Heat Attenuation and the Thermal Mass Effect

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ABSTRACT. The determination of the optimum thermal mass level and distribution should be one of the main objectives of an energy building design in which the dual requirement of cooling and heating the building is taken into account. However, this is not an easy task for the designer because relevant quantitative guidelines are not available. A research programme which will result in these guidelines should be initiated. Due to the interrelation of most of building phenomena with the thermal mass, the use of a simulation tool, like ESP, seems to be necessary provided that it will be enriched by subroutines, experimentally verified, dealing with the various passive cooling techniques. Criteria of thermal mass optimality should also be reassessed taking into account either the free-running state of a building or that with an auxiliary cooling and heating plant. It is expected that the thermal mass guidelines will be in widespread use only if they are accompanied by a simplified design method accounting prorerly for the thermal mass effects in line with the guidelines and if adequate information concerning physical and optical properties of mass-produced or produced at local level thermal mass materials become easily available to the designer. A measurement campaign to complete the available data of this type is necessary.

INTRODUCTION

Scientific and empirical evidence point out the significance of thermal mass on building thermal performance. Thermal mass, in its capacity to store energy, has an effect on most of the heat flows taking place in a building and thus indirectly on

- the quality of indoor thermal comfort,
- the effectiveness of capacity (installed power) of special building elements and plants, which are installed in order to satisfy the required quality of thermal comfort at any time, and
- the building total energy consumption.

Among the most well known effects of thermal mass on the building thermal performance is that on the swing size and occurence time of peak values of indoor air temperature (1),(5), (7),(8),(9).

The determination of the optimum thermal mass level and distribution over the building (exterior walls floors and ceilings, interior partitions, etc.) should be one of the main objectives of a building energy design. So far most of the scientific work has been devoted in satisfying this objective in a frame of overcoming the building heating requirements, and relevant guidelines, in qualitative and quantitative form, have been available (7),(8),(18). The relevant scientific work in a frame of overcoming the cooling or the heating and cooling requirements is limited and general unified guidelines are not available. An attempt for the formulation of thermal mass guidelines in passive cooling is found in Reference 1. According to them, the thermal mass effectiveness should be considered after all the measures to reduce the heat gain have been taken (shading, thermal insulation, etc.).

ANALYSIS TOOLS OF THERMAL MASS PERFORMANCE

The dynamic performance of a building element with thermal mass can be modelled in detail by partial differential equations in time and space domain. By solving these equations, the temperature distribution inside the elements, the heat flows at their boundaries and inside the elements and the stored energy by their mass over a time period can be determined. Depending on the technique of solving these partial differential equations, two different types of methods dealing with the dynamic performance of building elements can generally be distinguised :
- the response function method and
- the numerical method (2).

Thus, by using one of these methods and by means of a computer, the accurate simulation of the real performance of any building element under various surrounding conditions can been achieved.

The dynamic performance of a building element with thermal mass can not be studied separately from most of other phenomena taking place in the building due to strong interrelation between them. Phenomena like surface convection, internal and external longwave radiation exchange, solar radiation absorptance by external and internal surfaces, shading, air flow between building spaces, casual heat gains from lighting installations, occupants and other miscellaneous equipment, plant dynamic performance, moisture fluctuations, etc. have their own effect on the dynamic performance of a building element with thermal mass. This explains the fact that the above mentioned methods, the response function and the numerical method, by incorporating the models of other building phenomena, have eventually taken the form of total building dynamic performance methods (2),(3). Thus, by studying the total building dynamic performance, the study of the effects of thermal mass becomes not an easy task, requiring among other things, appropriate computer capacity, special skills by the user and plenty of time for the execution of the relevant parametric analysis which may lead to more concrete and general answers on the optimum thermal mass level and distribution over the building.

Evidence of the interrelation of most of the individual building phenomena on the performance of building elements with thermal mass is rather numerous (4),(5),(6),(7),(8),(9),(10),(12). However the study of the optimum thermal mass level and distribution is very limited due to reasons, mentioned above. The presentation of studies which can be considered as representative of them follows.

STUDIES ON THE OPTIMUM THERMAL MASS LEVEL AND DISTRIBUTION

The work by Shaviv (5), based on a numerical method, was developed in the right direction of dual study of buildings, that is, during heating and cooling periods of time. Although the results refer only to

- particular climatological conditions,
- thermal mass of side external walls (at the innermost position) and partitions only,
- one type of thermal mass material (concrete),
- a building of particular orientation and overall U-value and
- two cooling techniques, hybrid and natural ventilation,

they are very significant because they show

- the interrelation of mode of use of a building (24-hour use against day-time use), the type of ventilation and the building thermal mass performance. More specifically, the maximum effectiveness of thermal mass is expected with 24-hour building use. If outdoor conditions are proper, the night ventilation is quite beneficial technique of cooling, especially if good heat transfer is achieved between air and thermal mass.
- that there is an optimum level of thermal mass depending on the place to be put and that it is not enough to add just a thermal mass to a building but this additional thermal mass should have adequate surface area that is able to exchange energy with the indoor environment.

There is no doubt that the enhancement of heat transfer coefficient between thermal mass and the indoor air would also have a positive effect. In practice, this may not so easy or economical.

The year-round energy consumption and the summer maximum indoor air temperature were used as energy-related criteria of thermal mass optimality. It should also be added that the building indices on which emphasis was given in Shaviv's work were :

i. Total thermal mass level.
ii. Thermal mass distribution between side external walls and partitions.
iii. Thermal mass volume to surface ratio in partitions.

The work by Clarke (6), based also on a numerical method, deals with the cooling period of time. Although the results refer only to a specific thermal mass and insulation level of a building envelope they are important because they show the interrelation between the mode of cooling plant operation (continuous against intermittent) and the relative position of thermal mass and insulation at the building envelope. Continuous operation leads to higher energy consumption but lower plant power. The innermost position of thermal mass is the best position for continuous plant operation but not for intermittent. In this case the best results are obtained when isulation is split equally either side of thermal mass. The position of thermal mass is more critical for the level of energy consumption in the case of intermittent operation.

The energy consumption and the required plant power to cover peak load were used as energy related criteria of thermal mass optimality. The building index associated with the optimal position of thermal mass seems to be the U-value between internal surface of envelope and internal surface of thermal mass.

The interrelation of plant mode of operation and the thermal mass level has also been experienced in case of swedish buildings during heating periods from relevant measurements. According to these measurements, overnight temperature reduction was more beneficial to lightweight blocks of flats (10).

Swiss numerical studies have also shown that the change of plant mode operation, caused by different control strategies, during the heating period, had similar effects like the change of thermal mass (12).

The most systematic and complete work on thermal mass in buildings is that by Balcomb and co-workers (8),(9). They managed to give quantitative answers to the question of optimum thermal mass level and distribution in case of residential buildings, incorporating the basic passive solar heating elements, by simplifying the response function method. Key element in their methodology is the diurnal heat storage effects - the 24-hour cycle of daytime heat storage and nigthttime heat release. Recently, the methodology was extended to take also into account long term heat storage effects (9). Although the results of Balcomb's work can not be extended to include the case of passive cooling, have, nevertheless, revealed some important facts :

The optimum thermal mass level and distribution strongly depends on the particulatity of the various phenomena which take place in buildings. In other words, the case of buildings with direct gain passive elements is different from that with mass wall elements and that with sunspaces, etc. Furthermore, the effectiveness of thermal mass in direct-gain buildings, depends on its place with order of effectiveness from sunlit floors to walls and ceilings and finally to non-sunlit floors. Trombe walls constructed from common building materials have an optimum thickness which is larger for the denser of them. Water walls have no optimum thickness, that is, the performance continues to improve as the wall is made thicker. Thermal mass larger than a level is necessary in sunspaces. Mass may indefinitely be added in them and still produce a beneficial effect on passive solar heating performance, but the effect diminishes as the mass becomes larger. Furthermore, Balcomb's work also stressed the importance of building material physical properties (density, specific heat, conductivity) and optical properties (absorptivity, reflectivity) on thermal mass effectiveness and its optimum level and distribution.

There is no doubt that analogous results are expected in the case of passive cooling in the sense that they are strongly dependant on the particularity of the phenomena related to the performance of individual passive cooling techniques.

The energy consumption with limiting the indoor air temperature swing on a clear winter day to no more than 7 C was used as criterion of thermal mass level and distribution optimality.

The most significant building indices, used in Balcomb's work, are as follows :

i. Thermal mass level.
ii. Place of thermal mass (sunlit, non-sunlit but radiatively coupled with sunlit mass, etc.).
iii. Thermal mass surface area to solar element glass surface area ratio.
iv. Thermal mass volume to surface ratio.
v. Thermal capacity-thermal conductivity product.

vi. Surface short-wave optical prorerties.
vii. U-value between internal surface of the envelope and internal surface of thermal mass.
viii. Load to solar element collection ratio.

Experimental evidence has supported most of Balcomb's results on thermal mass (7). Littler et al. has also highlighted, with experimental (and simulation) evidence, either the detrimental effect of thermal mass, especially, for non-sunlit rooms or the rather neutral one for floors in sunlit rooms for climatic conditions of Britain (9). In any way, more experimental evidence is needed to verify simulation results. There is no doubt that in the frame of European Projects, like PASSYS and MONITOR, the state of knowledge on thermal mass effects will be improved, especially, by those subgroups that have as one of their objectives the study of these effects under climatic conditions of dual building energy requirements, heating and cooling (14),(15).

THERMAL MASS IN SIMPLIFIED DESIGN METHODS

Both methods, the numerical and response factor method, have also been used extensively for the development of simplified design methods for the calculation of cooling load in which the thermal mass effect is taken into account. For example, numerical method SERI-RES has been used for the simplified design method introduced by Bida et al. (11) and the response factor method for that introduced by ASHRAE (Cooling Load Temperature Difference -CLTD- and Cooling Load Factor -CLF- Method) (4). The thermal mass effect is expressed via an empirical formulation which is function of specific indices related directly or indirectly to thermal mass. The formulation has been developed by correlating the actual cooling load (from hourly simulation) to that calculated at a first stage by the simplified design method. Similar methodology has been used for the development of simplified design methods for the calculation of heating load (e.g utilization factor of solar and internal free gains as function of thermal mass per squared meter of floor area and free gain to load ratio) (13),(17).

It is important to note that although these simplified design methods recognise the significance of thermal mass on cooling (or heating) load, they can not be used for the calculation of optimum thermal mass level and distribution. They have been developed in such a way that as thermal mass is added to the space, the cooling (or heating) load will decrease to an asymptotic minimum value or will decrease in a discrete manner to a minimum value. This is in controversy with the existence of a peak value experienced in some of simulation works.

Nevertheless, indices, used in certain simplified design methods for accounting the thermal mass effect, should be given more consideration as possible parameters in a systematic study of optimum thermal mass level and distribution in buildings with cooling requirements :

Bida et al. (11) calculates the actual monthly cooling load as the product of monthly cooling load in massless building and mass effect coefficient-1, MEC1, and the actual temperature swing in the building space as the product of maximum allowable temperature variation in space and mass effect coefficient-2, MEC2.

MEC1 is calculated as function of four dimensionless indices :

i. Monthly averaged daily thermal storage to heat removal ratio.
ii. Monthly averaged solar utilizability of all transparent elements of the envelope.
iii. A building to ambient temperature difference ratio.
iv. The fraction of load due to solar gains.

MEC2 is calculated as function of three dimensionless indices :

i. An ambient temperature difference to maximum allowable temperature variation in space ratio.
ii. The monthly averaged daily thermal storage, based on the maximum allowable temperature variation in space, to heat removal ratio.
iii. The building to ambient temperature difference ratio.

Having in mind that Bida's simplified design method has been developed only for residential and small commercial buildings, indices (ii) and (iv) should become more general if the same methodology would be used for other types of buildings, for both cooling and heating periods. Thus,

- the monthly averaged solar utilizability of all opaque and transparent elements of the envelope and
- the fraction of the load due to solar and internal free gains

seem to be better substitutes for indices (ii) and (iv), respectively.

CONSIDERATION OF THERMAL MASS EFFECTS BY DESIGNERS

In Reference 1, eleven projects using passive and hybrid cooling techniques and components are described. Approximately in half of them an explicit reference to the general merits of thermal mass as a passive cooling component is given. Although the descriptions are short, they show that the question of thermal mass level and especially its distribution over the building was not generally one of the main preoccupations of the designers. This may traced to lack of appropriate guidelines for buildings with cooling requirements, guidelines similar to those developed by Balcomb.

A design tool survey presented in Reference 1, has shown that approximately half of the design tools calculate the cooling load modulation due to thermal mass. So, depending on the design tool, which a designer uses, the matter of thermal mass effects may be overlooked.

OUTLINE OF A EUROPEAN RESEARCH PROGRAMME ON THERMAL MASS EFFECTS

1. A research programme which will result in guidelines concerning the optimum thermal mass level and distribution in buildings should be initiated. These guidelines may be differentiated according to :

- type of building requirements related to indoor thermal comfort.
  There are buildings with heating and cooling requirements and

buildings with cooling requirements only (e.g. in tourist areas of Greece, some buildings are used only in late spring, summer, and early autumn). Due to the fact that the former type of buildings is the great majority of buildings, the respective guidelines should get the highest priority.

- mode of building use (residence, office, school, etc.). Priority should be given to those guidelines concerning the most common modes of use.
- type of passive cooling technique and passive solar elements (for heating purposes).
- mode of auxiliary cooling (if any) and heating plant operation.
  It is very important to study the free-running performance of buildings against that with an auxiliary plant in continuous or intermittent operation.

2. Two main approaches could be followed in elaborating the guidelines :

a. The adaptation of Balcomb's methodology to all types of building requirements.
b. The adoption of a simulation methodology, like that used by Shaviv (5).

The second approach and especially that of a numerical method has more advantages (2). A lot of european effort has been given in developing and validating the Environmental System Performance (ESP) simulation program and, due to this reason, this program should be a candidate of the highest priority for this type of work. However, the program should be enriched by appropriate subroutines dealing with the various passive cooling techniques. Additional effort should also be given to experimental validation of these subroutines.

3. Attention should also be given to the identification of criteria of thermal mass level and distribution optimality. The criteria should be different for free-running building performance without auxiliary plant operation from building performance with auxiliary plant operation. In the former case indices expressing the time varying deviation of indoor conditions from those of comfort should be examined as appropriate criteria (e.g. time integrated difference between indoor air temperature and maximum allowable indoor air temperature). In the later case indices expressing the year round energy consumption, which account for the possible different form of energy in the cooling period from that in the heating period, and the implication of the level of capacity (installed power) of the auxiliary plants seem to be more appropriate criteria. It is obvious that the last type of criteria makes the analysis more complicated because it introduces in the analysis the economics dimension.

4. An indicative list of important indices for the determination of thermal mass optimum level and distribution has already been given, when the works by Shaviv, Clarke, Balcomb and Bida were discussed. This list is expected to be enriched when the effect of various passive cooling techniques is accounted for. However, it is necessary to assess all these indices in view of establishing common ones for heating, cooling and free-running periods, wherever this is possible.

5. Apart from common indices, a common european simplified design method for all the periods of building performance, taking into account thermal mass effects with an appropriate

model, is also necessary. In other words, the work related to Eurocode (13) should be completed for cooling and free-running periods of building performance. The thermal mass effects model should be developed in such a way that the possible controversy between peak values, experienced in simulation works and expressed through the guidelines, and an asymptotic or in a discrete manner minimum value, experienced in existing simplified design methods, is overcome.

6. A wider application of thermal mass guidelines is expected if more information will be available on the properties (physical and optical) not only of mass-produced materials, e.g. concrete and brick, but also of materials produced and used at local level (16). This information could be the outcome of a campaign of measuring properties of building materials used within the European Communities. The necessity of producers' certificates being available to designers and including measured properties of common mass-produced materials, in accordance with relevant standards, should also be examined.

CONCLUSIONS

The determination of the optimum thermal mass level and distribution should be one of the main objectives of an energy building design in which the dual requirement of cooling and heating the building is taken into account. However, this is not an easy task for the designer because relevant quantitative guidelines are not available. A research programme which will result in these guidelines should be initiated. Due to the interrelation of most of building phenomena with the thermal mass, the use of a simulation tool, like ESP, seems to be necessary provided that it will be enriched by subroutines, experimentally verified, dealing with the various passive cooling techniques. Criteria of thermal mass optimality should also be reassessed taking into account either the free-running state of a building or that with an auxiliary cooling and heating plant. It is expected that the thermal mass guidelines will be in widespread use only if they are accompanied by a simplified design method accounting prorerly for the thermal mass effects in line with the guidelines and if adequate information concerning physical and optical properties of mass-produced or produced at local level thermal mass materials become easily available to the designer. A measurement campaign to complete the available data of this type is necessary.

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