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Measurement of the contribution of radiation to the apparent thermal conductivity of fiber reinforced cement composites exposed to elevated temperatures

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ABSTRACT

The contribution of radiation to the apparent thermal conductivity of fiber reinforced cement composites exposed to a thermal pre-treatment up to 1000 °C is investigated using Fourier transform infrared (FTIR) spectrometry. The transmittance spectra are measured in the wavelength range of 2.5–16 μm. The radiative thermal conductivity is then calculated using the spectral extinction and Rosseland mean extinction coefficients. Experimental results show that for the analyzed materials radiation can represent up to 4.54% of the apparent thermal conductivity. The expanded uncertainty of the measurement is found within the range of 12.4–15.9%, being affected by the accuracy of the FTIR spectrometer in the most significant way.

1. Introduction

Heat transport in porous media is generally a very complex phenomenon. Unlike homogenous solid bodies, it is affected by the structure and geometry of pores and grain size. Additionally, all modes of heat transport may occur and play a significant role. Thus, one needs to take into account solid conduction through the material matrix, gas conduction and natural convection in the pores, and radiation interchange through the participating media. Obviously, the role of the individual modes can be assessed by determining their contributions to the overall heat transfer. The latter may be expressed via the effective (or apparent) thermal conductivity – a generalization of the classical Fourier thermal conductivity that enables one to describe complex heat transfer problems in which such phenomena as moisture transport, phase transformations and chemical reactions can be also included [1–3]. The effective thermal conductivity has been studied for several types of porous materials before, among them fibrous insulations [4–10], aerogels [11–14], cement composites [15–18], foamed materials on a concrete [19–21], metallic [22,23], ceramic [24,25] or plastic [26,27] base. It was also determined for large nonhomogeneous samples, such as highly perforated ceramic blocks [28]. However, for a better understanding of heat transfer in porous materials, it is useful to focus on the individual contributions to the effective thermal conductivity separately, which can be done using specific experimental techniques.

Besides the conduction mode of heat transfer which is traditionally considered, also radiation may play a significant role in porous media and its influence is increasing with temperature [14,29]. Furthermore, according to the recent studies radiation is particularly involved in heat transport processes in highly porous materials such as thermal insulations. Namely, for silica aerogels at room temperature the radiative contribution was found to be ~10% and above 700 K it was as high as ~85% [12–14], for high-alumina fibrous insulators it was between 10 and 50% in the temperature range of 350–700 K [4], for glass wool reinforced by aluminum foil ~10% in a narrow temperature range of 300–320 K [8], and for rock wool ~5% at 300 K, increasing up to ~ 50% at 1300 K [5]. The radiative contribution to the thermal conductivity of foamed materials, such as expanded glass, expanded clay, or expanded perlite and foam glass, was found within the range of 20–60% at 370 K [6]. The contribution of radiation to the thermal conductivity of materials

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Nomenclature

A [m^2] cross-section area of the circular pellet
β_λ [m^{-1}] spectral extinction coefficient
β_R [m^{-1}] Rosseland mean extinction coefficient
c [J kg^{-1} K^{-1}] specific heat capacity
c_0 [m s^{-1}] speed of light
d [m] diameter of the pellet
h [m^2 kg s^{-1}] Planck constant
i [−] number of measurements
k [−] coverage factor
k_B [m^2 kg s^{-2} K^{-1}] Boltzmann constant
κ_λ [m^{-1}] absorption coefficient
L [m] equivalent path length
λ [W m^{-1} K^{-1}] thermal conductivity
λ^* [W m^{-1} K^{-1}] apparent thermal conductivity
λ_R [W m^{-1} K^{-1}] radiative thermal conductivity
m [kg] mass of pellet
m_{KBr} [kg] mass of potassium bromide
m_{SC} [kg] mass of SC-sample
n [−] refractive index of material
p [% kg kg^{-1}] mass percentage of the sample in the pellet
q [W m^{-2}] heat flux
q_r [W m^{-2}] radiative heat flux
$q_{R\lambda}$ [W m^{-2}] spectral radiative heat flux
ρ [kg m^{-3}] bulk density
ρ_m [kg m^{-3}] matrix density
σ [W m^{-2} K^{-4}] Stefan–Boltzmann constant (5.67 × 10^{-8} W m^{-2} K^{-4})
σ_λ [m^{-1}] scattering coefficient
T [K] temperature
T_{meas} [K] temperature during the measurement
T_λ [%] spectral transmittance
U expanded uncertainty
u_A standard uncertainty of type A
u_B standard uncertainty of type B
u_c combined standard uncertainty
ψ [% m^3 m^{-3}] porosity

with lower porosity was studied not as frequently but it was also proved although it was less important [29–32].

The main objective of the presented study is to investigate the radiation contribution to the apparent thermal conductivity of fiber reinforced cement composites (FRCC) exposed to high temperatures, which is of relevance for fire resistance of building structures. Using the loading temperatures of 600 °C, 800 °C and 1000 °C, the effect of thermal treatment on the radiation thermal conductivity is analyzed. The results are also compared with the untreated specimen, in order to emphasize the effect of thermal treatment.

2. Samples preparation

The FRCC investigated in this paper was prepared in the Research Institute of Building Materials, Brno, Czech Republic, using an OMNI MIXER 10 EV vacuum mixing device. The material's composition is given in Table 1. The studied samples were prepared on a cement base with an addition of glass and polypropylene fibers. In the experimental measurement, the samples were pretreated at several different temperatures by anisothermal heating. Namely, they were exposed to a gradual temperature increase up to 600, 800, and 1000 °C during 2 h, then they were kept at this temperature for two more hours, and finally slowly cooled to ambient temperature. These samples were labeled as SC-600, SC-800, and SC-1000, respectively, in the agreement with their loading temperature. In addition, a reference sample without temperature exposition (labeled as SC-25) was investigated.

For each type of samples its porosity, bulk density, and matrix density were measured (see Table 2). Note that the largest change in the porosity occurs between samples SC-25 and SC-600: the corresponding relative increase is as high as ~33%. For samples SC-600, SC-800, and SC-1000 the porosity variations were less than 10%. This behavior is in agreement with most Portland cement-based composites where the decomposition of calcium hydroxide at about 460–480 °C takes place [36].

3. Determination of radiative thermal conductivity

The studied materials are optically thick. That means, radiation travels only a short distance before being scattered or absorbed and the local intensity is the result of radiation from only nearby position being considered. In this situation, integral relation for the radiative energy can be approximated by diffusion equation like that for heat conduction [34,35]. Then,

$$q_R = -\lambda_R \ \mathrm{grad} \ T \tag{1}$$

with λ_R being interpreted as the radiative thermal conductivity and given as

$$\lambda_R = \frac{16\sigma\, n^2 T^3}{3\beta_R}, \tag{2}$$

where n is the refractive index of the material and σ is the Stefan–Boltzmann constant. The Rosseland mean extinction coefficient β_R is a weighted average of the inversed spectral extinction coefficient β_λ, using the temperature derivative of the Planck power distribution $u_T(\lambda)$ as the weighting function,

$$\frac{1}{\beta_R} = \frac{\int_0^\infty \frac{1}{\beta_\lambda}\frac{\mathrm{d}u_T(\lambda)}{\mathrm{d}T}\mathrm{d}\lambda}{\int_0^\infty \frac{\mathrm{d}u_T(\lambda)}{\mathrm{d}T}\mathrm{d}\lambda} = \frac{\pi n k_B^5 T}{2\sigma h^4 c_0^3}\int_0^\infty \frac{1}{\beta_\lambda}\left(\frac{\lambda_T}{\lambda}\right)^6 \frac{e^{\lambda_T/\lambda}}{\left(e^{\lambda_T/\lambda}-1\right)^2}\mathrm{d}\lambda, \tag{3}$$

Table 1
Composition of the FRCC (taken from Ref. [33]).

	Mass %
Cement CEM I 52.5	54.0
Quartz sand aggregates 0–1 mm	40.0
Microsilica	3.0
Glass fibers 12 mm length	2.7
Polypropylene fibers 30 mm length	0.3

Table 2
Basic physical properties of FRCC (taken from Ref. [33]).

Material	ψ [% m^3 m^{-3}]	ρ [kg m^{-3}]	ρ_m [kg m^{-3}]
SC-25	24 ± 1	2021 ± 20	2660 ± 27
SC-600	32 ± 1	1947 ± 20	2899 ± 29
SC-800	35 ± 1	1909 ± 19	2954 ± 29
SC-1000	33 ± 1	1871 ± 19	2799 ± 28