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The dependence of effective thermal heat capacity of non-homogeneous materials on location and climatic parameters

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Abstract

The effective thermal heat capacity of construction materials depends strongly on the external conditions such as solar radiation and ambient air temperatures in contact with those elements. The combination of these factors has not been correctly quantified so far. This work also describes a means for determining the thermal performance of non-homogeneous, multi-layered elements: a detailed numerical method that simulates two-dimensional heat transfer situations that occur in typical Portuguese building construction elements, such as brick walls and slabs, was developed as a tool to quantify effective thermal capacity.

Correlation factors between available solar radiation, ambient air temperatures and daily heat capacity were determined for a significant sample of construction elements to permit an easy and quick quantification of thermal heat capacity.

INTRODUCTION

The correct evaluation of the thermal heat capacity of construction materials is essential for the accuracy of any dynamic thermal simulation design tool. This concept is of particular importance when the temperature inside a building is variable.

The heat stored in a construction element depends on a large number of factors, such as the thermal and physical properties of the materials involved, the exposed surface area, the thickness of the storing element and its location within the building (e.g., as an external component or an internal partition), air temperatures on both sides of the element, and the solar radiation absorbed.

In a vast majority of the existing simplified simulation models, the heat capacity is however assumed as a constant, depending only on the thermal and physical properties of the materials, surface areas and thickness. At most, there is a distinction between envelope and internal partitions. Solar radiation incidence is never accounted for. The product of total mass by specific heat is the most common way to define its value. This total heat capacity of the whole mass of the element is much larger than its real ability for storing energy, because the inner mass suffers much smaller fluctuations of temperature than the mass in closer contact with indoor air, being a less efficient storage element [1]. So, the higher the temperature fluctuation suffered by the element, the higher the amount of heat stored. Moreover, if the element receives direct solar radiation, a more efficient storage takes place.

The combined influence of these two factors, temperature swing and solar radiation, on the heat storage ability of building components had not yet been precisely evaluated. The purpose of this work is to show how the external climatic parameters affect the thermal heat capacity of building components and how this influence can be correctly quantified.

Correlation factors between daily heat capacity, incident solar radiation and ambient air temperatures, have been developed, as described next [2].

DAILY HEAT STORAGE

To evaluate the amount of heat stored in a construction element during the day and later released during the night in a daily 24 hour cycle, Q_{sto}, a detailed model was developed [2]. The model describes the thermal performance of non-homogeneous, multi-layered elements and simulates unsteady two-dimensional heat transfer situations that take place in homogeneous and non-homogeneous materials, such as air gaps and hollow bricks commonly used in many parts of the world.

To evaluate the daily amount of heat stored, each construction element was subjected to 24 hour harmonic excitations: both sides of each element were under appropriate daily sinusoidal variations of temperatures and solar radiation. The effective heat capacity is calculated as the heat stored during the day and released at night, i.e., the difference between the maximum and the minimum values of this parameter during a 24 hour period, under quasi-steady state conditions.

Definition of Ambient Air Temperatures and Solar Radition

In order to determine the mathematical correlation factors between daily heat storage and the climatic parameters, it is necessary to define their typical daily profiles.

Solar radiation is a variable parameter which depends on the hour, location and season of the year considered, as well as on the duration of the incidence. So, the daily heat stored has been correlated with the total amount of incident solar energy received during a 24 hour cycle.

The ambient air temperatures were generated using typical daily profiles based on real weather data [3]. To create the typical daily harmonic temperature variation, the model uses two characteristic parameters: the mean temperature (T_{med}) and the daily temperature swing (ΔT).

$0h \le t \le H_{Tmin}$:

$$T(t) = T_{med} + \frac{\Delta T}{2}\cos\left[\frac{180}{24 - H_{Tmax} + H_{Tmin}}\left(t - H_{Tmax}\right)\right] \quad (1)$$

$H_{Tmin} \le t \le H_{Tmax}$:

$$T(t) = T_{med} - \frac{\Delta T}{2}\cos\left[\frac{180}{H_{Tmax} - H_{Tmin}}\left(t - H_{Tmin}\right)\right] \quad (2)$$

$H_{Tmax} \le t \le 24h$:

$$T(t) = T_{med} + \frac{\Delta T}{2}\cos\left[\frac{180}{24 - H_{Tmax} + H_{Tmin}}\left(t - H_{Tmax}\right)\right] \quad (3)$$

H_{Tmin} and H_{Tmax} are the hours when the maximum and minimum outdoor and indoor temperatures occur, obtained from the daily profiles (typically: $H_{T_{min}} = 8h$ and $H_{T_{max}} = 15h$ for outdoor temperatures and $H_{T_{min}} = 7h$ $H_{T_{max}} = 17h$ for indoor temperatures) [2].

The daily heat stored by the element, Q_{sto}, was then correlated with the temperature swing, ΔT, the only remaining variable in this model.

Effective Heat Capacity for Building Components

The quantification of the diurnal heat capacity was done for the most common construction elements used in Portuguese buildings, to cover different situations corresponding to different materials, homogeneous or non homogeneous layers, simple or multi-layered components, for a range of thicknesses, for different levels of insulation, etc.

Building components were classified into two main groups according to their location:

- interior partitions - two cases were considered within this group: those with or those without symmetric ambient air temperature boundary conditions on both surfaces (e.g. walls separating two "south facing" rooms and walls separating a south room from a cooler circulation zone).
- envelope components - only insulated elements have been considered, as non-insulated components are not allowed by most building regulations any longer [4]. Both outside insulation and insulation applied in the air gap between panes were addressed.

To determine the correlation factors between daily heat storage, Q_{sto}, daily temperature swing, ΔT, and incident solar energy, R_i, a statistical multi-linear regression program was used. It was first observed how the daily temperature swing affects the storage ability and, then, its dependence with incident solar energy was examined.

As an example, figures 1 to 4 show the variations of the heat stored with increasing values of temperature swing, and for different values of solar energy, for a massive building component and for a lighter one. The first two figures show the results for an 20 cm-thick concrete wall with 5 cm of expanded polystyrene on the outside and 1 cm of plaster on the inner surface (wall for the envelope of the building). Figures 3 and 4 show the results for an interior pavement made of a 15 cm-thick hollow brick slab (12 cm ceramic blocks covered by a 3cm layer of concrete) covered with light colored ceramic tiles.

For most of the homogeneous construction elements that were studied, the relation between Q_{sto} and ΔT was consistently linear, whatever the value of the total incident solar energy considered, as shown in Figs. 1 and 3.

In non-homogeneous elements, as well as in some lightweight homogeneous materials, the relationship between stored heat and incident solar energy is usually non-linear, as shown in Fig. 4. There is a tendency to reach a maximum constant value once a certain value of R_i is reached.

Taking into account these results, it was evident that either a linear or a quadratic function follow very well the values obtained with simulations. So, the stored heat can be obtained, for each value of ΔT, with a simple equation:

$$Q_{STO}=aRi^2+bRi+c \quad (4)$$

Type (4) equations were obtained for several values of temperature swing, ΔT, and a linear variation of a, b, c coefficients with this parameter was found. So, the dependence of the heat stored with temperature swing and with solar energy was statistically determined to follow the general format specified in equation 5:

$$Q_{STO}=A\Delta TRi^2 + BRi^2 + C\Delta TRi + DRi + E\Delta T + F \quad (5)$$

This equation can be used to evaluate the daily amount of heat that a certain construction element can store, knowing the daily amount of solar energy received by the element and the daily temperature amplitude on the inside.

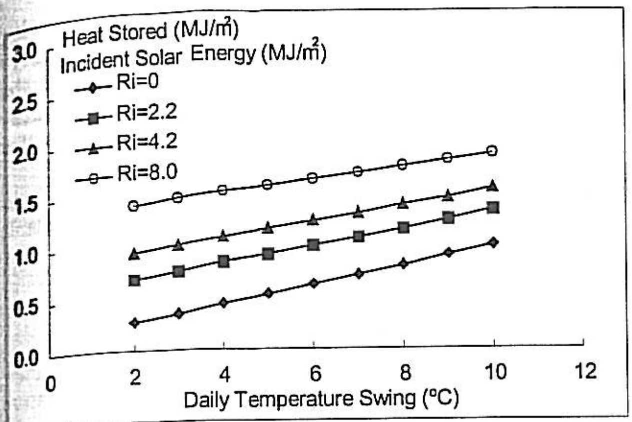

Figure 1 - Variation of stored heat with daily temperature swing for an envelope massive wall.

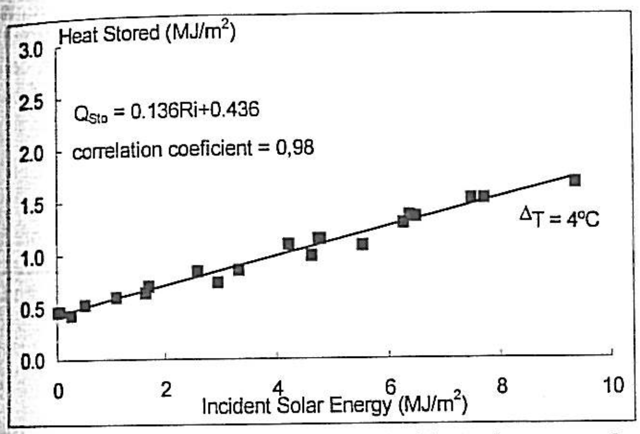

Figure 2 - Variation of stored heat whit incident solar energy, for $\Delta T = 4°C$, for an envelope massive wall.

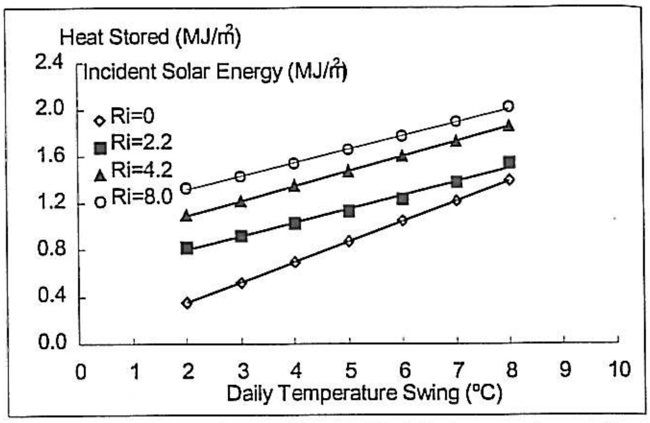

Figure 3 - Variation of stored heat with daily temperature swing for an internal hollow paver brick slab.

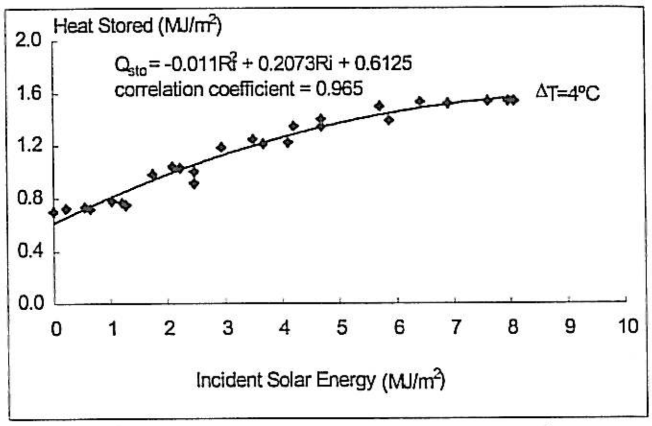

Figure 4 - Variation of stored heat whit incident solar energy, for $\Delta T = 4°C$, for an internal hollow paver brick slab.

Figures 5 and 6 show how the heat stored varies with the total amount of solar energy incident on the component and temperature swing indoors, for the two cases previously presented in this paper. These figures also show that the general equation 5 permits to evaluate the daily heat stored in any situation.

Correlations of the type shown in Figs. 5 and 6 are available for several hundred types of components common in Portuguese construction [1, 7], as specified by the supporting documents for the Portuguese thermal regulations for buildings [5,6,8], and they can be easily prepared for any other types of components with the program described in the previous section of this paper.

DISCUSSION

The main purpose for this study is to increase the accuracy with which the thermal behavior of buildings can be simulated. It is clear from Figs. 5 and 6 that the effective heat capacity of building components strongly varies with ambient conditions (temperature and solar radiation). This is an improvement over the constant values proposed by Balcomb [1] and Mathews and Richards [9]: while the latter just specifies one figure for the effective heat capacity of a building component, depending only on the thermal and physical properties of the materials involved, Balcomb specifies two levels of diurnal heat capacity, one for compo-

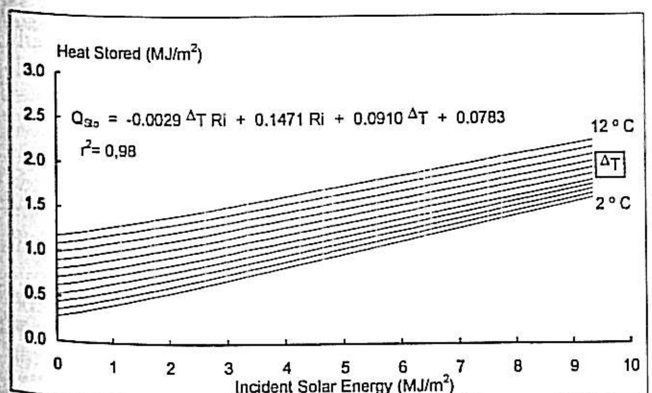

Figure 5 - Heat stored in an envelope massive wall.

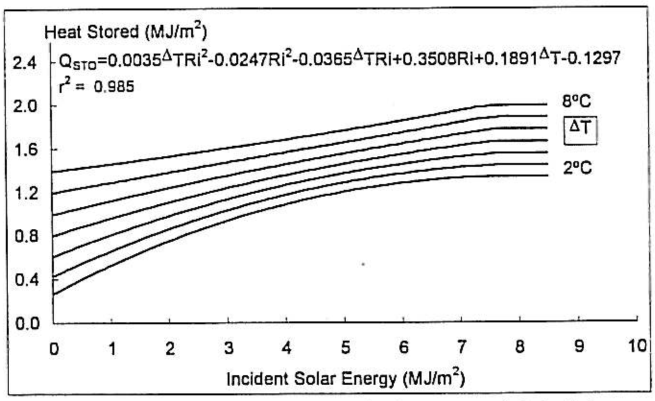

Figure 6 - Heat stored in an internal hollow paver brick slab.

nents in direct gain rooms (implicitly assuming that there is some solar radiation incident upon the component and a reasonable indoor temperature swing) and another for components in rooms without direct gain (which can be directly compared to the case with zero solar energy incident upon the component and low temperature swing indoors, in the formulation presented in this paper). Figure 7 shows the diurnal heat capacity of a 20 cm-thick massive concrete wall, insulated from the outside with 5 cm of polystyrene, located on the building envelope, as obtained with the proposed methodology and with those proposed by Balcomb and Mathews and Richards.

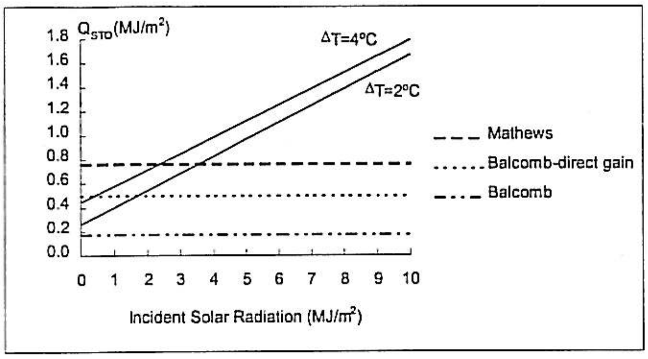

Figure 7 - Diurnal heat capacity of an external massive wall for an indoor temperature swing of 2°C.

Figure 7 allows the following conclusions:

- Balcomb's method, for a component located in a direct gain space, apparently underestimates the effective heat capacity of the component: it compares well with a component that receives a small amount of radiation (1.7 MJ/m^2) in a space with a small indoor temperature swing, which seems inadequate for most situations.
- for a component located in a space with no direct gain, Balcomb's method proposes a realistic value (no solar radiation and low indoor temperature swing).
- the effective heat capacity calculated with the method proposed by Mathews and Richards is larger than Balcomb's and would fit a component receiving a fair amount of radiation in a space with a significant temperature swing. On average, it seems a better value than what is proposed by Balcomb but, by assuming a constant value in all situations, it lacks the capability to simulate a series of different days, namely those with overcast skies when the amount of available solar radiation is small and the temperature swing indoors is not significant.

The variation of the heat capacity has a measurable impact in the simulation of buildings: as ambient conditions improve and more solar radiation is available, there is a tendency for higher temperature swings indoors - but, with the now proposed method, the effective heat capacity also increases, thereby reducing the predicted temperature swing indoors. The opposite occurs in cases of low solar energy availability. Thus, by letting the heat capacity fluctuate, the indoor temperature swings are kept within tighter bounds, closer to reality, than with the predictions by methods that assume constant heat capacity.

A simplified thermal simulation design tool has been produced using this method, producing interesting results. It is discussed elsewhere [10].

CONCLUSION

This work demonstrated the decisive importance of the incident solar radiation and the ambient indoor air temperature swing on the thermal heat capacity of building components. It was also shown that the constant values commonly used for the heat capacity of building components are not a correct way to describe the situation. With this new method, it is possible to quantify, in an easy way, the effective thermal heat capacity, to be used in building thermal simulation design tools for simulating the thermal performance of free floating buildings.

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