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A new Constructal Theory based algorithm applied to thermal problems

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ABSTRACT

Constructal Theory has been applied to evaluate system performance in several engineering areas like solid mechanics, refrigeration, heat exchangers, etc. It states that finite flow systems performance can be optimized by minimizing the resistances. It is usually formulated by the definition of geometric constraints and an optimization method like exhaustive search or Genetic Algorithm. In present work, Constructal Theory is used in its most fundamental sense, i.e., the geometric forms should evolve (grow) from a fundamental shape, named here as Elemental Constructal (EC), instead of by the application of an optimization method to a predefined geometry. In order to test the proposed algorithm, the isotherm cavity intruded into a heat generating solid body problem is solved with proposed algorithm and solution is compared with literature solutions obtained for several predefined shapes (I, T, Y, X and others). If a sufficient small EC were used to define the building blocks of the cavity, thermal performance obtained with current method is comparable with performance of the best shapes found in literature. Main goal is not to find best possible geometry for the cavity, but to understand how cavity form should grow in order to reduce the temperature in solid domain. Moreover, the cavity optimization problem has only been used as an application example of a much more general methodology used to predict how shape and structure may evolve in different flow problems.

1. Introduction

Forms in nature are created and modified along time in terms of configuration, shape and structure, pattern and rhythm. Into this subject, Constructal Theory establishes a new viewpoint about design in human and nature, proclaiming the idea that structures and geometric forms evolve in a deterministic way. Constructal Theory has shown that the generation of shape and structure in nature, human and engineering designs are deterministic and ruled by a physical principle [1–3]. The physical principle states that a finite flow system (animate or inanimate) with freedom to morph along the time will evolve in such way to improve the access to the internal currents that flow through it [1–5]. It suggests a rationalization about the construction process through the mapping of resistances to flow, delimited along a certain control domain (constraint). Its central aim is to maximize flows in finite systems by minimizing the resistances, i.e., facilitating the access of their internal currents [4–6]. For application of this physical principle for evaluation of flow systems, it is used a method based on constraints and purposes named Constructal Design or Design with Constructal Theory. This method has not only been employed to show that shape and structure in nature are deterministic, but also for geometric evaluation of the most varied sort of problems such as solid mechanics, refrigeration, electronic, cooling of internal combustion engines, heat exchangers, steam generators, renewable energy, tree nets for transporting people, goods and information and fundamental problems of heat transfer [7–15].

Fundamental heat transfer studies are important in Constructal Design realm, since several observations obtained about the influence of design over heat transfer problems can be extrapolated for other general flow systems. Moreover, many studies about fin arrays or cavities have been performed to improve the understanding about design in flow systems. There are many examples of the importance of these studies in the enhancement of heat transfer in many engineering applications, e.g., heat exchangers, refrigeration and steam generators [16–18].

First work in Constructal Design for evaluation of fins, cavities or high conductive pathways intruded into a heat generating solid was performed by Ref. [4]. In this work, it was solved a problem involving heat generation in a low conductivity finite solid volume (elemental volume) with an inserted high conductive pathway (low resistance medium) to remove the heat generated in the solid domain. Main purpose was to maximize the efficiency of heat dissipation of the solid domain with internal heat generation evaluating the design of inserted high conductive pathways. As a result, the conductive pathways with

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Nomenclature

A	Total Area [m^2]
A_c	Cavity Area [m^2]
CR	Cavity Resolution
d	Distance between an EC and the maximum temperature location
EC	Elemental Constructal
H	Height [m]
L	Length [m]
k	Thermal conductivity [W m $^{-1}$ K $^{-1}$]
q_0	Heat generation [W]
q'''	Volumetric internal heat generation [W m^{-3}]
T	Temperature [K]
x, y	Cartesian coordinates [m]

Greek symbol

θ	Non-dimensional excess of temperature
Φ	Cavity to solid (H x L) area fraction

tree-shaped form were obtained [4,5].

Afterwards, many studies were performed evaluating the influence of several cavities, fins and high conductive pathways shapes over the thermal performance of the solid domain seeking to minimize the non-dimensional maximum excess of temperature. Moreover, the effect of geometric ratios over the thermal performance of the problems was also studied. Concerning the cavities study (which is the scope of this work) one of the precursor works was performed by Ref. [19], where I and T-shaped cavities were evaluated. Results proved that, for the same thermal conditions, the T-shaped configuration behaved better than the I-shaped one. Xie et al. [20] optimized completely the T-shaped isothermal cavity intruded within a trapezoidal solid body. In a following work Biserni et al. [21], studying the H-shaped cavity, it was observed that its thermal performance is three and four times higher than the T- and I-shaped cavities, respectively. In Lorenzini et al. [22] it was observed that T and Y-shaped cavities reduced their overall excess temperature with the increase in volumetric fraction of their single branches (stem). They also demonstrated that the best configurations for the Y-shaped cavity led to a performance 35% superior than those reached for I-shaped one, considering the same thermal and geometric conditions. Afterwards, Lorenzini et al. [8] evaluated a Y-shaped cavity considering the influence of convection heat transfer coefficient over the geometric configurations and thermal performance of the studied cavity. Once the required number of simulations were strongly high, the evaluation of first degrees of freedom were performed by association of Constructal Design with Exhaustive Search (ES) (trying all geometric possibilities) and for more complex problems the optimization was done with Genetic Algorithm (GA). Other contributions about the employment of heuristic methods for cavities evaluation was also performed with Simulated Annealing (SA) and Luus-Jaakola methods [23,24]. In all these studies, the Exhaustive Search (ES) was employed as a benchmark solution to validate the employment of optimization techniques. The seek to reduce the maximum temperature inside the solid domain led to study of other complex configurations for cavity as X-shaped [25], T-Y shaped cavity [26] and T-Y-shaped cavity with lateral intrusions [27]. Recently, Hajmohammadi (2017) [28] evaluated numerically with exhaustive search and Constructal Design a configuration named ψ-shaped cavity.

In a general sense, it is possible to notice that several contributions for the state-of-the-art have been devoted to evaluation of new pre-defined shapes for the cavity or concerning the optimization techniques associated with Constructal Design for geometrical evaluation of cavities. In these works, cavity optimizations have been assumed, and the relationship among their dimensions (height, length, width and others) were optimized. Moreover, studied shapes were not determined or created, being generally chosen based on previous experiences and/or observations of the authors.

Current work follows the ideas proposed by Souza and Ordonez [29]. In their work, it was proposed a construction algorithm that, starting from a low conductivity solid body with internal heat generation, a network channel of high conductivity was built in order to cool down the system. Two other important works, from which some of the ideas developed in this work were inspired are the works of Ordonez et al. [30] and Errera et al. [31].

In present work, a method based on Constructal Theory is proposed in order to build cavity geometries. Only assumption about cavity geometry is that it is formed over a squared grid which size dictates the smallest cavity edge dimension. The construction process is based on the Constructal Theory so that cavity configuration evolves towards to the points of maximum temperature in each evolution step. Thermal diffusion equation is numerically solved for every step of this constructive process.

2. Problem description

A solid body, with dimensions H and L is shown in Fig. 1. The body is assumed to be two-dimensional with constant thermophysical properties. Internal heat generation is imposed to the solid parts and an isotherm cavity is used to cool down the body.

External body surfaces are insulated ($\partial T/\partial x = 0$ and $\partial T/\partial y = 0$) while cavity walls are kept at constant temperature T_0.

For a 2D problem of heat conduction in the solid domain at steady state condition, with internal heat generation and constant thermal conductivity, heat diffusion equation may be expressed as

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

where k is the thermal conductivity [W/m K], T the temperature [K], x and y the Cartesian coordinates [m] and q''' the volumetric internal heat generation [W/m^3].

In terms of total heat generation, q_0, Eq. (1) can be rewritten as

$$k\frac{\partial^2 T}{\partial x^2} + k\frac{\partial^2 T}{\partial y^2} + \frac{q_0}{(A - A_c)W}=0 \tag{2}$$

where A is the total area ($A = H\,L$) [m^2], A_c is the cavity area [m^2] and W the solid width [m]. For current 2D model, $W = 1$ m.

Problem is solved in non-dimensional form on which the following non-dimensional variables are defined:

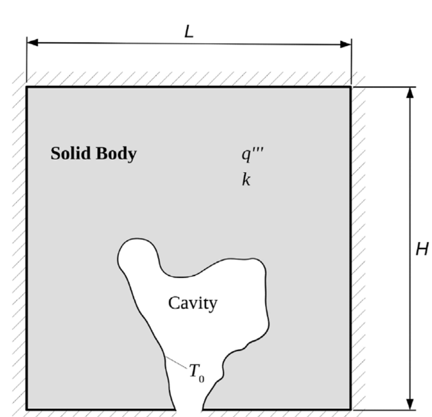

Fig. 1. Problem description.