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Constructal design for "+" shaped high conductivity pathways over a square body

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ABSTRACT

A heat generating model with "+" shaped high conductivity pathway over a square body is built in this paper. For the specified areas of the high conductivity pathway and square body, the constructal optimizations of the square body with single and multilevel "+" shaped high conductivity pathways are carried out by taking minimum dimensionless peak temperature as optimization objective. The optimal constructs of the "+" shaped high conductivity pathways and triple minimum dimensionless peak temperature of the square body are obtained. The results show that the minimum dimensionless peak temperature of the square body with multilevel "+" shaped high conductivity pathway is reduced by 75.79% compared with that with X shaped one. The heat transfer performance of the square body is obviously improved by adopting the multilevel "+" shaped high conductivity pathway, and it can be further improved by increasing the dimensionless thermal conductivity and area fraction of the high conductivity material. Thermal stress performance should be also considered in the constructal design of a heat generating body. The results obtained in this paper can provide some guidelines for the designs of electronic devices.

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1. Introduction

When the length scale of an electronic device drops to a certain level, the heat conduction in high conductivity channel will become an effective way to remove the heat generated in the electronic device comparing with the heat convection in cooling channel. Based on this consideration, Bejan [1] inserted the tree-shaped high conductivity channels into a rectangular body of a heat generating device, and analytically optimized the configuration of the body based on constructal theory [2–16]. Based on this work [1], many scholars further used the analytical methods to optimize various heat conduction models with high conductivity channels [17–28].

Comparing with analytical methods, numerical methods provide more exact and true solutions for the optimal designs of heat transfer devices. Many scholars carried out constructal designs of heat generating problems by using numerical methods, such as heat conduction problems with high conductivity channels [29–41], heat convection problems with external [42–46] and internal [47–57] surfaces, etc. In the numerical investigations of heat conduction problems, Ledezma et al. [29] and Almogbel and Bejan [30,31] used the finite element code to solve the two-dimensional heat conduction problems with branch angles, spacing tips and nonuniform high conductivity trees, respectively, and reduced the global thermal resistances of the heat generating bodies by using the optimal heat conduction trees. Rocha et al. [32] carried out constructal optimization of the looped-shaped high conductivity trees in a disc by using MATLAB PDE toolbox, and obtained a better heat transfer performance of the loop-shaped networks surpassing those of the radial- and branched-pattern trees. Sharifia et al. [33] and Daneshi et al. [34] further investigated tree-shaped high conductivity trees in a disc by considering the incomplete variable cross-section and micro and nano-scale high conductivity trees, respectively. Lorenzini et al. [35] carried out constructal design of a square heat generating body with X-shaped high conductivity pathway, and reduced the maximum excess of the body temperature by 51% compared with that with I-shaped high conductivity pathway. Lorenzini et al. [36] improved the model in Ref. [35] by using X-shaped high conductivity pathway with non-uniform lengths and thicknesses, and optimized the branch angles and length ratios by taking the minimization of maximum excess temperature as optimization

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objective. The results showed that the maximum excess temperature was reduced by 10% compared with that with uniform X-shaped pathway. dos Santos et al. [37] optimized the distribution of a Y-shaped high conductivity pathway over a square heat generating body, and reduced the peak temperature by 13% than that of the X-shaped one in Ref. [35]. Hajmohammadi et al. [38] built two heat generating models with folk-shaped high conductivity pathways over a square body, and obtained the optimal constructs of them. The results showed that the peak temperatures of the heat generating bodies with folk-shaped pathway were reduced by 52% and 64%, respectively, compared with that with X-shaped one. Hajmohammadi et al. [39,40] built Phi, Psi and V-shaped high conductivity pathway models to further improve the heat transfer performances of the heat generation bodies, and also considered a three-dimensional heat conduction model [41] with different heat generation conditions.

In this paper, a "+" shaped high conductivity pathway over a square heat generating body will be considered. Constructal optimizations of the square body with single and multilevel "+" shaped high conductivity pathways will be carried out by taking minimum peak temperature as optimization objective. Performance comparisons of the square bodies with "+" shaped high conductivity pathway in this paper and X shaped high conductivity pathway in Ref. [35] will be performed, and the thermal stress performance of the square body will be also considered.

2. Constructal optimization of "+" shaped high conductivity pathway over a square body

Consider a square body ($2L \times 2L$) embedded with a "+" shaped high conductivity pathway as shown in Fig. 1(a). Assumed that the thickness of this body is sufficient larger than its length and width, this body can be viewed as two-dimensional one. The heat is uniformly generated in the low conductivity material (thermal conductivity k_0), and the heat generating rate per unit volume is q'''. The length and width of one branch of the "+" shaped high conductivity pathway (thermal conductivity k_p) are L_0 and D_0, respectively. For the symmetry of the square body, only a quarter of the body (area $A = L \times L$) as shown in Fig. 1(b) is required to be considered. For simplification, the shape of the heat sink (temperature $T_{\min}$) is ignored [26,32–34], and it is viewed as a line in Fig. 1(b). The boundary of the square body is adiabatic except for the heat sink section M_0. For the specified length and width of square body, the length and width of high conductivity branch are free to vary.

The equations for two-dimensional heat conductions in the low conductivity material and high conductivity pathway of Fig. 1(b) can be, respectively, given as

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{q'''}{k_0} = 0 \tag{1}$$

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0 \tag{2}$$

The corresponding boundary conditions are

$$T = T_{\min}, \quad x = 0, \quad 0 < y < D_0/\sqrt{2} \tag{3}$$

$$\frac{\partial T}{\partial x} = 0 \begin{cases} x = L, & 0 \leqslant y \leqslant L \\ x = 0, & D_0/\sqrt{2} \leqslant y \leqslant L \end{cases} \tag{4}$$

$$\frac{\partial T}{\partial y} = 0 \begin{cases} y = 0, & 0 \leqslant x \leqslant L \\ y = L, & 0 \leqslant x \leqslant L \end{cases} \tag{5}$$

The area A_p of the high conductivity pathway is

$$A_p = D_0 L_0 + D_0^2/4 \tag{6}$$

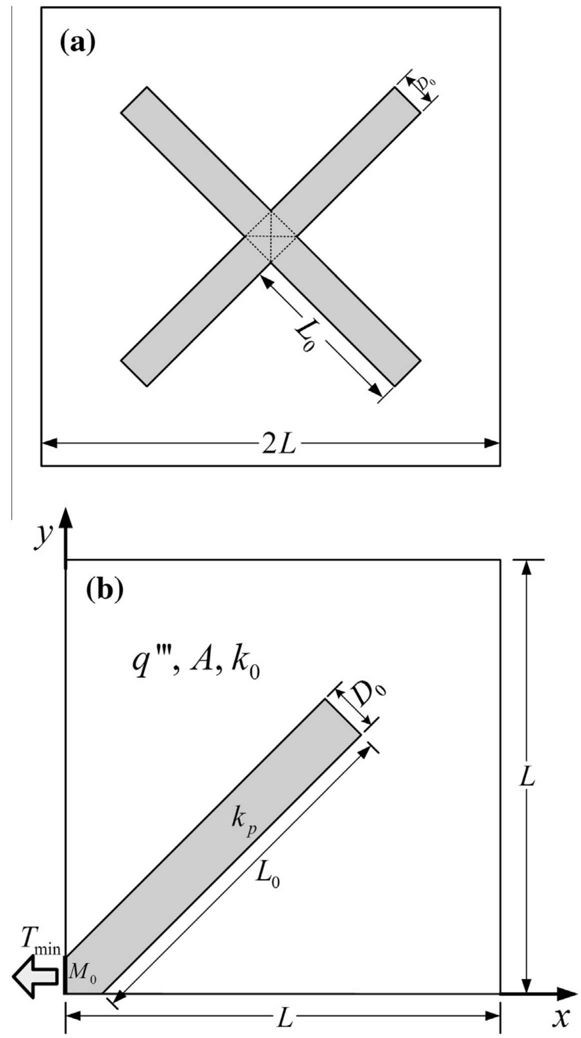

Fig. 1. Square heat generating body with "+" shaped high conductivity pathway: (a) whole square body (b) quarter of the square body.

The dimensionless temperature and dimensionless size variables are defined as follows

$$\tilde{T} = \frac{T - T_{\min}}{q''' \cdot (4A)/k_0} \tag{7}$$

$$\tilde{L}_0, \tilde{D}_0 = \frac{L_0, D_0}{L} \tag{8}$$

For the specified area of the high conductivity material, the fraction ϕ is defined as the high conductivity material allocated to the whole square body

$$\phi = \frac{A_p}{A} = \tilde{D}_0 \tilde{L}_0 + \tilde{D}_0^2/4 \tag{9}$$

From Eq. (7), the dimensionless peak temperature $\tilde{T}_0$ of the square body in Fig. 1(a) can be given as

$$\tilde{T}_0 = \frac{T_{\max} - T_{\min}}{4q'''A/k_0} \tag{10}$$

For the specified dimensionless thermal conductivity $\tilde{k}\,(= k_p/k_0)$ and the fraction ϕ of the high conductivity material, $\tilde{T}_0$ is a function of $\tilde{D}_0$, and the constructal optimization of the "+" shaped high conductivity pathway in the square body can be carried out by optimizing $\tilde{D}_0$.

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