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"Volume-point" heat conduction constructal optimization based on minimization of maximum thermal resistance with triangular element at micro and nanoscales

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ABSTRACT

The triangular assemblies of a "volume-point" heat conduction model at micro and nanoscales are investigated by using constructal theory. The optimizations of the triangular assemblies are carried out by taking minimization of maximum thermal resistance as optimization objective. The optimal constructs of the triangular assemblies with size effect are obtained, which is evidently different from those without size effect. The results show that with the increase in the internal complexity of the construct, the heat transfer performance of the construct does not always decrease, and different optimal internal design structures should be adopted according to different parameters. The "volume-point" heat conduction constructal optimization based on maximum thermal resistance minimization with triangular element can effectively reduce the maximum temperature limitation of the triangular assembly, and enhance its system safety. The optimization results obtained based on triangular element will provide some significant guidelines for the structural designs of micro-electronic devices.

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1. Introduction

With the development of the science and technology, one development trend of the electronic devices is the miniaturization and high integration. The smaller of the device and the higher of the chip integration are, the higher of the thermal current density in the device becomes. How to effectively carry out thermal management for the electronic device is one of the important questions needed to solve. One of the methods to solve this problem is inserting the high conductivity material in the electronic device to enhance its heat transfer performance, and many scholars have carried out performances optimizations of the electronic devices by searching for the optimal distributions of the high conductivity materials.

Bejan put forward the constructal theory [1–15], and inserted the tree-shaped high conductivity channels into the rectangular heat generating body of an electronic device. He firstly introduced this theory into the constructal optimization of the "volume-point" heat conduction model with rectangular element [16], and obtained the optimal construct of this model. Ghodoossi and Egrican [17,18] solved the "volume-point" heat conduction models with rectangular and triangular elements analytically by adopting the exact solution. Wu et al. [19] revised the approximate solution, and the result obtained was consistent with the exact analytical solution in Ref. 16. Furthermore, the high effective conduction channel distribution was optimized by Wu et al. [20] again without the assumption that the next order assembly was assembled by the optimized last one. Moreover, some scholars re-optimized Bejan's "volume-point" heat conduction model [16] based on the minimization of maximum temperature difference by getting rid of the perpendicular condition of the high and low conductivity channel [21], adopting nonuniform tree structure [22], calculating precise heat generating areas [23], considering variable cross-section high conductivity channels and variable elemental shapes [24–26], arbitrary shapes [27] as well as three-dimensional heat conduction models [28–30].

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Nomenclature

A	Area of the assembly, m^2
D	Width of the high conductivity channel, m
H	Width of the assembly, m
k	Thermal conductivity coefficient, $W/m/K$
$\tilde{k}$	Ratio of the thermal conductivity coefficient
L	Length of the assembly, m
n_1, n_2	Number of the last-order assemblies in the new-order assembly
q	Total heat generation rate, W
q'''	Heat generation rate per unit volume, W/m^3
R_t	Maximum thermal resistance, K/W
T	Temperature, K

Greek symbols

λ	Critical width, m
ϕ	Volume fraction of the high conductivity material
ΔT	Temperature difference, K

Superscripts

b	Size effect vanishes in D_0 channel
bb	Size effects vanish in D_0 and D_1 channels
bbb	Size effects vanish in D_0, D_1 and D_2 channels
n	Size effect presents in D_0 channel
nb	Size effect presents in D_0 channel, but vanishes in D_1 channel
nbb	Size effect present in D_0 channel, but vanishes in D_1 and D_2 channels
nn	Size effects present in D_0 and D_1 channels
nnb	Size effects present in D_0 and D_1 channels, but vanishes in D_2 channel
nnn	Size effects present in D_0, D_1 and D_2 channels

Subscripts

m	Minimum
max	Maximum
mm	Double minimum
opt	Optimal
$0, 1, 2$	Elemental volume, first order assembly, second order assembly

The heat conduction constructal optimization problems mentioned above were solved at conventional macro scale. However, when the size reduces to micro and nanoscales, some new phenomena and laws will present in the micro-scale heat transfer processes [31–33], and some scholars have made plentiful work in this field [34–43]. In the analysis of the "volume-point" heat conduction constructal problem, considering the size effect presented in high conductivity material at micro and nanoscales, Gosselin and Bejan [41] re-optimized Bejan's "volume-point" heat conduction model [16] by taking the minimization of maximum temperature difference as objective at micro and nanoscales. The new optimal constructal shape of the "volume-point" heat conduction model at micro and nanoscales were obtained, and the performance comparisons of the two optimal constructs at nanoscale and conventional scale were carried out. Chen et al. [42] optimized the "disc-point" heat conduction disc at micro and nanoscales by taking the minimization of the hot spot temperature as optimization objective, and obtained the optimal constructs of the disc different from the convectional scale. Daneshi et al. [43] further carried out constructal optimizations of the discs with tree-shaped and looped-shaped high conductivity channels by using finite element method, respectively, and the results showed that increasing the order of the construct did not always lead to a better heat conduction performance.

Heat conduction problems can be investigated based on various elements, such as rectangular element [16,17,19–23,25–27,41], triangular element [18], and tapered element [24]. On the basis of the triangular heat conduction model at macroscales in Ref. [18] and the rectangular heat conduction model at micro and nanoscales in Ref. [41], the "volume-point" heat conduction model with triangular element at micro and nanoscales will be optimized by taking the minimization of maximum temperature difference as optimization objective in this paper. The optimal constructs of the triangular "volume-point" heat conduction model will be obtained. The triangular heat conduction model at macroscales is transplanted to that at micro and nanoscales, which is a transplantation method. The optimization results obtained in this paper can provide some guidelines for the constructal designs of electronic devices, and the transplantation method used in this paper can provide some inspirations for the readers to solve other similar design problems.

2. Optimization of triangular elemental volume

A triangular elemental volume ($H_0 \times L_0 \times 1/2$) with uniform heat generating rate (q''') is shown in Fig. 1[18]. The total heat generation rate q of the elemental volume is $q''' \times H_0 \times L_0 \times 1/2$. A high conductivity channel (width D_0, thermal conductivity coefficient k_x) is inserted in the triangular area (thermal conductivity coefficient k_0). The heat is first collected by D_0 channel, and then flows to the heat sink located at the point M_0. The outer boundaries of the triangular elemental area are adiabatic except for the point M_0. The parameters are considered independent of the third dimension of the elemental volume, and this model is simplified into the two-dimensional one. For the specified elemental area $A_0(= H_0 \times L_0/2)$, the ratio H_0/L_0 is free to vary. The volume fraction of the high conductivity material allocated to the rectangular elemental area is $\phi_0 = 2D_0/H_0$. It is assumed that $k_0 << k_x$, $\phi_0 << 1$ and $H_0 << L_0$, the heat transfers in k_0 and k_x materials are simplified into one-dimensional ones, respectively.

When the width of D_0 channel reduces to micro and nanoscales, the thermal conductivity coefficient k_x of D_0 channel will vary with its width due to the size effect. One of the models to reflect this characteristic is shown as [41].

$$\frac{k_x}{k_b} = \begin{cases} \dfrac{D}{\lambda} & (D \le \lambda) \\ 1 & (D > \lambda) \end{cases} \tag{1}$$

where λ is the length bound (10–100 nm). When the width D is not larger than λ, the size effect will present in D channel, and the thermal conductivity coefficient k_x depends on the width of D channel. Otherwise, k_x keeps constant at the value of k_b.

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