Computers & Fluids 103 (2014) 49–70

Contents lists available at ScienceDirect

Computers & Fluids

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

Entropy generation-based computational geometry optimization of the pore structure of high-conductivity graphite foams for use in enhanced heat transfer devices

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ARTICLE INFO

Article history:
Received 30 September 2011
Received in revised form 25 June 2014
Accepted 16 July 2014
Available online 24 July 2014

Keywords:
Graphite foams
Porous media
Computational geometry optimization
Entropy generation minimization
Enhanced heat transfer

ABSTRACT

A computational fluid dynamics-based shape optimization process is employed to determine a pore-level geometry for high-conductivity graphitic foams which is optimal with respect to the criterion of entropy generation minimization, under operating conditions relevant to the implementation of such a foam in an enhanced heat transfer device. The optimization procedure is applied to a single pore, subject to operating conditions which reflect a typical pore in the bulk of the foam, far removed from the influences of the macroscopic boundaries of the porous region. Constraints are imposed upon the geometry to ensure the pore structure arrived at may be manufactured by a reasonable process, and to ensure the validity of the analysis. The optimal, ellipsoidal pore geometry obtained is found to achieve a significant reduction in the resistance to convective thermal exchange between constituents, at the cost of an increased resistance to fluid flow.

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1. Introduction

In recent years, there has been a great deal of interest in the use of high-porosity, high-conductivity, open-celled foams in enhanced heat transfer devices. These materials are attractive for such devices because they provide a large amount of exposed surface area for convective heat transfer in a given volume, resulting in designs which may be much lighter and more compact than those based upon conventional extended surfaces. At the same time, the high effective solid constituent thermal conductivities of such foams minimize the resistance to thermal diffusion through their interconnected solid constituents. Accordingly, high-conductivity foams have found a variety of application in the field of enhanced heat transfer, including heat exchangers for aircraft and heat sinks for electronic devices, where compactness and light weight of the thermal management system are of key importance [1]. In the present work, we are particularly concerned with high-conductivity graphite foams of the type illustrated in Fig. 1(c) [2,3]. The interfacial surface area between solid and fluid constituents, per unit volume, arising from the pore-level geometry of such a foam is typically much greater than that found in foams based upon aluminum or other metals [3]. Similarly, the effective solid constituent thermal conductivities of presently available graphite foams are typically much larger than those found for other metal foams, due to the extremely high material conductivity of the graphitized carbon matrix [4]. As a result of the high solid constituent effective thermal conductivity, the resistance to thermal diffusion through the solid matrix of graphite foams tends to be very small. However, the large exposed surface area per unit volume and the characteristics of the pore-level geometries of presently available high-conductivity graphitic foams also lead to a generally strong resistance to fluid flow through the foam, so that large pressure gradients are often required to induce the desired flow rates.

Considering the recent study of Straatman et al. [3], in which the hydrodynamic and thermal performance of simple heat exchangers based upon a variety of graphite foams were compared with previous results for aluminum foam devices, it is evident that a substantial potential exists for the improvement of presently available graphitic foams. Though the graphite foams considered by Straatman et al. [3] possess solid constituent effective thermal conductivities which are typically greater than those of the comparison aluminum foams by an order of magnitude or more, greatly reducing the resistance to diffusion of heat through the pore structure, the heat dissipated by the aluminum foams under identical conditions is often similar. At the same time, the pressure drops observed in the graphitic foams are in all cases much greater, so that the pore-level geometry of the graphitic foam results both

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http://dx.doi.org/10.1016/j.compfluid.2014.07.012
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Nomenclature

a	spherical pore radius (m)
a_i	ellipsoid semi-axis length in x_i direction (m)
a_{sf}	specific surface area (m^{-1})
A	area (m^2)
A_{sf}	interfacial surface area within averaging volume (m^2)
b	cube side half-length (m)
b_i	hexahedron side half-length in x_i direction (m)
Be	Bejan number
Bi	Biot number
c_p	constant pressure specific heat (J/kg K)
d	pore-level length scale (m)
$\mathbf{d}$	line search direction vector
d_{eq}	equivalent spherical diameter (m)
D	averaging volume length scale (m)
$\mathbf{D}$	vector between associated periodic points (m)
$\widetilde{\mathbf{D}}$	diagonal mapping matrix
$\mathbf{e}_i$	Cartesian unit vector in direction x_i
$\mathbf{e}_i^{\boldsymbol{\kappa}}$	unit vector in direction $\boldsymbol{\kappa}_i$
Ec	Eckert number
f_i	constraint function defining feasible region
$\mathbf{H}^{-1}$	positive definite estimate to inverse of objective function Hessian tensor
k	thermal conductivity (W/m K)
J	general objective function
$\tilde{J}$	augmented objective function
$\dot{m}$	mass flow rate
$\mathbf{n}$	outward normal unit vector
N_{opt}	number of optimization parameters
N_S'''	local volumetric entropy generation number
$\overline{N}_S$	total average entropy generation number
Nu_{sf}	interfacial Nusselt number
P	fluid pressure (Pa)
Pr	Prandtl number
q	rate of heat transfer (W)
$\mathbf{q}''$	heat flux vector (W/m^2)
q'''	volumetric heat load (W/m^3)
Re_1	Reynolds number based on streamwise semi-axis length
$Re_{int,1}$	Reynolds number based on intrinsic velocity and streamwise semi-axis length
$Re_{int,23}$	Reynolds number based on intrinsic velocity and transverse semi-axis length
s	specific entropy (J/kg K)
S'''	general volumetric source term
$\dot{S}_{gen}$	total rate of entropy generation (W/K)
$\dot{S}_{gen}'''$	volumetric rate of entropy generation (W/m^3 K)
t	time (s)
T	temperature (K)
T_b	bulk temperature (K)
$\mathbf{u}$	fluid velocity $\mathbf{u} = u_i\mathbf{e}_i$ (m/s)
U	mean inlet velocity (m/s)
$\hat{\mathbf{u}}$	advecting velocity (m/s)
V	averaging volume or general volume (m^3)
$\mathbf{x}$	Cartesian coordinates $\mathbf{x} = x_i\mathbf{e}_i$ (m)
$\mathbf{X}$	mapping function (m)
$\langle\rangle$	denotes volume averaging

Greek symbols

δ	characteristic grid spacing (m)
δ_∇	tolerance for satisfaction of critical point criterion
δ_{feas}	tolerance for satisfaction of feasibility criteria
ε	porosity of porous medium
$\tilde{\gamma}$	penalty parameter
Γ	diffusion coefficient
φ	general scalar, vector, or tensor function
$\boldsymbol{\phi}$	vector of dependent variables
Φ	viscous dissipation function (s^{-2})
$\boldsymbol{\kappa}$	vector of optimization parameters
$\hat{\boldsymbol{\kappa}}$	optimal point in space of optimization parameters
$\boldsymbol{\kappa}'$	critical point in space of optimization parameters
$\Delta\boldsymbol{\kappa}_i$	finite difference step size for calculation of derivatives with respect to $\boldsymbol{\kappa}_i$
λ	line search step size
$\boldsymbol{\Lambda}$	scaling matrix
μ	kinematic viscosity (kg/m s)
η	ratio of ellipsoid semi-axis length to corresponding hexahedron side half-length
Ψ	advective flux limiter
$\theta,\ \tilde{\theta}$	dimensionless temperature
Θ	dimensionless heat load
ρ	density (kg/m^3)
Ω	spatial domain in three dimensions (m^3)
$\boldsymbol{\Omega}_{\boldsymbol{\kappa}}$	feasible region
$\partial\Omega$	area bounding Ω (m^2)
$\partial\boldsymbol{\Omega}_{\boldsymbol{\kappa}}$	boundary of feasible region

Subscripts and superscripts

bnd	boundary node
f	fluid constituent
ip	face-centered integration point
nb	face neighbor of node P
P	cell-centered node under consideration
s	solid constituent
svp	spherical void phase
*	denotes dimensionless quantity

in greater resistance to local thermal exchange between constituents, and in greater resistance to fluid flow through the pore structure, as compared with the aluminum foam pore geometry. Indeed, though the total interfacial surface area between fluid and solid constituents is typically significantly greater for graphite foams than for aluminum foams [3], the results of the recent computational study of Karimian and Straatman [5], who considered the pore-level fluid flow and heat transfer problems in an idealized periodic spherical void phase foam, illustrated in Fig. 1(a) and (b), suggest that much of the interfacial area provided by the pore structure of actual graphitic foams is inaccessible to the flow. This poor interconnectedness of the fluid constituent between pores obviously leads to substantially greater resistances to both convective heat transfer and fluid flow in the presently available foams than would be the case for a foam more closely approximating the idealized structure. These observations are further supported by the findings of Betchen and Straatman [6], who developed a volume-averaged form of the local volumetric entropy generation function valid for fluid flow and heat transfer in high-conductivity porous foams under the assumption of local thermal non-equilibrium, and employed it to consider the entropy generation characteristics of presently available graphite foams. In that work, it was found that in spite of the high resistance to fluid flow observed in present foams, the entropy generation is strongly dominated by the resistance to thermal exchange between constituents. Then, motivated by the foregoing discussion, the present

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