What is the effective thickness of a thermally activated concrete slab?

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SUMMARY

A Thermo-Active-Building-System is a modern sustainable efficient cooling system with pipes installed in the structural concrete slabs of multi-storey buildings. Due to the high thermal mass the accumulation or releasing of heat may occur at different times with respect to the heat load. The issue is how much of the concrete slab will actively be involved in the accumulation of energy. The paper shows the results of dynamic FEM analysis on how deep the room drifting temperatures of 6K penetrate into the concrete structure covered by various floor types (no covering, tiles, wood, acoustic insulation, raised floor). The fluctuations decrease exponentially with the depth while the attenuation ratio and time delay hardly depends on the floor type. Generally, the effective slab thickness is 15 cm, 10 cm for wall. The vertical position of pipes should be considered approx. 7.5 cm from ceiling surface according to operational mode (heating or cooling) and floor type.

INTRODUCTION

The modern architecture and building design follow the sustainable development by applying of energy efficient building systems. Requirements for insulation of building envelope increase in order to reduce the energy demand in winter however may thus increase cooling needs in summer especially by high internal load. Thermo-Active Building System (TABS) is a cooling system with pipes usually installed in the structural concrete slabs of multi-storey buildings. TABS performs as a heating or cooling elements fully integrated into the main building structure. Due to the high thermal mass the accumulation or releasing of heat may occur at different times with respect to the heat or cooling load (occupancy, sun radiation) [1]. Asynchronous operation of the conditioning system and thermal loads results in energy savings, shifts the fraction of loads to night time and reduces (shaves) the daytime peak load. The simulations [2] already showed how a TABS with 25 cm thick ceiling slab covered by the carpet dynamically behaves. The issue is how much of the concrete slab will actively be involved in the accumulation and release of energy during daily or weekly room temperature and load variations. Therefore it is important to investigate how deep the room drifting temperatures penetrate into the concrete structure, and the paper provides the analysis on this issue using computational method.
METHODS

The paper provides a dynamic software Finite Element Method (FEM) analysis [3] of the concrete structure exposed from the room side by drifting temperatures that follow the sinusoid curve (1) in range from 20 °C to 26 °C:

\[
y = 23 + 3 \cdot \sin \left( \frac{2 \pi \cdot x}{24} \right), \quad (1)
\]

where \( x \) is the time [h] and \( y \) is the temperature [°C].

The results of the simulation will show the ability of penetration of drifting room temperature in various depths of a concrete structure. Heat transfer was modelled according to following two-dimensional thermal conductance equation:

\[
div(a \cdot \nabla T) = \frac{dT}{dt}, \quad (2)
\]

where \( dt \) is time and \( dT \) is temperature.

The thermal properties of the concrete structure without floor surface covering and with a thermal insulation was treated by mathematical model represented by heat transfer equation (2) in the investigated domain - the rectangle representative part of the slab 1m x 1m - given as the 2D section and with Newton boundary condition on the surface of a slab. The bulk temperature is considered as a periodic function (1). The simulation was carried out for four commonly used floor structures (Figure 1, Table 1) with different thermal resistance of surface covering \( (R_{\lambda,B}) \): no floor surface covering (ceramic tiles), with a light carpet of 1 cm thickness, with an acoustic/thermal insulation of 2 cm and 4 cm thickness was analyzed.

![Figure 1. Simulated cases with a concrete and floor structures with reading points](image)

**Table 1. Parameters for calculated cases**

<table>
<thead>
<tr>
<th>Calculation case</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of floor structure</td>
<td>No covering</td>
<td>Carpet (1 cm)</td>
<td>Rockwool (2cm)</td>
<td>Rockwool (4cm)</td>
</tr>
<tr>
<td>( R_{\lambda,B} [m^2K/W] )</td>
<td>0</td>
<td>0,1</td>
<td>0,5</td>
<td>1,0</td>
</tr>
<tr>
<td>( \rho ) [kg/m³]</td>
<td>-</td>
<td>300</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>( \lambda ) [W/m.K]</td>
<td>-</td>
<td>0,1</td>
<td>0,04</td>
<td>0,04</td>
</tr>
<tr>
<td>( C ) [J/kg.K]</td>
<td>-</td>
<td>1000</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>Case corresponds to</td>
<td>No covering, Ceramic tiles</td>
<td>Light carpet, wooden (floor) parquets</td>
<td>Floor with an acoustic insulation layer</td>
<td>Raised floor</td>
</tr>
</tbody>
</table>

An issue was to select the constant value of total heat transfer coefficient \( (h_t, [W/m^2K]) \) as the software is not capable of dynamic recalculation of \( h_t \) value per each time step separately.
Although the $h_t$ may vary during the day, in our simulation $h_t$ changes periodically according to sinusoid periodicity, in range of 6 - 11 depending on the position of the surface (wall/ceiling/floor) and temperature difference between surface and space (if there is heating or cooling). The value $h_t$ of 8 belongs to wall heating and cooling, $h_t$ 11 corresponds to floor heating and ceiling cooling, 7 to floor cooling and 6 to ceiling heating [4].

By periodic drifting room temperatures difference between surface and space is sometimes positive, and occasionally negative. It means that a surface performs partially as a cooling and partially as a heating element related to the room environment temperature. The $h_t$ dynamically changes all the time in range approx. from 6-10. The $h_t$ constant input value was finally chosen to 8.0 W/m²K that covers with sufficient approximation all of available system types and boundary conditions.

RESULTS

The temperature fluctuations decrease exponentially with the depth of the concrete structure (Figure 1), while the attenuation ratio hardly depends from the $R_{L,B}$. It is obvious that the accrued time delays of fluctuations can be observed by all of simulated cases but the most by raised floor structure (Figure 2). The conclusion will follow the assumption that the effective thickness of a concrete slab should be lower than such a concrete layer depth were the 10% of room temperature fluctuations is achieved.

Figure 2. Daily temperature fluctuations inside a concrete structure. a) without surface covering, b) with acoustic insulation
DISCUSSION

However the floor surface coverings may differ in buildings and even from a room to another one. In residential buildings the acoustic insulation should be applied in order to keep the entire privacy. No surface covering floor structure is mostly used in non-residential, storage or industrial spaces. In domestic spaces occupied by persons (apartments and one-family houses) the wooden floor or ceramic tiles are usually used. Although the carpets may perform as a significant indoor pollution source they are still quite popular in some countries, though it might cover the room floor area just partly. The raised floor construction creates in office spaces creates a hollow trapped air layer that is available for leading the electric and IT cables, HVAC water distribution pipes or fresh air ducts, etc. Occasionally in some of the countries are room acoustic issues solved with a small additional acoustic insulation layer on ceiling of $R_{\lambda B}=0.1$. The higher is $R_{\lambda B}$ the lower is the effect of room temperature fluctuations on the mean slab temperature (Figure 1) and thinner part of a concrete layer is available for the heat exchange under the day cycle.

The results of the simulation may be concluded for three significant groups of cases with relatively low $R_{\lambda B}=(0~0,1; \text{case A B})$, relatively high $R_{\lambda B}=(0,5~1,0; \text{case C D})$ and the case with ceiling slab of thickness more than 150 mm. The ceiling slab with a low $R_{\lambda B}$ should not be of higher thickness then 10~15cm and the hydronic pipes should be located in mean slab level. A thicker slab might dispose higher thermal mass capacity, but it does not really matters, as the slab core would most likely be thermally passive. For cases with a high $R_{\lambda B}$ it is recommended to place the TABS pipes should be positioned closer 7,5~10 cm (or even less) to the ceiling surface in order to be included to heat transfer process following daytime cycle. The active slab thickness is approx. 10~15cm, and in any case should not exceed 20cm.

The height or extended column distance of a building may however sometimes affect sizing of load bearing structure. In this case the ceiling slab may be estimated to even more than 20 cm thickness. As such a slab will mostly not be fully activated it is reasonable to put hydronic pipes closer to the surface with lower $R_{\lambda B}$, usually ceiling surface up to 7,5 cm. Here the application of the raised floor structure comes suitable. This kind of construction is especially favourable by ceiling cooling system as the $h_t$ achieves quite high value of 9-11. Even in case when a small acoustic ceiling insulation is applied.
The effective thickness of a thermally activated concrete slab is recommended to be 15 cm. The vertical position of pipes should be considered according to operational mode (heating or cooling), thermal resistance of floor covering and if a thin acoustic ceiling arrangement is present. The trend of last 10-15 years used to be of a build up the TABS with the slab from 20 to 30 cm thickness [1]. The recent simulations showed that there is no reason to dispose with so high building thermal mass as it is not effective from the point of daytime cycle. Naturally, it might be reasonable for long term heat storage (accumulation). But if for some reason the slab is too thick, the pipes should keep the position recommended above.

The paper describes an idea of an effective slab thickness from the point of view of the potential in all of its structure mass – even in the mean slab level - to be included into the heat exchange inside the room. It means that the whole slab is actively involved in the heat exchange under daily or weekly varying loads. On the other hand the study does not claim that the slab of a recommended thickness (10 - 15cm) is able to store certain amount of heat e.g. sufficient to cover high cooling loads just by using of night operation.

The accuracy of the results might be influenced by at least three facts. The \( h_t \) value was selected as a constant value because of the software imperfection; however, in reality \( h_t \) varies dynamically all the time. In a real room the fluctuations do not follow the same curve day after day but rather vary in the amplitude and the temperature drifts usually achieve in most of the days up to 4 K. Nevertheless the chosen sinusoid curve approximates the tendency quite well, because an extreme case was chosen for. By following this approach all of results should certainly be in range of those cases achievable under real - also extreme - boundary conditions.

REFERENCES

3. ANSYS, Inc., ANSYS Professional
4. EN15733-1, 2005: Design of embedded water based surface heating and cooling systems: -Part 1: Determination of the design heating and cooling capacity, European Committee for Standardization, Brussels, Belgium, 2005