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Constructal design of a comb-like channel network for self-healing and self-cooling

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ABSTRACT

The present work shows how to minimize the global pressure drop in a comb-like channel network with self-healing and self-cooling functionalities implementing the concept of constructal design. A thick channel distributes the fluid flow to many thin channels that are perpendicular to the thick channel. The flow regime throughout the network is assumed to be fully developed laminar flow with negligible local losses. We systematically investigated the degrees of freedom of the fluid channel network, and determined the optimal internal and external aspect ratios of the flow architecture such that the total pressure drop is minimum.

1. Introduction

Vascularization is emerging as the design solution while pursuing the maximum density of heat and mass transfer in the design of smart materials [1–4]. The vascular flow configurations can efficiently provide volumetric healing and cooling agents to the sites of crack and heat generation of smart composite materials such that the mechanical strength and cooling performance can be restored continually [5,6].

Vascular flow configurations require higher pumping power to flow than conventional channel arrangements of heat exchangers because they employ micro-channels in response to the need of compact design [7–13]. Thus, minimizing pressure drop should be a top priority in designing and optimizing the vasculature of smart materials. The methodology is presented in Refs. [1,4,14,15], in which the optimized design constructs were derived, and illustrates and reinforces the emergence of tree-shaped configurations of fluid flowing.

Constructal design of vascularization for smart composite materials has been proposed to the design of self-healing and self-cooling functionalities that have better flow access and cooling performance [1–6]. The approach that has been chosen is constructal theory [6,16,17], which is a mental viewing that the occurrence of flow configurations in nature is a natural phenomenon that evolves over time toward greater and easier flow access [18].

The constructal law describes the time direction of the evolution of flow configuration that has freely morphing for better evolution [18–20]. This approach spreads the flow imperfections through the complex system, so that the system reaches globally a high level of flow performance. In other words, the distributing and redistributing of imperfection through the complex system is accomplished by making changes in the flow architecture. A prerequisite then is for the flow system to be free to morph. The morphing of structure is the result of the tradeoff between the global objective and global constraints [21].

Tree-shaped architectures are the flow configurations derived from the constructal law when the flow is between a point and an area or volume [6,16,17]. Tree-shaped designs, which were not used previously, have invaded the field of engineering such as electronics cooling, fuel cells and compact heat exchangers. For example, Refs. [1–4] showed how to develop vascular flow architectures in smart composite materials with better self-healing and self-cooling performances. They showed that the multiple scales should be pursued in order to approach equilibrium flow architectures [21,22]. Constructal theory is about strategy, about

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Nomenclature

a	diameter ratio
A	area, m^2
b	aspect ratio
C	factor, Eq. (2)
d	elemental length scale, m
D	diameter, m
$D_{h,i}$	hydraulic diameter, m
H	height of system domain, m, Fig. 1
L	length of system domain, m, Fig. 1
L_i	channel length, m
m	scale factor of channel length
$\dot{m}$	mass flow rate, kgs^{-1}
n	number of channel
N	system size $(= m \cdot n)$
Po	Poiseuille constant
R	flow resistance
S	cross section shape factor
Sv	svelteness number, Eq. (1)
V	total volume, m^3
V_c	total flow volume, m^3

Greek symbols

ΔP	pressure difference, Pa
ν	kinematic viscosity, m^2 s^{-1}
ϕ	porosity
μ	flow rate nonuniformity, Eq. (12)
Ψ	non-dimensional global flow resistance, Eqs. (7) and (8)

Subscripts

c	channel
i	channel rank, or mesh current of flow
b	branch
m	minimized
mm	double-minimized
opt	optimal

the lessons of how to discover shape and structure, which are fundamental and universally applicable.

In this paper, we explore the merits of a comb-like tree channel network as shown in Fig. 1 that has functionalities of self-healing and self-cooling. The chief function for the stream is to bathe a volume. A single stream enters through the thick channel and splits into many thin channels. The outlets of the thin channels experience the same reservoir pressure P_0. The distance between consecutive thin channels is constant, d, and it is known and fixed. The composite material is a slab of thickness d. The flow through the network is modeled as steady and incompressible. The optimal designs of the network were developed with two objectives: to determine the internal diameter ratio D_2/D_1 and the external aspect ratio H/L of the vascular volume.

2. Model and pressure drop formulation

The comb-like channel network is defined in Fig. 1. There is one thick channel as the periphery with a diameter D_1, which has many thin channels, i.e., branches, with the same diameter D_2. The fact that D_2 should be smaller than D_1 stems from earlier studies based on the constructal law [1–4,6]. The flow regime through all the channels of the network is assumed to be fully developed laminar flow, dominated by Poiseuille fluid friction, in other words, the local losses at junctions are assumed to be negligible. In order to for the above assumption to be applicable, the svelteness of the flow network, Sv, must be greater than 10 [23].

$$Sv = \frac{(HL)^{1/2}}{V_c^{1/3}} = \frac{\text{external length scale}}{\text{internal length scale}} \tag{1}$$

in which V_c is the total channel volume and $H \cdot L$ is the system domain size. The pressure drop through a straight duct with rank i is

$$\Delta P_i = C \cdot \frac{\dot{m}_i \cdot L_i}{D_{h,i}^4} \tag{2}$$

where $C = 2 \cdot Po \cdot \nu \cdot S/\pi$, and $S = \frac{\pi}{4} \cdot D_{h,i}^2 / A_i$ is the cross section shape parameter proposed in Ref. [24], and A_i is the cross section area of a duct i. Furthermore, $D_{h,i}$ is the hydraulic diameter, and the constant C is determined by the duct shape of cross section. The cross section shape factor S is to measure the deviation of the actual shape from

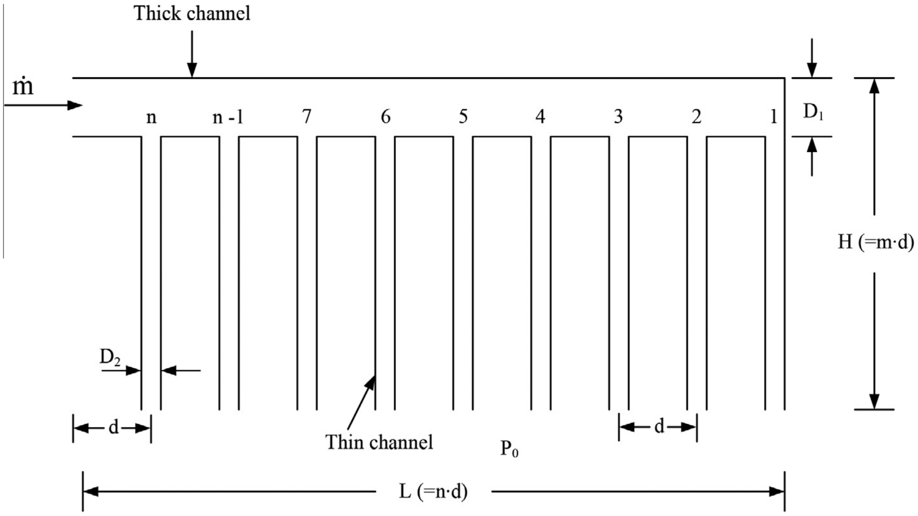

Fig. 1. Comb-like flow network with two diameters (D_1, D_2).