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Phi and Psi shaped conductive routes for improved cooling in a heat generating piece

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ABSTRACT

Because the cost and occupancy of high conductivity materials are the elements of major concern, searching for a better design of high conductivity pathways embedded into a heat generating body is a formidable challenge. The central goal of this paper is to show that the competition still continues. To accomplish this, two types of high conductivity pathways (inserts) with 'Phi' or 'Psi' shape are introduced. Although 'Phi' and 'Psi' shaped inserts are classified as 'tree' shaped configurations, the curled parts used in those configurations make them different with the tree-shaped configurations already mentioned in literature (such as T, H, I and X-shaped configurations). It is shown that the 'Phi' and 'Psi' configurations are superior in reducing the peak temperature of the piece. For example, numerical results show that, by utilizing the so-called configurations of conductive pathways, the maximum temperature can be reduced by 50% compared with an X-shaped pathway (the latest tree-shaped configuration introduced in literature), with the same amount of high conductivity materials.

1. Introduction

After remarkable technological progress, the technology of electronic cooling has been made on pushing the frontier. In this technology, the most formidable challenge is to keep the maximum temperatures of the heat generating body below an allowable level [1], owing that the performance of equipment has a direct relationship with its temperature. Since the frontier is being pushed in the direction of miniaturization and density integration of electronic devices, continuing works have been conducted in the related field. Among them, convective channels and conductive routes have attracted more attentions. However, according to Bejan [1], there comes a point where miniaturization makes convection cooling impractical, owing to the too much space occupied by ducts. Besides, providing the pumping power for the convective routes is a major concern and cooling fluid may have adverse impacts upon the performance of electronic devices. Knowing that conduction paths also take up space, effective conduction routes must be designed to be well suited for the miniaturization evolution.

Fortunately, Bejan in his valuable paper [1], sheds light toward the 'volume-to-point' flow problems. He considered a finite-size volume in which heat is generated at every point and which is cooled through a heat sink in the rim. The objective was to minimize the maximum temperature by determining the optimal distribution of high conductivity material when a limited amount of high conductivity material is available. On the basis of constructal law of design and evolution [2–4], he indicated that the solution to this problem is a 'tree', with far reaching implications in physics, mathematics and the natural evolution of living systems.

After Bejan's paper [1], many contributions as listed in Refs. [5–16] were defined relying on the achievements reported by Bejan [1]. For example, Almogbel and Bejan [5] proposed a non-uniformly distribution of high conductive material and achieved a remarkable improvement in the global performance. Optimal configurations of highly conductive materials at micro- and nano-scales were proposed by Gosselin and Bejan [10]. Discrete variable cross-section conducting paths of inserts were proposed by Wei et al. [12]. Most recently, Lorenzini et al. [15,16] have conducted a very valuable research on the optimization of conductive inserts. Instead of the previous patterns where a single path was inserted, they introduced uniform [15] and un-uniform [16] X-shaped pathways of higher thermal conductivity and proved that the studied shape is superior in minimizing the maximum temperature.

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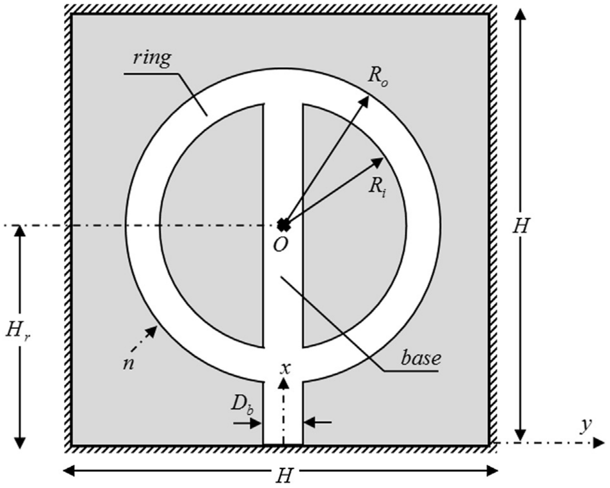
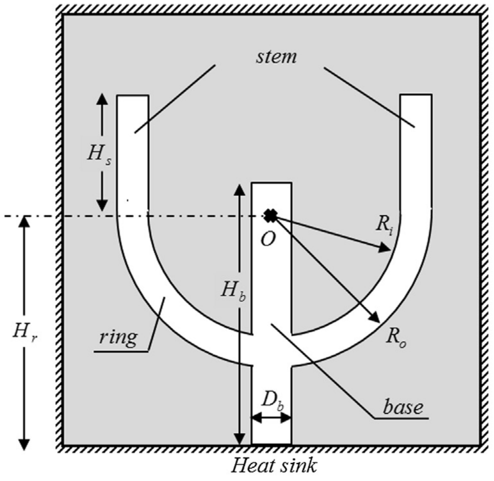
In this study, it is shown that the competition for the achievement of 'better' design of highly conductive pathways still continues. In this sense, new types of conductive pathways with 'Phi' or 'Psi' shape are introduced. Although these pathways are in the same class as the 'tree' shaped configuration discovered in the very first Bejan's paper [1], it is shown that the curled (bend) parts that are placed in 'Phi' and 'Psi' shaped inserts improve the tree-shaped configurations (such as X, T, H and I-shaped configurations). For example, when the objective is minimization of the peak temperature, it is shown that the maximum temperature can be reduced by 50% compared with the X-shaped pathways (the latest tree-shaped pattern found in literature). Due to the concerns associated with the cost and space of high conductivity materials, the foregoing achievement and the improvements achieved in the future are very important to engineers engaged with the empirical design of highly conductive pathways.



Phi (Φ) - shaped configuration



Psi (Ψ) - shaped configuration

Fig. 1. Geometry and coordinate system definition of high conductivity pathways (inserts) intruding a square heat generating piece.

2. Physical problem: Phi and Psi-shaped conductive pathways

Consider two-dimensional heat generating bodies intruded by a Phi-shaped or a Psi-shaped high conductivity material ('the insert') as sketched in Fig. 1. The external dimension is (H) for the square piece, (D_b, H_r, R_i, R_o) for the Phi-shaped insert and (D_b, H_b, H_r, R_i, R_o, H_s) for the Psi-shaped insert. Here, 'b' stands for the *base* shaped part, 'r' for the *ring* shaped part and 's' for *stem* shaped part of the insert, as sketched in Fig. 1. The total volume occupied by the entire system (heat generating body and insert) is fixed,

$$V_{\mathrm{tot}} = V_{\mathrm{l}} + V_{\mathrm{h}} = H^2 W = \mathrm{Const.} \tag{1}$$

where l and h stand for the *low* conductivity material (heat generating body) and *high* conductivity materials (insert), respectively. W is the thickness of the body, perpendicular to the plane of Fig. 1. For the sake of simplicity, the variability of all parameters along the W dimension is assumed negligible. Thus, the area of square body, $A_{\mathrm{tot}} = H^2$ can also be considered fixed. The volume occupied by the insert is fixed as well, i.e.

$$\begin{aligned} V_{\mathrm{h}} &= V_{\mathrm{r}} + V_{\mathrm{b}} \approx W\left[\pi\left(R_{\mathrm{o}}^2 - R_{\mathrm{i}}^2\right) + D_{\mathrm{b}}(H_{\mathrm{r}} + 2R_{\mathrm{i}} - R_{\mathrm{o}})\right] \\ &= \mathrm{Const.} \quad \text{Phi-shaped insert} \end{aligned} \tag{2a}$$

$$\begin{aligned} V_{\mathrm{h}} &= V_{\mathrm{r}} + V_{\mathrm{b}} + V_{\mathrm{s}} \approx W\left[\frac{\pi}{2}\left(R_{\mathrm{o}}^2 - R_{\mathrm{i}}^2\right) + D_{\mathrm{b}}(H_{\mathrm{b}} + R_{\mathrm{i}} - R_{\mathrm{o}}) \right. \\ &\quad \left. + 2(R_{\mathrm{o}} - R_{\mathrm{i}})h_{\mathrm{s}}\right] \\ &= \mathrm{Const.} \quad \text{Psi-shaped insert} \end{aligned} \tag{2b}$$

The volume constraints (1) and (2) are expressed by the relations,

$$\begin{aligned} \omega &= \frac{V_{\mathrm{h}}}{V_{\mathrm{tot}}} \approx \frac{\pi\left(R_{\mathrm{o}}^2 - R_{\mathrm{i}}^2\right) + D_{\mathrm{b}}(H_{\mathrm{r}} + 2R_{\mathrm{i}} - R_{\mathrm{o}})}{H^2} \\ &= \mathrm{Const.} \quad \text{Phi-shaped insert} \end{aligned} \tag{3a}$$

$$\begin{aligned} \omega &= \frac{V_{\mathrm{h}}}{V_{\mathrm{tot}}} \approx \frac{\frac{\pi}{2}\left(R_{\mathrm{o}}^2 - R_{\mathrm{i}}^2\right) + D_{\mathrm{b}}(H_{\mathrm{b}} + R_{\mathrm{i}} - R_{\mathrm{o}}) + 2(R_{\mathrm{o}} - R_{\mathrm{i}})h_{\mathrm{s}}}{H^2} \\ &= \mathrm{Const.} \quad \text{Psi-shaped insert} \end{aligned} \tag{3b}$$

where, ω represents the volume fraction occupied by the high conductivity materials (insert). The solid is assumed isotropic with constant thermal conductivity, k_{l}, and generates heat uniformly at the volumetric rate q''' [W/m^3]. The outer surfaces of the heat generating body are perfectly insulated. The generated heat current ($q'''A_{\mathrm{l}}$) is removed by the high conductivity materials with constant thermal conductivity, k_{h}, to a heat sink at the minimum temperature level, T_{min} located in the rim. Due to the high conduction resistance of the heat generating body, the temperature level in the body rises to levels higher than the minimum temperature in the rim. Such highest temperatures (the 'hot spots') are normally registered at points on the insulated perimeter. The hot spot (peak) temperature of the body may exceed the allowable temperature level. Knowing that the performance of equipment has a direct relationship with its temperature, it is important to keep it at an acceptable temperature level. Therefore, the design objective is represented by the minimization of the global thermal resistance $(T_{\mathrm{max}} - T_{\mathrm{min}})/(q'''A)$. The numerical optimization of geometric parameters of the insert consist of calculating the temperature field in a large number of configurations (with different geometric parameters of a Phi-shaped or a Psi-shaped), determining the global thermal resistance for each configuration, and selecting the configuration with the smallest global resistance. Symmetry allows us to perform calculations in only half of the domain.