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Parametric Studies on Combined Conduction-Convection-Radiation from a Discretely and Non-Identically Heated Rectangular Electronic Board

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Abstract

This paper reports the numerical results of the problem of combined conduction-convection-radiation from a discretely and non-identically heated rectangular electronic board. Three discrete heat sources with identical rate of volumetric heat generation are embedded centrally and axially along the board in the descending order of their size starting from the bottom to the top end of the board. Air is considered to be the cooling medium and it is assumed to be radiatively transparent. The governing equations for temperature distribution within the board are obtained by appropriate energy balance between heat generated, conducted, convected and radiated. The resulting non-linear partial differential equations are converted into algebraic form using finite volume method and are subsequently solved by Gauss-Seidel iterative method. An exclusive computer code is written in C++ to solve the problem and exhaustive parametric studies are performed bringing out the contributory effects of thermal conductivity, convection heat transfer coefficient and surface emissivity on local board temperature distribution, peak board temperature and convective and radiative components of board heat dissipation. The prominence radiation assures in the thermal design of the electronic device has been adequately highlighted.

Keywords: Conduction, Convection, Radiation, Interplay, Rectangular electronic board, Discrete heat sources

Introduction

Literature on multi-mode heat transfer contains several analytical, numerical and experimental studies involving interplay between conduction, convection and radiation from different kinds of geometries with various complexities. Zinnes [1] is one of the initial researchers, who provided analytical and numerical results of the problem of multi-mode heat transfer from a vertical plate with arbitrary surface heating over it. Afterwards, several other researchers produced their results on problems of this kind. Specifically, if one looks into the last few decades, Anand et al. [2] studied, numerically, the effect of wall conduction on free convection between asymmetrically heated vertical plates for the case of uniform wall temperature. Cole [3] presented the results of the problem of conjugate heat transfer from a small heated strip. Gururaja Rao et al. [4] presented results of conjugate mixed convection with radiation from a vertical plate equipped with a discrete heat source. Kanna and Das [5] provided an analytical solution for conjugate forced convection heat transfer from a flat plate exposed to a laminar jet flow making use of the boundary layer theory. Gururaja Rao [6] solved, numerically, the problem of combined conduction-convection-radiation in a vertical channel with multiple discrete heat sources in the left wall. Very recently, Shah et al. [7] tackled the problem of conjugate convection with surface radiation from a square-shaped electronic device with multiple identical discrete heat sources.

A review of the literature concerning multi-mode heat transfer from different geometries typically encountered in electronic cooling applications suggests that detailed simulation studies on a discretely heated rectangular electronic board with multiple and non-identical embedded heat sources are not adequately explored. In view of this, the present paper takes up a detailed numerical investigation into interaction of combined conduction-convection-radiation from a discretely and non-identically heated rectangular electronic board.

Description and Formulation of the Problem

Figure 1 shows the schematic of the problem geometry considered in the present study. It consists of a vertical rectangular electronic board of height L and width W provided with three non-identical discrete heat sources embedded in it. The heat sources are located centrally and axially in the descending order of their dimensions with the largest ($L_{h1} \times L_{h1}$) and the smallest ($L_{h3} \times L_{h3}$) located at the bottom and the top ends of the board. The heat source of medium dimension ($L_{h2} \times L_{h2}$) is at the geometric centre of the board. The thermal conductivity of the board material is k, the rate of volumetric heat generation in each of the heat sources is q_v, the surface emissivity of the board is ε and the convection heat transfer coefficient is h. The cooling medium is air at a characteristic temperature T_∞ and assumed to be radiatively transparent. The heat generated in the three heat sources is conducted both axially and transversely in the board and is subsequently foregone by the board by combined modes of convection and radiation.

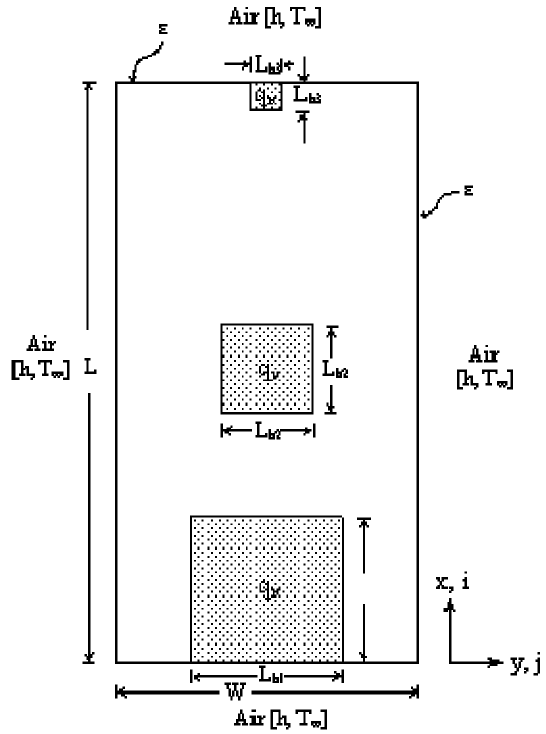

Fig. 1 Schematic of the problem chosen for study along with the system of co-ordinates.

The governing equations for temperature distribution in the entire computational domain are obtained upon performing energy balance between the heat generated, conducted, convected and radiated. For example, the governing equation for temperature distribution in each of the three heat sources is the two-dimensional Poisson's equation given by

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{q_v}{k} = 0 \qquad (1)$$

The interior portions of the non-heat source portions of the electronic board satisfy the two-dimensional Laplace's equation. The interior elements of the board at the interface between the heat source and the non-heat source portions have their governing equations appropriately modified. With regard to the temperature distribution along the boundaries of the computational domain, for example, performing energy balance on a typical element along the top boundary (other than corners), in particular, belonging to the heat source region, one gets:

$$q_{cond,y,in} + q_{cond,x,in} + q_{gen} = q_{cond,y,out} + q_{conv} + q_{rad} \qquad (2)$$

Upon substituting the relevant expressions for various terms in the above equation and simplifying, the following non-linear partial differential equation would be obtained:

$$\frac{\partial^2 T}{\partial y^2} - \left(\frac{2}{\Delta x_1}\right)\frac{\partial T}{\partial x} + \frac{q_v}{2k} - \frac{2h}{k\Delta x_1}\left(T_{i,j} - T_\infty\right) - \frac{2\sigma\varepsilon}{k\Delta x_1}\left(T_{i,j}^4 - T_\infty^4\right) = 0 \quad (3)$$

Picking up a typical element along the left boundary of the electronic board (excluding corners) and making energy balance,

$$q_{conv} + q_{rad} + q_{cond,x,in} = q_{cond,x,out} + q_{cond,y,out} \quad (4)$$

Substitution of component expressions and subsequent simplification converts the above equation into:

$$\frac{\partial^2 T}{\partial x^2} + \left(\frac{2}{\Delta y_2}\right)\frac{\partial T}{\partial y} + \frac{2h}{k\Delta y_2}\left(T_\infty - T_{i,j}\right) + \frac{2\sigma\varepsilon}{k\Delta y_2}\left(T_\infty^4 - T_{i,j}^4\right) = 0 \quad (5)$$

A similar approach is used to handle the bottom boundary, right boundary and the corners of the computational domain as well.

Broad Solution Procedure and Parameters Employed

The governing equations for temperature distribution in the entire computational domain obtained as above are non-linear partial differential equations and thus are transformed into algebraic form using finite volume method with boundary conditions alone handled using finite difference method. The resulting algebraic equations are solved simultaneously using Gauss-Seidel iterative technique. Full relaxation (relaxation parameter = 1) is employed on temperature with a stringent convergence criterion (δ_c) equal to 10^{-8} used for terminating iterations. A computer code in C++ is specifically written to solve the problem. The dimensions of the rectangular electronic board, the bottommost, the central and the topmost discrete heat sources are: $L \times W$ = 20cm × 10cm, $L_{h1} \times L_{h1}$ = 5cm × 5cm, $L_{h2} \times L_{h2}$ = 3cm × 3cm and $L_{h3} \times L_{h3}$ = 1cm × 1cm, respectively. The cooling medium is air and its characteristic temperature (T_∞) is considered to be 25°C. The volumetric heat generation (q_v) is taken to be 5×10^4 W/m^3. The surface emissivity (ε) of the board is varied from 0.05 to 0.85, with the lower and upper limits indicating, respectively, good reflector (say highly polished aluminum) and good emitter (say black paint). The thermal conductivity (k) of the board is varied between 0.25 and 10 W/m K. The range of convection heat transfer coefficient (h) is considered to be 5 – 100 W/ m^2 K, with the lower and upper limiting values implying the asymptotic free and forced convection limits, respectively.

Parametric Studies and Inferences

Study of local temperature profiles in the electronic board with surface emissivity

Figure 2 is plotted to study the nature of variation of the local temperature distribution along the mid-planes of the electronic board in the x (vertical) direction, for three values of surface emissivity, viz., ε = 0.05, 0.45, and 0.85, and for a fixed input as indicated in figure. It can be seen that all the three local temperature profiles in each of the figures exhibit a similar pattern. From Fig. 2(a), it can be observed that each of the temperature profiles has three local peaks, one per heat source, with the maximum of the three peaks occurring in the bottommost heat source with the other two seen in the central and the topmost heat sources. Further, at any given location along the device, the temperature decreases with increasing surface emissivity of the device. In the present example, the maximum device temperature, there is a drop of 21.87% in T_{max} as ε increases from 0.05 to 0.85.

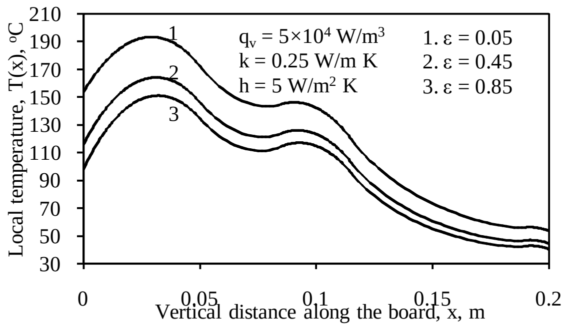

Fig. 2 Profiles of local temperature along the mid-plane of the electronic board in vertical direction for various coatings of the board.

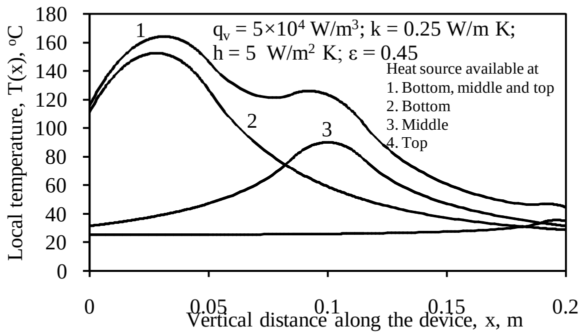

Fig. 3 Local temperature profiles along the mid-plane of the board in vertical direction plotted with various heat source configurations.

Study of local temperature profiles in board with various heat source configurations

In order to bring out the contrast between the local temperature profiles pertaining to the cases, viz., (1) all the three heat sources present, (2) the bottommost heat source alone present, (3) the central heat source alone present and (4) the topmost heat source alone present, Fig. 3 has been obtained. As can be seen, the profile pertaining to case (1) resembles what has been obtained in Fig. 2(a). The profile (2) corresponds to the case that has only the bottommost heat source in the board. Thus, the local peak temperature here, after reaching peak somewhere near to the top end, the temperature gradient diminishes quite considerably. Similarly, in cases (3) and (4), where only central heat source is present and the topmost heat source alone is present, respectively. It is further clear that the value of T_{max} with all the heat sources present is greater than any of the peaks noticed in cases (2), (3) and (4). This is attributed to the fact that the net rate of heat generation is the largest in case (1) and peters down progressively as one moves upto case (4).

Study of effect of convection heat transfer coefficient on maximum board temperature for various thermal conductivities of the board

The variation of maximum board temperature (T_{max}) with convection heat transfer coefficient (h) for different thermal conductivities (k) of the board is shown in Fig. 4. Seven values of h and three values of k are chosen for this study as depicted in the figure. For a given k, T_{max} decreases rather sharply as h increases from 5 to 25 W/m^2 K, while the decrease in T_{max} gets diminished towards larger values of h.

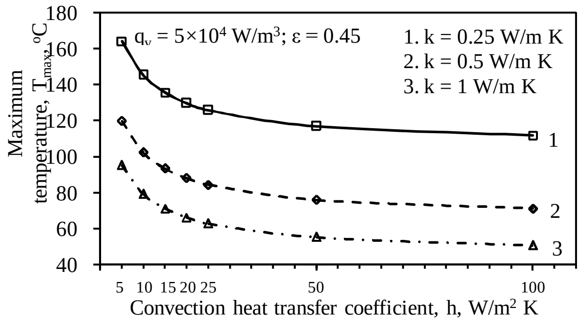

Fig. 4 Dependence of peak device temperature on convection heat transfer coefficient for various thermal conductivities.

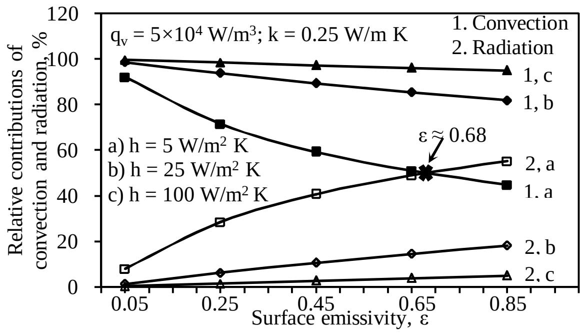

Fig. 5 Contributions of convection and radiation in board heat dissipation with its emissivity in different convection regimes.

The figure further shows that T_{max}, for a given h, decreases with increasing k. Here again the decrease is quite large between k = 0.25 and 0.5 W/m K, while a subsequent increase in k from 0.5 to 1 W/m K brings a lesser pronounced drop in T_{max}. In this example, for k = 0.25 W/m K, T_{max} decreases by 23.32% as h increases from 5 to 25 W/m^2 K. while T_{max} is decreasing by just 11.2% due to a further increase of h to 100 W/m^2 K. Likewise, for h = 5 W/m^2 K, for example, T_{max} is coming down by 27% as k increases from 0.25 to 0.5 W/m K. In contrast, the decrease in T_{max} is lesser between k = 0.5 and 1 W/m K and is by 20.52%.

Study of relative contributions of convection and radiation in heat dissipation from the board

A study bringing out the relative contributions of convection and radiation in net heat dissipation from the device is performed with the results shown in Fig. 5. The figure shows that the contribution of convection to total heat dissipation progressively decreases with increasing ε, while that of radiation exhibits a mirror image increase. As expected, convection plays a lead role in total heat dissipation, for all values of ε, in forced convection dominant regime with a meager role showing radiation. When once the flow regime transits to free convection, radiation starts showing an improved effect. With respect to the curve belonging to h = 5 W/m^2 K, the contribution of radiation increases from 7.89 to 55.2% as the surface coating of the board transforms from a good reflector (ε = 0.05) to a good emitter (ε = 0.85). The two curves belonging to convection and radiation, for h = 5 W/m^2 K, cross each other at ε ≈ 0.68, where convection and radiation take an identical share in total heat dissipation with radiation overriding thereafter. A similar trend, though not as pronounced as above, is observed in the roles played by convection and radiation even towards larger values of h. These results caution the designer not to overlook radiation in any regime of convection owing to the fact that it contributes about 5% to heat dissipation even for h = 100 W/m^2 K when the board is coated with black paint (ε = 0.85).

Concluding Remarks

The problem of effect of combined conduction-convection-radiation from a discretely and non-identically heated rectangular electronic board has been numerically solved. A computer code in C++ is explicitly written to meet the above job. The results have been initially tested for energy balance for certain typical sets of independent parameters. A detailed parametric investigation has been carried out to bring out the roles of thermal conductivity, convection heat transfer coefficient and surface emissivity in influencing various results concerning the problem. The results included the local temperature distribution, maximum board temperature and the relative contributions of convection and radiation. It has been identified from the studies that the effect of surface radiation in problems of this class cannot be overlooked in any regime of convection, more so if one is working in a free convection environment. The studies also revealed that effective control of heat dissipation, and thus the peak channel temperature, is possible by just changing the surface coating of the board from a poor emitter to a good emitter, even when one has no control over other parameters involved in the problem.

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