The influence of thermal mass on the predicted climate cooling potential in low energy buildings

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ABSTRACT

Even in Northern European climates, overheating in many Nearly Zero Energy Buildings is a barrier to year round occupant satisfaction with the indoor thermal environment. Improved energy performance and enhanced thermal comfort should not be perceived as a rigid dichotomy of concepts. However, an acceptable thermal environment, during extended cooling periods now present in NZEB's, can come at a high energy cost if mechanical cooling is used. Passive cooling through the integration of natural ventilation principles with the building morphology and materials has long been championed as a viable alternative to mechanical cooling. This paper presents findings from an investigation into the effect incorporating energy storage can have on the assessment of climate cooling potential for low energy buildings. A method to include the energy accumulation in the steady state energy balance equation for predicting the balance point temperature used to assess the ventilative cooling state is proposed. The energy accumulation in the thermal mass is restricted to an amount that raises the temperature of the material by less than 1K thereby supporting an assumption that the approach is steady state. To achieve this the thermal mass is estimated based on the dimensions of the structure but the depth is assumed as sufficiently large to facilitate a low utilisation of the available capacitance in the structure thus resulting in a temperature change of less than 1K. The approach is applied to a case study in Cork Ireland. Results show that even a modest energy accumulation significantly influences the prediction of ventilative cooling hours in winter months. Required cooling airflow rates are also modified significantly. Simplified approaches to incorporating thermal mass in early stage assessment of climate cooling potential should be considered further and can influence whether or not a passive strategy may be adopted for a building design.

KEYWORDS

Cooling potential, thermal mass, single-sided ventilation

1 INTRODUCTION

The cooling demand in both residential and commercial buildings in expected to increase substantially in 2050 (Santamouris, 2016). This presents unique and unpreceded challenges, in ensuring that the energy consumed in the building stock is reduced to, and maintained at nearly zero energy levels. Avoiding extended periods of overheating will contribute largely to reducing the cooling energy cost of future climate change. Overheating mitigation in nearly zero energy buildings (nZEBs) is one challenge, another challenge is maximising the use of untreated outdoor air to reduce the reliance on mechanical energy systems in nZEBs. Previous studies on overheating have focused on low energy or passive buildings in particular (Dodoo & Gustavsson, 2016; McLeod, Hopfe, & Kwan, 2013; Rodrigues, Gillott, & Tetlow, 2013), and in Europe a large amount of this research has been presented in climates that are moderate, where designs focus on reducing heating season energy consumption (Gupta, 2013; Psomas, Heiselberg, Duer, & Bjørn, 2016; Rohdin, Molin, & Moshfegh, 2014; Tabatabaei Sameni, Gaterell, Montazami, & Ahmed, 2015). Considering overheating in the design stage has been seen as vital to reducing future overheating (Gul et al., 2015). Unfortunately, past experiences with the housing industry leaves at lot to be desired, as current or future overheating has been seldom considered in the design stage within this industry (Lavafpour & Sharples, 2014). This overheating risk could be further underestimated in practise, as overheating is expected to have a more pronounced effect in low energy buildings when compared to traditional buildings (Dodoo, Gustavsson, & Bonakdar, 2014). Exposed thermal mass, external solar shading and defined ventilation strategies like night ventilation have been shown to be vital in reducing overheating (Holmes & Hacker, 2007). Furthermore, proven examples of low energy mixed-mode buildings have shown that exemplary comfort and energy performance can be achieved for a range of climate zones and building types (O'Sullivan, O'Donovan, Zhang, & Carrilho da Graca, 2017). Therefore, design stage tools that incorporate, climatic cooling, ventilation strategies, and mitigation measures like thermal mass could prove vital in informing designers to make the right decisions from both comfort and energy perspectives. Estimations of the available climatic cooling potential from natural sources has been put forward by many researchers (Artmann, Manz, & Heiselberg, 2007; Axley & Emmerich, 2002; Campaniço, Soares, Hollmuller, & Cardoso, 2016; Chiesa & Grosso, 2015; Panchabikesan, Vellaisamy, & Ramalingam, 2017). While the approaches used above are by no means ideal they provide designers with a critical insight into the potential of the climate they are planning to build in and offer simple overview as opposed to the detailed approach of whole building simulation which can take more time. The drawbacks of some of the climate cooling potential approaches are that they tend to over or underestimate the contribution from thermal storage in a buildings thermal mass, with some approaches not accounting for thermal mass and others assuming thermal mass was infinite. Gandhi, Brager and Dutton also present examples of early phase simulation tools that can be used by designers for simulating mixed-mode buildings (Gandhi, Brager, & Dutton, 2015). In more recent work, as part of objectives set out in IEA EBC Annex 62, a cooling potential analysis tool was developed by (Annamaria Belleri, Marta Avantaggiato, 2017) which can be used easily by designers in the early phases of building design. While this tool does not look specifically at the airflow configuration of a building or account for thermal mass, it gives the user an insight into required airflow rates when using untreated outdoor air for a minimum or enhanced airflow rate, evaporative cooling, and for a specific climate and building (Belleri & Chiesa, 2017). This paper aims to investigate whether the inclusion of a nominal amount of energy accumulation (due to thermal storage) in the energy balance model for estimating climate cooling potential will result in a significant change in the predicted number of hours requiring enhanced ventilative cooling (VC) for a given location and building. It also investigates whether there is a change in the required ventilation rates for the enhanced VC and if this improves the likelihood of single sided ventilation as a viable cooling strategy. The method of inclusion of an energy accumulation term in the balance point temperature equation is presented. Results are also presented and discussed.

2 METHODOLOGY

2.1 Existing cooling potential analysis tool

Assessing the cooling potential of a location requires knowledge about the local climate and the building which the assessment will be carried out for. The approach suggested by Emmerich and Axley uses a single zone steady state energy balance model that, in its basic form, does not account for any thermal storage in the energy balance. It assumes that because the indoor temperature is assumed as a constant in the estimation of the balance point temperature, then no thermal mass is present for modulating the temperature. The method then calculates the balance point temperature (T_{bp}) at each time step using Equation 1 below and uses different criteria to determine whether the zone is in heating mode, the minimum airflow rates for hygiene is sufficient for cooling, or whether an enhanced VC airflow is needed to meet cooling demand. Where, Q_T is calculated as the sum all gains to the air node at each time step.

$$T_{bp}(t) = T_{sp}(t) - \frac{Q_T(t)}{\dot{m}_n c_p + \sum UA} \quad (1)$$

These criteria are shown in Equation 2 below with T_e representing external air temperature from weather data, T_{bp} representing the balance point temperature, T_{cu} and T_{cl} the upper and lower thermal comfort limit values respectively and T_{cr} an upper comfort limit temperature offset to ensure valuable cooling is available.

$$VC\ mode = \begin{cases} 0, & \text{if } T_e \leq T_{bp}, \\ 1, & \text{if } T_{bp} \leq T_e < T_{bp} + (T_{cu} - T_{cl}), \\ 2, & \text{if } T_{bp} + (T_{cu} - T_{cl}) \leq T_e < T_{cu} - T_{cr}, \\ 3, & \text{if } T_e \geq T_{cu} - T_{cr} \end{cases} \quad (2)$$

A drawback of this approach is that it may overestimate the number of cooling hours given the magnitude of the instantaneous gains that are assumed to enter the air node. This can lead to a larger heat gain, requiring removal using an enhanced VC airflow rate. Using this method also results in the prediction of some very high air change rates (ACRs) for cooling. Consequently, in early stage design this may rule out the use of otherwise appropriate strategies such as single sided ventilation, a strategy well adapted to retrofit projects. Thermal storage in the building structure can reduce the amplitude, time and occurrence of heat gain to the air node in a homogenous thermal zone. Taking account of its effect can be complex given the dynamic nature of the charging and discharging of energy from the storage mass, as well as the coupled nature between the indoor air temperature and thermal mass temperature, with either influencing the other respectively. However, when assessing the cooling potential of a given building and associated climate the approach is based on a steady state method that uses a constant for indoor air temperature. The methods proposed generally assess whether the external air temperature (T_e) is above or below the value that would result in no additional heating or cooling required to maintain the desired indoor air temperature set-point (T_{sp}). If cooling is needed then as long as the external temperature is below the upper thermal comfort limit defined by the adaptive thermal comfort model, useful cooling is available.

2.2 Proposed inclusion of energy accumulation in thermal mass

As long as a differential in temperature exists between the indoor air and thermal mass there will be some energy accumulation in the thermal storage, charging when the differential is positive in the direction of heat flow into the thermal mass, discharging when the differential is positive in the direction out of the thermal mass. Assuming a constant temperature difference can be a simplified way of allocating a portion of the energy to storage at each time step. With the assumption of a constant air temperature (T_{sp}) in the energy balance model and assuming that only a small portion of the available thermal mass is utilised, we can reasonably assume that there also exists a broadly constant thermal mass temperature (T_{tm}) and therefore it is possible to incorporate an energy accumulation to the thermal mass at each time step using the steady state energy balance model to estimate the balance point temperature (T_{bp}, see Equation 1). In a structure that can be assumed to be infinitely massive there is a large potential for energy storage without large changes to the temperature of the thermal mass. A large amount of energy accumulation is required to increase the temperature of the structure. In a similar but more realistic scenario where we define a zone and associated thermal storage potential, if we are to reasonably assume that the temperature of the thermal storage will remain constant, we can limit the energy accumulation in the thermal storage to below that required to raise the temperature by 1 degree Kelvin during each day. This approach is suitable in order to validate the assumption of a constant thermal mass temperature in the modified energy balance equation. Using a constant thermal mass temperature allows an assessment of how sensitive the climate cooling potential analysis approaches are to the assumption that there is no thermal mass present, where all gains are assumed to act instantaneously in the air node. The proposed approach here does not investigate different levels of thermal mass, i.e. lightweight versus heavyweight, rather it seeks to quantify whether there is a significant effect on the number of hours requiring enhanced cooling when some energy accumulation is allowed to take place, and what the subsequent influence on the required ventilation rates might be. To include the energy accumulation term we provisionally propose the replacement of Q_T with an adjusted total heat gain value ($\hat{Q}_T$) that incorporates the energy accumulation in the thermal mass:

$$\hat{Q}_T = Q_T - Q_{acc} \tag{3}$$

Where the energy accumulation term ($\hat{Q}_{acc}$) is calculated as:

$$\hat{Q}_{acc}(t) = Q_s\alpha(t) - Q_s\alpha(t-\tau) + hA(T_{sp} - T_{tm})(t) \tag{4}$$

The three terms on the right hand side represent the fraction of solar gain which charges the thermal storage directly at the current time step, the fraction of solar gain which discharges from the thermal storage based on a pre-defined time lag τ, (proposed as being between 1 hour and 3 hours, taken as 2 hour for this study), and a convective energy transfer into the thermal storage from the air node. At each time step in the hourly assessment method, the accumulated energy term is then subtracted from the total energy accumulation term giving an adjusted value ($\hat{Q}_T$) used for the estimation of the balance point temperature. This modified balance point temperature shifts the external air temperature value at which cooling will now be required, thus adjusting the number of cooling hours. To ensure the constant thermal mass temperature assumption remains valid, and in turn a constant temperature differential between the air and thermal mass, the solar charging fraction for the thermal mass α, the time lag τ, and the heat transfer coefficient h, have been set to ensure that the total energy accumulation over a given daily occupancy period (in this analysis taken from 08:00 to 17:00), does not exceed the energy required to raise the thermal storage by 1°K for any of the annual occupancy days. This is completed by assessing the following expression for each occupancy period:

$$E_{acc} \leq E_{1k} \tag{5}$$

Where E_{1k} is the energy necessary to raise the thermal storage by 1°K. The total energy accumulated in a given day is calculated as:

$$E_{acc} = \sum_{t=1}^{n} \hat{Q}_{acc}(t)\,\Delta t \tag{6}$$

In the example used for this study the thermal storage has been estimated based on the details in Table 1 below. Using these details, E_{1k} is estimated to be 31,752 kJ/K. The amount of available thermal storage each day is therefore restricted from exceeding this value. By way of example, Figure 1 presents typical energy accumulation profiles for a day in January, and a day in July.

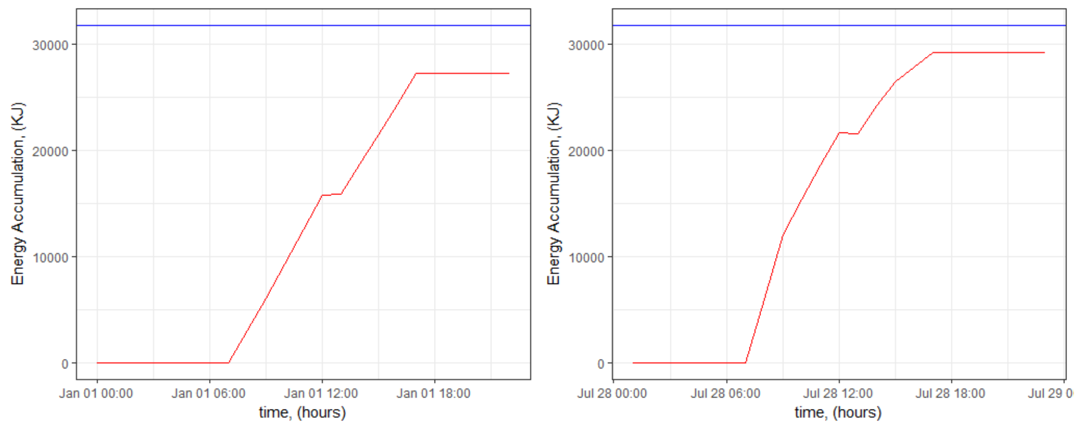

Figure 1: Energy accumulation within the thermal mass throughout a typical winter day (January 1st) and a typical summer day (July 28th). Energy accumulation shown in red, energy required to limit temperature increase to 1°K shown in blue.

It can be seen that using mid-range values for the respective energy charging components of Equation 4 the E_{1k} chosen still allows reasonable hourly charging and discharging without saturating. To ensure that the accumulated energy at the end of each occupancy period can be sufficiently dissipated from the structure, the heat removal potential from night-time VC is estimated and compared with the previous days building up. This involved calculating the maximum heat removal potential of the ventilation opening in the zone during each night and assessing whether this value exceeded the total energy accumulation during the previous occupied period. An indoor cooling set-point of 23°C was taken to estimate the heat removal potential. We provisionally set the cooling hours to be from 00:00 to 07:00 though these would change depending on the cooling demand and limits relating to boundary conditions. The integral of energy removal throughout the nigh-time period is calculated by using the external air temperature for each hour to estimate the heat removal rate using a nominal ACR value. It was found that for the annual period a maximum daily night-time ACR value of 1.75 ACH is required to ensure that there is sufficient heat removal potential to discharge the energy accumulated in the thermal mass throughout the previous day. The actual value varies each day with 1.75 ACH being the maximum required value. It is reasonable to assume that this range of ACR values would be achievable when required and as such the assumption that all energy accumulated in the thermal mass is removed by the beginning of each day appears reasonable. The number of hours where cooling is available during the night can also be increased. As the purpose is to test how sensitive the approach is to the effects of an energy sink in the energy balance model, this limit was deemed acceptable for the purpose of this paper. Evidently it restricts the extent to which energy accumulation can be incorporated into the model and therefore the study doesn't seek to present a comprehensive assessment of how thermal storage can influence cooling potential and its associated VC ventilation rates. Here, the study specifically seeks to quantify whether or not a notional energy storage can have a significant influence on the outcome for the assessment method. A northern European location is selected for investigation of the effect of an allowance for energy accumulation in the energy balance model. A building in Cork, Ireland was assessed for this study, the building details are included in Table 1 below.

Table 1: Building details

Input Parameter	Units	Values
General		
Name		PartL2017new
Building Type	(-)	Office
Comfort Category	(-)	III
Geometry		
Floor to ceiling height	(m)	3.0
Depth of room	(m)	8.0
Width of room	(m)	12.0
Area of external glazing	(m^2)	14.4
Depth of internal wall (for thermal storage)	(m)	0.1
Thermal Characteristics		
U-Value External Wall	(W/m^2K)	0.21
U-Value Glazing	(W/m^2K)	1.60
G-Value Glazing	(-)	0.70
U-Value External Roof	(W/m^2K)	0.20
U-Value Floor	(W/m^2K)	0.21
Heat capacity of internal wall	(J/kg K)	840
Density of internal wall	(kg/m^3)	2000
Additional		
Shading control set point	(W)	80
Minimum Ventilation Rate	(l/s/p)	12
Number of Occupants	(QTY)	-
Occupant Density	(m^2/p)	10
Occupant Sensible heat Gain	(W/p)	90
Internal heat gain	(W/m^2)	25
Heating set point temperature	(°C)	20
Cooling set point temperature	(°C)	23

The change in VC hours from employing thermal mass is presented. The distribution of when the VC hours are required is also compared. This is to identify whether or not the thermal mass has an impact on cooling requirements outside the summer period as the current approach estimates a high proportion of VC during winter. The distribution of ACR values for a scenario with and without energy accumulation is also investigated.

3 RESULTS

Figure 2 presents the variation in monthly enhanced VC hours when thermal mass is applied and outlined in Table 1 above. Large reductions in VC are noticeable during winter months with the lower energy gains more affected by the amount of accumulation available with the thermal mass. In summer months there is less of an impact on whether or not cooling is needed.

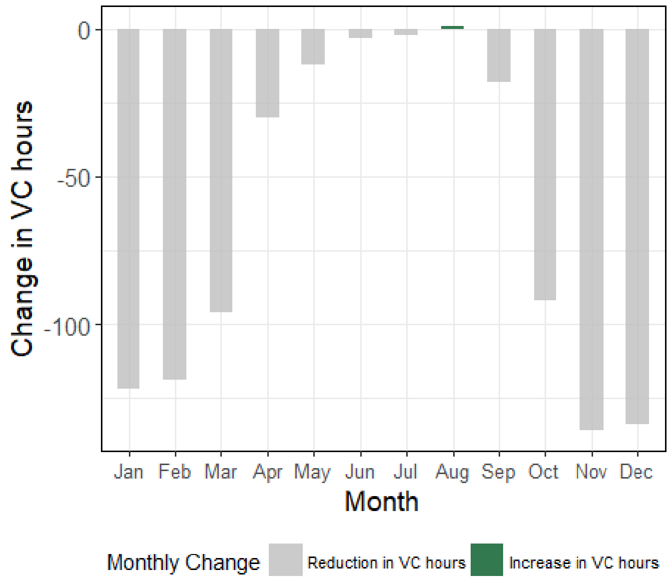

Figure 2: Change in VC hours when an energy accumulation term is used in the energy balance equation

Even with some accumulation of energy in the thermal mass there is still a sufficiently large energy load in the space to require VC during summer. Table 2 summarises actual change in all modes of operation for the analysis method. However, this result demonstrates that even with a notional allowance for energy accumulation in the simplified approach there is an effect on the outcome of the tool. This evidently doesn't allow for the coupled dynamic heat transfer interaction effects between air and mass temperatures.

Table 2: Summary of annual occupancy hours according to VC mode.

Mode	Description	No Thermal mass (hrs)	Thermal mass (hrs)
0	Heating mode	321	704
1	Cooling with Min airflow	454	834
2	Cooling with VC airflow	2875	2112

Figure 3 shows how the required ACRs have been affected when thermal mass is incorporated into the calculation. Table 3 provides summary statistics.

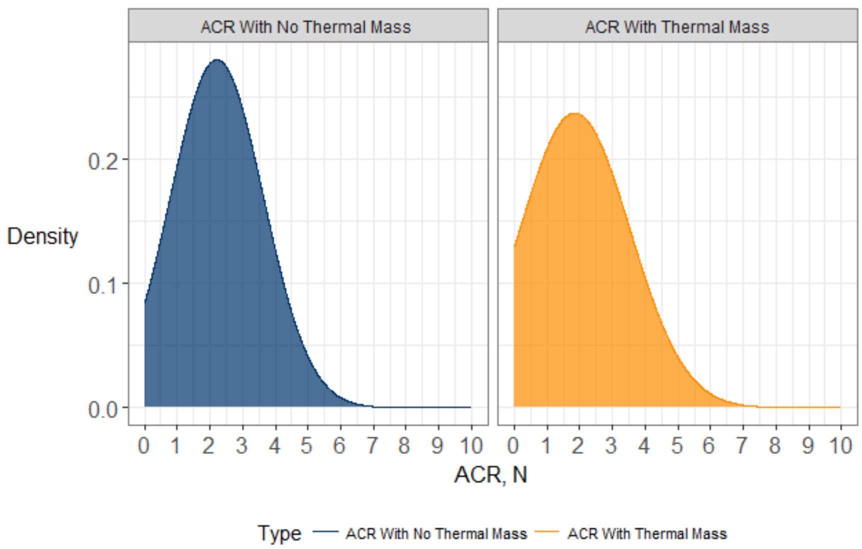

Figure 3: Change in range of ACR values when an energy accumulation term is used in the energy balance equation

The mean air change rate required throughout the occupied hours reduces from 2.8 ACH to 1.9 ACH, a 32% reduction. While the standard deviation of ACR values does not change significantly the distribution of values shifts left with the maximum ACR value reducing from 14.9 to 12.3 ACH, an 18% reduction. The skewness increases from 0.14 to 0.42 when thermal mass is introduced demonstrating the increase in minimum airflow values in the thermal mass dataset. In general introducing some energy accumulation results in ACR values that are lower making the likelihood of strategies such as single sided ventilation more acceptable to meet the cooling requirements for the building.

Table 3: Summary of annual occupancy hours according to VC mode.

Type	mean	median	max	Std. dev.
No Thermal Mass	2.8	2.9	14.9	1.8
Thermal Mass	1.9	2.3	12.3	1.7

4 CONCLUSIONS

When using early stage assessment tools to establish the climate cooling potential for a given combination of location and building the approach often omits the effects of energy storage in the building thermal mass. This is usually due to the complicated interaction between the air and storage material. However, adopting a simplified approach that limits the storage mass to a constant temperature can facilitate an initial investigation into the potential effect energy accumulation might have on the extent of ventilative cooling needed and the magnitude of associated cooling airflow rates. The approach presented here, while not comprehensive in its treatment of the relationship between thermal mass and internal zone air, does demonstrate the importance of developing early stage techniques that account for its presence. A significant reduction in VC hours during winter months was shown to exist when thermal mass is incorporated along with a reduction in the magnitude of required ventilation airflow rates. More work is needed on properly allowing for the dynamic interaction between the thermal mass and air mass within the zone.

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