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Influence of internal and external boundary conditions on the decrement factor and time lag heat flux of building walls in steady periodic regime

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HIGHLIGHTS

- Dynamic behaviour of building walls subjected to sinusoidal and actual loadings.
- The joint action of more temperature and heat flux loadings has been considered.
- Dynamic parameters were defined by the internal and external fluctuating heat flux.
- Use of the Total Harmonic Distortion to determine the number of harmonics required.
- Study of the influence of external and internal loadings on dynamic parameters.

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ABSTRACT

The dynamic behaviour of opaque components of the building envelope in steady periodic regime is investigated using parameters defined by the fluctuating heat flux that is transferred in the wall. The use of the heat flux allows for the joint action of the loadings that characterise both the outdoor environment and the indoor air-conditioned environment to be taken into account.

The analysis was developed in sinusoidal conditions to determine the frequency response of the wall and in non-sinusoidal conditions to identify the actual dynamic behaviour of the wall. The use of non-dimensional periodic thermal transmittance is proposed for the sinusoidal analysis in order to evaluate the decrement factor and the time lag that the heat flux undergoes in crossing the wall as well as the efficiency of heat storage.

In the presence of non-sinusoidal loadings, the identification of the dynamic behaviour of the wall is obtained using several dynamic parameters: the decrement factor in terms of energy, defined as the ratio between the energy in a semi-period entering and exiting the wall; the decrement factor and the time lag in terms of heat flux, considering the maximum peak and the minimum peak. These parameters allow for the identification of how the form of the heat flux trend crossing the wall is modified.

The number of harmonics to be considered for an accurate representation of heat fluxes is determined by means of the introduction of the Total Harmonic Distortion (THD), which quantifies the distortion of a non-sinusoidal periodic trend compared to a sinusoidal trend.

The methodology developed was used to evaluate the influence of external and internal loadings on the dynamic characteristics of two commonly used walls on a monthly and seasonal basis. The external loadings were changed considering two climatically different locations and different orientations of the walls; the internal loadings were changed by varying the operating mode of the plant and the shortwave radiative heat fluxes contributions on the inner surface.

1. Introduction

Energy efficiency is a valuable tool to limit the use of primary energy in processes and in end use, with benefits in terms of reducing greenhouse gas emissions, of dependence on energy from abroad, as well as economic terms.

European Directive 2010/31/EU [1] on the energy performance of buildings and the subsequent 2012/27/EU [2], on measures to promote energy efficiency, reinforced studies and research for the development of innovative technological solutions to achieve a reduction in total energy consumption.

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Nomenclature

$[A]$, $[B]$	heat transfer matrix
c	specific heat capacity (J/kg K)
C	steady areal heat capacity (J/m^2 K)
e	relative percentage error (%)
f	decrement factor (–)
G	specific air flow rate (kg/(m^2 s))
h	heat transfer coefficient (W/(m^2 K))
k	harmonic order (–)
n	n-th harmonic
P	period of oscillation (s)
R	thermal resistance (m^2 K/W)
s	layer thickness (m)
t	time (s)
T	temperature (K)
THD	Total Harmonic Distortion
U	steady thermal transmittance (W/(m^2 K))
y	thermal quantity
Y	generic complex thermal parameter
$[Z]$	heat transfer matrix of the multilayered wall from surface to surface

Greek symbols

α	absorption coefficient (–)
Δt	time lag (s)
ΔU	instantaneous internal energy variation (W/m^2)
ε	periodic thermal storage efficiency (–)
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)
τ	non-dimensional periodic thermal transmittance (–)
φ	heat flux (W/m^2)
ψ	argument of the thermal quantity oscillation (rad)
ω	angular frequency of the variations (rad/s)

Subscripts

a	air
c	convective
e	external
ei	from outdoor to indoor environment
eq	equivalent
g	global, referring to the join action of external and internal loadings
i	internal
ie	from indoor to outdoor environment
ig	internal heat gain
k	k-th harmonic
l	light
max	max value
min	min value
n	n-th harmonic
pl	plant
r	radiative
s	surface
s, e	referring to the solar load
sky	referring to the sky load
sr	shortwave radiation
ts	referring to the transmitted solar radiative heat flux
v	ventilation
w	wall
Σ	referring to the sum of all the harmonics

Superscripts

e	referring to the external heat flux
i	referring to the internal heat flux
max	referring to the maximum peak of the heat flux
min	referring to the minimum peak of the heat flux
sum	referring to the summer period
u	referring to the instantaneous internal energy variation
win	referring to the winter period

Symbols

–	mean value
~	oscillating value in the time domain
^	oscillating value in the complex domain
| |	amplitude of an oscillating value
arg	argument of an oscillating value

Buildings, due to their high energy needs, mainly due to winter heating and summer cooling, represent one of the sectors most involved in the reduction of energy consumption and the use of energy from renewable sources to achieve the target of nearly/net zero energy balance.

In [3] Lu et al. have presented a comprehensive review on the issues related to the design and control of the Nearly/net zero energy buildings (nZEBs), i.e. the effects of climate/site on design, design optimization methods, uncertainty and sensitivity analysis for robust design and system reliability, efficient and optimal control of high efficient generation systems and energy storage systems for alleviating/shifting the peak load, model predictive control for fast responses to the smart grid, and the adoption of advanced smart technologies.

In order to realise these buildings, the recent literature proposes innovative technological solutions that concern the stratigraphy of walls and the windows, through the use of phase change materials [4–6], of new silica aerogel-based insulating [7,8], of green vertical system [9,10] and of green and cool roofs [11–16], and the use of heat sources which employ solar radiation and geothermal [17–19].

The need to reduce energy consumption occurs significantly in existing buildings [20] and in historic buildings, where the necessity to preserve architectural heritage does not allow typical invasive retrofit interventions [21–25].

In particular, the thermal exchanges through the envelope contribute significantly to the determination of energy requirements that the plant must supply. Their reduction requires a correct evaluation of the dynamic characteristics of opaque envelope components considering actual boundary conditions.

The dynamic thermal characterisation of a building component is obtained by parameters that identify its thermal behaviour when it is subjected to loadings that are variable in time. The reference standard EN ISO 13786 [26] describes the thermal exchange in a steady periodic regime between the indoor environment and the outdoor environment by means of a matrix formulation, which allows for the calculation of the periodic thermal transmittance, used to evaluate the decrement factor and time lag, the periodic thermal admittances and the areal heat capacities.

These parameters are determined by considering a sinusoidal variation of the external air temperature of unitary amplitude and period equal to 24 h, convective–radiative heat transfer coefficients for the external and internal surface heat exchanges and the internal air temperature constant. These quantities are used by technical regulations to verify the dynamic performance of the