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A new procedure for the experimental measurement of the effective heat capacity of wall elements

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ABSTRACT

The dynamic thermal characteristics of envelopes strongly impact the thermal performance of buildings. Among these dynamic characteristics, the effective heat capacity is a particularly relevant parameter. Current methods for calculating the effective heat capacity of a building element require knowledge of its thermo-physical properties. Yet, the materials used in construction are often heterogeneous and their thermo-physical properties are not accurately known.

In this paper, a new method for experimentally measuring the effective heat capacity of a wall element is presented. To do so, an analytical model based on the thermal quadrupole method, where the required inputs are the boundary conditions only is first developed. The wall element can be heterogeneous and has to be symmetrical. Then, experimentally, the wall element is placed under sinusoidal boundary conditions in a climatic chamber. The measures of the parietal temperatures and fluxes are used as inputs in the analytical model, and the calculation is performed.

The method is applied to the experimental measurement of the effective heat capacity of a clay hollow brick. Its thermal characteristics – particularly the air alveoli – are not easily known, and vary under unsteady conditions. The method is therefore a powerful tool to calculate the effective heat capacity of a symmetrical heterogeneous material.

1. Introduction

According to the International Energy Agency, the building sector accounts for around one-third of current global final energy consumption [1]. In the European Union (EU), the building sector is responsible of approximately 40% of the final energy consumption [2]. In recent years, EU Member States have implemented policies to reduce energy consumption in the building sector, particularly in the residential building.

In the residential building, the thermal performance improvement of building envelope is one the key points to save energy. Indeed, the heat flow through the exterior wall of a building takes a large part in the cooling/heating load. Several studies have shown the link between the building envelope and the energy consumption. Shi and Zhang [3] have shown that the optical parameters of the building exterior surface play significant roles in energy saving for buildings. Fang et al. [4] have studied the impact of exterior wall insulation on cooling energy consumption. They compare a chamber constructed using a thermal insulation system for the external wall with a basic chamber constructed according to the general design for residential buildings of the 1980s and 1990s. The results show that use of an external wall insulation system improve building energy efficiency.

Reducing the impact of the outdoor temperature on the temperature at the interior surface of the building envelope is a good way to minimize the energy consumption. Thermal inertia of the building envelope is one of the most important parameters for reducing this impact. According to Ng et al. [5], thermal inertia refers to the degree of slowness with which the temperature of a body approaches its surroundings.

Contrary to the thermal insulation, which can be characterized by the thermal resistance, the thermal inertia is not quantified by a single parameter. Researchers have proposed different indicators to characterize the thermal inertia:

1.1. Temperature evolution

Necib et al. [6] investigated the thermal inertia of a brick by studying the temperature fluctuations of the inner surface of a brick with and without phase change material (PCM). Their results

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Nomenclature

c	specific heat capacity [kJ kg^{-1} K^{-1}]
HC	heat capacity [J m^{-2} K^{-1}]
h	heat transfer coefficient [W m^{-2} K^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
L	thickness [m]
P	period [s]
q	heat flux [W m^{-2}]
Δq	amplitude of flux [W m^{-2}]
t	time [s]
T	temperature [°C]
ΔT	amplitude of temperature [°C]
S	surface [m^2]
x, y, z	Cartesian coordinates
Z	impedance surface [m^2 K W^{-1}]

Greek letters

δ	thickness of a layer [m]
ϕ	complex heat flux [W m^{-2}]
Φ	heat flux in the Laplace domain
φ	phase shift [rad]
$\boldsymbol{\theta}$	complex temperature [°C]
Θ	temperature in the Laplace domain
ρ	density [kg m^{-3}]
ω	angular frequency [rad s^{-1}]

Subscripts

ˆ	complex
e	exterior environment
esf	exterior surface flux
eff	effective
es	exterior surface
i	interior environment
in	input
$init$	initial condition
is	interior surface
isf	interior surface flux
ist	interior surface temperature
out	output
tr	transfer

showed that the average temperature of the inner surface is almost constant over 24 h for a brick with PCM while the external temperature varies. The average temperature of the inner surface fluctuates for a brick without PCM. The authors concluded that the PCM introduced in square holes could considerably improve the thermal inertia of a brick.

1.2. Time lag and decrement factor

The time lag and the decrement factor of the parietal temperatures and heat fluxes are often used to characterize the thermal inertia of walls [7,8]. The decrement factor is indicative of the heat storage capacity, and the time lag characterizes the heat transmission delay. Several studies have sought to assess the decrement factor and time lag of walls. Stephan et al. [9] have evaluated the impact of insulation on the thermal inertia, using the decrement factor and time lag of the temperature as indicators. The results show that the insulation has no impact on the decrement factor. However, the insulation affects the time lag. Zhang et al. [10] have analyzed the influence of the thermo-physical properties of block materials on the thermal performance of a hollow block wall. In their study, the thermal resistance, the decrement factor, and the time lag of the temperature are the evaluation indexes. Kontoleon et al. [11] have studied how the variations of the density and thermal conductivity of concrete, as well as the relative placement of the concrete and of the insulation layers, affect the decrement factor and the time lag. In [12], Sun et al. have studied the impact of the outside temperature on the decrement factor and time lag. When the wave of the outside temperature is non-sinusoidal, they show that the time lag of the peaks of the parietal temperatures does not equal the time lag of the crests. Ruivo et al. [13] have analyzed numerically the influence of the azimuth on the time lag and decrement factor. Their results show that the azimuth has a small impact on the decrement factor and an appreciable impact on the time lag. The influence of wall orientation and solar absorptivity on the exterior surface on time lag and decrement factor have also been studied in [8]. It has been shown that solar absorptivity has a very important effect on time lag and decrement factor.

Works cited above show that the decrement factor and time lag depend on several factors: the characteristics of the building envelope, the climate conditions, the azimuth of the building envelope, etc. As the decrement factor and time lag are coupled to these multiple factors, they cannot be used to easily characterize and compare the inertia of different walls.

1.3. Time constant

Other authors use the time constant to characterize the thermal inertia. For example, Orosa and Oliveira [14] studied the thermal inertia of a new and old school buildings. The index selected to identify the thermal inertia was the time constant. To obtain these time constants, indoor ambience in the schools was simulated under constant weather conditions of 10 °C and 80% of relative humidity. The linear regressions of the logarithmic differences of temperature with respect to the outdoor conditions were obtained. The time constant is the inverse of the coefficient of the straight line given by the linear regression. Tsilingiris [15] proposes another method to calculate the time constant of a building element:

$$\tau = \frac{HC}{S.\sum H} \quad (1)$$

where HC is the heat capacity of the building element, $\sum H$ is the sum of the convective heat transfer coefficients on the exterior and interior surfaces of the building element and S is the building element surface.

1.4. Effective heat capacity

According to Perna et al. [16], the heat capacity is a parameter that describes the real capacity of a building element to accumulate heat. Tsilingiris [15] defines the effective heat capacity for a homogeneous building element as the product of the building element mass and its specific heat capacity. In the case of a composite building element with n homogeneous layers of mass m_i and of specific heat capacity c_i, the heat capacity is defined as:

$$HC = \sum_{i=1}^{n} m_i \cdot c_i \quad (2)$$

Conventionally, instead of the previous quantity, the areal effective heat capacity (expressed in J m^{-2} K^{-1}) is used. It is defined by Tsilingiris as:

$$HCA = \frac{HC}{S} = \sum_{i=1}^{n} \rho_i \cdot c_i \cdot \delta_i \quad (3)$$

where ρ_i, δ_i, and S are the wall layer density, thickness, and surface, respectively.