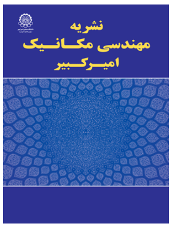

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Geometric Optimization of Highly Conductive Inserts with Variable Thickness Embedded in a Fin

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ABSTRACT: In the present study, it is proposed to reduce the thermal resistance of a straight fin by embedding highly conductive routes with variant thickness into a fin. Due to economic constraints, only a limited fraction of fin's volume can be devoted to these materials. Therefore, in this research, an optimal geometric structure for the inserts is presented. The purpose of optimization is to maximize the heat transfer from the fin by increasing the degrees of the freedom-to-morph under the constraint of the fixed volume fraction of the inserts. The geometric structure of conductive materials is presented by distributing the inserts with variable thicknesses or a linear distribution. The effects of several parameters such as the aspect ratio of the fin, Biot number, the volume fraction of highly conductive materials and the thermal conductivity ratio on the optimization results are presented in detail. It is shown that the increment in the number of insert branches with different thicknesses results in higher heat transfer. It is also indicated that the linear distribution performs the best.

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1. Introduction

For enhancing the heat transfer in micro-scale mediums, it is required to optimize the cooling process. Fins are widely used for cooling purposes. However, their conductive resistance is a penalty. Therefore, highly conductive materials might be used in order to reduce the thermal resistance. The limitation of the use of these highly conductive materials requires an optimization problem so that the geometric configuration of these materials is designed in an optimum manner.

Many research works have been carried out to use highly conductive inserts and fins [1-3]. For example, Hajmohammadi and Ahmadian [4] investigated the effect of using these materials to enhance the thermal performance of a straight fin. They indicated that the use of highly conductive inserts in the internal structure of the fin could greatly reduce the thermal resistance of the fin and increases its thermal performance. They investigated a simple geometric structure, the structure in which the highly conductive insert has a constant thickness. In the present paper, it tried to design the highly conductive inserts with variable thickness to achieve more thermal improvement by adding the degrees of freedom-to-morph. For this purpose, two, four, or eight highly conductive branches with different thicknesses are placed in the fin. Then, the thickness of each branch is optimized for several values of physical parameters, such as the Biot number (Bi), the ratio of the thickness of the fin to its length ($\frac{H}{L}$), the volume fraction of highly conductive materials (ϕ), and the ratio of the thermal conductivity of the highly conductive insert to the fin ($\frac{k_i}{k_f}$).

2. Description of the Physical System

For a Two-Dimensional (2D) fin intruded by N number of highly conductive materials with different thicknesses, the geometry description is shown in Fig. 1. The volume of the fin and the insert is considered fixed. The volume fraction of high conductivity materials (ϕ) is assumed constant. The thermal conductivity of fin, k_f and that of the highly conductive materials are considered invariant with temperature. The contact resistance is neglected. The left side of the rectangular fin is considered at fixed temperature and the right side and bottom side are assumed insulated. Heat transfer occurs by convection between top surface and the surroundings. The heat transfer coefficient, h, is uniform along the top surface.

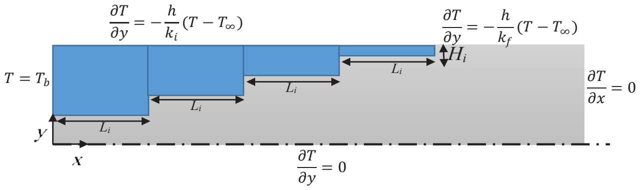

Fig. 1. Embedding highly conductive branches with variable thickness in Fin

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Heat transfer enhances by the high conductive materials with constant thermal conductivity, k_i.

3. Equations

The following Partial Differential Equations (PDE) of the conduction equation must be solved to deliver the temperature field,

$$\frac{\partial^2\theta}{\partial\hat{x}^2}+\frac{\partial^2\theta}{\partial\hat{y}^2}=0, \tag{1}$$

where

$$\theta=\frac{T-T_\infty}{T_b-T_\infty} \qquad (\hat{x},\hat{y})=\frac{(x,y)}{H} \tag{2}$$

The boundary conditions are:

$$\begin{aligned}&\theta=\theta_b \quad @\,\hat{x}=0\\ &\left.\frac{\partial\theta_f}{\partial\hat{x}}\right)=0 \quad @\,\hat{x}=\frac{L}{H}\\ &\left.\frac{\partial\theta_f}{\partial\hat{y}}\right)=0 \quad @\,\hat{y}=0\\ &\left.\frac{\partial\theta}{\partial\hat{y}}\right)=Bi\,\theta \quad @\,\hat{y}=1\end{aligned} \tag{3}$$

The objective is to maximize the heat transfer in the fin by optimizing the thickness of each insert. Dimensionless heat transfer is defined:

$$\hat{q}=\frac{q_{wi}}{q_{ni}}=\frac{-k_f\int_0^{H-H_i}\left.\frac{\partial T}{\partial x}\right|_{x=0}dy-k_i\int_{H-H_i}^{H}\left.\frac{\partial T}{\partial x}\right|_{x=0}dy}{-k_f\int_0^{H}\left.\frac{\partial T}{\partial x}\right|_{x=0}dy} \tag{4}$$

In the case where the highly conductive thickness is constant ($N = 1$), the direct search method is used, since only one optimization variable exists. In the next steps, the highly conductive structure becomes more advanced, a highly conductive with variable thickness is embedded in the fin. Then this material is embedding linearly into the fin. The number of optimization variables is increased (Table1) and due to the high time cost, the pattern search optimization method [5] is used.

Table. 1. Optimization Variables

Insert geometric structure	Optimization Variables
N=2	$\frac{A_2}{A_1},\frac{H_1}{L_i}$
N=4	$\frac{A_2}{A_1},\frac{A_3}{A_2},\frac{A_4}{A_3},\frac{H_1}{L_i}$
N=8	$\frac{A_2}{A_1},\frac{A_3}{A_2},\frac{A_4}{A_3},\frac{A_5}{A_4},\frac{A_6}{A_5},\frac{A_7}{A_6},\frac{A_8}{A_7},\frac{H_1}{L_i}$
Linear	$\frac{H_2}{H_1},\frac{H_1}{L_i}$

The numerical code benefits from the MATLAB PDE Tool Box. The results obtained by the present code are compared with those reported by Almogbel and Bejan [6] in Table 2. The maximum relative error of 0.83 % indicates that the present code is well-validated.

Table. 2. The comparison of the maximum dimensionless temperature in a square-shaped body that is reported by Almogbel [6].

$\frac{k_i}{k_l}$	$\widetilde{T}_{max}$ Present work	$\widetilde{T}_{max}$ Almogbel [15]	Relative error in %
10	0.37227	0.37539	0.83
100	0.15388	0.152994	0.58
300	0.13517	0.135408	0.17
1000	0.12888	0.128979	0.08

4. Results and Discussion

The effect of the number of highly conductive branches on maximum heat transfer is indicated in Fig. 2 for several $\frac{k_i}{k_f}$ when $Bi = 0.1$ and $\phi = 0.1$. Fig. 2 shows that an increment in the number of highly conductive branches results in enhancing the heat transfer from the fin. For example, when eight number of highly conductive branches, heat transfer from the fin is increased about 6% compared to the case of one highly conductive branch (with uniform thickness). The optimum geometric configuration of highly conductive materials with one, two, four and eight branches together with the highly conductive pathway with the linear variation of the thickness are shown in Fig.3 when $Bi = 0.1$, $1\frac{k_i}{k_f} = 10$, $\phi = 0.1$

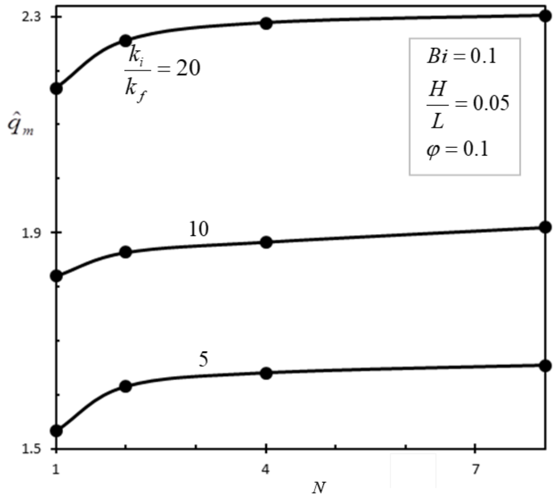

Figure. 2. The effect of the number of highly conductive branches on the maximum heat transfer

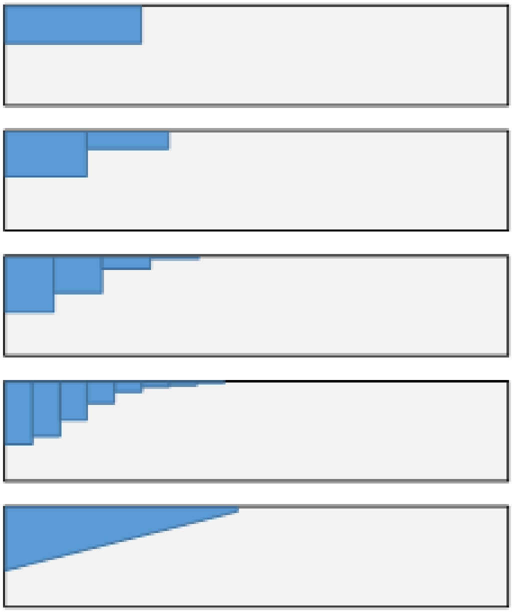

Figure. 3. The optimal configurations when Bi = 0.1, $\frac{H}{L}=0.05$, $\phi=0.1$, and $\frac{k_i}{k_f}=10$

and $\frac{H}{L}=0.05$. As it is observed, in the optimum geometric configuration, the thickness of the branches decreases in the heat flow direction in the fin. The optimum configurations in a similar case but with Bi = 0.01, are displayed in Fig. 4. As it is shown, by increasing the Biot number, the optimal shape of the branches tends to be elongated.

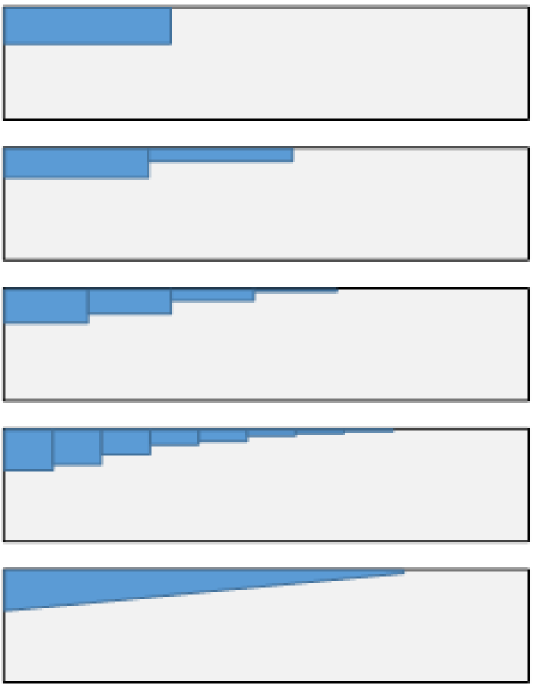

Figure. 4. The optimal configurations when Bi = 0.01, $\frac{H}{L}=0.05$, $\phi=0.1$, and $\frac{k_i}{k_f}=10$

5. Conclusions

In this paper, the optimal design of highly conductive pathways with variable thickness embedded in a straight fin is considered. The following conclusion can be drawn from this numerical work:

•For highly conductive branches, there is an optimal thickness for every branch of the highly conductive materials.

•By increasing the degrees of freedom of the geometric structure of the material, the total heat transfer from the fin is increased, so that the variable-thickness highly conductive branch is much better than the fixed-thickness highly conductive branch.

•In the optimum geometric configuration, the thickness of the branches decreases in the heat flow direction in the fin.

•By increasing the Biot number, the optimal shape of the branches tends to be elongated.

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