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Constructal optimization for "disc-point" heat conduction at micro and nanoscales

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ABSTRACT

Based on constructal theory, the construct of a "disc-point" heat conduction model at micro and nanoscales is optimized by taking maximum temperature difference minimization as optimization objective, and the optimal constructs of the radial-pattern and first order branched-pattern discs under the effect of size effect are obtained. The results show that the size effect has an obvious influence on the optimal construct of the disc. The minimum dimensionless maximum temperature difference of the first order disc for structure form *nn* is relative to the number of elemental tributaries, but those for structure forms *nb* and *bb* are independent of the number of elemental tributaries. There exist the critical dimensionless radiuses, which determine whether the radial-pattern design or branched-pattern design for the high conductivity channels is adopted. The critical dimensionless radiuses of the first order branched-pattern discs for the structure forms *nn*, *nb* and *bb* are 1.25, 1.72 and 2.18, respectively. With the increase in the product of thermal conductivity ratio and the square of elemental high conductivity material fraction, the minimum dimensionless thermal resistance of the first order disc for structure form *nn* decreases, but that for structure form *nb* is undetermined. The optimal "disc-point" construct at micro and nanoscales improves the heat transfer performance of the disc.

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1. Introduction

Since Bejan firstly put forward the constructal theory [1–18] to solve the problem of cooling electronic devices [2], this theory has widely applied in the research of heat transfer problems [19–38]. In the heat conduction problems, a typical heat conduction model is "disc-point" heat conduction model, and some scholars have carried out constructal optimizations of this model by using constructal theory [39–44]. da Silva et al. [39] investigated a disc model with high conductivity blades inserted in the disc, and carried out constructal optimizations by using both analytical and numerical methods. The results showed that the analytical solution and the numerical results agreed with each other. Chen et al. [40] further re-optimized this model by taking entransy dissipation rate minimization as optimization objective, and obtained an optimal constructs different from that obtained in Ref. [39]. Rocha et al. [41,42] investigated the "disc-point" heat conduction model for cooling a heat generating volume, and obtained the optimal distributions of high conductivity channels with fractal- and loop-shaped tree networks, respectively. The results showed that there existed a critical dimensionless radius to determine whether the radial- or branched-pattern design of the disc with fractal-shaped high conductivity channels was adopted, and cooling structure of the disc with loop-shaped high conductivity channels did not change much if its structure was locally damaged. Xiao et al. [43,44] further re-optimized the "disc-point" model in Ref. [41] by taking entransy dissipation rate minimization as optimization objective [43] as well as by releasing the assumption that the perimeter of the branch-patterned disc was assembled by the optimized elemental sectors [44], respectively, and the optimal constructs obtained can effectively improve the heat transfer performance of the disc.

Noting that at micro and nanoscales, the convectional description of the heat transfer mechanism would break down [45–47], Gosselin and Bejan [48] considered a so thin high conductivity channels that their conductivity would exhibit size effect in the Bejan's "volume-point" heat conduction model [2], and obtained a new optimal constructs of this model by taking maximum temperature difference minimization as optimization objective. This work inspired us that the constructal theory could successfully be applied to the constructal optimization of heat conduction problems at micro and nanoscales. Based on Ref. [41], and following the research idea of "volume-point" heat conduction constructal optimization at micro and nanoscales in Ref. [48], the construct of the "disc-point" heat

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Nomenclature

A_p	area of the high conductivity material, m^2
A_0	area of the elemental sector, m^2
A_1	area of the central sector, m^2
D_0	width of the high conductivity channel in elemental sector, m
D_1	width of the high conductivity channel in central sector, m
H_0	half length of the elemental sector, m
H_1	half length of the central sector, m
k_b	thermal conductivity at convectional scale, W/K/m
k_x	thermal conductivity of the high conductivity material, W/K/m
k_0	thermal conductivity of the low conductivity material, W/K/m
$\tilde{k}$	dimensionless thermal conductivity
N	number of the peripheral sectors
n	number of the elemental tributaries
q	heat generation rate, W
q'''	heat generation rate per unit volume, W/m^3
R	radius of the whole disc, m
R_0	radius of the elemental sector, m
R_1	radius of the central sector, m
$\tilde{R}_{t0}$	dimensionless thermal resistance of the radial-pattern disc
$\tilde{R}_{t1}$	dimensionless thermal resistance of the first order branched-pattern disc
T	temperature, K

Greek symbols

α	tip angle of the central sector, rad
λ	length bound, m
ϕ_0	elemental fraction of the high conductivity material
ϕ_1	first order fraction of the high conductivity material

Subscripts

m	minimum
max	maximum
opt	optimal

Superscripts

b	elemental conduction regime for $D_0 > \lambda$
bb	first order conduction regime for $D_0 > \lambda$ and $D_1 > \lambda$
n	elemental conduction regime for $D_0 \leqslant \lambda$
nb	first order conduction regime for $D_0 \leqslant \lambda$ and $D_1 > \lambda$
nn	first order conduction regime for $D_0 \leqslant \lambda$ and $D_1 \leqslant \lambda$
$\sim$	dimensionless

conduction model at micro and nanoscales will be optimized by taking maximum temperature difference minimization as optimization objective in this paper. The optimal constructs of the radial-pattern and first order branched-pattern discs will be obtained, and heat transfer performance comparisons among the conventional, micro and nanoscales will be carried out.

2. Radial-pattern disc at micro and nanoscales

The heat conduction model of radial-pattern disc is shown in Fig. 1 [41]. The radius of the disc-shaped low conductivity material is R_0, and the thermal conductivity is k_0. The disc $(\pi R_0^2 \times 1)$ generates heat at a constant rate q volumetrically, and the heat generation rate per unit volume is constant $q''' = q/(\pi R_0^2 \times 1)$. The heat current ($q$) flows through the high conductivity channels (the number of the channels is N, the width of the channels is D_0, and the thermal conductivity of the channels is (k_x) into the center (T_0) of the disc. The maximum temperature T_{max} occurs on the adiabatic rim of the disc, and the minimum temperature T_0 occurs at the center of the disc.

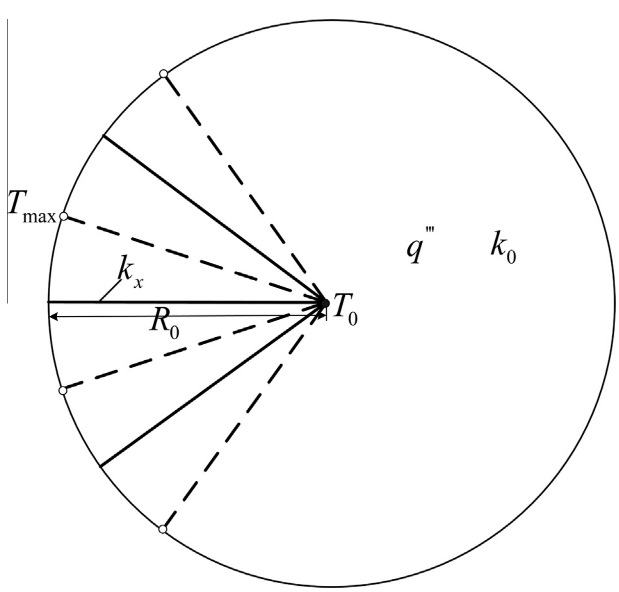

Fig. 1. Heat transfer model of radial-pattern disc at micro and nanoscales [41].

When the width D_0 of the high conductivity channel reduces to micro and nanoscales, the thermal conductivity of the high conductivity channel will change, which is caused by size effect. The model shown by Eq. (1) [48] reflects the change of the thermal conductivity of the high conductivity channel due to size effect

$$\frac{k_x}{k_b} = \begin{cases} \frac{D_0}{\lambda} & (D_0 \leqslant \lambda) \\ 1 & (D_0 > \lambda) \end{cases} \tag{1}$$

where λ is the length bound (10–100 nm), at which the size effect becomes significant in the high conductivity channel. When D_0 is sufficiently large, the thermal conductivity of the high conductivity

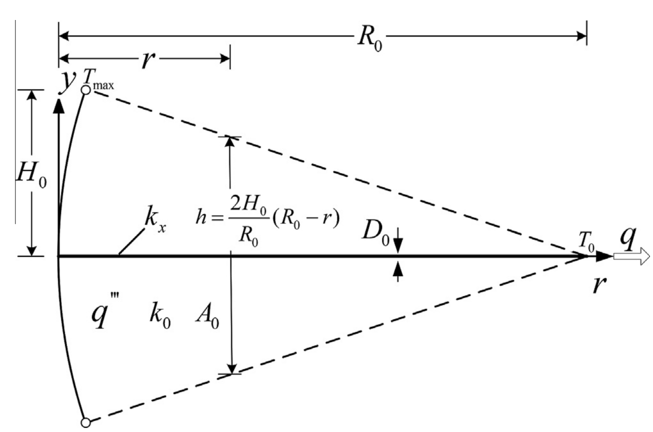

Fig. 2. Heat transfer model of radial-pattern elemental sector at micro and nanoscales [41].

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