Parametric Study on the Dynamic Heat Storage Capacity of Building Elements

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ABSTRACT

In modern, extensively glazed office buildings, due to high solar and internal loads and increased comfort expectations, air conditioning systems are often used even in moderate and cold climates. Particularly in this case, passive cooling by night-time ventilation seems to offer considerable potential. However, because heat gains and night ventilation periods do not coincide in time, a sufficient amount of thermal mass is needed in the building to store the heat. Assuming a 24 h-period harmonic oscillation of the indoor air temperature within a range of thermal comfort, the analytical solution of one-dimensional heat conduction in a slab with convective boundary condition was applied to quantify the dynamic heat storage capacity of a particular building element. The impact of different parameters, such as slab thickness, material properties and the heat transfer coefficient was investigated, as well as their interrelation. The potential of increasing thermal mass by using phase change materials (PCM) was estimated assuming increased thermal capacity. The results show a significant impact of the heat transfer coefficient on heat storage capacity, especially for thick, thermally heavy elements. The storage capacity of a 100 mm thick concrete slab was found to increase with increasing heat transfer coefficients as high as 30 W/m^2K. In contrast the heat storage capacity of a thin gypsum plaster board was found to be constant when the heat transfer coefficient exceeded 3 W/m^2K. Additionally, the optimal thickness of an element depended greatly on the heat transfer coefficient. For thin, light elements a significant increase in heat capacity due to the use of PCMs was found to be possible. The present study shows the impact and interrelation of geometrical and physical parameters which appreciably influence the heat storage capacity of building elements.

1. INTRODUCTION

During the last few decades various factors have caused a trend towards increasing cooling demand in buildings. Particularly in modern commercial buildings with extensive glazing, higher solar gains and higher internal loads are contributing to the rise in cooling demand. Additionally, due to gradual climate warming and increased comfort expectations in summertime the installation of air-conditioning systems is becoming more common, and cooling plays a more significant role in the overall energy demand of buildings even in moderate and cold climates such as in Central or Northern Europe.

Particularly in moderate climates, passive cooling of buildings by night-time ventilation appears to be a promising technique. If night-time temperatures are relatively low even in summer, the building can be cooled by ventilation with outdoor air. The ventilation can be achieved by mechanically forcing air through ventilation ducts, but also by natural ventilation through the windows. Hybrid systems combining the two methods are often also used. Thereby fans are only used if natural forces – thermal buoyancy and wind – are not strong enough to ensure sufficient ventilation rates.

As heat gains and night ventilation periods do not coincide in time, the energy of daily heat gains needs to be stored until it can be discharged by ventilation during the following night. A sufficient amount of thermal mass is therefore needed for a successful application of night-time ventilation. For effective utilisation of the thermal mass both a sufficient heat transfer to the surface and sufficient conduction within the element are needed. The purpose of this study is to evaluate the impact of different parameters such as material properties, slab thickness and heat transfer coefficient on the heat storage capacity of building elements.

2. MODEL OF A BUILDING ELEMENT

In this study a building element is represented by an infinite homogeneous slab with half-thickness d. One surface of the slab ($x = 0$) is exposed to a varying temperature, while the other surface ($x = d$) is considered adiabatic. Because of the symmetry this also represents a slab with thickness 2d with both surfaces exposed to the same conditions (surfaces at $x = 0$ and $x = 2d$, symmetry at $x = d$). The solution to the one-dimensional conduction problem in a slab with a sinusoidal surface temperature is given in Carslaw and Jaeger (1959).

Based on this solution Akbari et al. (1986) provided an analytical solution to the heat transfer problem in a slab with convective boundary condition and sinusoidally varying air temperature. The analytical solution gives both the temperature and heat flow profiles within the slab. Integrating the positive (charging) or negative (discharging) heat flow at the surface over one periodic cycle yields the dynamic heat storage capacity q of the element. This corresponds to the dynamic heat storage capacity as defined in European standard EN ISO 13786. A method to calculate the dynamic heat storage capacity of an element composed of layers with different thermal properties is also presented in EN ISO 13786.

The dynamic heat storage capacity can be calculated for different time intervals t, e.g. short term variations ($t = 1$ h), diurnal variations ($t = 24$ h) or seasonal variations ($t = 8760$ h). In this study the capacity was calculated based on a 24 h temperature variation, as the performance of night-time ventilation mostly depends on the diurnal heat storage.

The used model includes the following parameters:

- Heat transfer coefficient, h (W/m^{2}K)
- Half thickness of the slab, d (mm)
- Thermal conductivity, λ (W/mK)
- Volumetric heat capacity, ρc (J/m^{3}K)
- Time period, t (h)

These parameters completely describe the heat storage capacity of a building element exposed to a sinusoidally varying temperature. However, the model does not include internal and solar heat gains, the ventilation air change rate or climatic conditions, which certainly also influence the performance of night-time ventilation.

3. TEMPERATURE PROFILES

The analytical solution given by Akbari et al. (1986) was used to plot the temperature profiles in a 100 mm thick concrete slab (material properties are given in Table 1) with a convective boundary condition ($h = 10$ W/m^{2}K) and a sinusoidally varying air temperature, $T_{Air} = 24.5 \pm 2.5$ °C (Fig. 1).

Even at a relatively high heat transfer of $h = 10$ W/m^{2}K the amplitude of the surface temperature is reduced to 44 % of the air temperature amplitude. Compared to the surface temperature the amplitude of the core temperature is still 92 %. This indicates that even for a fairly thick element and a high heat transfer at the surface the thermal conductivity of concrete ($\lambda = 1.8$ W/mK) is sufficient to utilise the whole thickness of the slab.

4. HEAT STORAGE CAPACITY

The heat storage capacity of building elements exposed to a sinusoidal temperature variation with a periodic time of 24 h was evaluated depending on different parameters.

Table 1: Material properties

	λ	ρ	c
	W/mK	kg/m^3	kJ/kgK
Concrete	1.80	2400	1.1
Lime sand	1.10	2000	0.9
Gypsum	0.40	1000	0.8
MDF	0.18	800	1.7

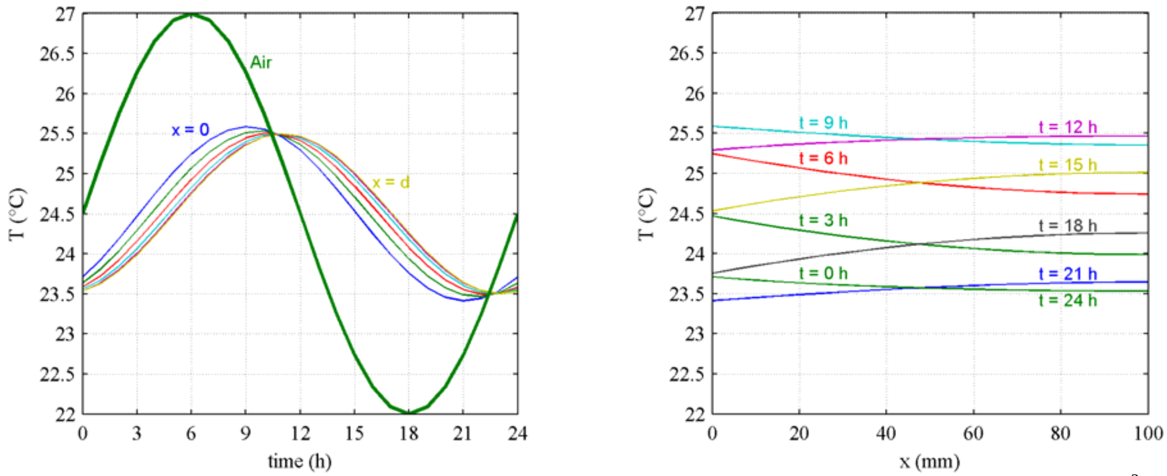

Figure 1: Temperature profile in a 100 mm thick concrete slab with convective boundary condition (h = 10 W/m^{2}K), exposed to a sinusoidal air temperature (24.5±2.5 °C) on one side (x = 0) and adiabatic boundary condition on the other side (x = 100 mm). Temporal profile at different layers of the slab, Δx = 20 mm (left) and spatial profile at different time-steps, Δt = 3 h (right).

4.1 Heat Transfer Coefficient

Figure 2 shows the diurnal heat storage capacity depending on the heat transfer coefficient for different materials and slab thicknesses. The properties of the different materials are given in Table 1.

The impact of the heat transfer coefficient depends greatly on slab thickness and the thermal properties of the material. For thin slabs (d = 15 mm) the heat storage capacity is almost constant for heat transfer coefficients higher than h = 3 W/m^{2}K. In contrast, for thick slabs increasing the heat transfer coefficient up to h = 30 W/m^{2}K significantly increases the diurnal heat storage capacity.

Generally, the storage capacity of thin elements, such as gypsum boards used for light-weight wall constructions or medium density fibreboards (MDF) used for furniture is rather small compared to thick and heavy elements such as a concrete ceiling or lime sand brick walls. However, especially at a low heat transfer coefficient and in consideration of its large surface area, furniture might still make a notable contribution to the total heat storage capacity of a room.

4.2 Slab Thickness

Increasing the slab thickness clearly raises the diurnal heat storage capacity until a maximum is reached. Beyond the maximum the capacity decreases slightly and converges to a constant value as the thickness approaches infinity (Fig. 3). This somewhat surprising effect has been described previously (e.g. Gruber and Toedtli, 1989) and is explained by the superposition of an incident wave and a reflected wave. With increasing heat transfer coefficient the maximum becomes more distinct. Additionally the optimum thickness of a concrete slab increases from about d = 90 mm to 140 mm if the heat transfer coefficient increases from h = 5 W/m^{2}K to h = 30 W/m^{2}K.

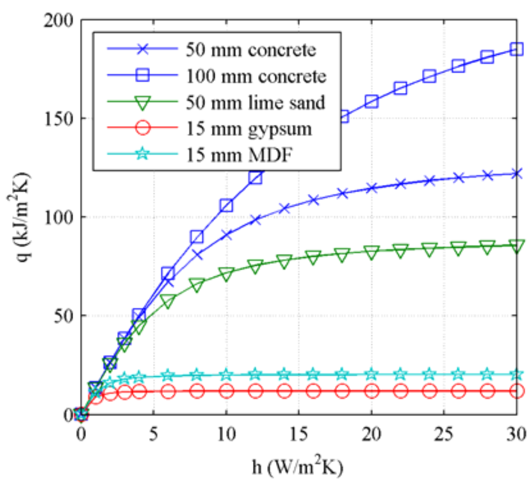

Figure 2: Diurnal heat storage capacity, q depending on the heat transfer coefficient, h for different materials and slab thicknesses.

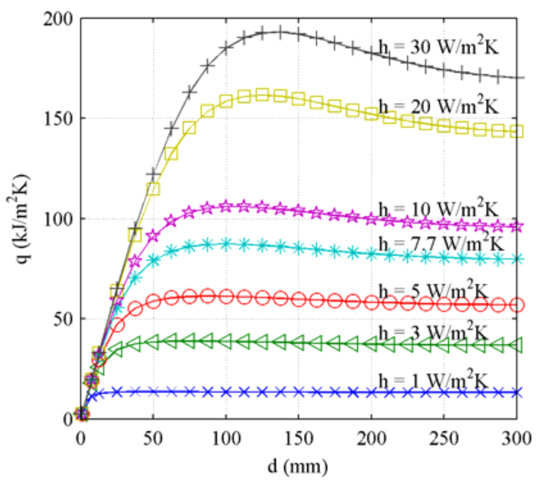

Figure 3: Diurnal heat storage capacity, q of a concrete slab depending on the thickness, d for different heat transfer coefficients, h.

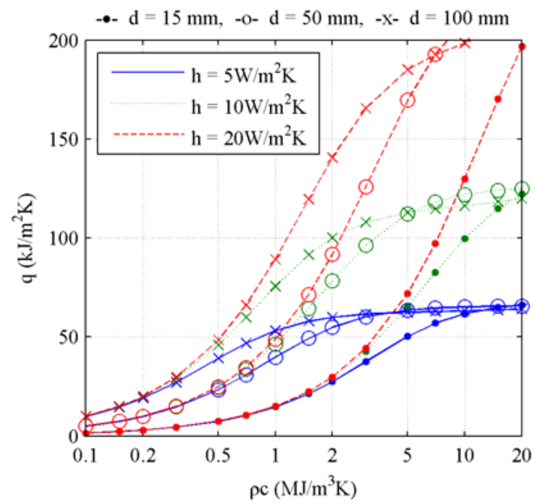

Figure 4: Diurnal heat storage capacity, q depending on the heat capacity, ρc for different heat transfer coefficients, h and slab thicknesses, d; λ = 1.8 W/mK.

The most significant decrease between the maximum capacity and the capacity of an infinite slab also occurs at the highest heat transfer coefficient and amounts to about 12 % for h = 30 W/m^{2}K.

4.3 Volumetric Heat Capacity

The impact of the volumetric heat capacity, ρc is displayed in Figure 4. The heat storage capacity of very light materials such as insulation materials with ρc < 0.1 MJ/m^{3}K is generally very small. Even for a slab with half-thickness d = 100 mm and a high heat transfer coefficient, h = 20 W/m^{2}K, the heat storage capacity is only 10 kJ/m^{2}K. Increasing the thermal capacity to the value of concrete (ρc = 2.6 MJ/m^{3}K) significantly improves the storage capacity, especially at high heat transfer coefficients (h = 10 to 20 W/m^{2}K) to maximum 158 kJ/m^{2}K. Further improvement for capacities above ρc = 2.6 MJ/m^{3}K is only achieved for thin slabs (d = 15 mm) or at very high heat transfer coefficients (h = 20 W/m^{2}K). These are the cases in which the use of phase change materials appears to be promising.

4.4 Thermal Conductivity

Figure 5 shows the impact of the thermal conductivity, λ of the slab material. For thin slabs (d = 15 mm) there is almost no impact of the conductivity in the range from λ = 0.05 W/mK and λ = 50 W/mK. For thicker slabs the heat storage capacity increases with increasing conductivity. However, in most cases the storage capacity increases only slightly for conductivities above 1.8 W/mK (concrete). Only in the case of a very thick slab (d = 100 mm) in combination with a high heat transfer coefficient (h = 20 W/m^{2}K) does the storage capacity increase with conductivities up to 50 W/mK.

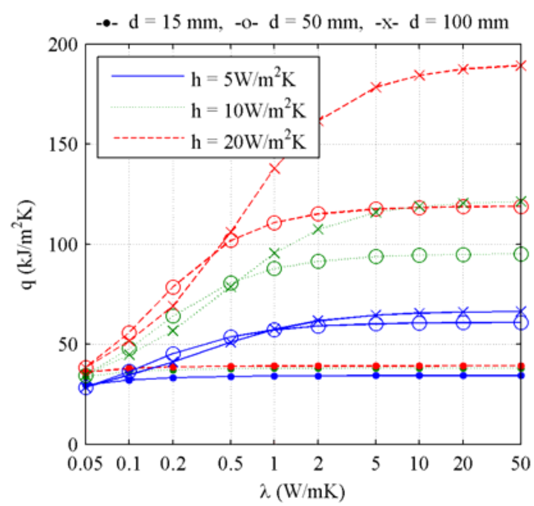

Figure 5: Diurnal heat storage capacity, q depending on the thermal conductivity, λ for different heat transfer coefficients, h and slab thicknesses, d; ρc = 2.6 MJ/m^{3}K.

5. PHASE CHANGE MATERIALS

A well known possibility for increasing the thermal heat capacity of building elements is the integration of phase change materials (PCM). PCMs, like paraffins or salt hydrides, absorb and release a considerable amount of heat during the melting and solidification process. If the melting temperature of the PCM lies in the range of thermal comfort, the latent heat can be utilised to increase the heat storage capacity of a building element. A possible approach is the integration of micro-encapsulated PCMs into gypsum plaster boards or plaster (Schossig et al. 2005).

PCMs are characterised by an increased heat capacity at melting temperature, as the heat of fusion needs to be applied for a further temperature increase. Ultra-pure materials show a sharp melting temperature, but typically the heat of fusion is introduced within a certain temperature range. The thermal conductivity also depends on the temperature and especially differs for the solid and liquid phase. These non-linear thermal properties complicate the representation of PCMs in physical models.

For a rough estimation of the effect of PCMs on the heat storage capacity a very simple model was used in this study. Assuming that the heat of fusion, ΔH_{fusion} is introduced continuously over the range of the temperature fluctuation, ΔT, the PCM was considered by applying an increased heat capacity:

$$c_{PCM} = c_{sensible} + \frac{\Delta H_{fusion}}{\Delta T} \quad (1)$$

The temperature fluctuation ΔT was set to 5 K, according to the comfort range given in prEN 15251 (2006), category III. For a building material with integrated PCM, the resulting volumetric heat capacity, ρc and the conductivity, λ were calculated according to the weight proportions. The values yielded for gypsum with 20 % and 40 % PCM ($\lambda = 0.2$ W/mK, $\rho = 800$ kg/m^3, $c_{sensible} = 2.0$ kJ/kgK, $\Delta H_{fusion} = 200$ kJ/kg) are given in Table 2.

Table 2: Properties of gypsum including PCM

	λ	ρc
	W/mK	MJ/m^{3}K
Gypsum, 20 % PCM	0.36	8.7
Gypsum, 40 % PCM	0.32	15.9

The heat storage capacity of a 15 mm thick gypsum plaster board with different PCM contents compared to concrete slabs is shown in Figure 6. Even at relatively low heat transfer coefficients, h < 5 W/m^{2}K, a significant effect of the PCM can be recognised. While the heat capacity of the plain gypsum plaster board is constant for heat transfer coefficients above 3 W/m^{2}K, the capacity of the boards with integrated PCM continuously increase with increasing heat transfer coefficients up to 30 W/m^{2}K. The plaster boards with 20 % and 40 % PCM content show similar performance to a 50 mm and 100 mm thick concrete slab, respectively. This clearly shows the feasibility of PCM integration for improving the thermal performance of light-weight wall constructions.

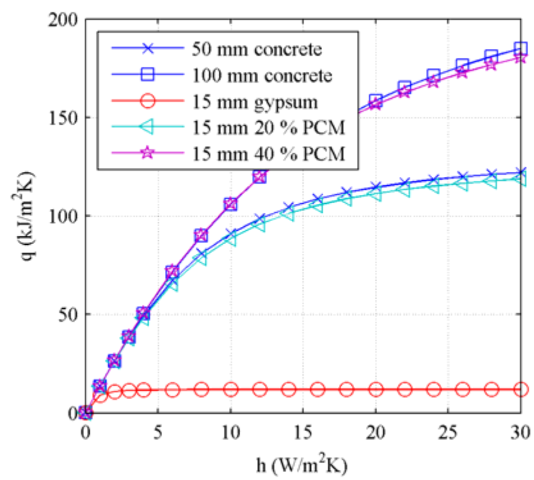

Figure 6: Effect of integrated PCM on the diurnal heat storage capacity, q depending on the heat transfer coefficient, h. Gypsum plaster board with different PCM contents compared to concrete slabs.

However, considering the simplicity of the PCM model, the presented results should be seen as a rough indication only. The heat of fusion was divided by the maximum temperature range expected for the operative room temperature, although the temperature variation inside the building element might be significantly smaller (cp. Fig. 1). This leads to an underestimation of the heat storage effect of the PCM. On the over hand if the melting range of the PCM lies partly outside the material's temperature fluctuation, the latent heat capacity might not be utilised. For a more detailed PCM model the dynamic melting and solidification processes and the temperature dependency of the material properties need to be considered. A possible approach for the numerical modelling of PCMs has been presented by Egolf and Manz (1994).

6. CONCLUSIONS

An analytical solution to the heat transfer problem in a slab with convective boundary condition and sinusoidally varying air temperature was used to investigate the impact of different parameters on the heat storage capacity of building elements. The following effects were found:

- The heat storage capacity of thick thermally heavy elements significantly increases with an increasing heat transfer coefficient up to 30 W/m^{2}K.
- The heat storage capacity of thin thermally light elements is almost constant for heat transfer coefficients higher than 3 W/m^{2}K.
- The optimum thickness of an element depends on the heat transfer coefficient; the optimum half-thickness of a concrete slab increases from about 90 mm to 140 mm if the heat transfer coefficient increases from 5 W/m^{2}K to 30 W/m^{2}K.
- In most cases the thermal conductivity of concrete (λ = 1.8 W/mK) is sufficient; only at a high heat transfer coefficient (h = 20 W/m^{2}K) does the storage capacity of a very thick slab (d = 200 mm) increase with conductivities up to 50 W/mK.
- The integration of phase change materials can significantly increase the heat storage capacity of building elements. A 15 mm gypsum plaster board with 40 % PCM content shows similar performance to a 100 mm thick concrete slab.

The heat storage capacity of building elements is an important precondition for the application of night-time ventilation. However, the effectiveness of night-time ventilation also depends on other parameters such as internal and solar heat gains, outdoor air temperature and ventilation air change rate, which were not considered in the model used in this study. Additionally, several building elements with different properties are typically present in a real room. If the different elements have different surface temperatures, energy is not only transferred by convection to the room air, but also by radiation between the elements. The impact of the heat storage capacity compared to other parameters, the interaction of different building elements and the impact of convective and radiative heat transfer needs to be investigated in more detail e.g. by building energy simulation.

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