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Thermal characterization of insulating materials

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ABSTRACT

The strict energy saving standards are based on the declared values of the materials, i.e. U-value, thermal conductivity or thermal capacity. To this end, proper knowledge of the thermophysical properties of the wall components is needed, especially with regard to new lightweight technologies that are being used in building construction/refurbishment, under the dynamic conditions of the Mediterranean climate, where one of most important parameters of building materials is their heat capacity because of the influence of solar radiation energy. With this regard, the actual heat capacity value, obtained in laboratory tests, is typically quite different from the nominal one. So, this paper reviews several methods of calculating the heat capacities of materials and several worldwide applications, with the aim of providing an overview of the thermal behaviour of lightweight insulation materials and their implications for energy and indoor comfort. Finally, the authors propose a simple method able to evaluate the specific heat capacity of real scale building materials with a ~5% of uncertainty.

1. Introduction

At present, the worldwide trend of primary energy demand for the supply of heat, light, and industrial and transportation power is continuously rising [1]. In this context, buildings account for 30–40% of the total global primary energy use and 24% of the global generation of greenhouse gasses [2,3].

In EU countries, several energy goals have been achieved by virtue of policies enacted to strive to meet targets set for 2020 [4–6], and considerable attention has been paid to the energy refurbishment of existing buildings to address their primary energy demand, which, in Europe, amounts to approximately 40% of the total [7].

Existing building stocks are the most difficult to make energy efficient, as users are induced to make incorrect use of HVAC systems [8], artificial lighting systems and shading devices [9–12] that often are not provided with smart control devices [13–16].

In Italy, recent research studies [17–19] have classified the residential building stock into several categories according to age, material and typology criteria, and these studies have highlighted the poor building envelope performances of many buildings (typically built before 1960), which are either completely devoid of insulation systems or are very difficult to retrofit for energy-related concerns [20–22]. These findings emphasize the problem facing the scientific community with regard to the achievement of nZEB targets for existing buildings [23,24], which, although the particular criteria depend on primary conversion weighting factors (which differ from country to country) [25], is becoming increasingly necessary for the achievement of overall targets [26].

In this context and specifically in refurbishment field, the wall insulation (i.e. thermal coat system) is a fundamental action able to improve energy performance of buildings, through a detailed knowledge of envelope thermal inertia, U-values, hydrophobic properties, building insulation levels and insulation material parameters [27,28]. That being said, where this kind of retrofit action occurs, commonly, architects and engineers base their energy calculations on the declared values, given by manufacturers, that differs from the real one, with particular reference to the specific heat capacity.

In this context, the objectives of this work are: a) to review several scientific methods that have been developed and experimentally applied throughout the world to calculate the heat capacities of materials while overcoming inaccuracies arising from general procedures; b) to present scientific experiences in the testing of innovative and traditional insulation materials and finally, c) to propose a method of experimental analysis in a climatic chamber.

The authors believe that this paper can aid researchers and skilled people involved in the thermal characterization of insulation materials, thereby contributing to the improvement of building energy performance. Indeed, the determination of specific heat values for such materials is not a simple task because they are generally characterized by high porosity, low conductivity, low density and low thermal capacity. So, in the following section, several suitable calculation methods are collected and described.

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Nomenclature

Φ	heat flux [W]
λ	thermal conductivity coefficient [W/mK]
c	specific heat capacity [J/kgK]
K_s	heat transfer coefficient [W/m^{2}K]
K_r	heat transfer coefficient [W/m^{2}K]
α	thermal diffusivity [m^2/s]
q	heat flux density [W/m^2]
Φ_s	blank-corrected net heat flow rate [W]
Φ_h	blank-corrected net heat flow rate [W]
m_s	mass [g]
$K_F(T)$	calibration factor [-]
ΔT_{es}	temperature changing on the ext surface [°C]
ΔT_{is}	temperature changing on the int surface [°C]
φ_{isf}	interior-surface phase shift [rad]
φ_{esf}	exterior-surface phase shift [rad]
Δq_{es}	heat flux density changing on the ext surface [W/m^2]
Δq_{is}	heat flux density changing on the int surface [W/m^2]
P	period [s]
DF	decrement factor [-]
$T_{s,i}$	internal surface temperature [°C]
$T_{sa,e}$	outdoor sol–air temperature [°C]
Q′	integral of the measured heat flux [Ws/m^2]
TCHCM	Temperature-Change Hot Chamber Method [-]
R_{wall}	thermal resistance of the wall system [K m^2/W]
Q	thermal energy [J]
c_v	volumetric heat capacity [J/m^{3}K]

2. Specific heat of building materials: calculation methods

The heating process of a material begins with a phase of non-stationary conduction and then proceeds to a stationary phase in which the material achieves a certain heat capacity [29]. As is well known, in recent years, it has become increasingly important to describe the microstructures of materials using geometrical and mathematical approaches [30,31].

In general, a steady thermal flow is defined as a thermal flow that occurs at a constant temperature difference, and as is well known, the relationships between the physical parameters of the thermal conduction process can be described according to Fourier's law [32–34] (Eq. (1)):

$$\Phi = -\lambda A \frac{\Delta T}{\Delta x} \tag{1}$$

where Φ is the heat flux [W], λ is the thermal conductivity coefficient [W/mK], ΔT is the temperature gradient [K], and Δx is the material thickness [m].

Given this description, in addition to the thermal conductivity λ and the density ρ, the specific heat capacity c [J/kgK] is another major physical property that is necessary for calculating the transient thermal behaviour of materials and building components [35].

In the UNI 10351:2015 standard [36] and the UNI EN ISO 10456:2008 standard [37,38], λ [W/mK] and ρ [kg/m^3] values for many materials are tabulated for use in calculations.

However, for material assessments performed under dynamic conditions, the effective values of the properties c, ρ and λ must typically be calculated differently.

For this purpose, several researchers have used Differential Thermal Analysis (DTA) [39]. In detail, DTA is based on a comparison between results obtained by applying an identical thermal cycle to a certain material of interest and a reference sample. Such an analysis requires an apparatus consisting of three major components: a sample holder, a controlled source of heat, and a device for measuring the heats of reaction [40]. It analyses the transferred differential heating curve (inside and outside of the sample) according to the following Eq. (2) and Eq. (3):

$$\frac{dq_s}{dt} = K_s(T_w - T_s) + \sigma\,(T_r - T_s) + \alpha_s(T_o - T_s) \tag{2}$$

$$\frac{dq_r}{dt} = K_r(T_w - T_r) + \sigma\,(T_s - T_r) + \alpha_r(T_o - T_r) \tag{3}$$

where dq/dt denotes the rate at which heat is received by the reference material (subscript r) or the sample material (subscript s), whereas K_s and K_r are the corresponding heat transfer coefficients between the materials and the furnace wall.

DTA has been used by several authors [41–43] to investigate energy storage performances, the thermal properties of phase-change materials, and other material properties of interest for building applications.

Furthermore, Derbal et al. [44] proposed a theoretical analysis of measured data that enables the thermal characterization of materials and as stated by the authors, the experimental apparatus is very light, cheap and easy to set up. Furthermore, the proposed method allows the simultaneous determination of the thermal conductivity and volumetric heat capacity of a given material. The experimental set-up is based on the unidirectional heat transfer assumption, as expressed in Eq. (4) [45,46]:

$$\frac{\delta T}{\delta t} = \alpha \frac{\delta^2 T}{\delta x^2} \tag{4}$$

where α [m^2/s] is the thermal diffusivity.

The numerical model is based on a matrix with the form given by Eq. (5):

$$f_{i,j}(p) = \frac{T_{meas}(i,j) - T_{sim}(i,j,p)}{\max(T_{meas}) - \min(T_{meas})} \tag{5}$$

where $f_{i,j}$ is the weighted difference between the simulated and measured temperatures in iteration i = 1, …, n and at the interface j = 1, 2, whereas p is the vector of the parameters to be defined (λ and ρ). Therefore, the objective function is defined as shown in Eq. (6):

$$F(p) = \sum_{i,j} (f_{i,j}(p)). \tag{6}$$

The reported results indicate that with regular temperature measurements, this procedure is particularly suitable for materials that exhibit good homogeneity, for which it yields a calculation accuracy of approximately 7%.

Another method of interest relies on a Differential Scanning Calorimetry (DSC) procedure [47,48]. DSC is a well-known technique that allows the heat flow rate to a sample to be monitored while the sample's own temperature is controlled [49]. One of the most important advantages of this method is the elimination of the need for a separate calibration run using a sample material with a known heat capacity. Because of the temperature and heat flux calibration requirements for static methods, such a separate run is usually necessary to properly establish the temperature calibration, whereas in the case of DSC, the calibration can be approximate.

In this context, Ramakumar et al. [50] described a complete hybrid procedure for calculating the specific heat capacity c [J/kgK] according to Eq. (7), based on the assumption that the calibration factor $K_F(T)$ remains constant with time and temperature.

$$c_s = \frac{K_\Phi(T)(\Phi_s - \Phi_b)}{\beta m_s} \tag{7}$$

where (Φ_s-Φ_b) represents the blank-corrected net heat flow rate for the sample [W], β = $\Delta T/\Delta t$ is the heating rate, m_s is the mass (g) of the sample, and $K_F(T)$ is the calibration factor.

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