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The influence of concrete density and conductivity on walls' thermal inertia parameters under a variety of masonry and insulation placements

K.J. Kontoleon *, Th.G. Theodosiou, K.G. Tsikaloudaki

Laboratory of Building Construction & Building Physics (LBCP), Department of Civil Engineering, Faculty of Engineering, Aristotle University of Thessaloniki (A.U.Th.), Gr-541 24 Thessaloniki, Greece

HIGHLIGHTS

- Modelling of multi-layered insulated wall assemblies with thermal circuits.
- Variable concrete and insulation placements and variable concrete density–conductivity variation.
- Optimal decrement factor and time lag of wall assemblies.
- Proportional and relative metrics for selecting concrete density.

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ABSTRACT

In this study the variations of concrete density and concrete thermal conductivity of various wall assemblies are considered to analyse their influence on the dynamic thermal characteristics, such as the decrement factor and time lag. The assemblies under study refer to insulated walls with variable concrete density and the concrete placement in one or two layers. The insulation is also placed as one or two equivalent layers giving rise to a total of six typical wall configurations. The thermal inertia parameters are determined using the thermal-circuit modelling approach and the analysis is based on the nodal solution method. Density and conductivity variations of the concrete layers are seen to interrelate non-linearly with the walls' *RC*-sections corresponding parameters with consequences on its inertia parameters. As such variations, together with the studied insulation placements, affect the decrement factor and time lag in a different fashion, metrics for assessing the walls' thermal behaviour from a proportional (*PDM*, *PTM*) and a relative (*RDM*, *RTM*) point of view are introduced. Computer results, showing the impact of the variations of concrete density and conductivity on the decrement factor, time lag and the proposed metrics are presented for all the studied wall assemblies.

1. Introduction

The building envelope is a vital component of any facility, as it protects the residents and plays a major role in maintaining proper indoor conditions. The properties of the materials that form the various layers of the building envelope define its thermal behaviour, under varying annual outdoor conditions and indoor comfort requirements. The geometrical characteristics and thermophysical properties of the employed materials specify the thermal resistances and capacitances in the heat flow paths of the building set-up. Accordingly, these elements, as well as their spatial position and distribution, modify critically the heat propagation through the building's shell. Consequently, the ability of a building envelope to scale down the energy demands and ameliorate the indoor environment strongly depends on the attributes of the building's layer materials.

With the aim of controlling adequately the indoor environment and avoid its degradation, wall assemblies primarily incorporate masonry and insulation. Due to their high heat capacity, masonry materials are characterized by their ability to store energy, while they can also shift (delay) the time point at which the peak temperatures appear at the interior surface of a wall. Thickening the masonry layer can increase the thermal resistance of a wall; however, insulating a mass wall in a composite multilayer construction is the most rational practise. The insulation layer is characterised by a low thermal conductivity that increases the thermal resistance of the wall. Due to this, insulation materials respond like heat barriers that cause an evidential diminish of the temperature variations in the direction of heat flow. On the other hand, their low volumetric heat capacity decreases their ability to store energy. Apparently, an appropriate combination of both masonry and

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* Corresponding author. Tel./fax: +30 2310 995772.
E-mail address: karolos_kontoleon@yahoo.com (K.J. Kontoleon).

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insulation can lead to a steadier indoor environment with reduced temperature fluctuations and peak temperatures.

Up to now, several studies have dealt with the assessment of the dynamic thermal characteristics of wall elements. Asan and Sancaktar [1], in their novel work have investigated the effects of thermophysical properties and thickness of a wall on decrement factor and time lag using the *Crank–Nicolson* scheme. Their work has mainly applied on individual layer walls by examining the single and combined effects of their thermophysical properties and thicknesses. Moreover, in [2,3] Asan has studied the effect of wall's insulation thickness and position on decrement factor and time lag. In his study he determined the optimum insulation position for minimum decrement factor and maximum time lag. In an analogous study, Ozel and Pihtili [4], have determined the optimum location and distribution of insulation for various types of wall configurations. In another study Al-Sanea and Zedan [5] have analysed numerically the dynamic thermal characteristics of insulated building walls with the same thermal mass and optimised insulation thickness, under steady periodic conditions, using the climatic data of Riyadh. Their results have shown that the optimum thickness of a single insulation layer is autonomous of its position in the wall, and that, when more than one insulation layers are incorporated, their total optimum thickness is identical to the optimum thickness of a single layer. The progress achieved was solely due to the developed allocation of the insulation layers. More recently Al-Sanea et al. [6,7] have examined numerically the effects of a varying amount and location of thermal mass on the dynamic heat-transfer characteristics; also, the influence of the type of masonry material and surface absorptivity on critical thermal mass thicknesses, for insulated building walls with a fixed nominal resistance under steady periodic conditions and for the severe climatic conditions in Riyadh. The influence of wall orientation and the exterior surface solar absorptivity on time lag and decrement factor have also been studied in [8,9]. These studies considered periodic temperature oscillations of the outdoor environment corresponding to the southern Mediterranean region by taking into account the variable effect of solar radiation and orientation. In [10], Ulgen, has evaluated experimentally and theoretically the decrement factor and time lag for different wall compositions by also considering the solar energy. Another experimental investigation, by Ng et al. [11,12], deals with the thermal inertia parameters of newspapers sandwiched aerated lightweight concrete wall panels. In addition, surface temperatures were predicted by employing the finite difference method, while these outcomes were compared with the actual recorded test measurements. On the above basis, Jin et al. in Ref. [13] proposed two new dynamic thermal parameters that correspond to the heat flux decrement factor and heat flux time lag that are useful for reducing the energy demands and improve the indoor thermal conditions.

This paper analyses in detail the impact of the concrete density and conductivity variations on decrement factor f and time lag φ on six insulated wall assemblies. Such variations alter the concrete's thermal conductivity with immediate consequences on the walls' inertia parameters. Evidently, an increase in the walls' concrete density lowers its thermal resistance but increases its potential for thermal storage that delays and reduces the heat propagation through the wall. The analysed assemblies correspond to insulated concrete walls with the concrete and insulation split in one or two equivalent layers. In overall, the variation of the concrete density and conductivity, its placement and the allocation of insulation have an important bearing on the walls' thermal behaviour. For each wall configuration proportional (*PDM*, *PTM*) and relative (*RDM*, *RTM*) metrics are evaluated for the decrement factor and time lag respectively. All numerical simulations are conducted using a thermal-network model that simulates the transient process of a sinusoidal heat wave through the multilayer wall assemblies. The heat flow path makes provision for: (a) conduction through the wall construction, (b) combined convection and radiation at the external and internal surface boundaries and (c) the forcing functions at both limits of the circuit outline. In the following sections the above issues are analysed in detail.

2. Dynamic thermal characteristics of wall assemblies

An integral part of an efficient building design is the determination of the thermal behaviour of the elements that constitute the building envelope. The thermal performance of an opaque element depends on how well its materials restrain the heat, how fast the heat propagates through it and, finally, the outdoor/indoor forcing conditions and constraints at both its boundaries. This last issue is decisive and depends on the local spatial circumstances and uncertainties and the time-point throughout the year. Regarding the temperature profiles at the outdoor environment of a building it is important to mention that they vary periodically during a day through the year period. These profiles are derived by the sol-air concept that specifies the outdoor diurnal forcing function. As to the temperature profiles of the indoor environment, these are assumed steady for the period of the analysis. During this transient process, a heat wave flows from outside to the inside of a wall assembly causing the temperature profiles at each point to vary significantly. The propagation of the heat wave depends on the properties of the materials, their particular distributions and the temperature difference between the outdoor environment and the internal space. The decreasing ratio of its temperature amplitude during this transient process is defined as decrement factor or decreasing ratio of temperature amplitudes, f. The time it takes for a heat wave with period P to propagate from one side of a wall to the other is defined as time lag or phase lag, φ. The case of a sinusoidal heat wave, propagating from the outside to the inside of an opaque layer is delineated in Fig. 1; the thermal inertia parameters are defined as [1–13]:

$$f = \frac{T_{i,\max} - T_{i,\min}}{T_{e,\max} - T_{e,\min}} \tag{1}$$

$$\phi = t_{Ti,\max} - t_{Te,\max} \tag{2}$$

where $t_{Ti,max}$ and $t_{Te,max}$ indicate the time points when the inside and the outside temperatures are at their peaks, respectively. Moreover, $T_{i,max}$, $T_{i,min}$, $T_{e,max}$, and $T_{e,min}$ refer to the maximum and minimum temperatures on both the interior and the exterior surfaces of the assembly.

It is essential to point out, that the impact of the thermal resistance is always decisive, while the issue of the thermal capacity is mostly profound, when the outdoor temperatures cycle is above or below the desired indoor temperatures, within the 24-h day period. High-mass walls are most profitable in moderate climate areas that show wide daily temperature swings; also, for buildings that consume large amounts of cooling energy. This is the case for most buildings situated in the Mediterranean area, for a quite broad period throughout the year. Therefore, for wall assemblies with the same thermal resistance and different thermal mass, the thermal behaviour and indoor comfort conditions differ significantly; high-mass wall systems delay heat exchanges compared to low-mass wall systems. Also, the thermal response of opaque walls with similar thermal resistance and thermal mass can vary due to the position of the various materials within the wall assembly. As it is clear, the cautious utilization and placement of materials that participate in building envelopes is one important goal for passive cooling design that enables the establishment of better indoor conditions.