Thermal mass vs. thermal response factors: determining optimal geometrical properties and envelope assemblies of building materials

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ABSTRACT

In this study, a thermal-network model is employed for the determination of the characteristic thermal inertia factors and more specifically the decrement factor *f* and the time lag *φ*. These parameters are very important, especially during the warm period of summer (when passive cooling is essential), when a periodic thermal wave propagates through a wall’s cross sectional area, from its outer to its inner surface. Initially, the analytical procedures are carried out for the investigation of the sole effect of the thickness *d*, which is a geometrical property, on thermal inertia factors, for typical building materials of wall formations (simple wall configurations constructed from the more frequently used construction materials, such as masonry and insulation material). Moreover, the extracted results can consequently lead to optimal decisions for the building envelope assemblies.

1. INTRODUCTION

The larger part of the building shell mainly consists of the outer walls which act as the main barriers (thermal block) for the protection of the building’s interior from the outside weather or other conditions, such as cold in the winter, heat in the summer, humidity, rain, wind and noise. The current work aims to the analysis of the thermal response of wall formations via the study of thermal inertia factors. The determination of these parameters is indispensable for the estimation of the thermal storage abilities of the wall formations, which are related with the desired thermal comfort levels of the interior climate and the energy consumption savings (Givoni, 1994).

Therefore, the thermal mass of the building shell elements restricts considerably the temperature deviations that appear in the inner surfaces of building envelopes as well as in the interior of them. As a consequence, a more stable indoor environment, with respect to the thermal comfort conditions of inhabitants, can be achieved. This can also lead to the reduction of the energy demands (low energy cooling), while in several occasions the operation of active cooling systems is avoided (passive cooling). In this way, the negative environmental impact which is due to the irrational spending of natural resources is beneficially reduced (Asimakopoulos et al., 1996; Santamouris and Asimakopoulos, 1996).

In the present work the relation between thermal mass and thermal response of building materials is investigated via the utilization of a thermal-network model. The thermal response concerns the assessment of the decreasing ratio and phase delay of the evolved peak temperatures. Their determination has an intense effect on the improvement of the built environment. The effect of the geometrical properties of building masonry and insulation materials (thickness *d*) that form specific envelope structure assemblies is considered. The relation between the thickness of materials (with detailed thermophysical properties) and the thermal resistance *R* (heat transmission) and thermal capacitance *C* (heat mass storage) of a building zone appears to be linearly dependent. However, this is not the case between material thickness and thermal response factors.

Results, aim to propose the optimal geometrical properties, which lead to the best values of the above thermal inertia factors.

2. THERMAL INERTIA FACTORS

The exterior wall surfaces temperature swings, during a day period (24-h), affect the temperatures which are developed on the interior wall surfaces. On the other hand, heat transfer through solid means is not a momentary stationary process, instead it results to a time delay which is due to the time required by the material itself to absorb heat. The rate a construction material absorbs or rejects heat is defined as thermal inertia *b*, and depends on the thickness *d* (m), the thermal resistance *R* (K/W) and thermal capacitance *C* (J/K) of the wall formation material. Thermal inertia also characterizes the speed of heat transfer in the case of two bodies being in contact and having different temperatures. This is given by the following relation:

$$b = (\lambda \cdot \rho \cdot c_p)^{1/2} \qquad (1)$$

where λ (W/m·K) represents the coefficient of thermal conductivity, ρ (Kg/m^3) bulk density and c_p (J/kg·K) specific heat of the wall material which expresses the heat amount required for the temperature increase of the material mass unit. Hence, thermal inertia *b* gives a dynamic character to the process of heat transmission.

The variation and swing of the external environmental temperatures result to a heat propagation process by a periodic thermal wave (thermal excitation or thermal vibration or thermal load) from the outside to the inside of a wall with the flux always taking place from the hotter to the colder surface of the cross section-arrangement of the wall. The thermal wave, which propagates from the external (entry) to the internal (exit) surface of the wall, is diminished and shows a time delay (phase difference) which is due to the thermal mass of the materials. Thus, it can be defined: (a) "as decrement factor *f* (-)" the decreasing amplitude of the thermal wave during its propagation process from outside to inside and (b) "as time lag φ (h)" the time it takes for a heat wave, with period *P* (24-h), to propagate from the outer surface (minimum or maximum external temperature peaks) to the inner surface (minimum or maximum internal temperature peaks) of the wall formation. The determination of decrement factor and time lag is particularly significant and to obtain their desired values allows a compensating wall formation design. The above parameters are defined respectively by the following equations (Asan et al., 1998):

$$f = \frac{T_{i,\max} - T_{i,\min}}{T_{e,\max} - T_{e,\min}} \qquad (2)$$

$$\phi = \begin{cases} t_{Ti,\min} - t_{Te,\min} \\ \\ t_{Ti,\max} - t_{Te,\max} \end{cases} \qquad (3)$$

The period *P* (h) of the heat wave (wave length) which corresponds to the periodical variation of temperatures in the external wall environment is 24-h (day duration) and is considered to present a sinusoidal variation. The heat wave propagation through a non transparent-opaque wall surface cross section and the above two characteristic thermal inertia factors are represented in Figure 1.

3. THERMAL ANALYSIS & THERMAL-NETWORK MODEL

The usual method of thermal analysis and evaluation of the surfaces of the building shell is stationary (static) and without considering the ability of heat storage by the construction elements of the investigated cross sectional arrangements. The determination of the exact dynamic thermal behavior of a cross sectional arrangement of a wall formation, or more generally of the surface of a building shell, requires the consideration of the thermophysical properties of the materials from which the formation is composed. More specifically, the coefficient of thermal conductance λ (W/m·K), the bulk density ρ (kg/m^3) and the specific heat c_p (J/kg·K) of the

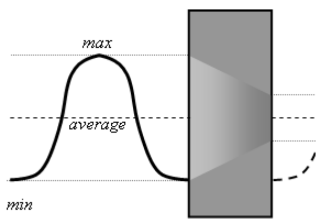

Figure 1: Thermal wave propagation through the cross sectional arrangement of a non transparent-

material means constitute the physical properties which attribute a dynamic character to the process of heat transfer. Thus, while the low values of the coefficient of thermal conductance λ of the insulation material diminishes thermal losses, the high values of the product $\rho \cdot c_p$ of the masonry material delays the process of heat transfer propagation. The time delay which is observed is due to the required time of heat absorption or rejection from the material itself. As mentioned formerly, the rate of heat absorption or rejection is called thermal inertia.

The thermal behavior analysis of the building shell imposes the use of contemporary methods for their modeling and analysis. Towards this direction, it is found that lumped thermal network models offer flexibility, precision and they are suitable for their best design. The model is based on the fundamental principles of thermal circuits; hence, the well-known analogies between the thermal and electrical laws. This model takes into account the environmental boundary conditions, as well as the structure attributes of opaque envelope surfaces. One of the basic advantages is that this model offers a "natural network" which allows the general and systematic lay out of the necessary equations for the solution. In the present study the thermal analysis of the model is achieved via the nodal method. The development of the model and the solution methodology have extensively been described in a previous study (Kontoleon and Bikas, 2002).

The application of the thermal network models, especially at the early design stage of the wall formation is definitive and can lead to useful decisions, which can be based on the study of the characteristic property values of thermal inertia.

4. RESULTS & DISCUSSION

The estimation of the optimum thickness *d* of both types of material, by assuming specific values of their characteristic thermophysical values, is a demanding procedure. The thickness *d* has a straightforward and linear effect on the thermal resistance *R* (heat transmission) and thermal capacitance *C* (heat mass storage) of the assumed wall materials. However, this is not valid for the relation between material thickness *d* and the thermal response factors *f* and φ. Based on the above and via the utilization of the thermal-network model, it is possible to propose the best building material geometrical properties, which can lead to the optimum values of thermal inertia factors. The results are vital when it is desirable to form and obtain suitable and proper thermal comfort conditions in the buildings interior, with small temperature swings between the minimum and maximum temperature peaks (limited range of them) and large time shifts of the minimum and maximum temperature peaks of the thermal wave traveling through the solid element (satisfactory thermal behavior and thermal response).

The two types of the non transparent-opaque materials which are investigated are (a) masonry *M* with λ=0.6 W/m·K, ρ=1000 Kg/m^3, c_p=1000 J/kg·K and (b) insulation *I* having λ=0.03 W/m·K, ρ=50 Kg/m^3 and c_p=1000 J/kg·K. From the above it is obvious that the thermal resistance, *R* (K/W) of the insulation material is twenty times smaller than this of the masonry. Additionally, the thermal mass *C* (J/K) of the masonry is twenty times larger than that of the insulation material. The above thermophysical properties λ, ρ and c_p of these two types of building material are representative for masonry as well as insulation material and the results obtained by this analysis reflect, to a great extent, the actual practical situation. The thickness d_M (m) of the masonry is considered to vary between 0 and 30 cm (with a variable step), whereas, the thickness d_I (m) of the insulation material is considered to vary from 0 to 10 cm (with a variable step).

The distinction between these basic types of construction materials is based on their function and consequently their contribution and participation to the building shell thermal yield. Both types of building materials, i.e. masonry as well as insulation materials, contribute collectively to the thermal response of the construction, each one having a complementary effect on the inabilities of the other. In Figure 2(a)-(d) is illustrated the linear relation between the thickness *d* and the thermal resistance *R* and thermal capacitance *C*, for both the wall formation materials which have been considered.

4.1 Masonry Material

In the diagrams of Figure 3(a)-(b) and for certain values of the thermophysical properties λ, ρ

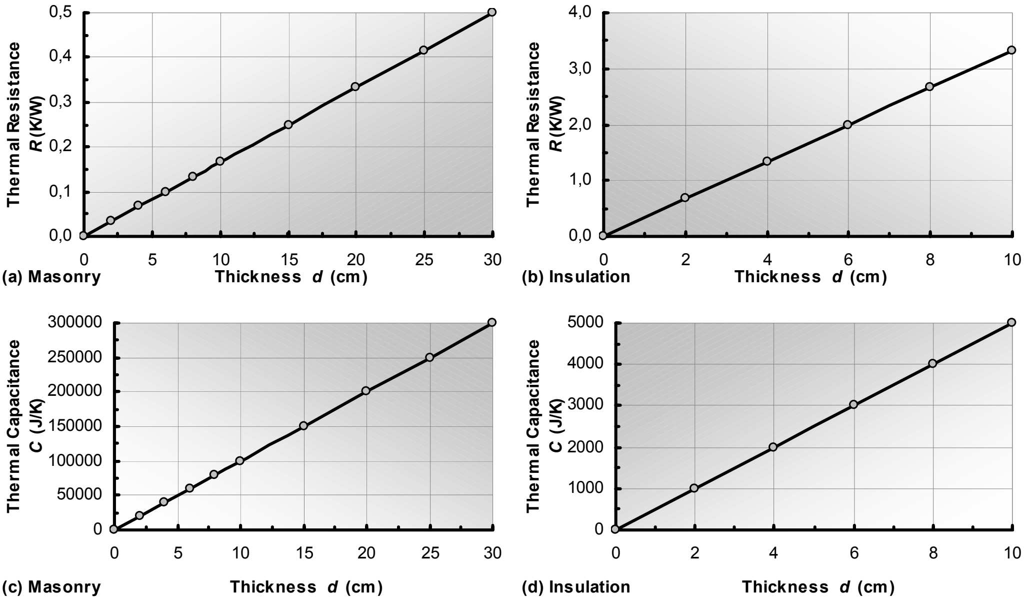

Figure 2: Linear relations between the thickness *d* and thermal resistance *R* for masonry (a) and insulation (b), as well as linear relations between the thickness *d* and thermal capacitance *C* for masonry (c) and insulation (d).

and c_p, are given the values of the decrement factor *f* and time lag φ, as a function of masonry thickness *d*.

The increase of masonry thickness *d*, results to the decrease, of the values of the decrement factor *f*, that is, its improvement. Thus, for a density $d = 0$ cm the value of the decrement factor is $f = 1$ (worst theoretic case). Thereafter, as the thickness *d* of the masonry increases, the value of the decrement factor *f* approaches zero (best value). For thickness values within the range 0 cm < *d* < 20 cm, the rate of decrease of the decrement factor *f* is steep (abrupt). For $d = 20$ cm, the value of the decrement factor is $f = 0.110$. From this point and then, i.e. for $d > 20$ cm, the decrement factor *f* does not practically present an important variation and its rate of decrease is small. Consequently, for $d = 30$ cm, the value of the decrement factor is $f = 0.090$. For this reason, in the building construction industry, the thickness *d* of masonry of the constructional cross sections of the wall formations, rarely exceeds the value of 20 cm.

Furthermore the increase of masonry thickness *d* agrees with the increase, that is upgrade, of the time lag φ values. This is the reason for the time lag φ value being zero (worst value), for a zero thickness *d*. Consequently, the increase of masonry thickness *d* is followed by an almost parallel linear increase of time lag φ, which for a density $d = 30$ cm it is $\varphi = 11$ h (best value).

4.2 Insulation Material

The graphs of Figure 4(a)-(b) show the decrement factor *f* and time lag φ values, as a function of insulation material thickness *d* and for certain values of its thermophysical properties λ, ρ and c_p.

As for masonry, increasing the insulation material thickness d results to the desired decrease of the values of the decrement factor f. For a zero thickness $d = 0$ cm the decrement factor value is $f = 1$. Afterwards, as the thickness *d* of the insulation material increases, the value of the coefficient *f* approaches zero. For thickness within the range 0 cm < *d* < 5 cm, the rate of decrease of the decrement factor *f* is large. Furthermore, for densities $d > 5$ cm, this factor *f* does not practically show any particular change and its rate of decrease is small. Thus, for $d = 10$ cm the value of the decrement factor is $f = 0.0343$. Consequently, few times in the wall formation cross-sections, used in the construc-

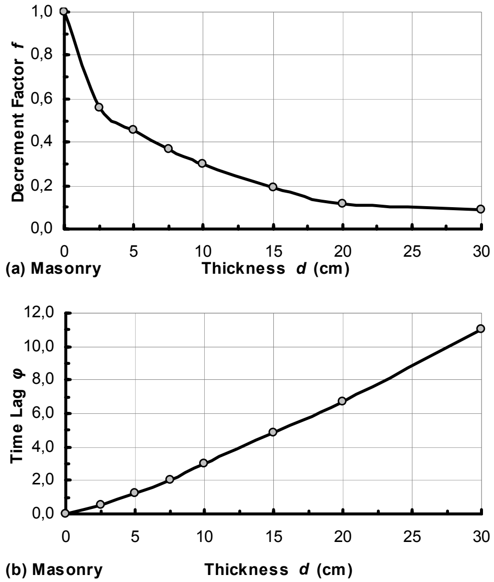

Figure 3: Variation of (a) decrement factor *f* and (b) time lag φ as a function of masonry thickness *d*.

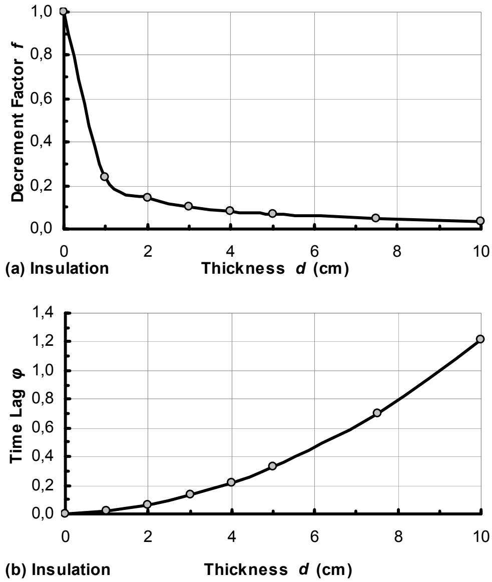

Figure 4: Variation of (a) decrement factor *f* and (b) time lag φ as a function of insulation thickness *d*.

tion industry, the insulation material thickness *d* exceeds the value of 5 cm.

Moreover, as for masonry, an increase of the insulation material thickness *d* leads to a beneficial increase of the values of time lag φ. For d = 0 cm, the value of time lag φ is zero (worst value). Further increase of the insulation material thickness *d* entails the linear increase of time lag φ and for a density d = 10 cm, its value is φ = 1.22 h (best value).

4.3 Interpretation of Results

From the above discussed results, which are shown in Figures 3 and 4, the following useful conclusions are obtained, in relation to the effect of the geometrical properties (thickness *d*) of masonry and insulation material on the characteristic values of thermal inertia factors *f* and φ:

a) The thickness *d* has a significant effect on the values of decrement factor *f* but only for a limited range of density values of each material type. This range defines their desired thickness *d* in the cross sectional arrangement of the wall formations. On the contrary, the thickness *d* affects significantly the time lag values φ, for all the range of thickness values of the building materials (linear variation).

b) Masonry, having a large thermal mass capacity (thermal capacitance *C*), can lead to higher time lag values φ than these of the insulation material. Consequently, with the usual thickness *d* of masonry in the building construction cross-sections, a large time shift φ of the thermal wave propagation, from the outer to the inner surface of the wall can be achieved. Thus, for a masonry thickness *d* of about 5 cm the value of time lag is φ = 1 h. On the contrary, to achieve with the insulation material time lag φ values larger than 1 h, masonry should have a considerably larger thickness *d* (*d* about 8 cm to 9 cm).

c) On the other hand, insulation materials, because of their large thermal renitence (thermal resistance *R*), lead to lower values of the decrement factor *f* than that of masonry. For this reason, insulation materials, with the practically used thickness *d* in the building construction cross sections, can give a large diminution of the internal surface temperatures in comparison to the temperatures of the external surface (thermal heat wave propagation from the outer to the inner surface of the wall).Thus, for an insulation material thickness *d* of about 3 cm, the value of *f* is about 0.1. In a contrary way, to get values of *f* lower than 0.1, the insulation material should have a considerably larger thickness *d* (*d* about 20 cm to 25 cm).

5. CONCLUSIONS

The determination of thermal inertia factors is of neuralgic value in the case of the design of passive zones in climatic conditions having considerable range of diurnal temperature fluctuations and in which the average day temperature of the external environment is within the thermal comfort zone. This is mainly the case of regions with a hot and dry climate which are prone to overheating phenomena.

In this study the extracted results can provide a valuable and essential aid in the direction of improving the building material properties design, with the aim to create a comfortable and livable environment, with small temperature peaks, low temperature swings and diminutive needs of mechanical equipment for the production of cooling energy. Therefore, as it is shown the proper selection of material geometrical properties forming the building shell can not only limit thermal losses but also can react effectively to temperature variations and heat fluxes from outside to inside and vice versa. Consequently, the release of heat stored during the day can be released during the night, when the external temperatures have become very low. This means that the heat stored by the thermal mass of the walls is gradually released, leading to the formation of a more stable indoor environment, while in the outdoor environment extensive temperature fluctuations exist.

REFERENCES

Asan, H. and Y.S. Sancaktar, 1998. Effects of wall’s thermophysical properties on time lag and decrement factor. Energy and Buildings Vol. 28 (No. 2): pp. 159-166.

Asimakopoulos, D.N., V.D. Asimakopoulos, N. Chrisomallidou, N. Klitsikas, D. Mangold, P. Michel, M.I. Santamouris and A. Tsangrassoulis, 1996. Energy and climate in the urban built environment. London: James & James.

Givoni, B., 1994. Passive and low energy cooling of buildings. New York: Van Nostrand Reinhold.

Kontoleon, K.J. and D.K. Bikas, 2002. Modeling the influence of glazed openings percentage and type of glazing on the thermal zone behavior. Energy and Buildings Vol. 34 (No. 4): pp. 389-399.

Santamouris, M.I. and D.N. Asimakopoulos, 1996. Passive cooling of buildings. London: James & James.