equations used for finding numerical solution are Eqs. 1 - 5. Out of which Eq. 1 is continuity, Eq. 2, 3, and 4 are momentum equations used for fluids in x, y, z directions. Eq. 5 is energy equation used for solid.

Continuity equation for fluid:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$  \hspace{1cm} (1)

x - momentum equation

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

y - momentum equation
\[
u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \frac{\mu}{\rho} \left[ \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right]
\]

z - momentum equation

\[
u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial z} + \frac{\mu}{\rho} \left[ \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right]
\]

Solid region: Energy equation

\[
u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} = \alpha \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right]
\]

The coefficient of heat transfer and flow parameters are calculated as shown in Eq. 6 - 8.

\[
h = \frac{q}{T - T_\infty}
\]

\[
Nu = \frac{hL_b}{k_f}
\]

\[
Re = \frac{uL_h}{\nu}
\]

The non-dimensional parameters viz. maximum temperature, thermal conductivity and heat flux are defined as given in Eq. 9 - 11.

\[
\theta = \frac{\Delta T}{T_\infty}
\]

\[
k^* = \frac{k_b}{k_f}
\]

\[
q^* = \frac{qL_h}{T_\infty k_f}
\]

The given cooling problem is solved for material thermophysical properties at \(T_\infty = 27 \, ^\circ\text{C}\) and 1 atm are shown in Table 2.

| Material  | \(k\) W/m K | \(\rho\) kg/m\(^3\) | \(C_p\) J/kg K |
|-----------|--------------|----------------|----------------|
| CCBSL     | 8.8          | 2050           | 1370           |
| CCBML1    | 40.5         | 2582           | 1276           |
| CCBML2    | 61.5         | 2796           | 1219           |
| Silicon   | 148          | 2329           | 700            |
| Dry air   | 0.02675      | 1.165          | 1005           |

BC’s used for given cooling problem are at inlet: \(x = 0, T = T_\infty\) and \(u = u_0 = 1.5, 2.5\) and \(3.5\) m/s. at outlet: \(x = L, p = p_\infty\) (Atmospheric pressure) [24].
2.2. Thermal design for selecting substrate material

Printed circuit boards are the heart of electronic devices. Design of PCBs must be adequate for smooth operations, reliability, safety and life of equipments. By adequate thermal design failures due to improper heat dissipation in the electronic devices can be minimised. To achieve that material selection for substrate board is important. The present study is carried out for high thermal conductivity substrate materials equipped with high heat flux IC chips. To achieve high thermal conductivity substrate board are constructed using copper layers and with FR4 layer. As copper clad board is composite structure it has two type conductivities i.e. in-plane thermal conductivity and through plane thermal conductivity. Out it these in-plane thermal conductivity is higher for copper clad boards, while it is very less along through plane direction. Hence two-dimensional heat dissipation is assumed in the present cooling problem. We have selected material namely, single layer copper clad board, multilayer copper clad board 1, multilayer copper clad board 2. Material properties are mentioned in Table 2. The material is selected are with increase in thermal conductivity value. Study is carried out for all the material to check the effect of substrate thermal conductivity for heat transfer enhancement which is required to dissipate heat properly. For calculation of effective in-plane thermal conductivity following relation were used.

$$k_{eff} = \frac{k_{FR4}t_{FR4} + k_{cu}t_{cu}}{t_{FR4} + t_{cu}} \quad (12)$$

As FR4 is homogeneous, effective thermal conductivity is substrate board thermal conductivity.

2.3. Grid independence test

The pre-processor generated free tetrahedral coarse mesh with 333579 grids has been employed for all simulations. Study mesh has 317696 number of domain elements, 32330 number of boundary elements, and 1728 number of edge elements. Study has free mesh time of 8.02 s and quality of 0.01872 for minimum elements. Comparative mesh study is carried out for grid numbers 309758, 333579, 360763, 385924, and 408750 that is from fine to extra coarse. It is noticed from the grid test that for all five grids employed with substantial difference in grid elements results in temperature $\leq 1^\circ C$. Hence the grid with 333579 was used for all simulations, which saves the cost and time of the simulations. Table 3 shows the grid sensitivity test and the % change in temperature for different grids. A mesh used for heaters and substrate boards is shown in Fig. 2.

![Figure 2. Mesh for heat sources and substrate board](image)
3. Results and discussion

The simulation results of optimal configuration found from 100 configurations using different Reynolds numbers, heat flux values, and substrate board materials are presented. A total of 27 number of cases (1 optimal configuration $\times$ 3 thermal conductivities $\times$ 3 heat fluxes $\times$ 3 velocities) were found. The flowing air velocities of 1.5, 2.5, 3.5 m/s corresponding to Reynolds numbers 938, 1563, and 2188, respectively. The different substrate board materials used are CCBSL, CCBML-1, CCBML-2, with thermal conductivity values of 8.8, 40.5, 61.5 W/m K, respectively subjected to very high uniform heat flux values of 10000, 12500, 15000 W/m$^2$ are used for the study. The laminar fluid flow forced convection numerical results of nine heat sources fixed on different substrates arranged in optimal placement (as shown in Fig. 1(b)). They fixed to the bottom walls of the horizontal channel are presented. Computer software generated temperature, and velocity contour plots are available after convergence of each simulation study. Few such representative plots to visualize clear insight into the physical phenomenon are given in these sections. Fig. 3 show the temperature, temperature contour, velocity and conductive heat flux plots for CCBSL at Re = 938, 1563, and 2188 using q = 10000, 12500, and 15000 W/m$^2$ respectively. CCBSL gives maximum temperature 86 $^\circ$C at Re = 938 using heat flux of 10000 W/m$^2$. The maximum temperature is in a suitable limit hence safe. The heat flux value 12500 W/m$^2$ gives maximum temperature of 83.8 $^\circ$C at Re = 1563 for 15000 W/m$^2$ heat flux and Re = 2188 required to keep the maximum temperature 85.1 $^\circ$C. It indicates that for higher heat flux, the requirements of Reynolds number should be higher to maintain the temperature within a safe operating limit. In velocity plot the black arrowheads show the air flow direction and the red lines indicate the streamlines [Fig. 3(d)]. Conductive heat flux plot show the heat flux available on the IC chips and substrate [Fig. 3(e)]. The temperature trend of all heat sources in first, second, and third rows is similar to that in Ref. [15, 31]. The maximum temperature is under predicted in the computation. The reason for the deviation in the computational results from experimental results is the different Reynolds numbers and heat inputs. Fig. 4 the temperature, temperature contour, velocity and conductive heat flux plots for CCBML-1 at Re = 935 and 1563 for q = 10000, 12500, and 15000 W/m$^2$ respectively. CCBML-1 gives maximum temperature 75.8 $^\circ$C for Re = 938 with heat flux of 10000 W/m$^2$. For heat flux of 12500 W/m$^2$, the maximum temperature of 87.6 $^\circ$C at Re = 938 is observed. For 15000 W/m$^2$ heat flux and Re = 1563 is required to maintain the maximum temperature 82.2 $^\circ$C. It indicates that for higher heat flux, the requirements of Reynolds number was increased. All the temperature for particular Reynolds number is suitable operating limits for all kinds of electronic equipment. The results for q = 12500, and 15000 W/m$^2$ for CCBSL, CCBML1 indicates that the requirement of Reynolds number is decreased for high thermal conductivity substrate board materials.
3.1. Comparative study of CCBML1, CCBML2

Thermal performance of higher thermal conductivity materials viz. CCBML-1 and CCBML-2 compared at Re = 938, 1563 and 2188 for q = 15000 W/m² has been shown in Fig. 5. It is seen that CCBML-1 gives maximum temperature 99.4 °C while CCBML-2 gives 97.5 °C for Re = 938. Whereas at Re = 1563 the maximum temperature obtained are 82.2 °C and 80.6 °C for

Figure 3. Temperature, temperature contour, velocity and conductive heat flux plots for CCBML for Re = 938, 938, 1563, and q = 10000, 12500, 15000 W/m².
Figure 4. Temperature, temperature contour, velocity and conductive heat flux plots for CCBSL for Re = 938, 1563, 2188 and q = 10000, 12500, 15000 W/m$^2$.

CCBML-1 and CCBML-2. At the maximum value of Re = 2188, CCBML1, and CCBML-2 results in 73.8 and 72.4 °C. It indicates that temperature drop in CCBML-2 compared with CCBML-1 is 1.83, 1.63, 3.47 °C, respectively, for the given heat flux of 15000 W/m$^2$ and Reynolds numbers 938, 1563 and 2188, respectively. It shows that using higher thermal conductivity material, the decrease in maximum temperature is not very significant. Therefore CCBML-1 is ideally preferred over CCBML-2 based on cost, reliability, and performance for very high heat fluxes, purely based on heat transfer point of view. In general, from this study, it is clearly...
revealed that the minimum temperature occurs for heaters placed in the initial row.

![Temperature plots for CCBML-1, CCBML-2 at Re = 938, 1563, 2188 and q = 15000 W/m².](image)

**Figure 5.** Temperature plots for CCBML-1, CCBML-2 at Re = 938, 1563, 2188 and q = 15000 W/m².

The temperature for heat source in the second row is greater than the initial row. The temperature in the third row heat sources was maximum for all Reynolds numbers and heat sources. It showed that temperatures obtained in the case of CCBSL are higher compared with CCBML-1 and CCBML-2. The temperature distribution on the substrate board is uniform
for higher thermal conductivity substrates. Furthermore, it is common to observe that for all cases using all Reynolds numbers, heat flux values, and substrate board materials, the maximum temperature occurs in the middle of the top row i.e., heat source B3. The common hotspot on the substrate board in the vicinity of B3. From Fig. 3 - 5 it is observed that higher Reynolds numbers and higher substrate thermal conductivities result in lower temperatures. Whereas higher heat flux values exhibit higher temperatures for the same Reynolds number and substrate thermal conductivity. The results obtained are significant in practical applications.

3.2. Variation of excess temperature with substrate material
Forced convection simulation results of nine heat sources mounted on CCBSL, CCBML-1, CCBML-2 arranged in the optimal configuration is studied. The variation of maximum excess temperature for all substrate materials, 10000 W/m$^2$ heat flux and Reynolds number have been presented. Fig. 6 shows the variation of excess temperature for all the material for Reynolds numbers 938, 1563, and 2188, respectively, and 10000 W/m$^2$ heat flux. At Re = 938 the maximum excess temperatures are 59, 48.7, and 47.5 $^\circ$C CCBSL, CCBML-1, CCBML-2, respectively. A similar trend shown for Re = 1563; the temperatures are 45.5, 37, and 36 $^\circ$C respectively, and that for Re = 2188 are 38.9, 31.5, 30 $^\circ$C respectively. It is an indication that the drop in the maximum temperature is significant when CCBML-1 used instead of CCBSL, as compared with the drop to CCBML-2 from CCBML-1. Therefore, it is found that the use of CCBML-1 is ideally preferred based on thermal performance and cost competency.

![Figure 6](image)
Figure 6. Excess temperature variation with substrate materials for different Reynolds number at q = 10000 W/m$^2$

3.3. Variation of heat transfer coefficient with substrate materials
Variation of heat transfer is studied with the substrate board materials at various uniform heat flux values with different Reynolds numbers of 938, 1563, and 2188, respectively. The heat transfer coefficient variation with substrate materials is as shown in Fig. 7 at Re = 938, 1563, 2188 and q = 15000 W/m$^2$. At Re = 938 heat transfer coefficient is 191, 217, 220 for CCBSL, CCBML-1 and CCBML-2 respectively. Similarly, at Re = 1563 and 2188 heat transfer coefficient are 244, 284, 289, and 287, 336, 343, respectively. There is increment in heat transfer coefficient by using higher thermal conductivity substrate and this increase is steep from CCBSL to CCBML-1, whereas from CCBML-1 to CCBML-2, it is flat. The heat transfer coefficient curves are asymptotic to each other for different Reynolds numbers.
Figure 7. Heat transfer coefficient variation with substrate materials for different Reynolds number at $q = 15000 \text{ W/m}^2$.

3.4. Nusselt number variation with Reynolds number

The study is carried out for Nusselt number and Reynolds number associated with different substrate board materials viz. CCBSL, CCBML-1, CCBML-2. Fig. 8 shows variation of Nu with Re for different substrate materials. Nusselt number is increased with increasing Reynolds number as well as increase of substrate board thermal conductivity. The variation obtained is typical for forced convection cooling problem. CCBSL gives Nusselt number values of 80, 103, 120 while CCBML-1 gives 91, 118, 140 and CCBML-2 gives 92, 120, 143 for Re = 938, 1563, 2188 respectively. The increment in Nusselt number is very high from CCBSL to CCBML-1, while it is less from CCBML-1 to CCBML-2. It is clearly visible that increment in heat transfer by use of higher thermal conductivity substrate.

Figure 8. Substrate materials and Reynolds numbers effect on Nusselt number at $q = 15000 \text{ W/m}^2$.

3.5. Substrate thermal conductivity effect on temperature of heat sources

The temperature distribution of heat source is studied for various substrate board material, heat fluxes, and Reynolds numbers. Fig. 9 shows variation of heat source temperatures of optimal configuration for $q = 12500 \text{ W/m}^2$ and Re = 938. It gives an understanding that temperatures of higher thermal conductivity substrate are less compared with lower thermal conductivity substrate. Furthermore, higher thermal conductivity substrate maintains uniform temperature distribution over the substrate board. The uniform temperature distribution is almost similar in the case of CCBML-1 and CCBML-2. Due to the uniform temperature distribution amount of thermal stresses are decreased, as a result, performance and life of PCB can be increased.
Figure 9. Temperatures of all heat sources for \( \text{Re} = 938 \) at \( q = 12500 \text{ W/m}^2 \) using CCBSL and CCBML-1, CCBML-2

3.6. Validation of numerical results with experimental study

Fig. 10 show simulation results of temperature plots using bakelite, CCBSL, CCBML-1 for \( \text{Re} = 625 \) and \( q = 1500 \text{ W/m}^2 \). The maximum temperatures are 53.1, 38.1, and 36.4 °C in the case of bakelite, CCBSL, CCBML-1, respectively. The temperatures are reducing with use of higher thermal conductivity substrate material. However, the temperatures in the case of CCBSL and CCBML-1 are uniform compared with bakelite. The highest temperature is found for a heat source placed in the middle of the third row.

Figure 10. Temperature °C, plots for bakelite, CCBSL and CCBML-1 for \( \text{Re} = 625 \) and \( q = 15000 \text{ W/m}^2 \).
Chen and Liu [15] experimentally studied the configuration of nine identical heat sources with a 1500 W/m² heat flux. The study covered a wide range of Reynolds numbers 465 - 1560, in the laminar regime. The experimental data of [Ref. [15]] are validated with the numerical results for nine heaters fixed on substrate board. For comparison with their results, 1500 W/m² heat flux and Re = 625 with bakelite substrate board of thickness 4 mm and CCBSL, CCBML-1 with a thickness of 1.6 mm are considered. The configuration is also analyzed for different substrate boards to check thermal conductivity effect on temperature distribution and increment in heat transfer. The current study results are compared with results obtained by [Ref. [15]] for the case S2/S1 = 1 (TYPE 1). It showed that the trend is exactly followed, and the excess temperature and heat transfer coefficient values are encouraging in the current study for the same heat flux, Reynolds number, and substrate board material. Fig. 11 show the results plotted for higher thermal conductivity materials CCBSL, and CCBML1. It indicates that for higher thermal conductivity substrate materials, the temperatures are significantly low. Substrate board size in the previous study [Ref. [15]] is about four times the size used in the present study. It shows that better results have been obtained with the consumption of less space. Miniaturization obtained is substantial. To remove same amount of heat as in [Ref. [15]] for maximizing heat transfer, a combination of figure four substrate should be placed one over the other. Due to this maximum temperature reduces and by which performance of electronic gadgets can be increased.

![Figure 11](image)

Figure 11. Temperatures vs heat sources for Re = 625 at q = 1500 W/m² using CCBSL and CCBML-1

3.7. Material selection for substrate board - Thermal aspect

Table 4 shows the selected substrate materials for different Reynolds numbers and heat flux densities for reliability, performance, and cost requirements of electronic devices. It is found from results that CCBSL is suitable for lower values of heat flux and Reynolds number. For higher values of heat flux requirement, high values of Re are required for low thermal conductivity substrate. For high heat flux values, CCBSL is suitable for higher Reynolds number, CCBML-1 and CCBML-2 are preferable for lower Reynolds number.

| Heat Flux W/m² | Re | Selected material |
|----------------|----|-------------------|
| 10000          | 938| CCBSL             |
| 12500          | 938| CCBML-1           |
| 15000          | 1563| CCBML-1           |

3.8. Proposed correlation

A non-dimensional maximum temperature based correlation, in terms of non-dimensional heat flux, thermal conductivity, Nusselt number, and Reynolds number, has been developed as an
empirical relationship and is given in Eq. 13.

\[ \theta_{\text{max}} = \exp\{0.06q^* - 0.01\text{Nu} - 8.4 \times 10^{-6}k^* - 1.2 \times 10^{-5}\text{Re}\} \]  

(Eq. 13)

Eq. 13 is based on 27 data points obtained from simulation results and is valid for variables in following range:

\begin{align*}
12.5 \leq q^* \leq 19 & \quad 29 \leq k^* \leq 2300 \\
63 \leq \text{Nu} \leq 124 & \quad 940 \leq \text{Re} \leq 2188
\end{align*}

Eq. 13 has coefficient of correlation 0.99 and a standard deviation 0.47. Fig. 12 shows a parity plot for non-dimensional temperature \( \theta \) drawn between correlated and simulated values. It is found that the deviation in the data is inside ±10%. The given correlation is useful for obtaining temperatures in electronic equipment having configurations similar to current study.

![Figure 12. A parity plot](image)

4. Conclusions
High thermal conductivity substrates mounted with nine heaters subjected to very high uniform heat fluxes and given Reynolds number in a horizontal channel has been carried out numerically. The conclusions are as follows: The highest temperature on the board is lowest in the case of CCBML-2, and it is increasing in order of CCBML-1, CCBSL for a given set of uniform heat flux, and Reynolds numbers. The temperature difference is very less in CCBML-2 and CCBML-1. Hence it is concluded that CCBML-1 is best suited material as substrate board for higher heat fluxes according to thermal considerations. The maximum temperature on the substrate board is determined by placement of heat sources, heat flux, Reynolds number, and substrate thermal conductivity. The temperature obtained in configuration is minimum when more substantial sized heat sources are at initial rows and sequentially decreasing sizes of heat sources. It is proposed that CCBML1 is optimum material as substrate board material for high heat fluxes as its performance is excellent compared with its cost i.e., CCBML-1 is more cost-effective compared with CCBML-2. The present work is beneficial for the electronic industry and gives useful guidelines for improving the performance and life of electronic gadgets subjected to very high heat fluxes. This study is suitable for electronic gadgets like laptops, digital cameras, and personal computers. With the use of higher Reynolds number, this material can also be used for higher heat fluxes. This configuration is suitable for electronic gadgets having heat dissipation in the range of 5 - 25 W. For high rates of heat dissipation; multiple substrates may be employed. Due to multiple substrate board, highest temperature on the board can be minimized. A non-dimensional maximum temperature correlation for thermal conductivity, non-dimensional heat flux, Nusselt number and Reynolds number shows a statistical goodness of fit.
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