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The impact of thermal mass on building energy consumption

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HIGHLIGHTS

- The transient energy ratio and effective *U*-value are defined.
- Energy consumption during intermittent occupancy is very different from that predicted by static analyses.
- In cold climates, high thermal mass structures will often use more energy than low thermal mass structures.
- Current assumptions regarding the energy savings of high thermal mass structures may often be flawed.

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ABSTRACT

This paper presents new metrics to measure the effect of thermal mass on the energy required to heat and cool buildings. Previous studies have been flawed as they have not considered the interaction between intermittent occupancy and thermal mass, which has a significant impact on overall energy use. However, existing parameters do not adequately capture these effects, so the new metrics developed in this paper are used to analyse the impact of thermal mass in hot climates with active cooling, and cold climates with active heating. The results agree with existing literature that high thermal mass structures are likely to be effective in hot climates; however, in cold climates the drawbacks of high thermal mass likely outweigh the advantages, and high thermal mass can cause an increase in energy use. This finding has implications for the design of buildings in cold climates, and contradicts the commonly-held assumption that high thermal mass is correlated with low energy use. The new metrics (transient energy ratio and effective *U*-value) provide a generalisable method to quantify these effects. They are further used here to analyse the dynamic performance of heavily insulated buildings and show that high thermal mass often leads to higher energy use in cold climates.

1. Introduction

It is taken as self-evident that a reduction in the energy required to heat and cool our homes, offices, factories and other buildings is an important goal. To this end, engineers and architects worldwide incorporate energy efficiency measures at many stages of the design, whether for a new build or a refurbishment project; and greater awareness of global warming and climate change means that energy efficiency measures have taken on a greater prominence than, perhaps, at any time previously. Such thinking is incorporated into building design codes and regulations in the majority of developed states; however, many codes – and designers – focus primarily or entirely on the thermal resistance (or transmittance, the '*U*-value'), to the exclusion of thermal mass [1].

The thermal mass of a building determines its ability to store heat energy, as either sensible or latent heat, and this in turn can have a large influence over indoor temperatures, power requirements and occupant comfort. By analogy with electrical circuits, the term thermal capacitance has gained wide currency, referring to the effect that large heat capacity components can have, buffering temperature changes and reducing the rate of change. Thermal mass is of importance during transient heating and cooling; this is also the dominant thermal mode for the majority of buildings globally, with comparatively few operating in anything like continuous, steady-state conditions. Domestic buildings occupied by working households, for example, might only be heated/cooled outside working hours, while the opposite might be true for office buildings.

There are three contributions to the thermal mass of a structure as a whole: the envelope and structural elements, the air volume, and the fittings, furniture and other objects. That the thermal mass of the building envelope is important, is easily shown by a simple calculation of the heat capacity of a typical room or building: the

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heat capacity of the air in a room of 25 m^2 would be around 75 kJ/K, whereas the heat capacity of the building structure for such a room might be of order 20 000 kJ/K (see 'Example diffusivity data'). Interestingly, the heat capacity of the fittings, furniture and other contents might be of order 1500 kJ/K, and will vary greatly depending on the building's use. There is an increasing body of research looking at the effect of furniture on indoor temperatures, and this will have an effect, but is usually discounted from both simulation and experimental studies due to its variability [2,3]. Neglecting, for the present study, the effects of the contents, it is clear that transient thermal behaviour is dominated by the heat capacity of the structure rather than that of the air.

Contributions to the heat capacity of a typical room

Each element of a room makes a contribution to the total heat capacity. To make an order of magnitude estimate of the relative contributions, it is sufficient to take the volumetric heat capacity of air as 1.2 kJ/m^3/K, and that for the walls as 1 MJ/m^3/K (construction materials have a typical range of about 0.9–1.4). Using the relationship total heat capacity is volumetric heat capacity times volume, and assuming a square room of side length 5 m, height 2.5 m, and wall thickness 0.3 m gives 75 kJ/K for the air and 15 MJ/K for the walls; the floor and ceiling will add to this. The mass of furniture will vary substantially; taking 30 kg per m^2 floor area as typical [3] and assuming this is mostly timber (2 kJ/kg/K) gives a figure of 1500 kJ/K.

Despite the importance of thermal mass, it remains an under-researched area by comparison with thermal resistance/conductivity. From the perspective of material performance, research has been carried out into the dynamic performance of individual structural materials, but even common structural materials such as concrete are not yet fully understood [4]. There are agreed standards relating to the dynamic thermal performance of building components ([5], and see also [6] relating to summer cooling), but these have failed to produce accurate results when compared to real data, perhaps due to the use of sinusoidal temperature profiles in the calculation procedure [7]. Where thermal mass is incorporated into building codes, it is often done so conservatively, or inappropriately [8]; many national building codes make no provision for thermal mass, restrict its use to cooling cases, or make no allowance for interactions between climate, occupancy and thermal mass (e.g. [9–11]). In terms of design and modelling, Kosny and Kossecka [12] showed that many simulation programs and codes provide inadequate results when modelling high-mass buildings, as they were developed for and tested with structures with much lower thermal storage capacity. An additional shortcoming is that many recent studies have been carried out using detailed simulation of one or a few buildings, sometimes combined with experiment; while these are likely entirely correct for the specific buildings and regions analysed, due to the very detailed nature of such work it is difficult to extrapolate from these studies to general conclusions [13,14]. A few parametric studies have been carried out to understand the influence of thermal mass on buildings in a more structured fashion; for example, Aste et al. [15] carried out a parametric study for a number of wall types, for heating and cooling cases; however, whilst useful, their study was restricted to a climate corresponding to that of Milan, Italy; and Asan [16] carried out a study into the effect of wall material and thickness on lag time and decrement factor for a wide range of homogeneous walls. A small number of studies have looked at the effects of varying the placement of insulation and thermal storage layers within a wall, usually relying on 1D studies and controlling for wall thickness [17,18].

A drawback common to all these studies is the lack of a unifying framework for assessing thermal mass. A number of attempts have been made to develop such a framework, such as the 'M factor' method and the 'DBMS' method; intended primarily for HVAC[1] equipment sizing and cooling climates, respectively, these methods have their applications but also significant drawbacks [19]. In particular, they neglect to allow for intermittent heating, which radically alters the impact of thermal mass. The underlying issue with developing a common framework, is the fundamental nature of transient behaviour by comparison with steady-state behaviour. While thermal conductivity is well-defined, with both length-independent ('thermal conductivity') and length-dependent ('*U*-value'/'*R*-value') measures that may be optimised, such parameters are lacking for dynamic thermal behaviour. Thermal diffusivity does not perform an equivalent role to conductivity; the nearest equivalent so far, is perhaps the time constant for a wall [20]. This has been used for parametric studies, but is not generalisable to multi-layer wall structures such as those common in modern construction [21,22]. This is of particular concern for models using lumped-mass methods of thermal analysis, which are popular but cannot adequately account for multi-layer behaviour unless each layer is treated separately; these problems are most apparent with low-order models, and at large Biot numbers [23–26].

Furthermore, there is a lack of research focussing on the performance of thermal mass in temperate and cold climates. Where research exists for temperate climes, the focus again is on detailed models of specific buildings making it hard to generalise [13,27]. Studies attempting to produce general results often involve unrealistic assumptions [28]. Many novel concepts have been proposed, some have been studied (e.g. [29–32]), but again, detailed studies of a limited range of buildings produce results that are hard to generalise. In the case of the referenced studies, the latter looks primarily at high mass as a means to reduce overheating, even in a mid-European clime (the Netherlands) – but in many parts of the world, including mid and northern Europe, the quantity of energy used for heating is far greater than that used for cooling.

Given the lack of a unifying framework, the research that does exist relating to cold climates is patchy and contradictory. Bojić and Loveday [18] examined the influence of thermal mass and insulation on energy requirements for intermittent heating, intermittent cooling and continuous cooling cases, with various positions of the insulation/masonry layers in a combined-material wall. They found that the greatest benefit from high thermal mass was found with an intermittent cooling case, where substantial reductions in energy use were found; in the case of continuous cooling there was no reduction in total energy use, though there was a reduction in the maximum cooling power requirement. In the intermittent heating case, thermal mass was found to increase the energy required. This is in line with other research (e.g. [27], and Tsilingiris' development of the time constant by defining anisotropic time constants [33]), and contradicts the assumption in many quarters that increased thermal mass causes a reduction in heating requirements. Where studies have found increased heating energy use due to high thermal mass, these results are often not followed up (many of these results being 'corner cases' such as occasional winter heating in cooling-dominated climates [14,34]).

Unfortunately, despite the importance of thermal mass, there are few studies looking at its effects in a generalisable, quantifiable sense. Much of the guidance aimed at building designers is of the form 'thermal mass is good', when its inappropriate use in some cases is a hindrance, increasing energy consumption rather than decreasing it [20]. Published research as well as advice from governments and industry bodies can be confused, or simply wrong,

[1] Heating, ventilation and air conditioning.