Experimental Thermal and Fluid Science 84 (2017) 67–77

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Experimental investigations on temperature-dependent effective thermal conductivity of nanoporous silica aerogel composite

Hua Liu [a], Xinlin Xia [a,*], Qing Ai [a], Xiangqian Xie [b], Chuang Sun [a]

[a] School of Energy Science and Engineering, Harbin Institute of Technology, Harbin, Heilongjiang 150001, China
[b] Beijing Institute of Nearspace Vehicle's Systems Engineering, Beijing 100076, China

ARTICLE INFO

Article history:
Received 14 July 2016
Received in revised form 18 January 2017
Accepted 29 January 2017
Available online 1 February 2017

Keywords:
Silica aerogel composite
Thermal conductivity
Temperature-dependent
High temperature experiments
Genetic algorithm

ABSTRACT

This paper presents an inverse method for retrieving temperature-dependent effective thermal conductivity of nanoporous silica aerogel composite at temperature ranging from 280 K to 1080 K and gas pressure between 0.01 Pa and 100 kPa from experimentally measured transient temperature data. This was achieved by combining a forward method solving combined conductive and radiative heat transfer accounting for temperature-dependent thermal conductivity, and an inverse method based on a real-valued genetic algorithm (GA) optimization. First, the sensitivity coefficients for the transient temperature profiles with respect to the variation of effective thermal conductivity were investigated. Then, several numerical experiments, in which the "experimental data" was numerically generated, were performed to illustrate the robustness and accuracy of the inverse method for retrieving the temperature-dependent effective thermal conductivity from transient temperature history. The experimental data were used to retrieve the effective thermal conductivities of silica aerogel composite, the results fell within 0.014–0.044 $W\cdot m^{-1}\cdot K^{-1}$ for the temperature between 280 and 1080 K and gas pressure from 0.01 Pa to 100 kPa, and showed nonlinear increasing trend with increasing temperature, and with increasing gas pressure.

1. Introduction

Silica aerogels are lightweight super thermal insulation materials featuring low density, high porosity (up to 99.8%), small average pore size (2–50 nm), high specific surface area (up to 1300 $m^2\cdot g^{-1}$), and very low thermal conductivity (0.005–0.02 $W\cdot m^{-1}\cdot K^{-1}$) at ambient temperature [1–5]. Pure silica aerogels are brittle and featuring poor mechanical properties [6], thus different types of fibers, such as glass fibers [7,8], ceramic fibers [9,10], and aramid fibers [11], are usually added in the silica aerogels as reinforcements to enhance their mechanical properties, the details about mechanical reinforcing strategies for silica aerogels can be found in the literature [5]. Moreover, the silica aerogels are semi-transparent in the near-infrared spectral range (3–8 μm) [12–14], thus the role of thermal radiation is expected to be significant, especially for high temperature applications. Fortunately, the strong radiative transfer can be reduced by adding opacifier particles such as TiO_2 [14], SiC [15], and carbon black [12,16], which attenuate strongly the infrared thermal radiation. The opacifier particles usually featuring spherical shape with diameters of about 2–5 μm, and occupy a small volume fraction in order to maintain the high porosity of the composites. The fiber reinforced and/or opacifier doped silica aerogels were also called nanoporous silica aerogel composite (NSAC), they have found excellent potential practical applications for thermal insulation systems including aerospace [17], energy storage [18,19], solar energy [20,21], construction and building [22].

Heat transfer in NSAC include contributions of solid conduction, gas conduction, coupled solid-gas conduction, and thermal radiation, gas convection can be neglected due to their nanoporous structures [23–25]. Radiative transfer in most opacified NSAC can be regarded as a diffusion process as the photon mean free path is usually much smaller than the characteristic length of the materials used in the practical applications [2,3,25]. Thus, the effective thermal conductivity $k_{eff}(T)$, written as the sum of solid thermal conductivity $k_{c,s}(T)$, gaseous thermal conductivity $k_{c,g}(T)$, solid-gas coupling thermal conductivity $k_{c,c}(T)$, and radiative thermal conductivity $k_r(T)$, can be used to characterize combined conductive and radiative heat transfer in the NSAC. Therefore, knowing the NSAC effective thermal conductivity is essential in the process of designing and evaluating the thermal insulation systems in the above practical applications.

---

* Corresponding author.
E-mail addresses: Xiaxl@hit.edu.cn, hitaiqing@hit.edu.cn (X. Xia).

http://dx.doi.org/10.1016/j.expthermflusci.2017.01.021

Nomenclature

c_p	specific heat, $J{\cdot}kg^{-1}{\cdot}K^{-1}$
c_v	volumetric specific heat, $MJ{\cdot}m^{-3}{\cdot}K^{-1}$
f_v	volume fraction
F	fitness function
k	thermal conductivity, $W{\cdot}m^{-1}{\cdot}K^{-1}$
L	thickness, mm
M	number of data points
n	index of refraction
N	number of sampling temperature points
P	pressure, Pa or kPa
q	heat flux, $W{\cdot}m^{-2}$
t	time, s
T	temperature, K or °C

Greek symbols

β	extinction coefficient, m^{-1}
χ	sensitivity coefficient
Δ	percentage change of thermal conductivity
ΔT	Temperature difference, K
ϕ	porosity
Φ	phase function of scattering
κ	density, $kg{\cdot}m^{-3}$
σ	Stefan-Boltzmann constant, $\sigma = 5.67 \times 10^{-8}\ W{\cdot}m^{-2}{\cdot}K^{-4}$
σ_s	scattering coefficient, m^{-1}
σ_T	temperature standard deviation, K
ω	scattering albedo
ξ	normal distribution random number

Subscripts and superscripts

ae	aerogel
c	conduction
C	center plane
c, c	solid-gas coupling conduction
eff	effective
com	composite
exp	experiment
f	furnace
fi	fiber
g	gas
g, c	gas conduction
H	high temperature
L	low temperature
m	the mth discrete thermal conductivity
λ	spectral
op	opacifier
pred	prediction
R	Rosseland mean
r	radiation
s	solid
S	steady-state
s, c	solid conduction

Numerous theoretical and numerical models have been developed to predict the effective thermal conductivity of NSAC based on their compositions, fractions, porosity, specific surface area, thermal conductivities of bulk materials, and their simplified microstructures. He and Xie [2] and Bouquerel et al. [25] have reviewed the models for predicting the NSAC effective thermal conductivity and its separated contributions, and there is no need to repeat the survey.

Compared with the theoretical and numerical models, experimental studies for measuring the effective thermal conductivity of NSAC at high temperatures remain relatively limited. The experimental methods can be divided into steady-state [7,26–28] and transient methods [23,31–38]. Yuan et al. [7] measured the effective thermal conductivity of glass fiber and TiO_2 particle loaded silica aerogel material at temperature between 300 °C and 700 °C from the steady-state method based on Fourier's law, the weight fractions of fiber and TiO_2 opacifier of the specimens were ranging from 10% to 25% and from 0 to 20%, respectively. Lee and Cunnington [26] investigated combined conduction and radiation in high-porosity NSAC, a series of experiments were performed to measure the effective thermal conductivity of NSAC using a guarded heat flow meter based thermal conductivity apparatus, the temperature range investigated was 350–1200 K. Smith et al. [27] measured the effective thermal conductivity of carbon opacified silica aerogels at ambient temperature with gas pressure between 1.0 and 10^5 Pa using a hot plate method. It should be noticed that the measured data based on steady-state method is usually regarded as the effective thermal conductivity at the mean temperature of the hot and cold surfaces of the specimen. This is true if the thermal conductivity is linear dependent on temperature, or the temperature difference between the two surfaces is small [28]. As the effective thermal conductivity of NSAC may increase nonlinear with increasing temperature due to radiation contribution, which is approximately proportional to the third power of temperature according to Rosseland diffusion approximation [29,30], thus a small temperature difference between the hot and cold surfaces of the specimen should be guaranteed to improve the accuracy of the measured effective thermal conductivity.

For transient methods, Wei et al. [31] measured the thermal conductivities of silica aerogels and their composite at temperature between 300 and 970 K and pressure from 0.045 Pa to 100 kPa by employing the transient hot-trip method [32]. Kwon et al. [33] investigated thermal conductivity of ambient-dried silica aerogel and TiO_2 powder doped composite for thermal insulation at temperatures between 25 and 400 °C using transient hot wire technique [34]. Transient plane source (TPS) method proposed by Gustafsson [35] is also be used to measure thermal conductivities of silica aerogels and their composite [23,36,37]. The Hot Disk thermal constant analyzer is one of typical instrument based on TPS method, it offers three types of sensors, i.e., the kapton, mica, and Teflon sensors, for experiments above 300 °C, only the mica sensor with thickness of 115 μm can be used. However, the use of mica sensor may overestimate effective thermal conductivity of materials with low thermal conductivity (less than $1.45\ W{\cdot}m^{-1}{\cdot}K^{-1}$) due to the non-negligible heat lose through the sensor side according to literature [36]. It can be seen that the effective thermal conductivity of NSAC measured from the transient experiments is generally below 1000 K. Besides, in order to measure the temperature-dependent effective thermal conductivity, the experiments should be performed several times as each single experiment can measure the effective thermal conductivity at only one specified temperature. Moreover, due to the excellent thermal insulation performance, the temperature uniformity of the NSAC specimen is difficult to be guaranteed when performing high temperature experiments.

This manuscript presents an inverse method for retrieving the effective thermal conductivity of NSAC at temperature ranging from 280 K to 1080 K and gas pressure between 0.01 Pa and