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A simple method for building materials thermophysical properties estimation

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HIGHLIGHTS

- We set up a new protocol for construction material's thermal tests.
- Simple, light apparatus used without any control of boundary conditions.
- Simultaneous thermal conductivity and volumetric heat capacity estimation.
- Good agreement between estimated and reference values.

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ABSTRACT

This article presents a light and easy to use method for simultaneous determination of thermal conductivity and volumetric heat capacity of a construction material without any control of boundary conditions. The material to be characterized is placed between two layers of materials with known thermophysical properties. Thermocouple probes are placed at the different interfaces and record the variations in temperature when the whole multilayer is subjected to stimulation. An inverse method based on a numerical model allows us to simultaneously identify the unknown thermal properties. This method was tested respectively on samples of polyvinyl chloride, expanded polystyrene, plaster and concrete.

1. Introduction

The majority of the existing buildings are responsible for an important share of the global energy consumption and they generate a large proportion of the greenhouse gas in the world. Recent studies have shown that residential buildings and tertiary activity buildings are responsible for more than 30% of the world's energy consumption [1]. The increasing demand for energy, the simultaneous decrease of its resources, an ever increasing cost added to the global impact it has on the environment has had the scientific community, the industrial actors and the political sphere reflect and take concrete measures to tackle this problem. One of the main solutions to improve the energy performances of the buildings is the limit the energy waste through the buildings envelope. This is a crucial concern during the building phase of a new building and also a reason for implementing ambitious renovation projects. The measures implemented to favor the thermal insulation of buildings do rank among the most relevant ones. New bio based thermal insulation materials are regularly imagined and designed to stop wasting energy and limit its environmental impact. These materials consume less energy than more commonly used materials [2,3]. During the development phase of these new materials their different physical characteristics have to be assessed and optimized. Their thermophysical properties in particular need to be assessed at various stages of their development. Different methods exist and they are commonly used by measurement laboratories where they are subjected to strict standards of use. However, it is particularly interesting to have access to simple, easy to use and inexpensive methods of characterization to effectively accompany the producers during the development phases.

The thermophysical properties of the materials such as thermal conductivity and diffusivity have been extensively studied and various methods of characterization have been developed and tested. Among the most commonly used methods for the thermal characterization of building materials, the following ones are to be mentioned: The guarded hot plate (ASTM C 177-97 and ISO 8302) which allows the determination of thermal conductivity. Its principle is to establish a temperature gradient at a steady state through a material with a known thickness [4]. It involves a long testing

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time, a certain sensitivity to contact resistance and normative restrictions that apply to the experimental device (symmetry of the device, heat loss limitations...). The guarded hot box method (ASTM C 1363-05 and ISO 8990) measures the total thermal resistance of a given sample subjected to a thermal gradient [5]. It is characterized by the measurement of a steady state flux and therefore also requires a long testing time, normative restrictions regarding limitations of the box heat loss and testing temperatures... Regarding the heat flow meter apparatus (ASTM C518 and ISO 8301), a sample of the material to be characterized is subjected to a steady temperature gradient thus establishing the fluxes to be measured. It requires at least a calibrated heat flux sensor "Fluxmeter", the definition of a steady flux and normative restrictions applying to calibration and apparatus set up [6].

However one can note that the standard methods, above mentioned, are designed to offer reference thermophysical properties values. That said, they cannot answer all the raised thermal characterization problems. They require heavy instrumentation with strict use conditions. Established permanent state which implies long test time and finally they are laboratory methods. Developing our method, we consider overcoming those methods constraints and plan an in situ use. Dual methods of characterization have been developed besides those more common approaches. Partly based on experimental set up and partly based on numerical modeling, both approach allow us to assess the thermophysical properties of building materials. Xu and Solaimanian [7] have developed a method to evaluate thermal conductivity and diffusivity. This method combines an analytical solution to heat transfer in bituminous concrete cylinders and a laboratory experiment under controlled conditions. This method requires strict conditions regarding both specimen and test chamber. The rate of its relative estimation errors is comparatively high. Monde et al. [8] have developed an experimental and analytical method allowing for thermal diffusivity and conductivity to be estimated regardless of the boundary conditions. This method assumes that the environment is semi infinite and imposes a high temperature gradient thus limiting the range of materials to which it is applicable and as a consequence concerns mostly metals. The strict conditions of this method clearly indicate it is to be used in laboratory setting. O'Donnell and O'Brien [9] developed an analytical and experimental method allowing for the estimation of thermophysical properties and of the heat generation rate induced by concrete hydration and therefore providing a model for the evolution of temperature inside a block of concrete. This method can only be used in the case of materials generating heat during a process such as hydration. The implementation of thermal probes is particularly delicate because of the absence of direct contact between the probes and the tested material. Some of the methods abovementioned are not applicable to multilayer materials such as those frequently used by the building industry.

The above mentioned dual methods are applied and valuable, however our method compared to one or another of those methods, consider improving test time or widen the rage of tested materials... to summarize, we consider facilitating the normative requirements and not having to rely on heavy apparatus and lengthy testing time, the simple characterization method of building material presented in this article will improve and widen the scope of its applications. It is based on solving the inverse problem of conduction heat transfer [10]. It does not require boundary conditions to be controlled, is easy to use and inexpensive.

2. Experimental design

The aim is in practice to identify the thermophysical properties of a given material inserted between two layers of material for which the following characteristics are known: thermal conductivityλ and volumetric heat capacity ρC. The multilayer sample is subjected to a unidirectional heat flux produced by a flat heating resistance. Thermocouples are placed at the different interfaces of the multilayered material to record temperature evolutions during the test (refer to Fig. 1). By using the measured temperatures as the system's boundary conditions, a finite differences model [11] will allow us to simulate the temperatures both within the sample and at its interfaces. Then an inverse method based on the Levenberg Marquardt algorithm [12,13] (hereafter referred to as the LMA in this article) will allow for the estimation of the thermophysical properties of the middle layer of the sample material by adjusting the simulated temperatures to the measured temperatures based on a nonlinear least squares method.

3. Numerical study

In this section, we first introduce the finite differences method applied to the heat equation. Applied to our experimental set-up, this approach leads to a numerical code implemented in Matlab® environment. This allows to solve numerically the direct heat conduction transfer. Then we describe the inversion algorithm based upon the combination of our numerical model and Levenberg–Marquardt minimization Algorithm that is a standard. This minimization algorithm is preset in Matlab® Optimization Toolbox. At the end of this section we make a sensitivity study to determine the ability of the inverse method to estimate simultaneously the unknown parameters.

3.1. Numerical model

In solid, nontransparent materials considered in the present work, heat transfers only occur through conduction without heat generation. The experimental set up has been designed to have unidirectional transfers. In this case the heat transfer is determined by the heat equation in its simplest form (Eq. (1)). Analytical solutions to this equation exist for the least complex cases. They are referred to in various bibliographical Refs. [14,15].

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \tag{1}$$

where α (m^2/s) is thermal diffusivity.

In the majority of the cases numerical modeling proves crucial to solve this type of heat conduction problem. The finite differences method is adapted to our unidirectional case study. Once programmed it allows for the resolution of the direct problem of heat transfer and simulates the temperatures at the chosen nodes after the field under study has been discretized through an unconditionally stable implicit scheme (refer to Fig. 2). The indexed nodes ($j = 1, \ldots, M$) are separated by a Δx distance. They represent the spatial variable x where the temperature will be simulated. In the same way, the testing time was discretized ($i = 1, \ldots, N$) with a Δt time step (in our case $\Delta t = 4$ s).

The input data of the numerical model are the temperature fields measured at the extremities and at the interfaces. The temperature fields recorded at the extremities a and b of the tri layered material $T_{exta}(i{\cdot}\Delta t)$ and $T_{extb}(i{\cdot}\Delta t)$ are the boundary conditions of

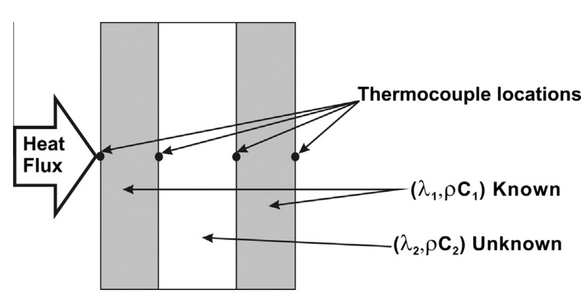

Fig. 1. Sample tested in "Sandwich" configuration.