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New equivalent parameters for thermal characterization of opaque building envelope components under dynamic conditions

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HIGHLIGHTS

- Evaluation of opaque components' thermal behavior in realistic boundary conditions.
- New approach to characterize the thermal inertia of the envelope.
- Determination of equivalent thermal parameters by means of dynamic simulation.
- New parameters applied to assess the heat transfer in steady-periodic conditions.
- Validation through comparison with the results of dynamic simulation.

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ABSTRACT

As reported in the scientific literature and mentioned in building energy performance legislation, the thermal inertia of the opaque building envelope can have a significant positive impact on the reduction of summer indoor overheating, of space cooling peak load and of electricity consumption.

At the early stages of the envelope design, there is a need to use simplified as well as effective parameters to correctly characterize the thermal performance of the opaque envelope under dynamic conditions.

In this work, a new methodology to describe the dynamic thermal behavior of opaque components is proposed. The approach is based on the harmonic parameters specified in ISO 13786 but it also takes into account realistic boundary conditions for different orientations and solar absorptance values. New equivalent thermal parameters are determined by means of dynamic simulations. The use of these parameters to assess the conduction heat flow rate by means of a simplified model is validated through a comparison with the results of a dynamic simulation.

The method presented in the article represents an improvement with respect to the parameters usually applied at the early design stage to thermally characterize the opaque envelope of the building under dynamic conditions. In fact, it allows simplified but reliable performance parameters referring to actual boundary conditions to be obtained. The application potential of the proposed methodology lies in the drawing-up of catalogues and technical standards that supply the values of the new equivalent thermal parameters for different technical solutions.

1. Introduction

In recent years, building energy efficiency has become a topical matter in order to comply with the Kyoto Protocol for the reduction of CO_2 emissions. The European Directive 2010/31/EU [1] on the Energy Performance of Buildings (EPBD recast) also raises the issue of reducing summer energy consumptions and peak cooling loads due to a rise in the number of air-conditioning systems, especially in Southern Europe.

The EPBD recast states that priority should be given to strategies that enhance the thermal performance of buildings during the summer period and that attention should be paid to measures that avoid overheating, such as shading and sufficient thermal capacity in the construction phase. Several studies focus on the reduction of energy consumption through strategies that also exploit the thermal inertia of the building and strengthen the actual importance of this topic [2,3].

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Nomenclature

Symbols

a	solar absorptance [–]
A	area [m^2]
c	specific heat capacity [J kg^{-1} K^{-1}]
f	decrement factor [–]
h	surface heat transfer coefficient [W m^{-2} K^{-1}]
I	solar irradiance [W m^{-2}]
q	heat flux [W m^{-2}]
s	thickness [m]
t	time [s] or [h]
T	time period [s] or [h]
U	thermal transmittance [W m^{-2} K^{-1}]
Y_{ie}	periodic thermal transmittance [W m^{-2} K^{-1}]

Greek symbols

α	thermal diffusivity [m^2 s^{-1}]
ε	emissivity [–]
φ	time shift [h] or [s]
σ	Stefan–Boltzmann constant [W m^{-2} K^{-4}]
λ	thermal conductivity [W m^{-1} K^{-1}]
θ	temperature [°C] or [K]
ρ	density [kg m^{-3}]
ω	angular frequency [rad s^{-1}]
ψ	phase difference of temperature [rad]
χ	phase difference of heat flow [rad]

Subscripts/superscripts

a	air
adm	admittance method
e	external, outdoor
eq	equivalent
i	internal
gr	ground
max	maximum
min	minimum
r	radiative
R	resistive
sin	sinusoidal regression
sk	sky
t	time

Diacritics

–	average value
~	sinusoidal function
^	complex amplitude

Acronyms and abbreviations

CondFD	Conductive Finite Difference
RMSD	Root Mean Square Deviation
TARP	Thermal Analysis Research Program

ISO 13786 [4] is the technical Standard adopted in the regulations of most European countries to evaluate the dynamic thermal characteristics of building components. The Standard is based on the admittance method introduced by Milbank and Harrington-Lynn [5], and specifies a simplified calculation model that considers 24-h sinusoidal boundary conditions.

Several studies have investigated the influence of material thermal properties and of layer distribution and thickness on dynamic thermal characteristics; furthermore, the effects of the wall boundary conditions have been examined.

Asan and Sancaktar [6] and Asan [7,8] focused on the optimization of the time lag and of the decrement factor by varying the thermal properties and thickness of walls, and the insulation position and thickness respectively. Al-Sanea et al. [9] optimized the insulation layer thicknesses by minimizing the cost of the insulation and the energy consumption. Furthermore, Asan [10] investigated the time lag and decrement factor for different building materials. In all these studies a numerical method, under periodic sinusoidal boundary conditions, was used.

Kontoleon and Bikas [11] and Kontoleon and Eumorfopoulou [12] investigated the influence of wall orientation and of exterior surface solar absorptance on the time lag and decrement factor for various insulated opaque walls in the summer period. The important influence of the boundary conditions on the thermal characterization of walls at design level was also emphasized by Ozel [13] and by Al-Sanea et al. [14]. More recently Kontoleon et al. [15] evaluated the influence of the concrete density and thermal conductivity variations of various wall assemblies on the dynamic thermal characteristics, such as the decrement factor and the time lag. In these analyses they used a lumped model by adopting the non-linear nodal method and by considering both a non-sinusoidal periodic temperature trend [11,12] and a sinusoidal one [15].

In another study Ulgen [16] experimentally and analytically examined the thermal response of various wall configurations under sinusoidal sol–air conditions. Instead, the study of Ng et al. [17] concentrated on the experimental investigation on aerated lightweight concrete wall panels in terms of thermal inertia, transient thermal behavior and surface temperature prediction using the finite difference method.

Only a few studies address the problem of defining a methodology for a more accurate assessment of the thermal inertia under real boundary conditions. Gasparella et al. [18] pointed out the issue, by assessing the deviation arising from the use of different approaches (Finite Difference Method and Transfer Function Method) for the calculation of the dynamic thermal characteristics of an opaque envelope element under periodic non-sinusoidal boundary conditions; in the same work the ISO 13786 procedure was mainly applied by decomposing the external forcing temperature by means of the Fast Fourier Transform analysis in order to propose corrections to the periodic thermal transmittance and to the time shift specified by the Standard. Al-Sanea et al. [19] also developed concepts like "thermal-mass energy-savings potential" and "critical thermal-mass thickness" and tried to define equivalent parameters like the "dynamic thermal resistance", in order to determine the thermal mass thickness required for a selected desirable percentage of energy saving; in these studies the daily values were used in order to determine a yearly average dynamic *R*-value.

Therefore, as specified in ISO 13786, the dynamic thermal characteristics may also be used in the product specifications of complete building components, in the calculation of the internal temperature in a room, of the daily peak power and energy needs for heating or cooling and of the effects of intermittent heating or cooling, and so on. The present work consequently investigates the main thermal dynamic parameters (i.e. the time shift and periodic thermal transmittance) arising from the literature and standards, in order to define a more precise evaluation methodology able to account for real boundary conditions. The outputs of a dynamic simulation model (EnergyPlus) [20] and of simplified calculation