Energy xxx (2014) 1–9

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Constructal design of cooling channels embedded in a ring-shaped heat-generating body

Mohammad Reza Salimpour*, Amir Menbari

Department of Mechanical Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran

ARTICLE INFO

Article history:
Received 20 March 2014
Received in revised form
5 June 2014
Accepted 7 June 2014
Available online xxx

Keywords:
Tree-shaped construct
Local pressure losses
Distributed pressure losses
Ring-shaped body
Optimization

ABSTRACT

This study outlines the fundamental problem of design and optimization of a tree-shaped flow structure for minimizing overall flow resistance. The flow paths are designed between many points located equidistantly on an internal circle centered at *O* and also many points that are located equidistantly on an external circle centered at *O*. The fluid enters points on internal circle and exits from external circle points. The global volume of channels is constrained. The study is performed on Y-shaped structures with suitable bifurcation. Obtaining the best geometric feature of tree-shaped structures for minimized overall flow resistance is purpose of design and optimization. The influence of several parameters on overall flow resistance is investigated such as number of ducts (n_0) that reach the points on the internal circle, number of branching, internal radius of body disc and mass flow rate. It is demonstrated that the increase in complexity or the number of pairing levels leads to increase in overall flow resistance; however, the best performance is obtained by increasing the number of bifurcations or more number of branching levels. Moreover, the results show that the impact of mass flow rate on the global flow resistance is negligible.

1. Introduction

In this study, suitable flow architectures (layouts) for minimization of global flow resistance are designed. Tree-shaped structure can be observed in the nature and engineering [1]. The applications of tree networks have been applied in the design of animate and inanimate flow systems: lungs, vascularized tissues, river basins and delta, etc [1]. Tree-shaped configuration has been applied in different fields: fluids, electricity, heat, information, etc. [2]. Tree networks used in engineering are mostly inspired from nature, i.e., they are first observed in the nature and then applied in action. The simplest classes of tree-shaped flows are T- and Y-shaped constructs [3]. The important aim of tree-shaped networks is to make suitable connection between one point (source and sink) and a continuum-an infinity of points (volume and area) and obtain architectures for maximum access. An application of dendritic constructs is cooling an electronic body. Cooling electronics and micro-channel bodies is done by two mechanisms of heat transfer: (i) conduction heat transfer [4–10], (ii) convection heat transfer [11–22].

In this article, Y-shaped flow paths are utilized for cooling electronic parts. The purpose of the design is to obtain suitable tree networks for cooling electronic parts such that overall flow resistance of the system is minimized. The minimization of global flow resistance implies on optimization of geometrical features of the system: diagonal of ducts, length of ducts and angle between bifurcations. Usually, in the problem of optimization of tree-shaped constructs for cooling electronics, there exist two sorts of constraint: i) global volume of ducts is fixed and ii) global area of ducts is fixed. In this research, volume constraint is utilized.

An important application of tree networks is cooling the electronics by mechanism of conduction heat transfer [4–10], which is done by embedding high-conductivity inserts in the electronics substrate. For example Lorenzini et al. [7,8] applied constructal theory to find the optimal configurations of uniform and non-uniform X-shaped high-conductivity inserts embedded within a square-shaped heat-generating body of low-conductivity material. Recently, Salimpour et al. [9] used constructal theory to analyze the radial and branching configurations of highly conductive incomplete inserts embedded in a disc for cooling purposes. Daneshi et al. [10] designed micro and nanoscale conductive inserts to cool electronic pieces.

Lorenzini et al. [11,12] used constructal method to optimize the geometry of X- and Y-shaped cavities intruded into a solid

* Corresponding author. Tel.: +98 31 33915210; fax: +98 31 33912628.
E-mail address: salimpour@cc.iut.ac.ir (M.R. Salimpour).

http://dx.doi.org/10.1016/j.energy.2014.06.022
0360-5442/© 2014 Elsevier Ltd. All rights reserved.

conducting wall. The objectives of these studies were to minimize the temperature of hot spots and global thermal resistance between the solid and the cavity, respectively. They further performed a numerical study to optimize the geometry of a C-shaped cavity intruded into a heat-generating body [13]. Salimpour et al. [14,15] invoked constructal theory to optimize the geometry of an array of micro channels and micro-channel heat sinks with different cross sections, respectively. Ghaedamini et al. [16] presented a new configuration for convective cooling of a circular disc using radial and dendritic micro channels. They showed that the usage of reverting micro channels leads to a superior thermal performance of the disc architectures. Wechsatol et al. [17] optimized a tree-shaped design for cooling a disc-shaped body by minimizing the pressure drop between one central point and many points located on the perimeter of the disc. In their work, they considered only distributed pressure drop and neglected the local pressure drops. They further optimized the previous tree structure used for cooling a disc by considering two criteria: minimizing thermal resistance and minimizing distributed pressure drop and observed that these methods lead to nearly the same combined performance [18]. They also neglected local pressure drop in this work.

To consider the local pressure losses, a new property called svelteness, Sv, was used by Lorente and Bejan [19]. This property is defined as the ratio of external (global) length scale to the internal length scale of the system. It is important to keep in mind the differences between svelteness and slenderness. In fact, slenderness describes the components of a system, while svelteness is a parameter which depicts the whole architecture. A complete discussion on this property can be found in Ref. [20].

The effects of svelteness and bifurcation angle on the pressure drop and the flow uniformity of dendritic configurations were studied by Ghaedamini et al. [21]. In this study, svelteness is invoked as a factor which illustrates the significance of bifurcation angle effect on pressure drop and flow distribution uniformity in tree-shaped networks. Their results show that as svelteness increases, flow uniformity is enhanced while the effect of bifurcation angle on the pressure drop is diminished.

Using svelteness, Wechsatol et al. [22] investigated the effects of junction pressure losses on the geometry of tree structures. They observed that the effects of local pressure losses are remarkable when $Sv^2 < 10$.

The present research outlines the design and optimization of dendritic path fluid flow for cooling the electronics with ring-shaped body with global flow resistance minimization. Actually, the present study is devoted to find the best architecture for flow paths with minimum overall resistance between many points located equidistantly on the internal ring and many other points situated equidistantly on the external ring. Moreover in this work, the effect of both local and disturbed flow resistances on optimum dendritic structure is studied.

2. Problem formulation

Our solution consists of designing dendritic flow paths for minimizing the flow resistance between points on internal perimeter of a disc-shaped area of radius r and points on the external perimeter of a disc-shaped area of radius R. The devised tubes in ring-shaped body are of several lengths (L_i, $i = 0,1,2, \ldots$) and diameters (D_i).The fluid flow for cooling is single phase. The coolant fluid on one hand enters tubes that are located on the internal perimeter of disc-body and on the other hand exits via tubes that are located on the external perimeter of disc-body. The regime of fluid flow passed from any tube is laminar and fully developed. The utilized constraint for this problem is that the volume occupied by the total tubes situated in ring-shaped body is fixed. The tree-shaped construct for studying this problem is displayed in Fig. 1.

This figure demonstrates how configuration of flow paths in tree network is utilized in this problem. The ducts with length L_0 and diameter D_0 are drawing radial from the rim of internal circle. The angle between two ducts with length L_0 and diameter D_0, is $\alpha = 2\pi/n_0$, where, n_0 is the number of ducts branched off the rim of internal circle (e.g., $n_0 = 4$ in Fig. 2). The transferred mass flow rate of any tube with length L_0 and diameter D_0 is $\dot{m}_0 = \dot{m}/n_0$. Creating one bifurcation will result in making ducts with length L_1 and diameter D_1 where, $n_1 = 2n_0$ is the number of ducts bifurcated from the first level ducts (L_0, D_0). The mass flow rate transferred in each duct of this level (L_1, D_1) is $\dot{m}_1 = \dot{m}/n_1$. The effect of internal radius of ring-shaped body on variations of flow resistance is investigated. In this problem, internal radius has become non-dimensional by external radius of ring-shaped body (R). In the current work, non-dimensional internal radii 0.0, 0.1, 0.2 and 0.3 were used, respectively. The goal is finding the best ratios of lengths and diameters of ducts such that the flow resistance is minimized. The global pressure loss of ducts (L_i, D_i) for laminar fully developed fluid flow is

$$\Delta P_{\text{tot},i} = \frac{128}{\pi}\nu\dot{m}_i\frac{L_i}{D_i^4} + k_i\frac{1}{2}\rho U_i^2 \tag{1}$$

where, the first and second terms on the right hand side of Eq. (1) indicate the distributed and local pressure losses, respectively. The volume occupied by total tubes situated in ring-shaped body is the constraint of the present problem which is given below.

$$V_{\text{tot}} = \sum_{i=0}^{p}\left(2^i L_i D_i^4\right) \tag{2}$$

The index i is the counter of the tube radial direction ($i = 0,1,2, \ldots, p$) such that $i = 0$ denotes tubes that join to the internal perimeter and $i = p$ denotes tubes that join to the external perimeter of the ring-shaped body.

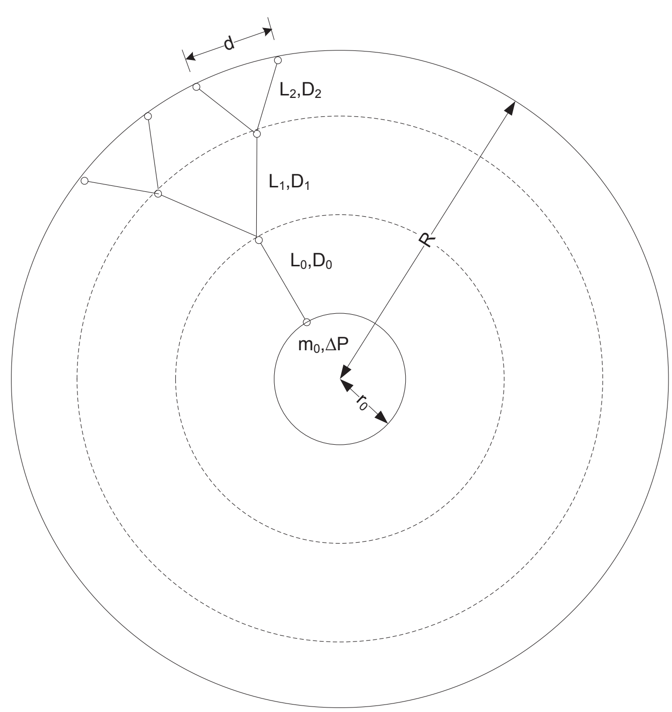

Fig. 1. Tree-shaped construct covering the area of ring-shaped body.