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Constructal design of I-shaped high conductive pathway for cooling a heat-generating medium considering the thermal contact resistance

G. Lorenzini [a,*], E.X. Barreto [b], C.C. Beckel [b], P.S. Schneider [c], L.A. Isoldi [d], E.D. dos Santos [d], L.A.O. Rocha [c]

[a] Università degli Studi di Parma, Dipartimento di Ingegneria Industriale, Parco Area delle Scienze 181/A, 43124 Parma, Italy
[b] Universidade Federal do Rio Grande do Sul, Programa de Pós-Graduação em Engenharia Mecânica, Rua Sarmento Leite, 425, 90050-170 Porto Alegre, RS, Brazil
[c] Universidade Federal do Rio Grande do Sul, Departamento de Engenharia Mecânica, Rua Sarmento Leite, 425, 90050-170 Porto Alegre, RS, Brazil
[d] Universidade Federal do Rio Grande, School of Engineering, Cx.P. 474, 96201-900 Rio Grande, RS, Brazil

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ABSTRACT

This study applies the constructal design method to obtain the configuration that provides the easier access to the heat flowing through an I-shaped high conductive pathway which is inserted into a volumetric medium with low thermal conductivity and heat-generating. A third material separates the high conductive material from the heat-generating medium representing the thermal contact resistance. The body is cooled by an isothermal heat sink with low temperature which is located in the rim. The objective consists in discovering configurations that facilitates the heat flow diminishing the maximal excess of temperature independent of the place where it is located. The total volume and the volume of high conductivity material are fixed, but their aspect ratio can vary. The results indicate that the thermal contact resistance is larger when thermal conductivity of the high conductivity material and the thermal conductivity of the material that represents the thermal contact resistance are smaller. It can increase the maximal dimensionless excess of temperature and the optimal aspect ratio by approximately 56% and 17% respectively. In addition, varying the external ratio can increase the maximum dimensionless temperature almost 20% taking into account the thermal contact resistance. However, changes in this ratio had almost no effect on the optimal geometry of the I-shaped high thermal conductivity pathway.

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1. Introduction

Cooling finite volume that generates heat at every point using inserts of high thermal conductivity was proposed by Bejan in 1996 [1]. This work was remarkable because it also presented the fundamentals of constructal theory [2,3], i.e., the view of design as science. After that several works have been published by studying large number of configurations that facilitate the heat flow, and, as consequence, diminishing the maximal temperature of the system [4–25].

In addition to the cited optimal designs in conductive cooling systems [4–25] there exist other important cooling systems for performance enhancement, e.g. the use of a heat source under a thick plate [26,27]. Convective cooling systems [28–35] and radiative cooling systems [36,37] have also been applied in the search for best configurations.

The enormous amount of work presented in the literature using high conductive pathways assumed perfect thermal coupling and that there was no temperature gradient in the interfaces. However, even flat surfaces that appear smooth to the common eye are actually rough under the microscopic point of view with numerous peaks and valleys. Thus, every surface is microscopically rough, no matter how smooth it may seem. When two surfaces are pressed against each other, the roughness peaks will form good contact points and the valleys will form voids commonly filled with air. The result is an interface with many gaps of different sizes which act as insulating elements due to the low thermal conductivity of air. Thus, the interface provides resistance and such resistance per unit of area of the interface is called thermal contact resistance, R_c [38]. The value of R_c depends on the surface roughness, material properties and the temperature, pressure and type of fluid interposed in the gaps of the interface. The thermal contact resistance has also been largely studied in the literature [39–44].

This numerical work proposes to apply constructal [45–55] design to study a system where the thermal contact resistance is taken into account in the interface between the heat generating body and the I-shaped high conductivity pathway. The elemental volume which generates heat uniformly per unit of volume is cooled by a heat sink at temperature T_0 that is located in the rim. The objective is to minimize the maximal excess of temperature

* Corresponding author.

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Nomenclature

A	area (m^2)
H	height (m)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L	length (m)
q	heat current (W)
q'''	heat uniformly at volumetric rate ($W\,m^{-3}$)
t	thickness (m)
T	temperature (K)
V	volume (m^3)
x, y	coordinates (m)
W	width (m)

Greek symbols

θ	dimensionless temperature, Eq. (6)
ϕ	area fraction

Subscripts

L	material that represents the thermal contact resistance
max	maximal
m	once minimized
mm	twice minimized
o	once optimized
oo	twice optimized
p	path (blades) of high thermal conductivity
0	isothermal wall, single blade

Superscript

(~)	dimensionless variables

T_{max}–T_0. For simplicity, it was assumed two-dimensional model. The aspect ratio between the thermal conductivity of the pathway and the thermal conductivity of elemental volume, the external aspect ratio of the elemental volume, and the area fraction between the volume of the high thermal conductivity pathways and the elemental volume are some design parameters.

2. Constructal design

Constructal design is the method based on constructal law [3] to discover the configurations that facilitate the access of the flow currents. The method applies the objective and constraints principle in such a way that the best architecture emerges deterministically. The applicability of this method to engineered flow systems has been widely discussed in the literature. E.g. in designing cavities [45–48] and assembly of fins [49,50]. Recently it has been applied to the study of technology evolution [51], evacuation from living spaces [52], vascularization for cooling and reduced thermal stresses [53], shell-and-tube heat exchangers [54], among others. It is important to notice that constructal design is not an optimization method. It is used to enunciate the problem, indicating the objective function, the constraints and the degrees of freedom to be studied. Sometimes it can be applied together an optimization method, for example the exhaustive search. However, it can also be used with Genetic Algorithm [23,31,47,48], Simulated Annealing [55], or another optimization method. It is important to mention that a special feature of this method is that the effect of each degree of freedom must be studied successively, i.e., it does not look only for the optimized configuration, but how the geometry evolves to this best shape.

3. Mathematical model

Consider the body shown in Fig. 1. The configuration is two-dimensional, with the third dimension (W) sufficiently long in comparison with the length L of the total volume. There is an I-shaped pathway of high thermal conductivity k_p material embedded in the body of lower thermal conductivity k. The solid body generates heat uniformly at the volumetric rate q''' (W/m^3). The outer surfaces of the solid are perfectly insulated. The generated heat current ($q'''AW$) is removed by the heat sink located in the rim of the body at temperature T_0. A third material with thickness t and thermal conductivity k_L is inserted between the solid body and the I-shaped high thermal conductivity pathway. This material represents the thermal contact resistance and its effect on the maximal temperature of the system will be studied by varying the value of k_L. The literature shows that the values of the contact thermal resistance can vary, for example, in the range between 0.000005 and 0.0005 [21]. Fig. 2 shows how this work simulates the contact resistance (see Fig. 2b) using a very thin layer of thickness t (see Fig. 2d).

The work consists to calculate the dimensionless maximal excess of temperature $(T_{max}–T_0)/(q'''A/k)$ and see what geometry $(H_0/L_0, H/L)$ facilitates the heat flow removal. According to constructal design, this search can be subjected to two constraints, namely, the total area constraint,

$$A = HL \tag{1}$$

and the area occupied by the high thermal conductivity material,

$$A_p = H_0L_0 \tag{2}$$

being H and L, respectively, the height and length of the solid body, while H_0 and L_0 are the height and length of the I-shaped pathway, respectively.

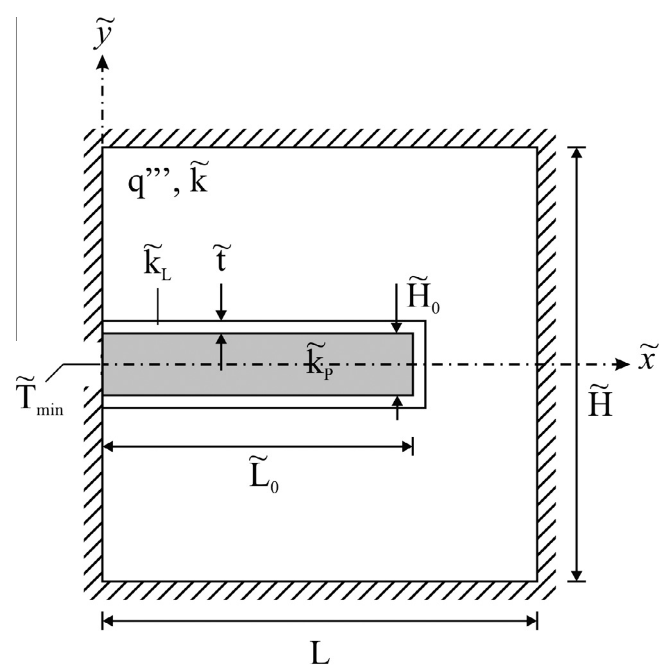

Fig. 1. I-shaped high conductivity pathway and the thermal contact resistance inserted into the heat-generating body.

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