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Research Paper

A novel concept of discrete heat source array with dummy components cooled by forced convection in a vertical channel

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HIGHLIGHTS

- A novel concept of discrete heat sources with dummy components on substrate boards is presented.
- Experiments are conducted to investigate the heat transfer behavior.
- Full three-dimensional simulations done with COMSOL Multiphysics 4.3b to study heat and fluid flow behavior.
- Single sided copper clad board is less expensive and gives significant heat dissipation.
- Seven heat sources with four dummy components configuration results in maximum heat dissipation.

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ABSTRACT

This paper investigates the use of dummy components along with heat sources on a substrate board. Three-dimensional steady state laminar forced convection cooling of a discrete heat source array in a vertical channel is studied numerically and experimentally. The main objective of this study is to find the optimal distribution of seven heat sources with dummy components to minimize the substrate temperature. Air cooling of circuit boards populated with heat sources is modeled and simulated to present heat transport in combination with the fluid flow. This work also aims to study the effect of substrate thermal conductivity on fluid flow and heat transfer characteristics by using substrate boards of different thermal conductivities. The experiments are performed without dummy components and with 2, 4, 6, 8 dummy components at three different air velocities of 0.6, 1.0, 1.4 m/s. A correlation for θ in terms of *Re*, and k^* is obtained.

1. Introduction

Placing dummy heat sources on printed circuit board (PCB) along with heat generating sources is a unique innovative concept in electronic thermal control techniques. Printed circuit board is the heart of almost all electronic devices. Design of PCB must be adequate for safe and reliable operation as well as increase in life of electronic device. Hence it is very important to design PCB with great care to improve the reliability and the life of electronic device. One of the excellent work in this area is by Mohamed [1]. The author experimentally investigated heat transfer rate from 9, 16, 25, 36 aluminum square module array with air velocities of 3.24–6.84 m/s in a rectangular channel. The results indicated that the average heat transfer coefficient was significantly higher with increasing the flowing air velocities. Several authors [2–11] numerically investigated natural, mixed or forced convection cooling of discrete heat sources with different geometries and obtained correlations. Numerical investigations have appeared in [12,13] that show heat transfer enhancement from multiple discrete heat sources using metal foam porous layers. Bhowmik et al. [14] conducted experiments under laminar natural, mixed and forced convection heat transfer from chips in a vertical channel using water. They obtained correlations for Nu, Re and Gr, based on channel hydraulic diameter and indicated that the heat transfer coefficient is strongly affected by Reynolds number. Zhang et al. [15] investigated experimentally natural convection cooled small heat source in a large rectangular cavity and measured temperature. Authors showed that the temperature gradient and the fluctuation are extremely large in the near wall regions of both the hot and cold

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Nomenclature

A	area of heat source, m^2
atm	atmospheric
B	width of the heat source, mm
CCB	copper clad board
D	depth of the heat source, mm
*D*1 *to D*8	dummy heat components from number 1 to 8
g	acceleration due to gravity, 9.81 m/s^2
h	heat transfer coefficient, W/m^2 K in Eq. (1)
H	height of the channel, height of heat source, mm
ICs	integrated circuits
k	thermal conductivity, W/m K
k_b	thermal conductivity of substrate board, W/m K
k_f	thermal conductivity of air, W/m K
k_s	thermal conductivity of solids, W/m K
k^*	non-dimensional thermal conductivity, $\frac{k_b}{k_f}$
L_h	length of the heat source, mm
Nu	Nusselt number defined in Eq. (3)
p	pressure, Pa
PCB	printed circuit board
q	heat flux, W/m^2
Re	Reynolds number based on hydraulic diameter in Eqs. (2) and (11)
t_{FR4}	thickness of the FR4 layer, mm
t_{cu}	thickness of the copper layer, mm
T	temperature, °C
$T_{excess,max}$	maximum excess temperature, °C
$T_{excess,min}$	minimum excess temperature, °C
T_h	heat source surface temperature, K
U	inlet air velocity, m/s
u, v, w	velocities in x, y, z directions, m/s
x, y, z	cartesian coordinates

Greek letters

α	thermal diffusivity of air, m^2/s
β	coefficient of thermal expansion, 1/K
ΔT	temperature excess with respect to inlet temperature of air, $(T - T_\infty),^\circ C$
ΔT_{ref}	reference temperature difference, $\frac{Q_{supply}L_h}{Ak_b},^\circ C$
λ	non dimensional geometric parameter
μ	dynamic viscosity of air, kg/m s
ν	kinematic viscosity of air, m^2/s
ρ	density of air, kg/m^3
θ	non-dimensional temperature of the heat source, $(T - T_\infty)/(T_{max} - T_\infty)$ in Eq. (11)

Subscripts and superscripts

eff	effective
f	fluid
∞	ambient/inlet
max	maximum value among the heat sources
min	minimum value among the heat sources

plates. McEntire and Webb [16] performed experiments to measure the local convective heat transfer from a heat source array for different air flow rates and found that the protruding heat sources yield higher heat transfer rates than flush mounted heat sources. Sudhakar et al. [17] conducted experiments and numerical study to validate laminar natural convection conjugate heat transfer from five identical heat sources and the temperatures of heat sources arranged in the optimal configuration. Sugavanam et al. [18] investigated heat transfer from a flush heat source on a conductive board in laminar channel flow and found that the temperature for a thicker board was much lower than that for a thinner board. Hotta et al. [19] performed experiments to study optimal distribution of five discrete heat sources under mixed convection employing non-dimensional geometric parameter λ which is identified to be the key parameter to decide the maximum temperature in the system.

The above references show that much work has been done in the area of air cooling of electronic components mounted on a substrate board. In spite of that still vivid description dealing with substrate conduction is rarely reported. Although there has been considerable work on convection air cooling of discrete heat sources available in the literature, forced convection air cooling considering the effects of substrate board thermal conductivity has received little attention. Combined experimental and numerical investigation on optimal distribution of heat sources are rarely reported. It is seen that much of the literature based on natural and mixed convection air cooling of discrete heat sources are available, whereas forced convection cooling of discrete heat sources is scarce. To the best of our knowledge this paper is the first attempt to explore the effects of fluid flow and heat transfer characteristics under forced convection air cooling of heat sources along with dummy components in optimal placement. Therefore, the main objectives of this work is to design the substrate board mounted with heat sources and dummy components in optimal placement that resembles printed circuit board of electronic package to control the temperature at the trailing edge of the substrate by increasing the heat transfer coefficient. Furthermore, to investigate the effect of substrate board thermal conductivity on heat transfer experimentally and numerically, and to present the correlation based on the parameters responsible for the enhanced heat transfer process to propose a cost effective technique that is very important in design of printed circuit boards. Study with dummy heat sources has excellent effect on heat transfer performance that involves minimal extra cost. It is not currently being used in thermal control of electronic devices. This concept ensures that in case of failure of some heat generating sources, these can act as dummy heat sources, contribute in heat dissipation and avoid replacement hence save cost of PCB and increase life of electronic device. This work is extension of Durgam et al.[20], in which a concept of dummy components was reported for six and eight dummies mounted on substrates, results show that six dummy case was better compared with no dummy and eight dummy cases. The present study investigates globally the flow and heat transfer effects for 0, 2, 4, 6, and 8 dummy components mounted on substrates of different thermal conductivities.

2. Configurations used in the present study

The computation of non-dimensional geometric distance parameter λ, can be viewed in Durgam et al. [21]. The procedure as given in literature [19,22,23] is used for the purpose of identifying the optimal configuration among all possible configurations of heat sources. The optimal configuration that gives minimum temperature excess using seven discrete heat sources obtained from the experimental and numerical investigations is considered in the present study and the details of parameters involved in the definition are given in Durgam et al. [21]. This optimal configuration involving seven heat sources (1 to 7), λ = 1.3 is referred as no dummy here. The typical optimal configuration with λ = 1.3 and four other optimal configurations with 2, 4, 6, 8 dummy components are found from numerical study of twenty-four configurations. In each case of no dummy, 2, 4, 6, 8 dummy components,