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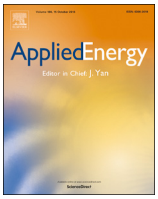

Passive thermal behaviour of buildings: Performance of external multi-layered walls and influence of internal walls

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HIGHLIGHTS

- The dynamic thermal performance of different multi-layered walls were analysed.
- The analysis were carried out using the heat transfer matrix method.
- The impact of layer sequence and thermal insulation placement were highlighted.
- The effect of internal walls on the dynamic behaviour of a room was also considered.
- The methodology can be used as guide for retrofitting actions of building envelope.

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ABSTRACT

In contemporary architecture, the opaque building envelope is usually realised by multi-layered walls; that is, a sequence of homogeneous layers of different materials. The layer sequence and distribution affect the wall behaviour in terms of its overall thermal inertia, or heat storage capability; hence, analysis of the thermal performance of a multi-layered wall becomes very important under dynamic heat transfer conditions, as usually occurs during summer.

In this study, the authors employ analytical models based on the heat transfer matrix method, with the aim of predicting the dynamic thermal behaviour of external and internal building walls. Although numerous studies have been devoted to investigating the dynamic thermal behaviour of walls, the approach followed and results obtained by the authors are original and have significant implications that are of practical interest. By using the analytical models, the effects of continuous variations in the positioning and thickness distribution of the insulation material on the dynamic thermal performance (dynamic thermal transmittance, decrement factor and time lag) are demonstrated with reference to different constructive solutions (from a light-weight wall with a surface mass of 85 kg/m^2 to a massive wall with a surface mass of 294 kg/m^2). Moreover, a simplified correlation is proposed, which allows for correction of the dynamic thermal transmittance and time lag of external walls to take consider the effect of the internal walls (partition walls and slabs) on the dynamic thermal behaviour of a room. The results presented in the paper can be used during the building envelope design stage as a guideline for the improvement of the dynamic thermal performance of multi-layered walls. Furthermore, the insight provided into the building envelope thermal behaviour could prove useful for understanding how to maximise the effectiveness of possible retrofit interventions.

1. Introduction

Buildings are responsible of a large share of total energy uses and CO_2 emissions. In Europe, in particular, the construction sector accounts for 40% of energy requirements and 36% of CO_2 emissions [1]. Provided that careful design strategies be employed, the building sector can be also identified as a source of significant possible energy savings, as approximately 75% of buildings are rated as energy inefficient [2].

One of the simplest and most effective ways of pursuing energy savings in buildings is by acting on their envelope, which represents the path for large amounts of heat flows. The thermal performance of the opaque building envelope plays such an important role in reducing building energy consumption that several studies were devoted to the evaluation of the influence of walls (especially external) thermal

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Nomenclature

C	specific heat capacity, J/kg K
C	surface thermal capacity, J/m^2 K
d, D	thickness, m
E	thermal effusivity, Ws$^{1/2}$/m^2 K
f_a	decrement factor, defined in Eq. (5), dimensionless
j	$j = (-1)^{1/2}$
ℓ	admittance, W/m^2 K
M_S	surface mass, kg/m^2
P	period, s
q, Q	thermal power, W/m^2
R	thermal resistance, m^2 K/W
S	surface, m^2
t	time, s
T	temperature, K
U	thermal transmittance, W/m^2 K
V	volume, m^3
z_{11}, z_{12}, z_{21}, z_{22}	elements of heat transfer matrix of internal walls
Z_{11}, Z_{12}, Z_{21}, Z_{22}	elements of heat transfer matrix of external wall
Z	heat transfer matrix of external wall;
Y_{ie}	dynamic thermal transmittance, defined in Eq. (5), W/m^2 K

Greek symbols

α	thermal diffusivity ($=\lambda/\rho c$), m^2/s
γ	dimensionless parameter, defined in Eq. (A3)
ζ	dimensionless parameter, defined in Eq. (13)
η	fraction of thermal insulation placed on internal side of concrete
λ	thermal conductivity, W/m K
Λ	total admittance, defined in Eq. (12)
μ	dimensionless parameter, defined in Eq. (14)
ν	weight of k-th internal wall
ξ	fraction of concrete externally disposed with respect to thermal insulation
ρ	density, kg/m^3
φ	time lag, defined in Eq. (5), s
ψ	time lag, defined in Eq. (14), s
ω	angular frequency, rad/s

Subscripts

C	concrete
e	external
k	k-th internal wall
i	internal
lim	limit value
n	n-th homogeneous layer

behaviour on building's energy consumption and on their energy saving potential [3–6]. As a rule, the external walls of buildings are multi-layered; that is, forming a sequence of homogeneous layers of different materials, some of which are endowed with resistive thermal properties (e.g. light and insulating layers), and others with capacitive thermal properties (e.g. heavy layers provided with mechanical resistance).

Under steady state conditions, the thermal behaviour of a multi-layered wall is defined by its thermal transmittance, the value of which is independent of the layer sequence. Dependence on the layer sequence order is obviously exhibited by the temperature variation inside the wall and, consequently, by the interstitial hygrometric behaviour. This, in turn, may affect the wall dynamic behaviour, as its thermo-physical properties are modified by the moisture content [7].

However, most importantly, the layer sequence and distribution affect the wall behaviour in terms of its overall thermal inertia, namely, its heat storage capability. A large amount of studies has been devoted to investigating this issue [8]. The so-called 'thermal flywheel effect', consisting of the reduction and phasing out of temperature fluctuations achieved inside a building when using massive walls, has been studied since the 80 s. Duffin and Knowles [9,10] optimised this effect by acting on the design of a multi-layered wall. Tsilingiris [11] studied the same effect by analysing the dynamic behaviour of increasingly heavier walls in terms of their ability to damp out and phase out internal heat flux. In another study, the same author [12] further investigated the combined distribution effects of heat capacity and thermal resistance in many different multi-layered wall types, highlighting the fact that the building envelope effective heat capacity is strongly affected by the distribution of resistive and capacitive layers.

The concepts of decrement factor and time lag were employed extensively to compare alternatives quantitatively by Asan [13,14]. The decrement factor is defined as the ratio between internal and external surface temperature oscillations, while the time lag identifies the delay between the occurrence of an external surface temperature event and its corresponding manifestation on the internal surface. By numerically solving the one-dimensional heat conduction equation using a Crank-Nicholson scheme and convection boundary conditions, Asan analysed several different multi-layered wall configurations by changing the insulation layer position and thickness.

Kossecka and Kosny [15] analysed the manner in which heating and cooling loads are affected by the wall configuration. They introduced a thermal structure factor that considers the spatial distribution of thermal resistance and capacity within the wall. The result was that performance is improved by concentrating the massive layers towards the internal environment, with an additional dependence on the climate type.

Al-Sanea et al. [16] used a finite-volume model based on numerical integration of the one-dimensional heat conduction equation in order to determine the optimum thickness of an insulation layer under Riyadh climate conditions. This was subsequently used to analyse the effects of different locations and distributions of the insulation layer. Optimal performance was obtained with three insulation layers, placed from the outside, from the inside and in the middle of the wall, respectively. In other studies by the same research group, the thermal mass amount and location were optimised [17], and the effects of the type of masonry material and surface absorptivity to solar radiation were analysed [18].

Significant contributions were also provided by Ozel and Pihtili [19]. By means of the numerical finite-difference solution of the one-dimensional heat conduction equation, these authors studied the effect of differently locating an insulation layer within a multi-layered wall in the climatic conditions of Elazığ, Turkey, also considering the influence of wall orientation. In their work, the distribution of insulation layers with three placements (from the outside, from the inside and in the middle) was found to provide optimal results. Furthermore, the optimum insulation thickness was determined using the same method in [20], and it was found that yearly transmission loads, and therefore also optimum insulation thickness, are not affected by insulation location, which agrees with the outcomes of other works [16].

Thermal insulation improvement was the aim of the work by Bond et al. [21]: an electrical analogy was used to describe one-dimensional heat conduction and compare several walls, where only the layer distribution was varied, in terms of their decrement factor and time lag. With the same objective of maximising insulation, Gori et al. [22] used