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Research paper

Simultaneous reconstruction of thermal degradation properties for anisotropic scattering fibrous insulation after high temperature thermal exposures

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HIGHLIGHTS

- A new model is developed to probe conductive and radiative properties degradation of fibers.
- To characterize mechanical degradation, a new parameter is introduced in the model.
- Thermal degradation properties are reconstructed from experiments by L–M algorithm.
- The effect of microstructures on the thermal degradation parameters is evaluated.
- The analysis provides a powerful tool to quantify thermal degradation of fiber medium.

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ABSTRACT

To probe thermal degradation behavior of fibrous insulation for long-term service, an inverse analysis model was developed to simultaneously reconstruct thermal degradation properties of fibers after thermal exposures from the experimental thermal response data, by using the measured infrared spectral transmittance and X-ray phase analysis data as direct inputs. To take into account the possible influence of fibers degradation after thermal exposure on the conduction heat transfer, we introduced a new parameter in the thermal conductivity model. The effect of microstructures on the thermal degradation parameters was evaluated. It was found that after high temperature thermal exposure the decay rate of the radiation intensity passing through the material was weakened, and the probability of being scattered decreased during the photons traveling in the medium. The fibrous medium scattered more radiation into the forward directions. The shortened heat transfer path due to possible mechanical degradation, along with the enhancement of mean free path of phonon scattering as devitrification after severe heat treatment, made the coupled solid/gas thermal conductivities increase with the rise of heat treatment temperature.

1. Introduction

High-porosity fibrous media are effective insulation materials for high temperature application, e.g. thermal protection system, owning to the ability of fibers to suppress radiative transport by absorption and scattering [1,2]. In their applications, they are subjected to intense heat over prolonged periods of time. So far, the most predominant fibrous products supplied for high temperature application are supercooled glass fibers and exist in an amorphous state. Devitrification and grain coarsening, with the attendant microstructure changes such as shrinkage, embrittlement and even sintering, can occur during normal service life of such products, which in most cases are harmful for the physical properties of the material. It is crucial to monitor thermo-optical properties degradation of fibrous materials, since such degradation directly affects their insulating performances and thus endangers the missions.

Though great experimental efforts have been made to explore the crystallization behavior and microstructure changes taking place in ceramic fibers submitted to high temperatures in recent years [3–7], the thermal properties degradation data induced by

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Nomenclature

A	linear coefficient of scattering phase function
C	a global property parameter
c	specific heat of the sample, J kg^{-1} K^{-1}
D^*_{ASL}	the ratio of the modified factor of extinction coefficient to the thickness of the infrared sample, m^{-1}
E	Young's modulus of fiber, GPa
e_b	blackbody emissive power, W m^{-2}
$e_{b\lambda}$	spectral blackbody emissive power, W m^{-2}
F_{SD}	an accommodation parameter
f_v	solid fraction ratio
f_ξ	modified factor of extinction coefficient
g_λ	anisotropy factor
I	radiation intensity, W m^{-2}
I_b	blackbody radiation intensity, W m^{-2}
K_c	thermal conductivity due to gas/solid conduction, W m^{-1} K^{-1}
K_g	thermal conductivity due to gas, W m^{-1} K^{-1}
K_s	thermal conductivity due to solid fibers, W m^{-1} K^{-1}
k^*_s	thermal conductivity of fiber parent material, W m^{-1} K^{-1}
k^*_{sa}	thermal conductivity of amorphous phase, W m^{-1} K^{-1}
k^*_{sm}	thermal conductivity of mullite crystal, W m^{-1} K^{-1}
k^*_R	equivalent Rosseland mean extinction coefficient, m^{-1}
L	insulation thickness, m
L_τ	sample thickness in spectral transmittance measurement, m
N	number of the measured temperature data
n	an exponent
P	imposed pressure, Pa
P_1	porosity due to parallel
P_2	porosity due to series
P_t	total porosity
q_c	conductive heat flux, W m^{-2}
q_r	radiative heat flux, W m^{-2}
q_t	total heat flux, W m^{-2}
T	temperature, K
t	time, s
T_0	initial temperature, K
T_1	hot side temperature, K
T_3	cold side temperature, K
T_{ci}	i th calculated temperature data, K
T_{mi}	i th measured temperature data, K
X	unknown vector
x	position, m
X_c	crystallinity of mullite

Greek symbols

β_λ	spectral extinction coefficient, m^{-1}
β^*_λ	weighted spectral extinction coefficient, m^{-1}
γ	fraction of the fibers oriented parallel to the heat flux
ε_1	emissivity of the upper bounding surface
ε_2	emissivity of the lower bounding surface
θ	fiber orientation, rad
λ	wavelength, m
μ	cosine of the angle between the x axis and the direction of radiation propagation
μ'	cosine of the polar angle of another direction
ν	Poisson's ratio
Π	porosity
ρ	density, kg m^{-3}
$\tau_{n\lambda}$	spectral transmittance
$\overline{\Phi}$	scattering phase function averaged over the in-scattering azimuth
ψ'	Azimuthal angle, rad
ω^*	equivalent Albedo of scattering
ω^*_λ	weighted spectral Albedo of scattering

microstructure changes are rather scarce, in spite of the importance of confidence level in thermal properties of fibers when used for high reliability components. The fibrous materials are semi-transparent, strongly anisotropic scattering, and of high porosity [8]. The heat conduction and radiation transportation within the material are strongly coupled together depending on the microstructural parameters of particles and application conditions [9]. The conjugate nature and complex scattering mechanisms make the thermal properties measurement be a difficult task. For the determination of thermal properties degradation of fibrous medium, the inverse identification method [10–15] provides a more prospective way than direct theoretical modeling [16–20], since it is far more difficult to acquire a very good morphological and physical knowledge of the degenerated fiber system needed for theoretical modeling, e.g. particle distributions, refractive index, and others. Coquard et al. [11–13] developed two dimensional simulations of transient coupled heat transfer to estimate the conductive and radiative properties of several foams from flash or hot-wire measurement experiments. They discussed the possibility to extend these methods to the low-density insulation materials where a significant part of heat transfer is due to the propagation of thermal radiation. Lazard et al. [15] provided a complete methodology to estimate the intrinsic diffusivity of semi-transparent media by theoretical and experimental study. Semi-analytical results based on conductive and radiative analysis were compared with the measured data of rear face temperature obtained by infrared detection for a wide temperature range and several radiation boundary conditions. The inverse method is superior to other experimental or theoretical methods in that multiple physical properties can be obtained simultaneously through limited experiments by using adequate materials. This method will be persued in the present paper to quantify the thermal–optical properties degradation in fibrous materials after thermal exposure.

In previous work [21], the microstructure and thermal properties changes of fibrous insulation were examined before and after thermal exposures at high temperatures. The initial understanding of thermal properties evolution mechanisms was obtained. For this investigation, the goal was to develop more in-depth thermal coupled analysis models to predict thermal properties degradation for fibrous insulation, on the basis of infrared transmission spectra and phase content, rapidly analyzed by X-ray diffraction. The material constants in the governing equations will be identified from the experimental temperature data by inverse technique, and the effect of microstructures degradation on the adjustable thermal parameters is discussed.

2. Materials and experiments

The material used in this study is a commercial amorphous alumino-silicate fiber material with nominal porosity of 95%. The