



# STUDY OF SUBSTRATE CONDUCTANCE EFFECT ON THE COOLING OF ELECTRONIC COMPONENTS

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## ABSTRACT

This article explores experimentally and numerically the effect of conductance on cooling of electronic chips by forced air flow in a vertical channel for thermal control. Experiments are conducted using substrates of FR4, bakelite, copper clad board (single layer) equipped with aluminum heat sources at uniform heat fluxes of 1000, 2000, and 3000 W/m<sup>2</sup> at  $500 \leq Re \leq 1500$ . Computer simulations are performed to validate experimental results using a finite element method based COMSOL Multiphysics 4.3b software and the results are in agreements of below 10%. The temperatures obtained showed high thermal conductance copper clad boards (CCBs) are very low compared to FR4 and bakelite substrates. Results showed that FR4 and bakelite are unsuitable for airflow velocity of 0.6 m/s and heat flux of 3000 W/m<sup>2</sup>. However, the temperature variation between single and multilayer CCB is 3 to 4 °C. The temperature reduction using CCB is 10 °C compared to FR4 and bakelite.

**Keywords:** *Conductance, Experimentation, Computer simulation, Channel flow, Thermal control of electronics.*

## 1. INTRODUCTION

Electronics devices continue to pervade all walks of our lives; therefore, its thermal control remains front and center as one of the most important enablers in electronic product realization. Electronic and IT industry facing challenges of high flux density at components because of miniaturization of electronic equipment. Efficient convection cooling techniques are become essential for faster rate of heat dissipation. Forced convection airborne cooling of electronic components in channels considering substrate boards of suitable thermal conductivity tailored for a specific need thus become popular in electronic industry due to its low cost, simplicity, reliability, and performance. Chiu *et al.* (2001) experimentally and numerically investigated conjugate heat transfer from heater block in a horizontal wind tunnel. They found conjugate heat transfer significantly affect the temperature distribution at the heater surface, and wind tunnel wall impact heat transfer. Yutaka and Mohammad (1989) have analysed 3-D laminar forced convection heat transfer from square heat source array on PCB. They found uniform temperature at each heated block at higher thermal conductivity. The quantitative estimation of thermomechanical behaviour of Printed Circuit board (PCB) assembly for stiffness has been analysed by Mittal *et al.* (1996). Fedorov and Viskanta (2000) numerically presented 3-D steady state heat transfer in microchannel heat sink (MCHS) for cooling of electronic device and validated with experimental results available in the literature. They found forced convection water cooled MCHS has a potential application for electronic cooling. Pansé and Ekkad (2021) experimentally and numerically studied forced convection cooling from additive manufacturing based single and double layer microchannels (MCs) for electronic, automotive, aerospace, and medical applications. Authors found better cooling performance from enhanced double layer MCs. Ikeda *et al.* (2021) have studied forced con-

vection cooling of surfaces under heat flux of 10 W/m<sup>2</sup> for multiple applications. They found it as a feasible option to remove electric power during cooling. Hotta and Patil (2018) have reviewed liquid jet impingement cooling of electronic components and found that due to high boiling point Fluorocarbon liquids are better for higher heat flux removal. Thepsut and Pratinthong (2019) have investigated passive and active convection cooling of heaters on PCB in various configurations. They found increase in temperature under natural convection with vertical arrangement and decrease in temperature with increase in velocity under forced convection. Kurşun (2018); Kurşun and Sivrioğlu (2018) have numerically presented mixed convective cooling of heaters on PCB in a wind tunnel using two rectangular and U shaped routing plates. They found increase in free convection for increased heat fluxes and low Reynolds using plates. Dede *et al.* (2015) have investigated conduction, convection heat transfer from anisotropic thermal conductivity multilayer copper clad board (CCB). Authors found decrease in temperature for PCB under natural convection and power densities in the range 1 - 10 W/cm<sup>2</sup>. Sarper *et al.* (2018) have conducted experiments and validated with simulation to study effect of clearance between two discrete flush heaters under free convection and radiation. They found increase in temperature of surfaces for heated walls and increased spacing between heaters to enhance convective heat transfer from second heaters. Experimental results and numerical predictions for validation of heater temperatures on different substrates for electronic components cooling are available in Durgam *et al.* (2019, 2020b); Durgam (2021). The findings of simulation results of temperatures of heated blocks are compared with the temperature results of machine learning methods as a viable option for determining temperatures of heated modules Durgam *et al.* (2022, 2020a, 2021). Jaluria *et al.*

(2020) have presented steady and transient heat transfer from data centers for its thermal management and reduced energy consumption by optimizing the cooling strategy. Singh *et al.* (2021) studied next generation high performance thin thermal management technologies using flattened heat pipe and piezoelectric fan. They used 1-6 mm thick modules for cooling of compact and portable electronic devices dissipating heat ranging from 3 - 68 W. The investigators found reductions from 48 W at 2.0 mm to 7 W at 0.8 mm. Kasten *et al.* (2010) have numerically studied micro-channel heat sink for cooling of microprocessor in data centers using inlet water temperature of 60 °C and flow rate of 0.5 l/min/chip. The authors found temperature difference of 8 °C at the solid-liquid interface, and high outlet water temperature of about 52 °C has created an option of waste heat recovery applications. Fukue *et al.* (2022) have numerically studied effect of rib height and pulsating flow for electronic equipment using water cooling. The researchers found better heat transfer performance by increasing rib height and increased pressure drop. Tian and Zhao (2019) have numerically studied Central Processing Unit (CPU) of a Personal Computer (PC) for varying rib height and fan ventilation and found enhanced thermal performance.

It is seen from the above literature that many authors have presented forced and free convective cooling of heater blocks on PCB in a channel using air, and liquids viz. water, nanofluids. However, the studies showing the effect of substrate conductivity on heat transfer are very limited. Therefore the combined experimental and numerical forced convection cooling of heat source mounted on PCB in a vertical channel to study heat transfer are presented here with an acceptable accuracy for electronic cooling applications.

## 2. DESIGN OF SUBSTRATE BOARDS AND CONFIGURATION

The substrates are made up of FR4, bakelite and CCBSL of size 175 × 175 mm. The FR4 and bakelite substrates has thickness of 5 mm and the CCB board thickness is 1.6 mm. The substrate boards are designed such that the distance of the heat source in first and fifth column from the vertical edges are 7 mm. The distance of the heat sources in first and third row from the upper and lower edge of the substrate is 19.5 mm. The distance between two rows and columns is 21.5 mm and 45.5 mm. The heaters are identical having sides of 15 × 15 and the thickness is 5 mm. The heaters are fixed in five columns and three rows. The configuration is depicted in Fig. 1.

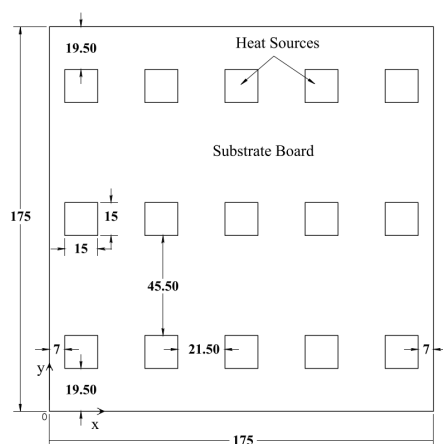
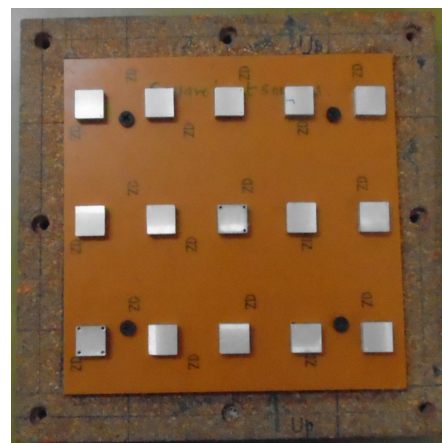


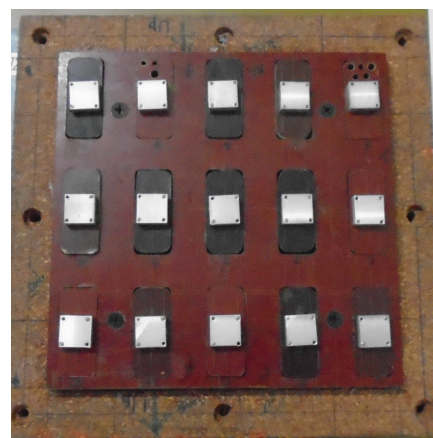
Fig. 1 Configuration, Dimensions in mm Durgam *et al.* (2019)

The cork board of dimensions 225 × 225 × 25 mm is fabricated to minimize heat loss from the back side of the substrate. The substrate fitted with the heaters in a each configurations then screwed to the cork board and fitted on the front wall of the channel. The nichrome heater wire joined to each heat source to supply DC power. The nichrome wires are removed from the small holes created on the cork board and attached

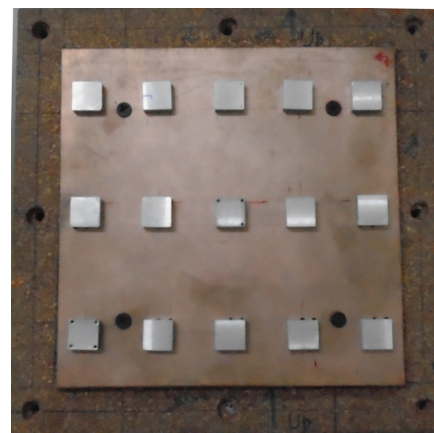
to the DC supply. The heat input of 7.8, 15.7, and 23.6 W are given to ensure the constant heat flux of 1000, 2000, and 3000 W/m<sup>2</sup>. Four K type (chromel-alumel) thermocouples are connected to the corners of each heat source. The thermocouples are attached to multiplexer and datalogger and then connected to the desktop PC to measure temperatures of individual heat source after reaching the steady state condition. The photographs of substrate boards equipped with heaters are as shown in Fig. 2.



(a) FR4



(b) Bakelite



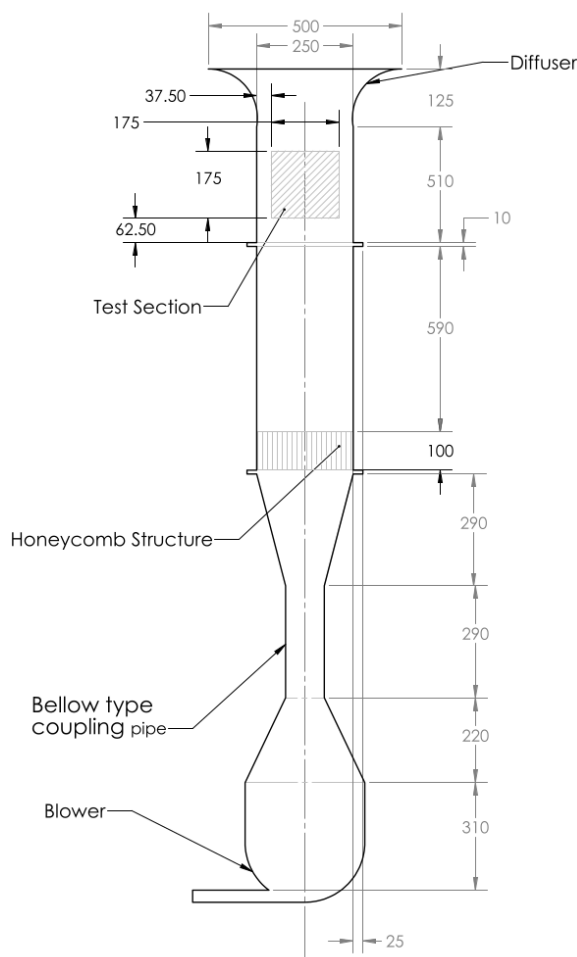
(c) Single sided CCB

Fig. 2 Photographs of substrate boards equipped with heaters Durgam *et al.* (2020b)

The heaters are mounted on pieces and then inserted in the substrate slots of bakelite. Whereas heaters are directly equipped on the FR4 and copper clad substrate boards and then fixed to the cork board before mounting the set up on the front wall of channel. The air will be blown off parallel to the substrate board at different velocities of 0.6, 1, and 1.4 m/s for cooling of heaters under laminar forced convection. The inlet air velocity is measured by digital anemometer mounted perpendicular to the direction of air flow.

### 3. EXPERIMENTATION

The schematic diagram of vertical channel test facility is depicted in Fig. 3. The total height of the vertical channel is 2345 mm. It is divided into three sub parts such as bottom section (1110 mm) where the blower and the bellow type coupling pipe exists. The middle part (600 mm) where the honeycomb structure is provided to ensure the uniform air distribution. The upper part (635 mm) where the test section and the diffuser are fixed. The substrate board equipped with the heat sources (test section) in each configuration is screwed to the cork board and fixed on the front walls of the channel. The dry air from the compressor is blown off parallel to the substrate board with a specified velocities for cooling. Air velocity is measured by digital anemometer. The temperature of each heat source is recorded from the desktop PC after the steady state condition is achieved. The back side of the cork board is covered with an insulating material to prevent the heat loss.



**Fig. 3** Schematic diagram of experimental set up (All dimensions are in mm)

The forced convection experiments are conducted using three sub-

strates FR4, bakelite, and CCBSL at constant heat fluxes of 1000, 2000, 3000 W/m<sup>2</sup>, and 500 ≤ Re ≤ 1500. A total of 27 number of experiments are performed for three substrates, three heat fluxes, and three Re (i.e., 3 k × 3 q × 3 Re).

#### 3.1. Estimation of Error

To ensure the accuracy and reliability of experimental results the uncertainty analysis is performed. Table 1 show the uncertainty in the measured primary physical quantities. The error propagation is performed using Eq. 1 following Venkateshan (2015).

$$\Delta\sigma = \pm \left[ \sum_{i=1}^n \left( \frac{\partial\sigma}{\partial x_i} \times \Delta x_i \right)^2 \right]^{\frac{1}{2}} \quad (1)$$

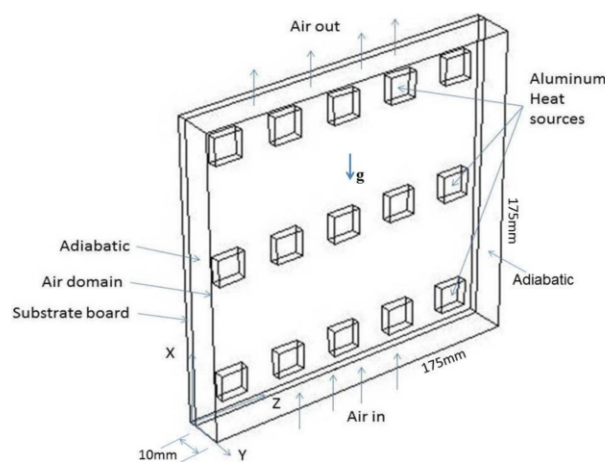
where,  $\sigma$  = derived quantity,  
 $x$  = measured quantity,  
 $\Delta x$  = error in measured quantity.

**Table 1** Error analysis of quantities

Error in the measured quantities		
No.	Measured quantity	± Error
1	Current	0.01 A
2	Voltage	1 V
3	Temperature	0.2 °C
4	Velocity	0.01 m/s
Error in derived quantities		
5	Input power	5.1%
6	Heat tr. coeffi.	4.8%
7	Nu	5.5%

### 4. MODELING AND SIMULATION

Fig. 4 Shows a 3-D physical model comprised of substrate board, heaters, air domain with air inlet and outlet. The lateral, bottom, and top boundaries of channel and edges of substrate are adiabatic. The position of xyz co-ordinate axes is as shown in the physical model.



**Fig. 4** A physical model Durgam et al. (2020b)

A total of 36 number of forced convection simulations are performed for four different substrate material viz. FR4, bakelite, CCBSL and CCBML (40 W/m K) with same heat fluxes, and Re as used in experiments (4 k × 3 q × 3 Re = 36 cases). The multiphysics used for this study is heat

transfer from solids and fluid, laminar. The air layer thickness above the substrate is 10 mm. Convection air cooling of a substrate with heated elements is modelled using software resembling cooling of electronic components [Comsol \(2009\)](#). For achieving better accuracy of simulations heat transfer and fluid flow module is used [Patankar \(1980\)](#). The detailed procedure and assumptions of modeling and simulation is described in [Durgam et al. \(2017\)](#) was followed. Eq. 2 - 6 show the governing equations i.e. transport, momentum and heat equations.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (2)$$

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{\mu}{\rho} \left[ \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right] \quad (3)$$

$$u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \frac{\mu}{\rho} \left[ \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right] \quad (4)$$

$$u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial z} + \frac{\mu}{\rho} \left[ \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right] \quad (5)$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} = \alpha \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right] \quad (6)$$

The forced convection boundary conditions are

at  $X = 0, T = T_{\infty}$  and  $u = 0.6, 1.0, 1.4$  m/s

at  $X = L, p = p_{\infty}$  (atm. pressure)

The calculation of CCB effective thermal conductivity is calculated using Eq. 7 taken from [Durgam et al. \(2018\)](#).

$$k_{eff} = \frac{(kt)_{FR4} + (kt)_{copper}}{t_{FR4} + t_{copper}} \quad (7)$$

The thermophysical properties of materials are shown in Table 2.

**Table 2** Properties of materials [Durgam et al. \(2019\)](#)

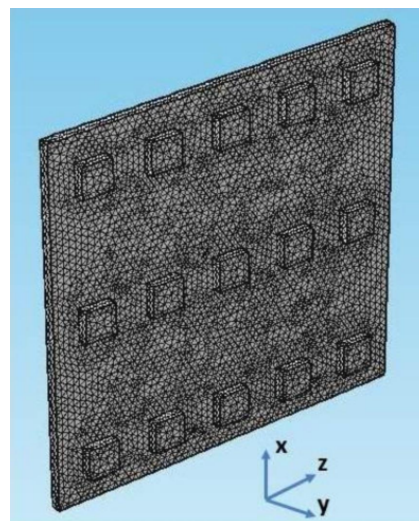
Material	k (W/m K)	$\rho$ (kg/m <sup>3</sup> )	$C_p$ (J/kg K)
Al	170	2710	910
FR4	0.4	1940	1380
Bakelite	1.4	1320	1460
CCBSL	8.8	2040	1320
CCBML	40	2580	570

CCBSL means single layer copper clad board

CCBML means multi-layer copper clad board

#### 4.1. Grid Responsive Study

The mesh used to simulate forced convection problems is calibrated for general physics. The computer generated free tetrahedral extremely fine 114326 grids are used for simulation study. The mesh consists of the domain, boundary, and edge elements of 105297, 24530, and 1300, respectively. A typical grid pattern used for this study by hiding air domain is shown in Figure 5. The convergence time for each simulation is about 2 to 3 hours. The relative tolerance is the convergence criteria value in COMSOL. This study used the default value of 0.01 to solve multiple equations.



**Fig. 5** A typical grid pattern used for solids

The grid responsive study at  $q = 1500$  W/m<sup>2</sup>,  $T_{\infty} = 30$  °C are given in Table 3.

**Table 3** Grid responsive study for bakelite

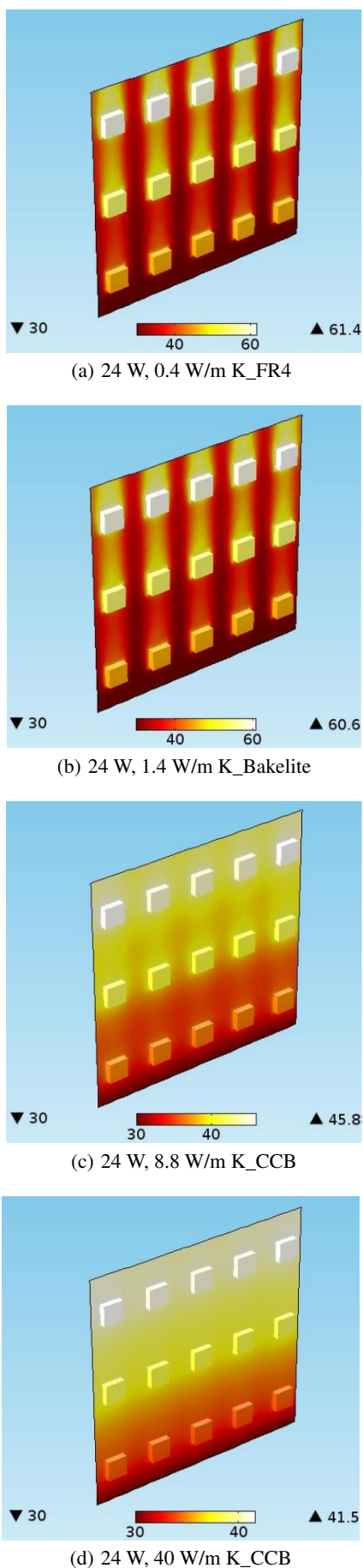
Number of grids	T °C	% $\Delta$ T
102026	54.9	-
105265	54.7	0.36
108787	54.3	0.73
114326	54.8	0.91
117656	54.5	0.55
126838	54.6	0.18
131163	55.2	1.08

## 5. RESULTS AND DISCUSSION

3-D, steady state, laminar forced convection simulation results generated by software of representative cases for heat source temperature, air velocity, surface temperature, and temperature contours of each material considering substrate conduction are presented.

### 5.1. Simulation Results: Forced Convection

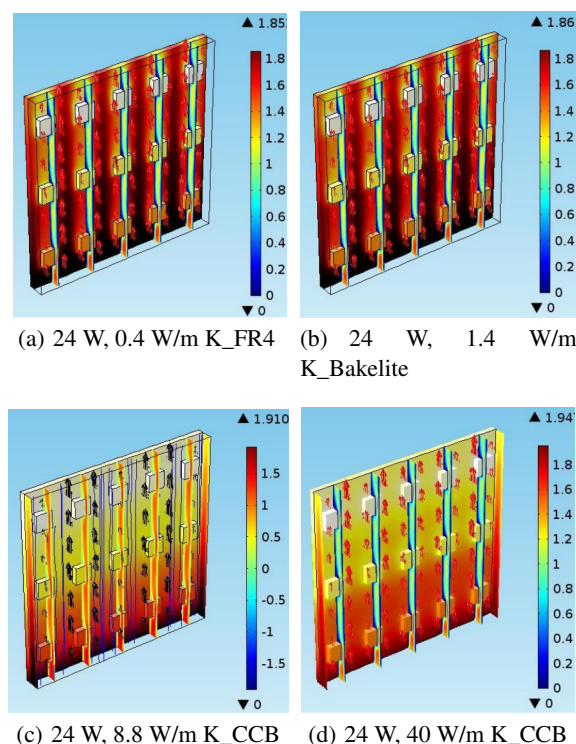
Fig. 6 shows the computer generated temperature plots for FR4, bakelite, CCBSL, CCBML for air inlet velocity of 1.4 m/s, and heat input of 23.6 W. These plots clearly reveal the effects of substrate conductance on cooling. The excess temperature of FR4 is 31.4 °C and for bakelite it is 30.6 °C respectively. There is not much temperature difference between these two low thermal conductivity substrate materials. It is to be noted that for a given air velocity and heat input temperature excess of both these substrate materials are within the specified limit of optimal working temperature for any electronic equipment rejecting heat of 10 - 25 W. In case of CCBSL the temperature excess is 15.8 °C and for CCBML it is 11.5 °C, both exhibits uniform temperature distribution. But temperature excess in both CCBSL and CCBML are very much less than the ambient and the specified optimal temperature limit of electronic components. It should be noted that, both single and multilayer CCB are suitable for little higher range than that of 25 W, considered in this study. It is observed that using CCBML there is an increase of 8.73% in heat transfer rate. But the CCBML is complicated in design and fabrication and is very costlier compared with CCBSL.



**Fig. 6** Forced convection temperature plots for FR4, bakelite, single and multi layer CCB at  $Re = 1312.5$ ,  $q = 3000 \text{ W/m}^2$

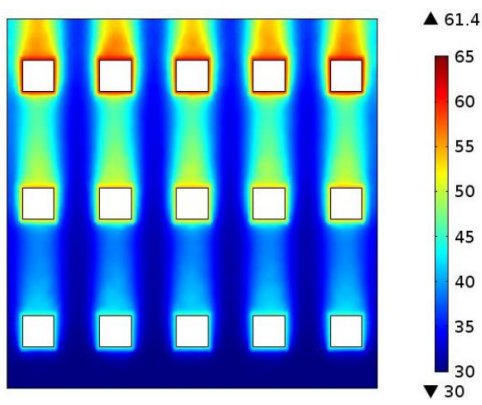
CCBSL is capable of dissipating heat input of 25 W, simple in design, fabrication, and easy to maintain and its cost is very low compared with CCBML. The temperature excess is also very much less than the ambient and specified limit of any electronic component. Hence CCBSL is preferred substrate material than CCBML for electronic equipment dissipating heat of about 25 W, for a given air flow.

Fig. 7 show the velocity plots for different substrates at  $Re = 1310$  and  $q = 3000 \text{ W/m}^2$ . The results show that for same inlet air velocity and heat input using different substrate boards materials, velocity at the exit of vertical channel is different. For FR4 and bakelite the exit velocity is 1.85 and 1.86 m/s. The difference is very low, as the difference in their thermal conductivity is very low. But exit velocity of single layer and multi layer CCB is 1.91 and 1.94 m/s respectively. It indicates that higher substrate conductance results in higher air flow velocity at the exit and that gives lower temperature excess as expected. The arrow volume shows the air flow direction. The blue lines indicate the streamlines in plot (c). The velocity at the solid and fluid interfaces is zero. The arrow volumes are shown in Fig. 7 (a) - (d) along the air flow direction.

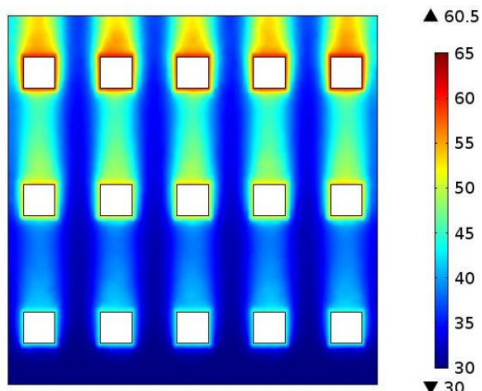


**Fig. 7** Forced convection velocity plots,  $Re = 1310$ ,  $q = 3000 \text{ W/m}^2$

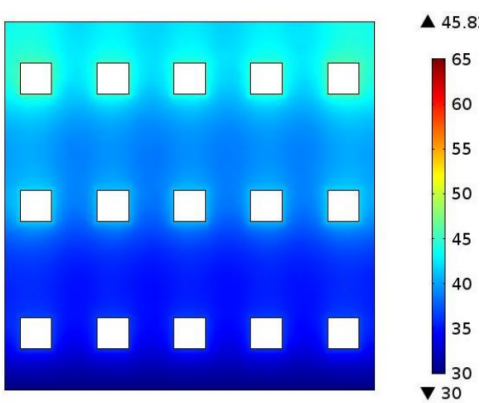
Substrate board temperature plots of FR4, bakelite, single and multi-layer CCB at  $Re = 1310$  and  $q = 3000 \text{ W/m}^2$  are given in Fig. 8. It shows that temperatures of heaters in the top row are highest, in general. The temperature in the bottom row are lowest. The FR4 and bakelite temperatures are greater compared with single and multi layer CCB. The hot spots in the upper row can be observed in case of FR4 and bakelite plot (a) and (b) respectively. Substrate board temperatures of single and multi layer CCB are lower therefore preferable over FR4 and bakelite. Very high temperatures of substrate boards results in malfunctioning of the electronic equipment and leads to frequent failure, damage or fire hazards.



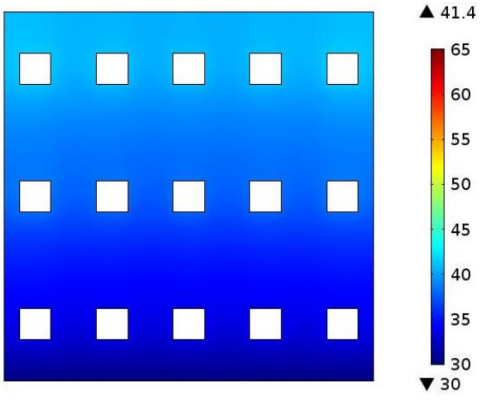
(a) 23.6 W, 0.4 W/m K\_FR4



(b) 23.6 W, 1.4 W/m K\_Bakelite



(c) 23.6 W, 8.8 W/m K\_CCB

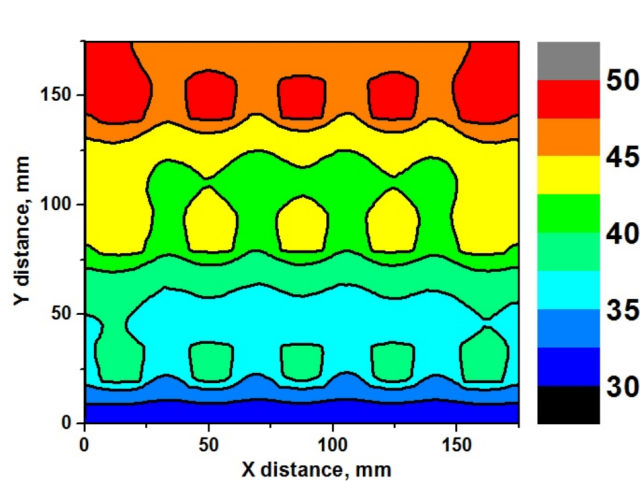


(d) 23.6 W, 40 W/m K\_CCB

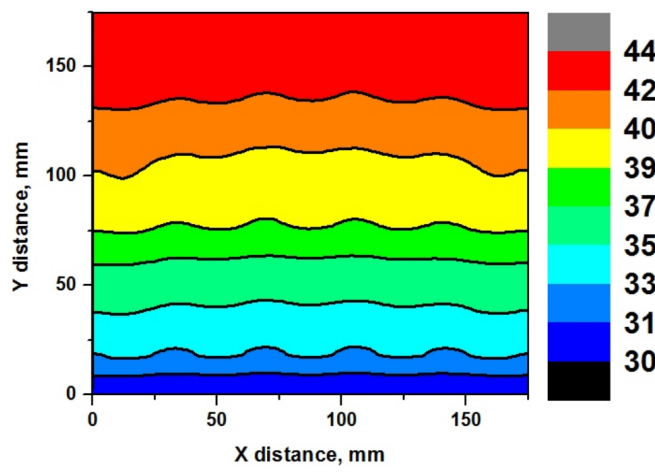
**Fig. 8** Forced convection surface temperature plots for FR4, bakelite, single and multi layer CCB at  $Re = 1312.5$ ,  $q = 3000 \text{ W/m}^2$

Hence the design and selection of suitable substrate board material is very important for safe and reliable performance of any electronic equipment. Temperature distribution for CCB is uniform. Hence there are no hotspots observed in CCB.

Fig. 9 show the forced convection temperature contour plots for CCBs at  $Re = 940$  and  $q = 3000 \text{ W/m}^2$ . The excess temperature occurred in single layer CCB is  $20^\circ\text{C}$  and that in multilayer CCB is  $14^\circ\text{C}$ . Though the heat input, and inlet velocity are same but both single and multilayer CCBs exhibits different heat transfer characteristics. It is because of the difference in thermal conductivity. Higher thermal conductivity substrate material results in more uniform heat distribution and vice versa. It is also noticed that for the maximum  $q = 3000 \text{ W/m}^2$  value single and multilayer CCB exhibits low temperature excess. It means that these substrates can be preferred for high heat flux.



(a) 23.6 W\_single layer CCB



(b) 23.6 W\_multi layer CCB

**Fig. 9** Temperature contour plots for single and multilayer at 1 m/s, 23.6 W

The black lines in plots of Fig. 9 (a) for CCBSL and plot (b) of CCBML indicates the temperature contours. It gives the magnitude of temperatures at various locations from the bottom of substrate board in the direction of air flow. For CCBSL and CCBML the maximum temperature excess obtained in the top row heaters are  $20.6$  and  $14.5^\circ\text{C}$  respectively. The maximum temperatures are occurring far from the bottom of substrate board. It is seen that the uppermost heaters exhibit maximum temperatures. It is due to fact that the inlet air at the entry is at ambient temperature, though all fifteen heaters are generating same heat, when at-

mospheric air enters at the bottom row it acquires some heat from them and become warmer. It moves up, as ambient air replace it and encounter heaters in the middle row, where the already warmer air acquires some heat from them and thus becomes hot. When it moves to the heaters in the uppermost row it has little tendency to extract heat from them. Hence these heaters experience higher temperature compared to heaters in the bottom and middle rows. The temperature contours shown in Fig. 9 (b) are based on simulation results. The excess temperature of single and multilayer CCB are 20 and 14 °C respectively. It is also noteworthy to see the gradual increment in temperature in the direction of air flow.

### 5.2. Substrate conduction effect on temperature

Fig. 10 and 11 shows the excess temperature of four substrates of different thermal conductance at  $q = 1000, 2000 \text{ W/m}^2$  and  $Re = 937$  to explore the conductance dependant temperature variation. It is indicated that the temperature of heaters on FR4 to CCBML decrease with increasing conductance. The temperature of FR4 and bakelite show very little difference. But there is significant decrease in temperatures of heaters in CCBs. The plots also show noticeable temperature difference in CCBs due to a large difference in conductance.

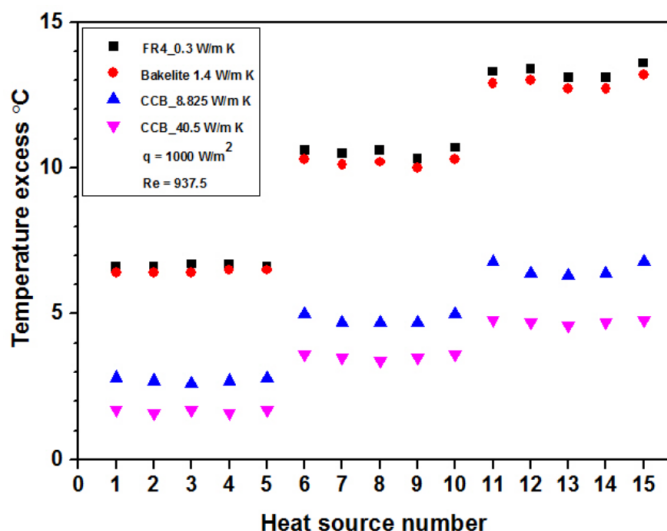


Fig. 10 Temperature excess vs. heat source number plots for 7.8 W

Fig 11 shows the distribution of temperature in fifteen heaters using all four substrate board materials for  $q = 2000 \text{ W/m}^2$  and  $Re = 937.5$ . The temperature variation using single and multi layer CCB was found to be about 3 - 4 °C. It is observed from this study that there is a reduction in temperature of about 10 °C in CCB compared with FR4 and bakelite. It indicates that increase in conductance of the substrate board results in decrease in temperature in each heat source as well as on the substrate. The maximum temperature was found in heaters located at the uppermost row. The temperature in all five heaters in a particular row are almost same. The temperature in heaters located near the bottom has lower temperatures and that in the upper row has maximum. The heaters in the central row have temperature value in between lower and upper row. Similar trend was observed in Fig 11 except the temperature excesses are high compared with that of Fig 10 and it is because of the higher heat inputs. The difference in excess temperature observed in CCBs was about 2 - 3 °C. Hence considering its low initial and maintenance cost single layer CCB can be preferred over its multilayer counterpart.

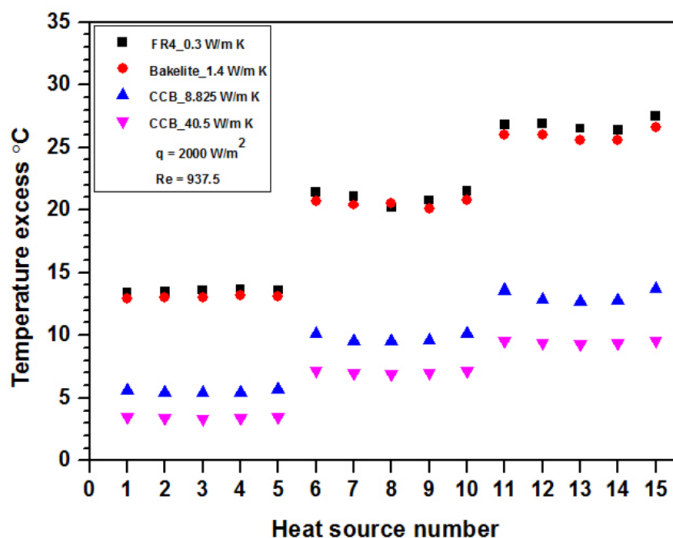


Fig. 11 Variation of temperature excess with each heat source at  $q = 2000 \text{ W/m}^2$

### 5.3. Substrate Conductance Effect on Heat Transfer Coefficient

Fig. 12 show the substrate conductance effect on heat transfer coefficient (htc) at  $q = 2000 \text{ W/m}^2$  and  $Re = 937.5$ . It is found that for CCBML the heaters in the first row have maximum heat transfer coefficient of 600  $\text{W/m}^2 \text{ K}$ . The minimum value of htc found in heaters in top row was 50  $\text{W/m}^2 \text{ K}$  associated with FR4 and bakelite. There is not any significant difference of htc in FR4 and bakelite.

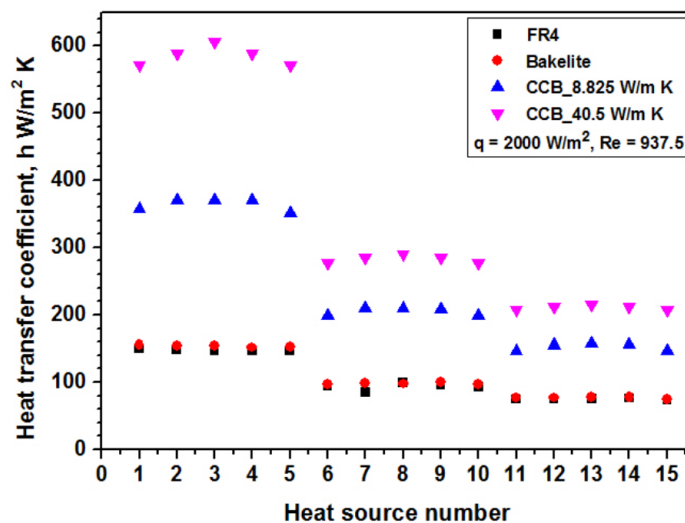


Fig. 12 Variation of heat transfer coefficient with each heat source for different substrates at  $q = 2000 \text{ W/m}^2$  and  $Re = 937.5$

### 5.4. Variation of Nusselt Number with Substrate Conductance

Fig. 13 describes variation of Nusselt number (Nu) with H. S. No. plot for all four substrates at  $q = 2000 \text{ W/m}^2$  and  $Re = 937.6$ . It is observed that Nu is maximum for CCBML compared to FR4 and bakelite and CCBML. The Nu for FR4 is the lowest but very close to that of bakelite. The

maximum value of Nu in all substrates is in row 1 (H. S. No. 1 - 5), moderate in row 2 (H. S. No. 6 - 10) and lower in row 3 (H. S. No. 11 - 15). Also, the difference in Nu in first five heaters is larger in CCBSL and CCBML, But in FR4 and bakelite Nu is almost same. It is an indication of high heat transfer rate with high conductive substrates.

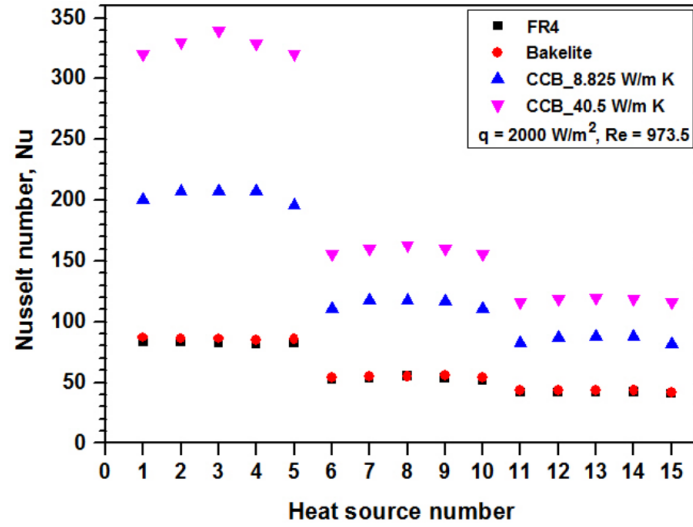
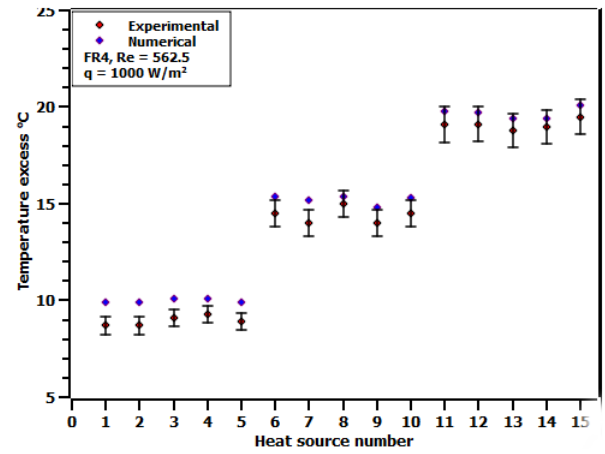


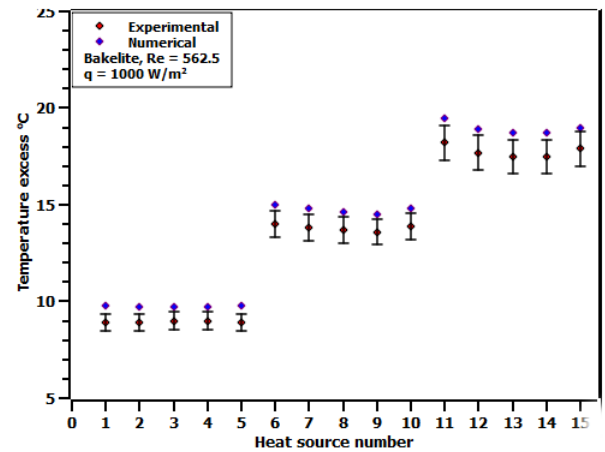
Fig. 13 Variation of Nusselt number with each heat source for different substrates at  $q = 2000 \text{ W/m}^2$  and  $Re = 973.5$

### 6. COMPARISON OF EXPERIMENTS WITH SIMULATION

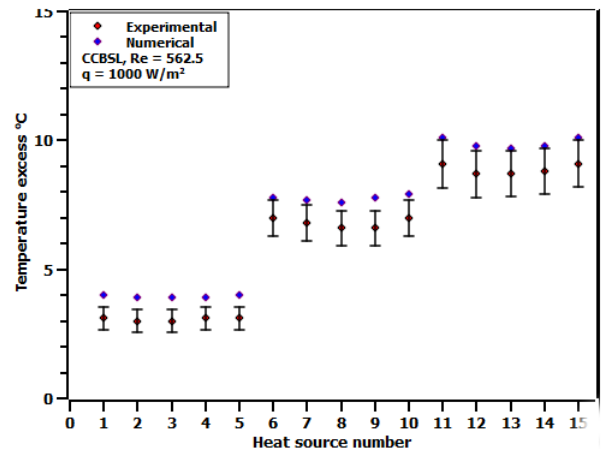
Force convection experimental and simulation results are compared here. Fig. 14 shows the variation of excess temperature with H. S. No. plots for FR4, bakelite, and CCBSL at  $q = 1000 \text{ W/m}^2$  and  $Re = 562.5$ . Excess temperatures are lowest for row 1 (H. S. No. 1 - 5), it gradually increases in row 2 (H. S. No. 6 - 10) and then reaches to the maximum in row 3 (H. S. No. 11 - 15) the top position. This trend is observed in all three kinds of substrate board materials. The heaters mounted at top row results in maximum temperature compared with the heaters in middle and bottom row. All the heaters are supplied with the same heat input and the sizes of all heaters are same, but the maximum temperature occur at heaters placed at top extreme right corner and the lowest temperature occur in the heaters placed near the bottom as they encounters colder ambient air. It is evident from the Fig 14 (a) and (b) for FR4 and bakelite that, the difference in temperature excess is merely  $1^\circ\text{C}$  as the difference in their thermal conductivities is small. Whereas there is about  $10^\circ\text{C}$  difference in Fig 14 (c) compared with Fig 14 (a) and (b). Fig 14 (c) is the plot for CCBSL of effective thermal conductance  $8.8 \text{ W/m K}$  that is much higher compared with that of other two substrates. The maximum excess temperature found in CCBSL is below  $10^\circ\text{C}$ . It indicates that the substrate board conductance plays a major role in the convection cooling of heaters. Compared to the numerical value of excess temperature of CCBML and CCBSL the difference is only  $3.4^\circ\text{C}$ .



(a)  $Re = 562.5, P = 7.875 \text{ W\_FR4}$



(b)  $Re = 562.5, P = 7.875 \text{ W\_Bakelite}$



(c)  $Re = 562.5, P = 7.875 \text{ W\_single layer CCB}$

Fig. 14 Comparison plots for FR4, bakelite, and CCBSL

This difference in temperature does not affect the performance of electronic device as the temperature excess available at CCBSL is already very much smaller than the normal ambient temperature. The CCBML is very expensive compared to CCBSL. The CCBSL can maintain a safe temperature range that is crucial for the safety, longevity, and effectiveness of electronic equipment in the working range of 10 - 25 W. Therefore, CCBSL is suitable over CCBML for moderate heat input range.



## 7. CONCLUSIONS

From the study of effect of substrate conductance on heat transfer following are the conclusions:

1. Forced convection for heat dissipation of 7.875, 15.8 and 23.6 using velocities of 0.6, 1.0 and 1.4 shown that FR4 and bakelite are good for all heat input and velocity combinations except with velocity of 0.6 m/s and heat input of 23.6 W. At higher air flow velocities of 1.0 and 1.4 m/s with all heat inputs both the materials perform better as it results in temperatures well below the operating temperatures limit for the electronic components rejecting heat of 5 to 25 W.
2. CCBSL and CCBML are not only suitable for dissipating heat of 25 W but considering all the heat input, velocity combination used in the study it can be preferred for high heat as the temperature occurred in both the materials are very low compared with the optimal operating temperature limits of electronic components.
3. Considering the cost of CCBSL and CCBML and the results obtained from the study it reveals that CCBSL is suitable for dissipating heat up to 25 W for all heat input and velocity combinations. Hence CCBSL is preferred over CCBML as it is less costly. But for higher rate of heat rejection a trade-off between cost and performance may be considered.
4. The results give some important guidelines to the electronic industry for heat input and velocity combinations to maintain operating temperature in safe limits for reliable performance of electronic components.
5. This study is limited to the heat rejection of 10 to 25 W only. For higher heat rejection multiple PCBs can be used in a stack.

## ACKNOWLEDGEMENTS

The author acknowledge the discussions with Professor S. P. Venkateshan and Professor T. Sundararajan on Air Cooling of Electronics.

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