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Research Paper

# Characterization of the thermal properties of fibrous insulation materials made from recycled textile fibers for building applications: Theoretical and experimental analyses

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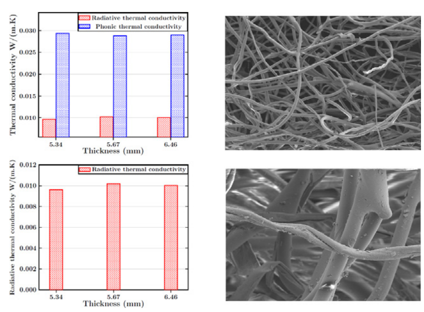
## HIGHLIGHTS

- The inverse method is used to obtain the radiative properties of the studied material.
- Radiative properties strongly depend on both wavelength and material thickness.
- Phonic thermal conductivity is deduced from the effective thermal conductivity.
- Radiative thermal conductivity is of very little effect.
- Material thickness exerts an influence on radiative and phonic thermal conductivity.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

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## ABSTRACT

The present study focuses on the thermal characterization of an insulation material made from recycled textile fibers for building applications, which qualifies as a semi-transparent medium. Experimental and numerical studies have been carried out to determine the radiative flux ratio for such a recycled textile fiber-based insulation for three thicknesses (5.35 mm, 5.67 mm and 6.64 mm). The inverse method, which relies on reflection and transmission measurements using a Fourier-Transform Infrared Spectrometer coupled to an integrating sphere, has been applied along with a least squares procedure. The relevant radiative properties of recycled textile insulation material are obtained by minimizing the deviation between experimental and theoretical data. The effective thermal conductivity of the fibrous insulation is measured at room temperature by means of a fluxmeter device. The radiative thermal conductivity is estimated by implementing the Rosseland model, while phonic conductivity is derived from the effective thermal conductivity. The radiative thermal conductivity displays a very limited effect in comparison with phonic thermal conductivity; the latter varies according to thickness, which in turn is determined by fiber density and size. Phonic thermal conductivity accounts for 26% of the effective thermal conductivity and moreover constitutes a large share (74%) relative to the radiative conductivity. The maximum radiative thermal conductivity value equals 0.0102 $W\,m^{-1}\,K^{-1}$ for a thickness of 5.67 mm, with this value dropping slightly to 0.010 $W\,m^{-1}\,K^{-1}$ for a thickness of 6.46 mm, and to a minimum value of 0.0096 $W\,m^{-1}\,K^{-1}$ at a 5.35-mm thickness.

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**Nomenclature**

| | |
|---|---|
| T | temperature, K |
| $T_c$ | temperature of cold plate, K |
| $T_h$ | temperature of hot plate, K |
| $\Delta T$ | temperature difference, K |
| $k_{eff}$ | effective thermal conductivity, $W\,m^{-1}\,K^{-1}$ |
| $k_c$ | phonic thermal conductivity, $W\,m^{-1}\,K^{-1}$ |
| $k_{conv}$ | convective thermal conductivity, $W\,m^{-1}\,K^{-1}$ |
| $k_r$ | radiative thermal conductivity, $W\,m^{-1}\,K^{-1}$ |
| $k_g$ | gas thermal conductivity, $W\,m^{-1}\,K^{-1}$ |
| $k_s$ | solid thermal conductivity, $W\,m^{-1}\,K^{-1}$ |
| $k_F$ | thermal conductivity due to conduction in fibers, $W\,m^{-1}\,K^{-1}$ |
| $k_G$ | thermal conductivity due to the gas in the material, $W\,m^{-1}\,K^{-1}$ |
| $P_\lambda$ | spectral phase function |
| $I_\lambda$ | spectral radiation intensity, $W\,m^{-2}\,\mu m^{-1}\,sr^{-1}$ |
| $I_o$ | incident radiation intensity, $W\,m^{-2}$ |
| $I^\circ$ | blackbody radiation intensity, $W\,m^{-2}$ |
| $T\lambda$ | spectral transmittance |
| g | acceleration due to gravity, $10\,m\,s^{-2}$ |
| $C_p$ | specefic heat of air at constant pressure, $kJ\,kg^{-1}\,K^{-1}$ |
| P | permeability of the solid skeleton |
| $Ra^*$ | modified Rayleigh number |
| $T^{dh}_{\lambda,th}$ | directional hemispherical transmittance |
| $R^{dh}_{\lambda,th}$ | directional hemispherical reflectance |
| $T^{d}_{\lambda,exp}$ | direct transmittance |
| FTIR | Fourier Transform Infrared Spectroscopy |
| $p_r$ | reflective power, % |

*Greek symbols*

| | |
|---|---|
| $\beta_\lambda$ | spectral extinction coefficient, $m^{-1}$ |
| $\beta^*_\lambda$ | weighted extinction coefficient, $m^{-1}$ |
| $\sigma_\lambda$ | scattering coefficient, $m^{-1}$ |
| $\tau_\lambda$ | optical thickness of the medium |
| $\omega_\lambda$ | albedo |
| $\kappa_\lambda$ | absorption coefficient, $m^{-1}$ |
| $\alpha_\lambda$ | spectral absorptance, % |
| $\lambda$ | wavelength, m |
| $\mu$ | cosine of the polar angle |
| $\mu_1$ | first direction |
| $\mu_{air}$ | dynamic viscosity of air, $kg\,m^{-1}\,s^{-1}$ |
| $\rho$ | density of the medium, $kg\,m^{-3}$ |
| $\rho_{air}$ | masse density of air, $kg\,m^{-3}$ |
| $\eta$ | volumetric thermal expansion coefficient of air, $K^{-1}$ |
| $d\Psi_0$ | solid angle, sr |
| $\varepsilon_S,\varepsilon_P,\alpha$ | structural parameters dependent of the porosity |
| $\xi_0$ | half-angle of incident beam |
| $\phi_{reference}$ | reference measurement |
| $\phi_0$ | reflection measurement without sample |
| $\phi^t_{sample}$ | transmission measurement with sample |
| $\phi^r_{sample}$ | reflection measurement with sample |

*Superscripts*

| | |
|---|---|
| * | weighted coefficient |

*Subscripts*

| | |
|---|---|
| $\lambda$ | spectral |
| E | thickness, m |

*Physical constants*

| | |
|---|---|
| $\sigma$ | Stefan-Boltzmann Constant, $5.67040 \times 10^{-8}\,W\,m^{-2}\,K^{-4}$ |
| $\chi_1$ | radiation constant, $1.19 \times 10^{-16}\,W\,m^{-2}$ |
| $\chi_2$ | radiation constant, $1.4388 \times 10^{-2}\,m\,K$ |

## 1. Introduction

Fibrous insulation materials perform well in controlling temperature and moisture for building applications [1]. Such materials allow minimizing the energy input required to maintain a fixed temperature. A low-density fibrous material thus behaves like a semi-transparent medium that remains entirely capable of both absorbing strongly anisotropic scattering and emitting thermal radiation [2]. The semi-transparent behavior of fibrous insulation materials at room temperature is the subject of a large body of studies aimed at describing their thermal properties [3–8]. Generally speaking, heat propagation can take place via various heat transfer modes, namely: (i) conduction in the interstitial fluid, mainly consisting of motionless air, as well as in a fibrous matrix; and (ii) radiation that propagates within the pores and interstices through the dual mechanism of fiber absorption, emission and scattering. It has been demonstrated that convection is often neglected in fibrous insulation materials [9], thus leaving two main modes for the heat transfer of insulation materials, namely radiation and conduction. Thermal radiation is the predominant heat transfer mode in a semi-transparent medium [7]; it is described by radiative properties, such as the extinction coefficient, scattering coefficient, absorption coefficient and scattering phase function, all of which have been defined for each wavelength. Radiative properties can be determined either by predictive methods based on theoretical models or by identification methods based on transmission and reflection measurements. In most previous works, the thermal radiation of fibers was examined by use of a direct method based on the interaction between fiber and radiation via the resolution of Maxwell's equations with the Mie theory [3–4,10–14].

In addition, determining the radiative properties of insulation materials with the inverse method has been reported in many recent investigations [5–6,15–19]. The inverse method is based on experimental infrared measurements of reflection and transmission in order to determine the radiative properties (i.e. albedo, optical thickness and phase function coefficients) of fibrous insulation. Several studies offering varying degrees of complexity were carried out to identify the radiative properties of fibrous insulation. Yajnik et al. [20] developed a powerful method for deriving the spectral scattering and absorption coefficients for two different medium (i.e. glass fibers and expanded polystyrene) from monochromatic directional-hemispherical reflectance and hemispherical-directional reflectance measurements. The nonlinear least squares method seeks to minimize the difference between reflectivity measurements and their theoretical values within the 2–40 µm wavelength range in an effort to identify the coefficient values. It was noted that the scattering albedo is low for glass fibers and high for expanded polystyrene foams. Baillis et al. [8] thus determined the spectral radiative properties (i.e. absorption coefficient, scattering coefficient and phase function) of open-cell polyurethane foam from parameter identification methods. Spectral transmittance and reflectance measurements are conducted in the infrared wavelength region of 2–15 µm with different identification strategies and different types of measurements (directional-hemispherical, combination of directional-directional and directional-hemispherical). The discrete ordinate method was implemented in order to solve the Radiative Transfer Equation (RTE). Similarly, the RTE is also solved by means of a direct method (matrix exponential method) with minimization being