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Modelling of Electrically Activated Thermal Mass

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Abstract

Recently, thermal mass activation (TMA) has attracted attention due to the potential benefits it can offer in terms of energy efficiency, particularly for shaving and/ shifting the load, emergency heating/cooling load, and for its economics and environmental impact. Shifting from peak periods to off peak periods can be done by electrically activating the concrete slab; i.e.: placing electrical resistance in the concrete slab. Integration of this technology in North American residential buildings for the purpose of shaving or shifting thermal load is a challenging issue, as these buildings are lightweight constructions and the main floors are made up of plywood and have no thermal mass. However, almost all residential buildings have a basement, and the basement is furnished with a concrete floor. The challenge is to use the concrete heated floor as TMA. This paper addresses the behaviour of proposed electrically activated slab assemblies on risks of overheating the cables. The TMA system is modelled using finite-element analysis and validated with CFD software. Simulation results show that there is no risk of over-heating for a continuous heating period of 10 hours. Also, using regular structural concrete instead of lightweight concrete increased the quantity of energy stored and reduced the floor surface temperature while the temperature in proximity to the cables increased.

Keywords – Thermal mass activation, FEM, radiant floors, thermal storage, northern climate, residential building, peak shifting

1. Introduction

The building and infrastructure sector is accountable for 40% of the total worldwide energy consumption [1] and one third of the worldwide GHG emissions [2]. The total energy consumption in developed and developing countries has increased, despite energy efficiency measures [3][4][5][6]. National energy efficiency reports mention that between the 1990's and 2009, the influence of improved energy efficiency actions is measurable, whether it is in the industrial, commercial or residential sector. However, the population size increase has led to higher nation-wide energy consumption. Note, for example, that in Canada there is an increase in the average liveable space per family (11,2%), appliance per house (40%), and percent of building air-conditioned (91,3%), which all equate to a higher energy consumption per habitant [6].

In Canada, 17% of the primary and secondary energy use can be attributed to the residential sector [6]. Thus, it is imperative to modify the use of energy related to space conditioning of buildings. Typical residential electricity consumption profiles include a significant peak power consumption in morning hours for the province of Quebec [7] and similar electricity demand profiles are seen in many cold regions [8] and mild climates such as Germany [9]. In a context where electricity consumption increases continuously, three solutions to this situation introduce themselves:

- Increase the electricity production and the distribution capacity of the grid,
- Increase the thermal resistance of building envelopes, thus decreasing the total energy consumption with respect to space conditioning,
- Reduce peak consumption by shifting the profile to off peak periods.

The application of the first two approaches, nonetheless, is very expensive. The case of Lombardy region, for instance, has shown that the cost of retrofitting a building to meet ZEB standards is approximately 4 times the cost of moderate renovations, where moderate renovations is defined as 3 to 5 interventions leading to 30-60% energy savings [10]. Also, an increase in energy efficiency usually reduces the price, and associated with this comes two possible responses: 1) savings in one sector increases the purchasing power in other sectors and 2) a decreased energy price can promote energy overconsumption [11]. This analogy is known as the "*rebound*" effect and it is believed to be responsible for the lack of decrease in total energy consumption despite increased energy efficiency of various sectors [12].

Thermal energy storage systems (TES) are believed to be the most cost effective method at reducing the peak power consumption related to space conditioning at the moment [13]. Radiant floor heating systems, in particular, have received considerable attention recently because of their potential for integration of renewable energy sources [14]. They are also widely known for the increased thermal comfort because of better temperature stratification, and lower power consumption [15]. The process of shifting peak power consumption is most often seen in commercial buildings for cooling or in regions with off peak tariffs, most often in mild climates [16].

In order to address the issue of morning peak power consumption, a study was conducted by Thieblemont et al. [17] to determine the potential of activated thermal mass in shifting the consumption to off peak hours. The particularity of this study is that the residential buildings are subjected to northern climates where temperatures can be as low as -35°C. In addition, homes are usually built from lightweight wood assemblies and therefore the building has limited thermal mass. The only thermal mass available lies in the foundation. The study revealed that the peak load could be completely shifted. Despite this, one major assumption that was made is that the heat input from the electrical heating cables can be approximated by a uniform heat flux [17].

Residential electric heating cables cannot be continuously active, as there is a possibility of over-heating the cables and inducing self-ignition. This can be an issue for peak shifting because the heating cables can charge the thermal mass throughout the night. This paper investigates the temperature of the cables of the assembly proposed by the previous works and determines if there is possibility of system failure.

2. Methodology

2.1 Studied System

Thieblemont et al. [17] have determined that the best assembly to shift the morning peak power consumption is composed of the following: (from ground-up) extruded polystyrene (0.1m), self-levelling concrete (0.02m), electric heating cables, self-levelling concrete (0.1m) and plywood (0.01m).

2.2 Proposed Method

The floor is modelled using the finite element approach. This approach has been extensively applied for modelling thermal diffusion in mass-heavy assemblies [18], [19][20][21][22][23][24]. The accuracy of such an approach depends on the level of discretization. In counterpart, a higher number of discretized of elemental volumes increases the computation time. Many simplified models have been developed for activated thermal mass, however these are most often for ventilated concrete assemblies or embedded water pipes [25]. Electrically activated thermal mass is usually modelled by representing the heating elements by a uniform heat flux. Some studies are available that have shown that this technique is acceptable when power consumption and space conditioning is the principle objective of the modelling [26].

However, a possible problem lies in this fundamental assumption. Assuming a uniform heat flux which implies a one-dimensional heat flow through the slab does not take into consideration horizontal heat diffusion and the fact that the concrete around the cable is at a much higher temperature than the rest of the slab. The risk of over-heating the cable depends on the power as well as the diffusivity of the thermal mass in which the cable lies. One can imagine that adding insulation below and above the thermal mass also increases the temperature of the concrete.

The radiant floor is analyzed in two dimensions with the electric heating cables running perpendicular to the two axes considered. The objective of this study is to analyze the temperature of the cable as well as the concrete in proximity to the cables. The size of the wires analyzed is 6.25 mm. The cable is assumed to be square, with dimensions of 6.25mm x 6.25mm. This dimension governs the size of the elemental volumes around the cable. **Error! Reference source not found.** shows how the concrete is divided around the cable as well as the node placement.

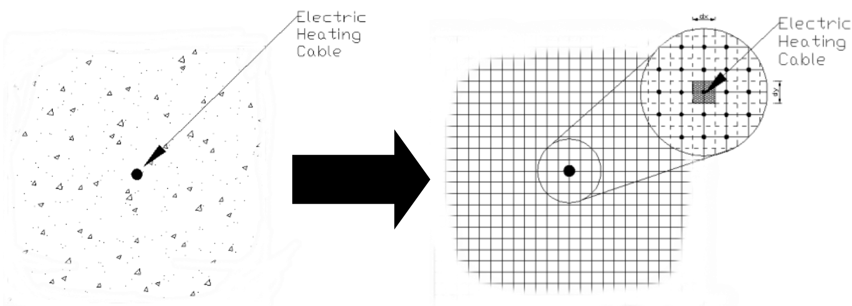

Figure 1 Discretization of Thermal Mass around Electric Heating Cables

2.3 Validation of the Model

The model was validated by comparing its prediction by the one made by the CFD modelling software called LISA. This simulation software is designed for matrix analyses using finite element analysis (FEA) for complicated geometries of many types such as structural, heat flow and acoustics. LISA has been used in papers for heat flow analysis such as in [27]. The discretization of the thermal mass and cables in the LISA graphical interface was executed to achieve much smaller elemental volumes. In addition, the arrangement of the nodes is done in a matter as to have nodes much closer to one another near the cable.

The mathematical model had a computation time much faster than the LISA software. The MATLAB script took 1.5 seconds to solve while the LISA solver took 2:05 minutes to assemble the matrix and 4 minutes in total to assemble and solve the system. There was good agreement between the predictions made by the two models. An error of 0.2% and 3.6% were observed for the floor surface temperature and electrical cable temperature, respectively.

2.4 Model Parameters

The properties of the materials have been previously mentioned in section 2.1. The convective heat transfer coefficient was set to 3.05 W/m^2 K as used by suggested by Thieblemont et al. [17]. The TRNSYS modeling interface calculates the radiation between all surfaces based on geometry, emissivity and temperature difference. In this study however, the radiation exchange between surfaces was linearized for easier integration to the mathematical model. The interior room air temperature and all boundary conditions are taken as the same as the study made by Thieblemont et al [17].

The studied scenario starts heating the concrete slab at 10:00 p.m. at which point the temperature at the height of the heating cables is equal to 21.85^{o}C, the floor surface temperature is equal to 20.72^{o}C and the room air temperature is equal to 19.17^{o}C. All simulations are started with the same initial conditions. Because the TRNSYS simulation assumes heat flow only in one direction, a linear temperature distribution is assumed for the slab assembly. At 6:00 a.m. the following morning, the cables stop heating the slab after an 8 hour period of continuous heating.

3. Results and Discussion

There is a perimeter around the basement where the temperature of the concrete is lower because of heat losses to the sides. It is therefore the electric heating cables at a certain distance away from the exterior walls that are prone to over-heating. The analysis is done on a cross section containing only one heating cable. Similar sections on either side should have similar temperature distributions, thus the edges of the analyzed floor section can be considered to be adiabatic.

The resulting temperature distribution after 8 hours of continuous heating is shown in the following figure.

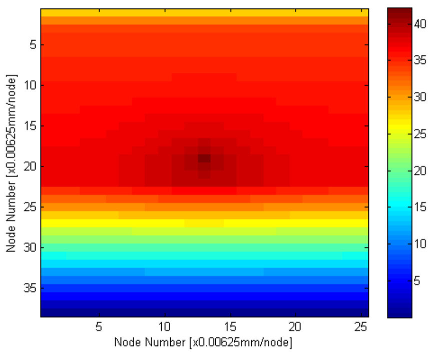

Figure 2: Temperature Distribution after 10 Hours of Continuous Heating

The predicted temperature at the heating cable height from Thieblemont et al.'s study was 32.38°C while the 2D MATLAB model predicts a temperature in close proximity to the cables of 35.48°C. This shows that a one-dimensional analysis of this type of system under estimates the temperature of the cables. However, when taking the average of the temperatures at the height of the cables from the 2D model output, one gets an average temperature of 31.11°C which is very close to the 1D model. The average surface temperature of the 2D model was 24.26°C with a range of 0.024°C. The floor surface is almost isothermal because of the thickness of concrete in the assembly. Nonetheless, the same quantity of heat has been stored in both models, with a difference of only 0.312%. The TRNSYS simulation over estimates the surface temperature by approximately 1°C. Also, this study has shown that the proposed assembly of Thieblemont et al. has no risk of over-heating the electric heating cables, even for a continuous 8-hour activity.

Based on TRNSYS simulations, it was shown that during the winter months when the heating cables are activated night after night, there is always residual heat left from the charging of the day before. The temperature at the height of the cables can be as high as 25.13°C before the charging period. The corresponding floor surface temperature is 23.38°C. These initial conditions were used in a second simulation with the 2D MATLAB model in order to determine the worst-case scenario for the system to failure due to over-heating. Note, however, that the material used in the first study is self-levelling concrete. A wide variety of cement-based products can be used as thermal mass for this type of application. Simulations were run with the 2D model with varying thermal conductivity, density and specific heat. The following three graphs show the effects of varying these parameters on the cable temperature, surface temperature and thermal energy stored.

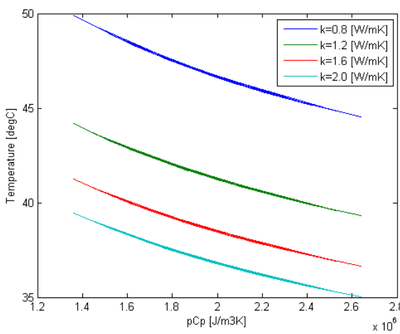

Figure 3: Maximum Cable Temperature Versus Storage Capacity (ρc_p) and Thermal Conductivity

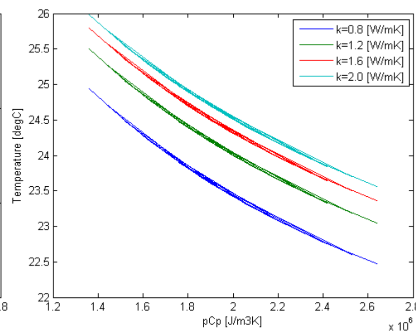

Figure 4: Maximum Surface Temperature Versus Storage Capacity (ρc_p) and Thermal Conductivity

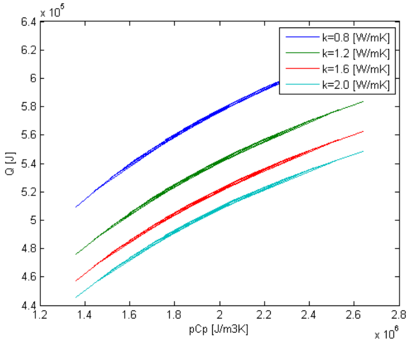

Figure 5: Maximum Energy Stored Versus Storage Capacity (pc_p) and Thermal Conductivity

These simulations were run in order to identify the worst-case scenario for system failure. Figure 3 shows that for any type of cement-based masonry, there is no risk of over-heating the cable. Note that this is only true for 8 hour heating periods with initial temperatures in the slab of 25 ^{o}C. Increasing the thermal storage of the thermal mass material can reduce the temperature of the cables and the floor surface. Increasing the thermal conductivity increases the surface temperature but reduces cable temperature. Simulations of more than 8 hours were also ran. All types of cement based products ended up having floor surface temperatures above 30 ^{o}C which exceeds the thermal comfort requirement condition set by the ASHRAE for a run time of 10 hours. Figure 5 shows that increasing the thermal storage (pc_p) and decreasing the thermal conductivity increases the total energy in the slab at the end of the charging period.

4. Conclusion

In this paper, an assembly composed of 10cm of XPS, 12 cm of self-levelling concrete covered with 1cm of plywood with buried electric heating cables was studied for possible over-heating of the cables. A finite element modelling approach, designed in the MATLAB environment, was chosen because of the possibility of integrating the model to building energy modelling software. The mathematical model was validated by its prediction with the one made using a CFD software called LISA. The assumption that the thermal mass could be discretized in a Cartesian grid and that the electric heating cable could be assumed to be square shaped induced an error as low as 3.6%. The FEM model showed that there was no risk in over heating the cables and that the floor surface temperature goes beyond the thermal comfort range for run times of more than 8 hours.

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