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Experimental and numerical investigation of constructal vascular channels for self-cooling: Parallel channels, tree-shaped and hybrid designs

O. Yenigun, E. Cetkin *

Izmir Institute of Technology, Department of Mechanical Engineering, Urla, Izmir 35430, Turkey

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ABSTRACT

In this paper, we show experimentally and numerically how a plate which is subjected to a constant heat load can be kept under an allowable temperature limit. Vascular channels in which coolant fluid flows have been embedded in the plate. Three types of vascular channel designs were compared: parallel channels, tree-shaped and their hybrid. The effects of channel design on the thermal performance for different volume fractions (the fluid volume over the solid volume) are documented. In addition, the effects of the number of channels on cooling performance have been documented. Changing the design from parallel channels to tree-shaped designs decreases the order of pressure drop. Hence increase in the order of the convective heat transfer coefficient is achieved. However, tree-shaped designs do not bathe the entire domain, which increases the conductive resistances. Therefore, additional channels were inserted at the uncooled regions in the tree-shaped design (hybrid design). The best features of both parallel channels and tree-shaped designs are combined in the hybrid of them: the flow resistances to the fluid and heat flow become almost as low as the tree-shaped and parallel channels designs, respectively. The effect of design on the maximum temperature shows that there should be an optimum design for a distinct set of boundary conditions, and this design should be varied as the boundary conditions change. This result is in accord with the constructal law, i.e. the shape should be varied in order to minimize resistances to the flows.

1. Introduction

Advanced technologies require great volumetric cooling capabilities especially in miniature designs [1,2]. Heat transfer surface area is limited in miniature designs, therefore, they cannot be cooled down with natural or forced convection when working fluid is air. Therefore, the current literature focuses on heat transfer enhancement with phase changing materials or forced convection with water, oil or nano-fluids working fluids [3–14]. These methods are essential in order to increase the rate of heat transfer. However, heat load can be of two kinds: deterministic and random [15]. In deterministic heating loads, the heating rate and the surface on which the heat flux is applied is known such as electronic circuits. In random type loads, neither heating rate nor on which surface it is applied are known such as thermal runaway phenomenon in accumulators. Advanced technologies require miniature structures with the capability of cooling itself under deterministic and random heating loads. This requirement can be satisfied with self-cooling structures, which can be obtained by embedding vascular channels inside the body [15–19].

Materials with smart features first suggested by White et al. [20] in 2001. They mimicked the self-healing mechanism of animals, i.e. clot occurrence at the wound in order to seal it. In their autonomic healing concept, healing agents were placed in spheres which can be used once. Later, Bejan et al. [21] discussed that circulating healing agents in embedded vascular channel network enables structure to heal itself countless time.

Kim et al. [16] showed that vascularized structures can also be used to cool a domain on which heat load is applied. Literature also documents how the pressure drop can be minimized with altering design in parallel channel and tree-shaped designs [16–18]. Because the tree-shaped designs promise lower pressure drop values than parallel channels and radial designs, their cooling performance was surveyed in the literature [22–26]. In our previous study, we also numerically investigated the cooling performance of some parallel channels and tree-shaped configurations [27]. Cho et al. [28] numerically investigated the hydrodynamic and

* Corresponding author.
E-mail address: erdalcetkin@gmail.com (E. Cetkin).

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Nomenclature

c_p	specific heat at constant pressure [J kg^{-1} K^{-1}]
d	vascular channel diameter [m]
∇	del operator
$\mathbf{I}$	unit matrix
k_f	thermal conductivity of the coolant fluid [W m^{-1} K^{-1}]
k_s	thermal conductivity of the solid [W m^{-1} K^{-1}]
L	plate width [m]
$L_{channel}$	distributing/collecting channel length [m]
$\dot{m}$	mass flow rate [kg s^{-1}]
n	vector normal to the fluid–solid interface
P	pressure [Pa]
q''	heat flux [W/m^2]
T	temperature [K]
$\mathbf{u}$	velocity vector

Greek symbols

ΔP	pressure drop [Pa]
φ	volume fraction
μ	dynamic viscosity [kg m^{-1} s^{-1}]
ρ	density [kg m^{-3}]

Subscripts

0,1,2,3	index of tree branches
i	index
max	maximum
min	minimum
peak	peak

Superscripts

n	index of mesh independency test
T	transpose of matrix

thermal performance of vascular designs with embedded parallel channels. They have documented the hydrodynamic and thermal characteristics of three different constructs where the complexity of the parallel channel network was altered. Later, Cho et al. [29] documented the performance of the three parallel channel vascular channel network mentioned in Cho et al. [28] numerically and experimentally. Cho et al. [29] documents the hydrodynamic characteristics of vascular channels in details. They have measured the surface temperature of the vascular plate from several locations via thermocouples, and these locations were chosen in the cooled region (active area). These locations do not correspond to the peak temperature values for each design.

Wang et al. [30] uncovered how the mechanical strength of a solid structure can be increased with embedding vascular channels and how it varies with changing the channel design and volume fraction. Later, Cetkin et al. [31] showed how the mechanical strength and cooling performance is affected by the volume fraction and by the shape of the channel configurations. Cetkin et al. [15] uncovered that vascularization provides required cooling for both deterministic and random heat loads. The current literature also shows how vascularization can increase the mechanical strength of a heated domain, and when the effect of thermal stresses can be neglected [31–33]. In addition to vascular channels on self-cooling structures, Cetkin [34] also documents how high-conductivity inserts on vascular channels effects cooling performance.

Here we show experimentally and numerically how a novel hybrid design gains self-cooling capability to a solid structure with minimum energy consumption, i.e. minimum pumping power requirement. The literature lacks of experimental studies on vascularized structures. This study documents both experimental results and their comparison with numerical study results. In addition, a hybrid of parallel channels and tree-shaped configurations is discussed in order to decrease fluid flow and heat flow resistances by following the principles of Constructal Theory, which is a physical phenomenon that states a flow system should evolve freely in order to adapt to the changing conditions [35–37]. Note that, vascularized structures are proposed as adjunct to the phase changing materials and nano-fluidic cooling methods, not to replace them.

2. Model & numerical method

Consider a plate with embedded vascular cooling channels which is subjected to a constant heat flux from one of its surfaces, as shown in Fig. 1. Coolant fluid flows along the embedded cooling channels. The fluid flow is driven by the pressure difference between the inlet and outlet ports of the vascular network. The volume of the vascular channels and the volume of the solid material are fixed. The outer surfaces of the plate are symmetry boundaries ($\partial T/\partial n = 0$) with only exception of the surface on which heat flux is applied, Fig. 1. The symmetry condition is selected because the plate is an elemental domain of a system which consists a number of identical elements. The coolant fluid is water and its thermo-physical properties as a function of temperature are given in Table 1. In addition, the fluid flow is steady and single phase. With these are in mind, the conservation of mass, momentum and energy equations can be written as

$$\rho \nabla \cdot (\mathbf{u}) = 0 \quad (1)$$

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot [-P\mathbf{I} + \mu((\nabla \mathbf{u})^T + \nabla \mathbf{u})] \quad (2)$$

$$\rho c_p \mathbf{u} \nabla T = \nabla \cdot (k_f \nabla T) \quad (3)$$

$$\nabla \cdot (k_s \nabla T) = 0 \quad (4)$$

where ρ, u, μ and P are the fluid density, the velocity vector in the fluid domain, the dynamic viscosity and the pressure, respectively. In addition, ∇ and $\mathbf{I}$ represents del operator and unit matrix. Here T, k and c_p are the temperature, the thermal conductivity and the specific heat at constant pressure. In addition, s and f indices denote solid and fluid. The conservation of the energy at the interfaces require

$$k_f \frac{\partial T}{\partial n}\bigg|_f = k_s \frac{\partial T}{\partial n}\bigg|_s \quad (5)$$

where n is the vector normal to the fluid–solid interface.

Conservation of mass, momentum and energy equations were solved by using a finite element software [38]. First, the plate with parallel cooling channels (semi-circular) was simulated, which is the case discussed in Cho et al. [29], detailed information about the design is given in Table 2. Mesh elements are non-uniform with boundary layer meshes in order to uncover the effect of sudden changes of the gradients near the boundaries. The mesh size was decreased until the criteria of $|(T^n_{peak} - T^{n+1}_{peak})/T^n_{peak}| < 5 \times 10^{-3}$ and $|(\dot{m}^n_{inlet} - \dot{m}^{n+1}_{inlet})/\dot{m}^n_{inlet}| < 5 \times 10^{-3}$ are both satisfied. Relative errors corresponding to the mesh size can be seen in Table 3. The residual was imposed as 10^{-6} in the numerical procedure. Table 3 shows