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Dynamic thermal response of building material layers in aspect of their moisture content

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HIGHLIGHTS

- Moisture storage and its effect on thermophysical properties of material layers are considered.
- The impact of hygrothermal properties and thickness of materials on the heat wave evolution is analysed.
- The influence of relative humidity on the decrement factor and time lag is shown.
- New metrics to assess the influence of moisture content on thermal response are introduced.

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ABSTRACT

This paper investigates the impact of moisture content on the thermal inertia parameters of building material layers. Moisture variation affects the energy storage and therefore the energy gains/losses through buildings. To this effect the decrement factor and time lag are determined for three types of concrete layers and one of solid clay-bricks masonry layer. Their consideration is essential to enhance the design of building elements, from a thermal point of view, when exposed to varying moisture content conditions. Moisture content and relative humidity variations of each analysed layer, as defined by specific moisture storage functions, are shown to interrelate non-linearly with the layer resistor–capacitor circuit section parameters (thermal conductivity and volumetric heat capacity) showing notable consequences on the thermal inertia parameters. The dynamic thermal analysis is accomplished by using the thermal-circuit modelling approach and the nodal solution method. The deterioration of decrement factor and time lag due to moisture content are illustrated by appropriate metrics. Computer results for the studied layers with thicknesses varying from 10 cm to 50 cm show the influence of the variation of relative humidity and thickness on the decrement factor and time lag.

1. Introduction

The presence, accumulation and the periodic variations of moisture in the mass and on the surface of building components affects its energy efficiency and causes various building materials' deterioration types and degradation mechanisms. Specifically, the accumulation of moisture in building materials (as a result of water vapour condensation, rainwater penetration, groundwater uptake, etc.), i.e. the substitution of the air in their pores by water, leads to the increase of their thermal conductivity and therefore to the decrease of their insulation capacity [1–9]. This phenomenon and its effect on the buildings performance is present for the majority of insulation materials. On the other hand, the increase of building materials moisture content leads to a parallel increase of their ability to store energy within their thermal mass. A detailed description of modelling and measurement of the effective thermal conductivity of porous bulk materials within a specific temperature range and for moisture contents below free water saturation is given in [1]. As it is shown, insulation materials exposed to severe environmental influences, such as moisture content caused by penetrating water (vapour), can decrease significantly their effective thermal resistance; thus, thermal losses may become higher than the design values. In another study [2], the measurements of complete sets of heat and moisture transport and storage parameters of selected thermal insulation materials in dependence on moisture content are presented. Their assessment is important towards calculating reliably the energy gains and losses through buildings. In [3] the ability of various thermal insulation materials to restrict heat flow, when exposed to significant ambient

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Nomenclature

d (m) thickness of layer
n (–) number of layer sections
A (m^2) surface area
μ (–) vapour diffusion resistance factor
w (kg/m^3) moisture content
w_f (kg/m^3) free saturation moisture content of material
$w(RH)$ (kg/m^3) moisture content of a material with regard to the relative humidity
RH (–) relative humidity (%)
b_w (–) approximation factor to account for the increase of a material's moisture content due to its varying relative humidity
$w_k(RH)$ (kg/m^3) moisture content storage in concrete with regard to the relative humidity
w_{80} (kg/m^3) moisture content corresponding to 80% of air relative humidity
κ_w (–) approximation parameter
v (–) the closest integer number to z_1
z_1 (–) approximation parameter
λ (W/m K) thermal conductivity
λ_o (W/m K) thermal conductivity of dry material
$\lambda(w)$ (W/m K) thermal conductivity of a material containing moisture
b_λ (–) coefficient to account for the increase of a material's thermal conductivity due to its moisture content
ρ (kg/m^3) bulk density
ρ_o (kg/m^3) bulk density of dry material
$\rho(w)$ (kg/m^3) bulk density of a material containing moisture
C_p (J/kg K) specific heat capacity
$C_{p,o}$ (J/kg K) specific heat capacity of dry material
$C_{p,w}$ (J/kg K) specific heat capacity of water
$\rho \cdot C_p$ (J/kg K) total volumetric heat capacity of a material containing moisture
R (K/W) thermal resistance
C (J/K) thermal capacitance
h (W/m^2 K) surface heat transfer coefficient
P_d (s) day period
υ_f (s^{-1}) heat wave frequency
Δt (s) time step
t (s) elapsed time
T (°C) temperature
f (–) decrement factor
φ (h) time lag
Ξf (–) deterioration percentage of the decrement factor due to the moisture content
$\Xi \varphi$ (–) deterioration percentage of the time lag due to the moisture content
Δf (–) variation of the decrement factor due to the moisture content
$\Delta \varphi$ (h) variation of the time lag due to the moisture content

Subscripts
j index of layer section
e exterior surface
i interior surface
min minimum value
max maximum value
dry dry state of material (RH = 0%)
moist moist state of material ($RH \neq 0\%$)
out outdoor environment (ambient air)
in indoor environment
W/C water-to-cement ratio

temperature and humidity variations, is studied. The results of this work can allow designers to assess accurately the thermal performance of building envelopes based on the actual properties of building layers. In [4] an experimental investigation was carried out to study the effect of moisture and porosity on the thermal conductivity, thermal diffusivity and specific heat of a conventional aluminous refractory concrete. Results have revealed a considerable influence of the moisture content on the thermal conductivity of the studied concrete. In another study [5] the influence of moisture content on the thermal properties of wood-concrete composite has been examined experimentally. As it was shown, lightening the concrete by incorporating wood shavings increases its thermal insulation capacity; moreover, thermal conductivity increases rapidly with water content. Its experimental evolution with water content was confirmed by the comparison with theoretical models. More recently [6] the effects of moisture content on the effective thermal conductivity of autoclaved aerated concrete (AAC) has been analysed experimentally by adopting a three-phase model; as it is shown, an increase of water content leads also to an increase of the examined material thermal conductivity. As it is mentioned, the knowledge on the thermal conductivity of materials is important for the thermal design of building envelopes. Furthermore, in [7,8] Pérez Bella et al. have analysed thoroughly the thermal design of building envelopes based on the actual temperature and moisture content of their materials (operating conditions); they have proposed a correction factor to consider the environmental conditions of each location and their influence on the design value of materials' thermal conductivity based on their normative values established in building regulations. Also, in [9] a comparison of the moisture content impact on the thermal conductivity for different types of building materials is given. Evidently, the awareness of the varying properties of building materials, due to the fluctuating environmental conditions, is important to determine consistently the heat flows and to take advantage of the thermal mass of building envelopes.

Depending on the building material and on the environmental conditions, frost attack, mold growth, reinforcement bars corrosion, salts crystallization and wood decay are only few examples of deterioration related to the presence and accumulation of moisture on the surface and in the mass of building components that may cause serious damages to the construction. In fact, moisture inside a building material (in its liquid, solid or gas phase), can act either as a direct aggressive agent (e.g. in the case of frost attack) or as a factor facilitating or/and accelerating the occurrence and the evolvement of several degradation mechanisms [10]. The presence of moisture in building components has also been correlated with respiratory and other symptoms in building inhabitants and users [11,12]; furthermore, via its effect on the materials and their function, it can be recognized as a factor related to buildings environmental and economic performance (e.g. the need of replacing or repairing building parts leads to resource and energy consumption, as well as to economic burdens). The range of damages in building components related to moisture includes both structural-safety related, as well as functionality related deterioration types; in the latter group, the effect of moisture on building components' thermal performance, and consequently on the buildings energy and environmental performance can be listed [13].

As moisture influences the thermophysical properties of materials, so also does on their dynamic thermal parameters, such as decrement factor and time lag (thermal inertia characteristics).