Applied Thermal Engineering 146 (2019) 569–576

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Simultaneous retrieval of high temperature thermal conductivities, anisotropic radiative properties, and thermal contact resistance for ceramic foams

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HIGHLIGHTS

- Simultaneous retrieval of multiple thermal parameters of foam was implemented.
- Transient thermal responses were measured at temperatures up to 900 K.
- Thermal contact resistance was incorporated in thermal models of ceramic foam.
- The identified parameters were compared with experimental and literature data.

ARTICLE INFO

Keywords:
Ceramic foams
Thermal properties
Anisotropic scattering
Thermal contact resistance
Inverse method

ABSTRACT

Open-cell ceramic foams exhibit outstanding thermal, mechanical and exchange properties that make them widely used in various industrial areas with high temperature hostile environments. Deficiency in reliable high temperature thermal properties as well as interface contact attributes brings demanding challenges to precise design and optimization of foams in conditions of usage. Aiming at this problem, the present paper interests in the determination of multiple high temperature thermal parameters for description of conduction and radiation transports taken place within the material as well as contact behaviors between ceramic foams, by inverse identification technology. The thermal contact effect arising from introduction of thermocouples in temperature measurements for ceramic foams was modelled in a new thermal model. On basis of the renewed heat transfer model, three categories of thermal parameters, i.e. conductive properties, anisotropic radiative properties, and thermal contact resistance, were simultaneously reconstructed from a simple and rapid transient thermal measurements. The reliability of the estimated thermal parameters was discussed by comparison with experimental measurements and literature data. It was found that the proposed inverse model demonstrates good behavior to determine critical thermal properties information as well as thermal resistance effect.

1. Literature overview

Open-cell ceramic foams exhibit outstanding thermal, mechanical and exchange properties that make them widely used in various industrial areas with high temperature hostile environments ranging from the core structures for high strength/insulation sandwich panels, burn rate enhancers for solid propellants, solar receivers and heat exchangers, etc. [1,2]. A precise characterization of heat transfer process for this kind of heat exchange material is critical to successful design and optimization of components working at high temperatures as mentioned above. Furthermore, it is also important to understand the fundamental relationship of thermal behavior with microstructures and constituent properties, which provide further guidance on development of novel materials. The thermal phenomena inside ceramic foam can be understood as the coupling and superposition of solid conduction of ligaments, fluid conduction, convection as well as radiation within it. For such porous lightweight material, the effect of free convection inside the foam structure on heat transfer is generally negligible.

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https://doi.org/10.1016/j.applthermaleng.2018.10.021
Received 14 January 2017; Received in revised form 28 September 2018; Accepted 7 October 2018
Available online 09 October 2018

Nomenclature

a	constant
b	constant
c	constant
C	fitted constant
C_p	specific heat of the sample (J·kg^{-1}·K^{-1})
d	constant
d_w	window diameter of pore m
D	pore diameter (m)
F	vector of difference between the measured and calculated values (K)
g	anisotropic scattering factor of phase function
$\widetilde{g}$	equivalent scattering factor of phase function
I	total radiation intensity (W·m^{-2})
I_b	total blackbody radiation intensity (W·m^{-2})
k	the kth iteration
L	thickness of ceramic foam sample m
m	fitted constant
N	number of the measured temperature data
n	fitted constant
q_c	conductive heat flux (W·m^{-2})
q_r	radiant heat flux (W·m^{-2})
t	time (s)
T	temperature (K)
T_0	initial temperature (K)
$T_{c,i}$	the ith calculated temperature data (K)
T_{cold}	cold surface temperature (K)
T_{hot}	hot surface temperature (K)
$T_{m,i}$	the ith measured temperature data (K)
x	spatial coordinate through the sample thickness (m)
x_i	the ith unknown parameter

Greek symbols

β	extinction coefficient (m^{-1})
$\widetilde{\beta}$	equivalent extinction coefficient (m^{-1})
δ	damping parameter
ε_1	emissity of the upper bounding surface
ε_2	emissity of the lower bounding surface
ζ	sensitivity coefficient matrix
θ	polar angle (rad)
Θ	scattering angle (rad)
$\widetilde{\lambda}_{\text{two-phase}}$	equivalent two-phase thermal conductivity (W·m^{-1}·K$^{-1)}$
μ	cosine of the angle between x axis and direction of radiation propagation
$\mu^{'}$	cosine of the angle between x axis and another direction of radiation
Π	identity matrix
ρ	density (kg·m^{-3})
ϕ	porosity
$\widetilde{\Phi}$	equivalent scattering phase function
Ψ	squares of the difference between measured and calculated temperatures
$\widetilde{\omega}$	equivalent scattering albedo

However, the contribution of radiation heat transfer is preponderant at high applied temperature. The heat transfer mechanism of radiation is far more complicated than conduction given the absorption, emission and scattering effects of radiative energy by the solid struts of porous foam. These high temperature phenomena are often hardly acknowledged either by pure experiments or by pure simulations. The characterization of high temperature thermal properties of foams remains to be an open problem.

Comprehensive reviews on the state of the art in determination of conductive and radiative properties of foam materials have been made by Coquard and his colleagues [3], from theoretical modeling to experimental study. As regards the conductive properties of the material, numerous empirical, analytical, or numerical methods [3–13] have been established to predict two-phase thermal conductivity of foams due to solid and fluid conduction. Most recent reports can be found in the research work of Kumar and Topin [14–16]. They firstly generated a database of two-phase thermal conductivity for open cell foams based on the tetrakaidecahedron unit cell and different strut shapes by using 3-D pore scale direct numerical simulations. In their work, the ratios of solid to fluid phase conductivity covered from 10 to 30,000 for porosity range 60–95%. And then, they derived several dependent/independent empirical models of thermal conductivity to account for the large range of solid to fluid phase conductivity ratios, variable porosities, morphological parameters and different strut shapes together. The proposed models were then validated against their numerical database and experimental values reported in literature and were found to yield accurate predictions of two-phase thermal conductivity for different metallic and ceramic foams. Theoretical prediction of radiation properties of high-porosity foams has been the main research focus of many researchers during the last few decades due to the complicated radiation behavior within the material [17–34]. Some of them attempted to generate equivalent regular structures (e.g., cubic, dodecahedral or tetrakaidecahedral) to approximate real foams. Then, a combination of geometric optics approximation, diffraction theory, and Mie scattering theory were usually employed to evaluate the contributions of various particles by considering the material as a dispersion of opaque particles of given shapes. And all the contributions of particles were then summed up to acquire the average properties of foam under the assumption of independent scattering [17–23]. In recent years, owing mainly to the progress in tomography scan imaging technique, researchers [28–34] have started developing models using the real structural data of foams obtained from 3-D reconstruction of CT-scan image. Radiative Distribution Function Identification, Monte Carlo Ray Tracing (MCRT), or radiation heat transfer equation were then used to evaluate the radiation transport within the materials. No matter conductive or radiative properties of foams, from theoretical modeling aspect, prior knowledge on the morphological information, solid properties, and fluid properties must be generally known as the inputs of the corresponding models. However, in practical engineering applications, most of these data are hardly available from standard tables or existing literatures, since small variations in composition, processing parameters and utilization conditions of materials may result in significant changes in their properties and behaviors. The introduction of impurities and additions during foam sintering may change noticeably the optical properties of constituent phases or lead to the forming of surface layers with unknown optical properties. As a consequence, the theoretical modeling method would mostly be restricted to the study of some special aspects such as the detailed structural effect of architecture, validation or calibration of simpler models. In view of this point, inverse method [35–39] has been favored by many researchers to determine thermal properties of high-porosity media, due to its obvious advantage in processing unknown information on ceramic architectures and basic phase properties. In this method, some means for predicting the conductive and/or radiative transport behaviors of the material in question is used in conjunction with experimental data to reconstruct the corresponding properties. The optical measurements are often combined with radiation transfer equation to identify the wavelength-dependent radiative properties [35–37]. If the temperature and heat flow or heat flux are used as experimental inputs [38,39], not only radiative properties but also conductive properties can be obtained. The