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Two-dimensional porosity optimization of saturated porous media for maximal thermal performance under forced convection

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ABSTRACT

The current global paradigm of ever-increasing energy consumption while imposing constraints on its generation – i.e., in order to hamper global warming – intensified the need for energy-efficient heat transfer devices, hence, techniques for increasing their global conductance are desirable. Using a canonical problem – forced convection between uniformly heated parallel plates under imposed pressure drop and filled with a saturated packed bed of spheres – the present paper indicates the possibility of augmenting heat exchanger performance by employing optimal 2-D structured porous media, which are found using a 2-D shape function formulation, to modify the flow pattern within the channel. Three types of porous media allocation methods are studied: uniform, 1-D (vertically layered) and 2-D variable porous matrixes. Uniform and 1-D distributions are seem to perform similarly and their performance is associated with the thickness of the thermal boundary layer. The optimal 2-D porosity distributions are observed to create obstacles that drive the core flow towards the heated spots adjacent to the wall. A parametric analysis of this thermal performance enhancing mechanism demonstrates that the minimization of wall temperature strongly correlates with increased flow velocity where heat is dissipated, which causes thinning of the thermal boundary layer and consequently an increase of the heat transfer coefficient. Moreover, due to the hydraulic nature of this technique, the optimal 2-D structures are shown to be independent of the thermal conductivity of the porous matrix.

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1. Introduction

The development of more efficient heat transfer equipment is important because it influences both energy generation – e.g., by impacting power plant efficiency [1] – and consumption – e.g., by affecting cooling power. Consequently, several approaches have been considered in order to enhance thermal performance, out of which a few examples are: the prospect of advanced heat transfer fluids (e.g., nanofluids [2], supercritical fluids [3], mixtures [4]); discovery of novel phenomena and techniques, such as the piston effect in near-critical fluids [5] and channeling effect in porous media [6]; enhancement of existing equipment and techniques, e.g., engineered heat transfer surfaces [7,8], and the design of extended surfaces [9].

In this context, theory-based optimization of thermal systems has an important role in improving existing heat transfer techniques. For instance, Refs. [9,10] discuss the optimization of extended surfaces in heat exchangers and how to design them, Ref. [11] uses a genetic algorithm to unearth a property group that influences heat transfer in prismatic cores, Ref. [12] uses analytical models to find the conditions for which using thermal enhancers in heat exchangers is beneficial. Also, scaling analysis has proven to be a rapid method for finding optimal solutions to heat transfer problems analytically [13]. More information on heat transfer optimization can be found in Ref. [14], which presents a review of several heat transfer studies using genetic algorithm.

While optimization studies have shown to be helpful in the design of heat transfer equipment, optimization studies of porous media are limited. Ref. [15] showed that there is an optimal porosity for natural convection driven flow between parallel plates. Ref. [16] developed a modified genetic algorithm to maximize heat transfer in porous media while simultaneously minimizing material cost in a boundary layer flow with vertically stacked uniform porosity matrixes. The results yielded optimal porosity values. Ref. [17] used a similar methodology for minimizing overheat in natural convection systems and Ref. [18] performed an optimization of a simultaneously finned and porous media-filled heat exchanger. Ref. [19] performed the optimization of a rotary heat exchanger with a porous core and showed that its performance can be improved by spatially adjusting the porosity of the thermal mass.

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Nomenclature

a	shape function coefficient [–]
b	shape function coefficient [–]
B	basis function
c	specific heat [J/(kg·K)]
D	pore characteristic length [m]
f	model function [–]
H	plate-to-plate distance [m]
k	thermal conductivity [W/(m·K)]
K	hydraulic conductivity [m^2]
L	channel length [m]
N	number of basis functions [–]
p	pressure [Pa], number of 1D shape functions [–]
Q	mapping function [–]
s	1-D shape function [–]
S	2-D shape function [–]
T	temperature [K]
u	velocity [m/s]
v	trial function [–]
w	second trial function [–]
x	Cartesian coordinate [m]
y	Cartesian coordinate [m]

Subscripts

e	effective
f	fluid
i	mesh index, basis function index
j	mesh index, 2-D shape function index
k	shape function element index
l	1-D shape function index
min	minimum
max	maximum
q	1-D shape function index
r	mapping coordinate system index
s	solid
T	thermal
x	x-direction
y	y-direction

Superscript

^{0}	standard
*	dimensionless
$\rightarrow$	vector

Greek symbols

α	thermal diffusivity [m^2/s], porosity distribution coefficient [–]
δ	boundary layer thickness [m]
μ	dynamic viscosity [Pa·s]
ϕ	porosity [–]
ξ	mapping variable
ρ	density [kg/m^3]
σ	standard deviation of Gaussian porosity distribution [m]
Ω	dimensionless number analogous to Peclét
Π	number of shape function elements in y-direction
Ξ	Number of shape function elements in x-direction

Dimensionless numbers

Be	Bejan number based on the channel length
$Be(D/L)^2$	Bejan number based on the pore characteristic length
Nu	Nusselt number
Pe	Péclet number

Other authors have also studied variable porosity porous media and their effect on heat transfer. Ref. [20] showed that the presence of a region of higher or lower porosity within a channel can appreciably modify flow patterns, creating inter-layer mixing or cross-flow. Refs. [21,22] have demonstrated that the fabrication of completely uniform packed porous media is difficult, and that variable porosity is a natural occurrence. Refs. [23–25] demonstrated that the influence of porosity gradients adjacent to the heated wall is significant, and that Darcy's law underestimates heat transfer due to its inability in predicting the channeling effect. More recently, Refs. [26,27] have demonstrated heat transfer enhancement in a stacking of variable permeability porous media with larger pores adjacent to the heated wall.

The present paper aims to discover porosity distributions in porous media that maximize heat transfer performance. The objective of minimizing overheating is pursued by considering a canonical parallel plate channel under imposed uniform heat flux and pressure drop, where Darcy's equation is solved numerically along with the local thermal equilibrium energy equation on a packed bed of spheres. A shape function formulation – generalized from what was introduced as an optimization technique by Ref. [28] – allows a genetic algorithm to search for and test several continuous porosity distributions using only a small number of degrees of freedom. The results are reported in terms of three different porous media configurations: uniform, 1-D layered and 2-D spatially variable matrixes.

2. Modelling

Consider a parallel plate channel of length L and plate-to-plate spacing H filled with a porous packed bed of spheres of thermal conductivity k_s and average pore characteristic length D, as shown in Fig. 1. A constant heat flux q″ enters the channel's upper and lower horizontal walls while a specified pressure gradient Δp is imposed between the channel's vertical boundaries, forcing the flow of a fluid of thermal conductivity k_f, density ρ_f, specific heat at constant pressure $c_{p,f}$ and viscosity μ along the channel. The objective is to determine the optimal porosity distribution ϕ, i.e. $\phi = f(x, y)$, that minimizes the overheating within the numerical domain (i.e., maximum temperature at any point within the channel), while using a shape function methodology [28], by studying the cases of constant porosity, 1-D layered porosity and 2-D porosity distributions. Naturally, given the nature of the boundary conditions, the maximum temperature is expected to always occur adjacent to the heated surface. Furthermore, the search for an optimal porosity distribution that minimizes the maximal temperature within the domain is analogous to the maximization the global thermal conductance of the system considered [13,29].

In order to model the fluid flow and heat transfer phenomena involved, the magnitude of the velocity field within the channel is assumed sufficiently small so that Darcy flow is considered [29]. Moreover, because high velocities are not expected, local thermal equilibrium model is assumed to model heat transfer

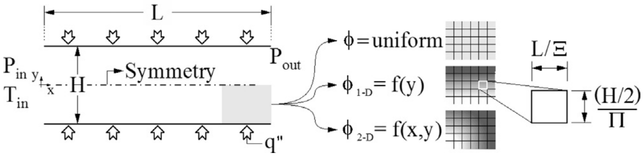

Fig. 1. Sketch of the parallel plate channel with three porous configurations.

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