EFFECTIVE HEAT-STORAGE IN HEAVY MASONRY WALLS

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1. INTRODUCTION

Passive solar energy has emerged as an energy-conscious response to the energy crisis of the seventies and early eighties. Within an overall strategy to save energy, for heating buildings, passive solar is a good second-step to energy conservation measures: while insulation and window caulking, for example, reduce overall energy needs, passive solar supplies part of the still needed heat by inteligently capturing the incident solar energy.

In passive solar, the radiation penetrates a space through glazed surfaces and is trapped within by the greenhouse effect. Then, internal radiation and convection phenomena, coupled to storage within the mass inside the space, redistribute the captured solar energy in a more uniform way towards those zones without direct solar incidence. While the "solar collection" mechanisms are well studied and are conveniently described by known models, the coupling between internal radiation, convection and mass storage is still hard to model due to the complexity of the phenomena involved.

Thermal storage is a typical case of where, due to the very small temperature differences in presence and a fully unsteady behaviour, practical models are hard to establish. This difficulty has resulted in overly simplified models in which thermal storage potential is obtained by multiplying mass by specific heat or in more complex models which weigh the different layers of a wall according to their real potential for energy storage[1]. The first type of model is totally inadequate for, in a passive solar building, the material in a wall is the more effective the closer it is to the surface in contact with the room air. Only the second type of models has the potential to truly represent storage capacity of the mass in a passive solar building.

This subject is of particular importance in massive buildings, where most of the thermal inertia is associated with the building itself rather than with the passive systems. Then, instead of having most of the mass concentrated in a few selected locations, suffering larger temperature swings and allowing for easier quantification of its effective thermal capacity, the mass is distributed, usually in smaller thicknesses, over a much larger area, without direct solar incidence. The temperature variations are smaller, even almost negligible a few centimeters away from the surface, and quantification is difficult.

A passive solar house -CTO- that was built in Oporto, Portugal, [2], has such a massive structure, and a detailed study of its effective thermal capacity has been under way. Although the study is still not completed, some of the results are presented here concerning the thermal behaviour of its massive walls.

2. METHODOLOGY

To study the thermal behaviour of a wall, namely its energy storage characteristics, it is necessary to know in detail the internal temperature distributions and resulting heat fluxes. As the wall is subjected to highly variable boundary conditions, no analytical solution of the basic heat transfer equation

$$\rho \, c_p \frac{\partial T}{\partial \tau} = \lambda \frac{\partial^2 T}{\partial x^2}$$

is possible, even in this simple one-dimensional format, which is valid only in the center of the walls, away from junctions with other walls, ceiling, floor or any other discontinuity.

Then, a numerical method was chosen to solve the equation, an explicit finite-difference time-marching solution [3] capable of studying homogeneous walls, with one or more layers, with or without an air gap.

3. PROGRAM CALIBRATION

With the validity of the heat-transfer simulation procedure already established in other studies [3], calibration of its output was necessary only to account for the influence of the properties of the materials used in the walls. In effect, when carrying out the numerical simulation of transient heat transfer through a wall, it is necessary to know the values of the thermal conductivity (λ), density (ρ) and specific heat (c_p) of the materials, as well as the heat transfer coefficients by convection and radiation on the surfaces.

These property values vary, even for the same type of wall construction, with the specific chemical composition of the building materials, which changes with the manufacturer and, for materials such as plasters, concrete, etc., also depend on the skills of individual construction workers. An additional source of variation lies on the moisture content of the different materials, which depends on factors external to the walls. This difficulty also precludes direct measurement of the properties, namely λ and c_p, using the traditional methods which require heating samples of the material to be studied, because heating changes the moisture level of the samples.

To study the thermal storage behaviour of the massive walls in the CTO, the property values of the materials that were used had to be determined.

Keeping in mind the difficulties that were mentioned, the selected methodology consisted of a mix of experimentation and simulation:

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i) A typical wall section was selected and instrumented, as shown in Fig.1. This wall, like all others in the CTO, was made of solid 20cm thick concrete blocks, covered on both sides by a 1.5cm thick layer of plaster. This wall separated a south-facing room, with direct gain and Trombe wall systems, from a corridor which had no solar gains except for what came from the south-facing zones.

ii) The temperatures and heat fluxes measured within the wall in the locations shown in Fig.1 were recorded both under normal operating conditions and under temperature cycles consisting of artificially high room temperatures (about 40°C) followed by abrupt temperature drops. By imposing these larger temperature differences, the details of the transient response were magnified and better accuracy was possible.

iii) A first numerical simulation of the temperatures and heat fluxes within the wall was made using property values that were known to be close to reality: Density, specific heat and thermal conductivity of samples of concrete and plaster used in the wall were measured by traditional techniques which involved heating a sample for the latter two properties; infrared emissivity of the wall surface was measured using an emissometer; convective heat transfer coefficents were estimated using common correlations based on measured temperature differences.

iv) Based on the results that were obtained, the properties were adjusted until a better agreement was obtained both in magnitude and rate of change for temperatures and heat fluxes.

Figs. 2 and 3 show the final agreement that was obtained under both experimental situations that were studied. A good agreement was obtained between simulations and measurements, and the changes in property values that were implemented were in the direction dictated by physics, i.e., higher moisture content in the wall than in the sample used for measuring the properties. Table 1 lists the final properties used in the simulation.

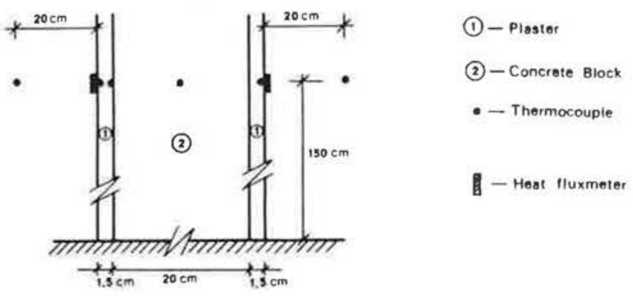


Fig. 1 - Schematic representation of monitored wall.

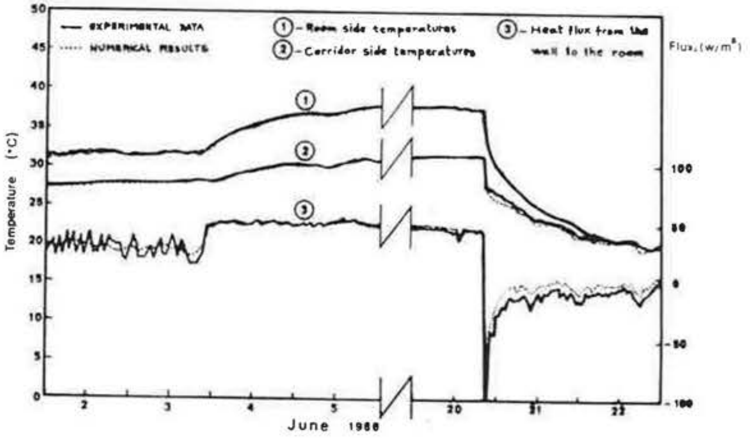


Fig. 2 - Comparison of measured and simulated temperatures and heat fluxes during step-up.

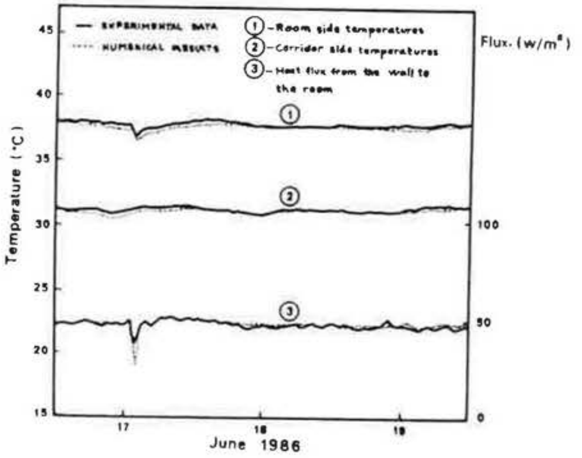


Fig. 3 - Comparison of measured and simulated temperatures and heat fluxes during normal conditions.

TABLE 1 - Property Values Adopted for Simulation

	ρ (Kg/m³)	c_p (J/Kg K)	λ (W/m K)
Plaster	1000	837	0,90
Concrete	2100	880	1,95

The convective heat transfer coefficients were also adjusted to obtain a correct behaviour on the surfaces. Inside the room, the value of 3.0W/m^{2}K is characteristic of a purely natural convection situation with a small temperature difference, while a value of 5.9 W/m^{2}K on the corridor side accounted for a slightly drafty environment where forced convection also played a part. Radiant heat transfer coefficients were calculated by the program based on the existing temperature differences.

4. EFECTIVE THERMAL STORAGE IN THE WALLS OF THE CTO

With the walls characterized in terms of their thermal properties, the amount of energy that was stored by them and released into the indoor air could be calculated in detail. The only inputs necessary for this study were the two air temperatures on both sides of the walls. Two situations were studied:

a) a wall separating two south-facing zones, with identical temperatures.

b) a wall separating one south-facing zone and a north-facing zone, like the wall that was instrumented and studied in section 3.

The air temperatures necessary for the simulations were recorded on an hourly basis for a full winter season.

It should be noted that the air temperatures on both sides of the walls are the result of energy balances which involve the energy exchanged with the walls. Very often, the studies of the effectiveness of the thermal mass for storage are made on the basis of such balances, with the air temperatures also being unknowns. This is not the case here. The air temperatures in all the zones of the house were continuously monitored and recorded and, thus, from these temperatures, the energy exchanged with the walls, on both surfaces, could be evaluated with precision.

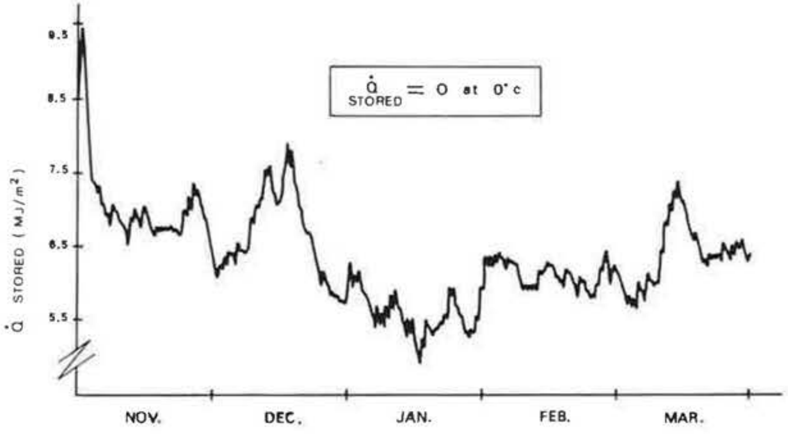
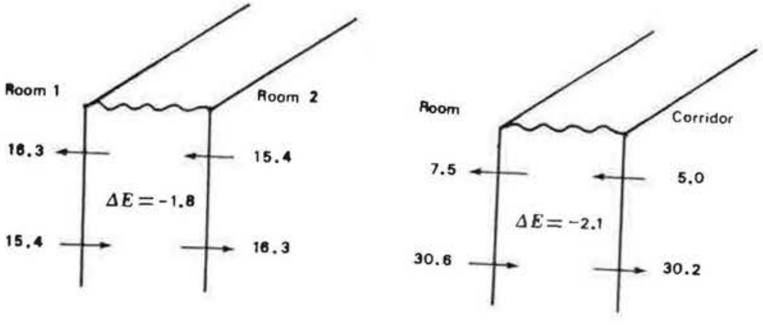


Fig. 4 - Heat stored within the wall for a full winter.

Fig.4 shows the evolution of the energy stored within the type b) wall. It can be seen that, after an initial dissipation of the energy stored during summer, the energy stored fluctuated according to the free-floating indoor temperature which, in turn, followed the variations of outdoor ambient temperature and available solar radiation. The useful energy stored never passed 3 MJ/m^2, a number smaller than the steady-state wall heat capacity. With the values listed in Table 1, the maximum heat capacity of the wall would be 4,4 MJ/m^2 for the 11°C variation (12°C-23°C) measured in the rooms.

Fig.5 shows the overall energy balances for a whole winter season (1 November thru 31 March) and for both types of walls studied. As no auxiliary heat was used in the house during this period, the walls played an effective part in the control of the indoor free-floating temperature. Fig.5 shows that, for the type b), 25% of the energy received by the wall from the south-room air is returned to that room at a later time. The other 75% is transmitted through the wall and contributes to heating the north zones of the house. There is also a non-negligible amount of energy received and later returned to the air of the north zone. This stored energy reduces temperature swings on those periods when strong solar energy rapidly heats up the whole house, because of strong convective currents that are then established.

The symmetrical behaviour of type a) walls is expected because both sides of the wall are subjected to similar air temperatures. The amounts of energy exchanged are smaller than for type b) walls because there is no net heat transfer through the wall, but the amount of energy returned to the room air is double than for type b) walls.



type a)

type b)

Fig. 5 - Overall energy balances of walls for a full winter (MJ/m^2)

5. OPTIMIZATION OF THE WALL THICKNESS

One question that arises from the results shown in section 4 is about the ideal thickness of the walls. The inertia associated with the 20cm-thick concrete-blocks is large, but it might be interesting to know if it is too large or if it could or should be increased still further.

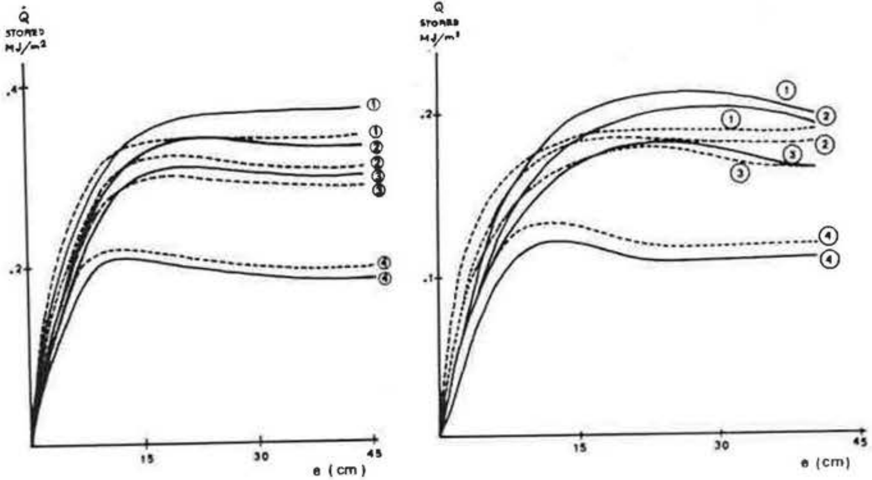
The obvious way to obtain an answer would be to "replace" the real wall by others differing in thickness or in structure, and perform studies similar to those carried out for the 20cm thick concrete-block wall. However, this would not be exactly correct, because, as stated earlier, the air temperatures were the result of energy balances in which heat transfer to and from the walls also participates. So, a different wall would also result in different air temperatures in the house.

So, rather than carrying out the lengthy winter season simulation, it was decided to compare the walls under a typical daily temperature cycle, as measured during the same winter season (sinusoidal variation inside the rooms with a mean of 16.6°C and an amplitude of 2.2°C; in the corridor the mean was 15.1°C and the amplitude was 0.6°C). The study was carried out for the same two wall situations described in section 4. The different walls were allowed to reach a periodic steady condition. The daily heat storage of walls made of different materials and with different thicknesses are shown in Fig.6.

① - Granite
② - Concrete Block
③ - Solid Brick
④ - Wood
—— Without plaster
----- With 1.5 cm of plaster on both sides

Property Values

	ρ (Kg/m^3)	c_p (J/KgK)	λ (W/mK)
Brick	1900	840	1.00
Granite	2600	880	3.00
Wood	650	2100	0.23
Concrete	2100	880	1.95
Plaster	1000	837	0.90



a) between two south rooms.

b) between a south room and the corridor.

Fig. 6 - Effective heat capacity of solid walls.

Fig.6 shows that 20cm of solid concrete-blocks are indeed more than what should have been necessary, as the maximum daily heat capacity of a concrete block wall with plaster on both sides is reached at a thickness of 15cm. Any increase above this limit will not be cost-effective and it will even produce a decrease in effective daily storage capacity.

One general conclusion that can be obtained pertains to the use of plaster on the walls, a standard practice in most buildings. Except for wooden walls, which have low heat storage capacity and where plaster always plays a beneficial role, plaster only increases the effective storage capacity of thin walls. Thus, if massive walls are used, plaster should be kept to the minimum dictated by the mechanical resistance of the layer.

6. CONCLUSION

Designing a house for high thermal inertia requires detailed knowledge of thermal behaviour of walls in different locations of the house. The thickness of the walls should be carefully selected because too much mass can indeed have a detrimental effect upon the thermal performance of the buildings.

In the case of the CTO, a thinner wall (15cm) would have been more effective than the 20cm wall that was adopted.

7. ACKNOWLEDGEMENTS

The authors wish to acknowledge LNETI - National Laboratory for Engineering and Industrial Technology, Portugal -, Department of Renewable Energies, for making the experimental facilities available and for providing financial support.

This work was also made possible by a scholarship granted to Mrs. Manuela Almeida by INIC.

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