International Journal of Thermal Sciences 48 (2009) 2046–2052

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Transient behavior of vascularized walls exposed to sudden heating

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ARTICLE INFO

Article history:
Received 17 October 2008
Received in revised form
7 January 2009
Accepted 31 March 2009
Available online 8 May 2009

Keywords:
Constructal
Vascularized
Turbine blade cooling
Dendritic
Volumetric cooling
Svelteness
Smart materials
Self-cooling
Optimal spacings
Designed porous media

ABSTRACT

Vascular flow architectures are proposed for controlling the temperature of walls that are subjected suddenly to intense heating from one side. After a short delay, single-phase coolant starts flowing from the other side, and fights off the heating effect. The time-dependent behavior of such vascularized composites is studied and optimized based on full numerical simulations of transient conjugate heat transfer. The focus is on the hot-spot temperatures that build up inside the composite – their evolution, spatial migration, and highest levels. Of interest are vasculature designs that keep the hot-spot temperatures below the safe level associated with long-term operation with steady heating from one side and steady coolant flow from the other side. It is shown that when the driving pressure difference is fixed, the approach to the steady-state temperature is the shortest when the dendrites have an optimal (finite) number of bifurcation levels. The allowable delay time is approximately the same as the duration that the hot-spot temperature reaches the steady-state hot-spot temperature in the absence of coolant.

1. Vascular designs

Constructal theory [1–3] is the view that the generation of flow configuration is a physics phenomenon, and summarizes it as a principle of physics (the constructal law): "for a flow system to persist in time (to live) it must evolve in such a way that it provides easier and easier access to the currents that flow through it" [2].

The current literature shows that the constructal law is used as a scientific principle in engineering design. This body of work was reviewed most recently in Refs. [1,4,5]. Special among the engineering flow architectures derived from the constructal theory are the dendritic (tree-shaped) designs. They are a promising replacement for the traditional engineering flow configurations such as arrays of parallel channels, because tree-shaped configurations are the most effective connections from a point to volume and from volume to a point. This advantage is why tree-shaped designs are now appearing in active technological domains such as manufacturing [6], electronics cooling [7], fuel cells [8], and compact heat exchanger [9–15].

The constructal design work that has been done so far is mainly for steady-state thermal/flow systems. The transient behavior however is critical in applications where sudden, time-dependent heating is the norm (electronics, avionics, thermal management of aircraft, etc.). In this paper we consider this fundamental phenomenon as a time-dependent problem of conjugate heat transfer in a vascularized wall with intense heating from the side and coolant flowing from the other side.

The tree-shaped flow (Fig. 1) endows the wall with the flow architecture that has a global flow resistance close to the lowest level possible [16,17]. At the time $t = 0$, the heat flux q'' impinges on the left side of the wall. After a short delay ($t = t_d$), the coolant flows from right to left, and is driven by the pressure difference imposed across the wall. Here we investigate the transient thermal performance of the vascular wall, by focusing on the evolution of the peak (hot-spot) temperatures inside the wall material.

2. Numerical formulation

We modeled numerically the transient response of a solid wall of thickness L that is heated with uniform heat flux q'' from the left side (Fig. 1). The right side is insulated. The wall is cooled by a single-phase fluid driven by a specified pressure difference ΔP. The wall has many elemental volumes of the kind shown in Fig. 1.

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1290-0729/$ – see front matter
doi:10.1016/j.ijthermalsci.2009.03.019

Nomenclature

Be	dimensionless pressure difference, Bejan number, Eq. (25)
c_p	specific heat at constant pressure, J/kg K
d	smallest length scale, m
D_i	channel diameters, m
H	height, m, Fig. 1
k	thermal conductivity, W/m K
$\tilde{k}$	ratio of thermal conductivities, Eq. (24)
L	length, m
$\dot{m}$	mass flow rate, kg/s, Fig. 1
p	number of pairing levels
P	pressure, Pa
Pr	Prandtl number, Eq. (24)
q''	heat flux, W/m^2
Sv	svelteness number, Eq. (2)
t	time, s
t_c	thermal inertia time, s
t_{ss}	characteristic response time, s, Eq. (26)
T	temperature, K
$\tilde{T}$	dimensionless excess temperature, Eq. (13)
u, v, w	velocity components, m/s
V_c	total volume of channels, m^3
x, y, z	Cartesian coordinates, m

Greek letters

α	thermal diffusivity, m^2/s
ΔP	pressure drop, Pa
μ	viscosity, kg/s m
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
ϕ	porosity, void fraction
τ	time delay fraction, Eq. (28)

Subscripts

d	delay
f	fluid
max	maximum, hot spot
min	minimum
out	outlet
s	solid
ss	steady state

All the channels are round, and the diameters of the channels are sized relative to one another in accordance with the Hess–Murray law [1,18,19],

$$\frac{D_i}{D_{i+1}} = 2^{1/3} \quad (i = 1, 2, \ldots, p) \tag{1}$$

The thickness of the element in the direction perpendicular to the figure is set equal to the spacing d. The vertical dimension H of one element is $2^{p+1}d$, where p is the number of pairing levels (e.g. $p = 3$ in Fig. 1). Several volume elements stacked in the vertical direction in Fig. 1 constitute a slab vascularized with line-to-line tree structures. In the present study we conducted simulations for structures with $p = 1$, 2, 3 and 4.

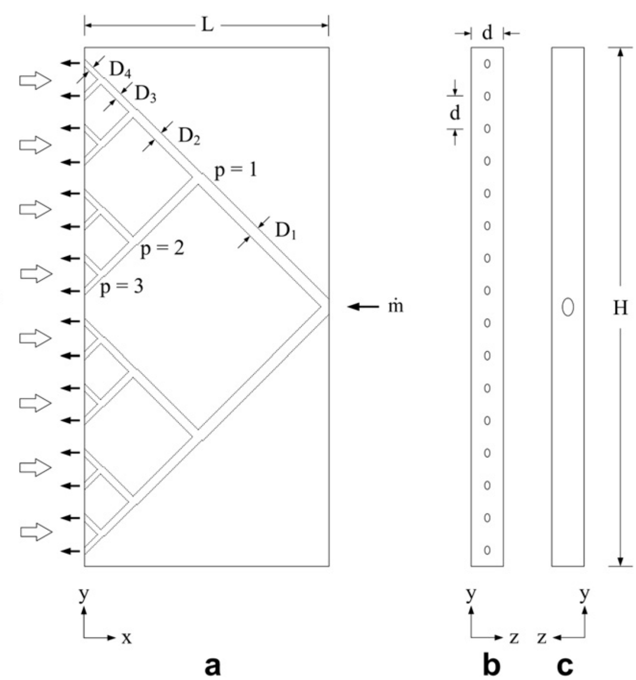

Fig. 1. Tree-shaped flow structure with three levels of bifurcation: (a) the mid plane of the flow element; (b) the view from the left, showing the outlets; and (c) the view from the right, showing the inlet.

The porosity was fixed at $\phi = 0.05$. By "porosity" we mean the volume fraction occupied by all the channels. The vascular structure is not a porous medium in the usual sense, yet, its volume fraction is fixed, for two reasons. Most applications of vascular designs for self-cooling are projected for future vehicles (e.g. aircraft). In such applications, the mass of the structure (mostly solid mass) is fixed, and so is its volume (solid and fluid). These mass and volume constraints translate into a fixed ϕ value, which is the choice made in the present work.

Eq. (1) was selected as a design rule because of its simplicity, and because it is a robust approximation [1] of the optimal ratio of diameters when the flow conditions deviate from the Hess–Murray scenario (Poiseuille flow, one stream divided equally into two streams). In this paper, junction losses and bifurcation asymmetry are taken into account, and consequently the ratio of the flow rates after bifurcation varies in the range 1.3–1.8. The more general form of the Hess–Murray bifurcation rule is given on p. 166 of Ref. [1]. In this paper the bifurcations are asymmetric to the point that each looks more like the letter λ, not Y.

The configuration of a single tree is based on the minimal-lengths method proposed in Ref. [17]. The bifurcations with 90° angles perform very close to the best bifurcations [16]. For example, the global flow resistance of a minimal-length Y-shaped structure exceeds by only 0.5% the global resistance of a fully optimized Y construct [16].

Tree configurations for convection have been studied several authors [3,7–13] by assuming fully developed laminar flow in all the channels. More recently, it was shown that the effect of junction losses is not negligible when the svelteness number Sv is less than 10,

$$Sv = \frac{\text{external flow length scale}}{\text{internal flow length scale}} = \frac{L}{V_c^{1/3}} \tag{2}$$

Svelteness is a global geometric property of the flow architecture [20]: it represents the "thinness" of all the lines of the drawing. In the $Sv < 10$ domain the channels are relatively thick, and full numerical simulations of the flow near every junction and corner are necessary.