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Prediction of varying thermal resistivity of organic insulation materials

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ABSTRACT

Temperature, humidity and aging have significant influence on the thermal performance of insulation materials. The assumption of constant material properties frequently leads to the wrong results for simulating heat transfer through insulation materials. Therefore, the impact of hygrothermal conditions and aging on the long-term behavior of insulation materials should be investigated. The objective of this work is to evaluate the influence of coupled hygrothermal conditions and aging on the thermal resistivity of organic foamy materials. A model of aging conversion coefficient for two organic foamy materials is proposed. The thermal resistivity ratio (TRR) is calculated using the coupled heat and moisture transfer model which introduces effective thermal conductivity for expanded polystyrene and extruded polystyrene. The comparison of predicted values with experimental data shows a good agreement. This paper provides an estimation approach to the aging conversion coefficient that affects the thermal conductivity of the organic foamy materials.

1. Introduction

Insulation materials are widely used in building envelope to improve building energy performances. Thermal resistivity is the primary property of an insulation material, and it can be found from the well-known data sources as ISO standards [1] or ASHRAE Handbook of Fundamentals [2]. The effective thermal resistivity of insulation materials reduces with temperature and moisture content increasing and, consequently, it increases the thermal losses of building. The measured thermal losses under operational conditions of building exterior walls are in most cases higher than the simulated values. This phenomenon is partly due to the assumption of constant material properties which leads to the wrong results. Thus, an accurate method to predict varying thermal resistivity for the insulation material is vital for simulating the heat loses through the wall.

Studies on the effects of temperature and moisture on insulation materials have been carried out somewhat extensively. Several researchers have investigated hygrothermal properties of insulation materials via experiments [3–7]. Cabeza et al. [3] compared the behavior of three typical insulation materials, polyurethane, polystyrene, and mineral wool. Al-Ajlan [4] reported the measuring technique and the measured thermal properties of some commonly used insulation materials produced by local manufacturers in Saudi Arabia. Among the thermal properties, the thermal conductivities of the same type of insulation material were measured for samples with different densities as well as at different elevated temperature levels. Jerman and Cerný [5] presented the measurements of complete sets of heat and moisture transport and storage parameters of selected thermal insulation materials in dependence on moisture content. The studied material parameters include bulk density, matrix density, porosity, saturation moisture content, thermal conductivity, specific heat, moisture diffusivity, water vapor diffusion coefficient, sorption isotherm, and water retention curve. Abdou and Budaiwi [6] investigated experimentally the impact of moisture content on the thermal conductivity of commonly used fibrous insulation materials. The relationship between thermal conductivity and moisture content was found to be affected by the initial conditioning moisture content level. Jannot et al. [7] presented a new method for thermal conductivity measurement of low-density insulation materials. They indicated that their method could achieve an accuracy of 95% or higher for the thermal conductivity measurements and that the accuracy of the thermal diffusivity measurements depended on the density of the material.

Other studies have focused on the effect of temperature and moisture on the thermal performance of insulation materials by numerical simulations [8–11]. Placido et al. [8] developed a geometrical cell model to be applied to the prediction of radiative and conductive foam insulation properties. Ochs et al. [9] presented a detailed description of modeling and measurement of the effective thermal conductivity of porous bulk materials at temperatures up to 80 °C and moisture contents below free water saturation.

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Nomenclature

a	thermal diffusivity of material (m^2/s)
c_p	specific heat (J/kg K)
D_a	vapor diffusion coefficient in air (m^2/s)
D_v	vapor diffusion coefficient (m^2/s)
f_a	aging conversion coefficient
f_m	moisture conversion coefficient
f_T	temperature conversion coefficient (1/K)
h_{lv}	latent heat of phase change (J/kg)
l	thickness (m)
p_{air}	ambient air pressure (Pa)
p_s	saturation vapor pressure (Pa)
T	temperature (K)
t	time (s)
W	volumetric water content (m^3/m^3)
x	coordinate

Greek symbols

Γ	(de)sorption rate or condensation rate ($kg/m^3 s$)
α	convective heat transfer coefficient ($W/m^2 K$)
β	surface moisture transfer coefficient ($kg/m^2 s Pa$)
δ_p	water vapor permeability (kg/m s Pa)
ε	porosity
λ	heat conductivity (W/m K)
μ	vapor diffusion resistance factor
ρ	density of dry material (kg/m^3)
ρ_v	density of water vapor (kg/m^3)
τ	characteristic time (s)
φ	relative humidity (%)

Subscripts

b	initial condition
in	inner air
out	outer air

Karamanos et al. [10] developed a model that allows the evaluation of stone wool under varying temperature and humidity conditions. The characteristics of performance for moisture and wetness were also verified by long-term laboratory experiments. Singh et al. [11] presented an artificial neural network approach for the prediction of effective thermal conductivity of porous systems filled with different liquids.

There are also specific studies focusing on long-term assessment of thermal–hygrometric behavior of insulation materials. Some of them studied the laboratory-induced deteriorations experimentally [12–15], and some used representative environmental boundary conditions for long-term hygrothermal calculations [16]. The thermal resistivity ratio (TRR) (the ratio of a material's wet thermal resistivity to its dry thermal resistivity [17]) of some insulation materials was evaluated in several laboratory tests by Tobiasson et al. [17]. Their work used the ASTMC518-76 to determine insulating ability of insulation specimen, with placing specimens of insulations in an apparatus that maintained an air temperature of 4 °C and relative humidity of 75% above and an air temperature of 29 °C and relative humidity of 100% below the specimen. These tests developed graphs of TRR vs. moisture content for fiberboard, perlite and cork, gypsum, insulating concrete, cellular glass, fibrous glass, expanded polystyrene (EPS), extruded polystyrene (XPS), foamed-in-place urethane, and phenolic insulations. Furthermore, TRR vs. moisture content equations had been developed for each material.

From the above review, it is evident that temperature, moisture and aging have a significant influence on the thermal performance of insulation materials. There is a strong need to predict the long-term thermal resistivity ratio of insulation materials. However, a full-scale hygrothermal test requires a long testing period, typically from several years to several decades, to study the effects of temperature and humidity conditions as well as the aging on TRR of insulations. Methodologies for calculating the TRR of insulation vs. long-term hygrothermal conditions need to be developed to reduce cost. This paper presents methodologies for predicting TRR of insulations, and proposes a detailed modeling approach which takes into account the impacts of coupling temperature, moisture and aging on thermal conductivity. In the next section, the governing equations and the numerical procedure are outlined. The subsequent sections give the relevant numerical results and comparisons.

2. Mathematical model

2.1. Governing equations of heat and moisture transfer

The following assumptions for the problem simplification are made:

(1) Heat and moisture transfer through the insulation is one-dimensional and the insulation material is isotropic.
(2) The local thermal equilibrium exists among all phases.
(3) The liquid is immobile in the insulation material.
(4) Volume changes of the insulation material due to the moisture and water content change are neglected.
(5) Diffusion within the insulation material is rapid so that the moisture content at the insulation material surfaces is always in sorptive equilibrium with that of the surrounding air.
(6) Free convection in the insulation is negligible.
(7) The latent heat of vaporization is neglected at material surfaces.

Based on the above assumptions, the heat and moisture transfer process through insulation material can be generally expressed as

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(x,t)\frac{\partial T}{\partial x}\right) + h_{lv}\Gamma(x,t) \tag{1}$$

$$\frac{\partial \rho_v}{\partial t} + \frac{\Gamma(x,t)}{\varepsilon} = \frac{\partial}{\partial x}\left(D_v(x,t)\frac{\partial \rho_v}{\partial x}\right) \tag{2}$$

where λ is the effective thermal conductivity of insulation, h_{lv} is the latent heat of phase change, $\Gamma(x,t)$ is the (de)sorption rate or condensation rate, ρ_v is the density of water vapor, ε is the porosity of material, and D_v is the effective vapor diffusion coefficient.

The heat and moisture transfer in insulation is coupled by (de)sorption rate or condensation rate. When there is no condensation in the insulation, the (de)sorption rate can be determined by

$$\Gamma(x,t) = \rho_{dry}(1-\varepsilon)\frac{\partial W}{\partial t} \tag{3}$$

The volumetric water content (W) is calculated based on the relative humidity and the sorption curve. The relative humidity can be obtained by

$$\varphi(x,t) = \frac{\rho_v(x,t)T(x,t)R_v}{p_s(T(x,t))} \tag{4}$$

The gas constant of water vapor is R_v = 461.5 J/(kg K). The saturation pressure can be calculated in the temperature range from 0 °C to 109.9 °C, using [9]

$$p_s(x,t) = 610.8 \cdot \exp\left(\frac{17.08085 \cdot \vartheta}{234.175 + \vartheta}\right) \tag{5}$$

where ϑ is Celsius temperature (°C).