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INVESTIGATION OF THE IMPACT OF USING THERMAL MASS WITH THE NET ZERO ENERGY TOWN HOUSE IN TORONTO USING TRNSYS

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ABSTRACT

A detailed model of the Net Zero Energy Town House in Toronto is developed in TRNSYS, incorporating a ground source heat pump integrated with an in floor radiant heating system. In order to minimize the heating and cooling loads, the building envelope is well insulated with the exterior walls having an R-60 insulation value. Much of the work done previously on the use of thermal mass in buildings has been experimental in nature and has focussed mainly on conventional brick construction in hot climates such as Asia and Africa. This research will analyze the impact of using thermal mass with a building envelope that is highly insulated, and of a light construction, such as that used in Low Energy or Net Zero housing. Furthermore, this analysis would also evaluate the impact of using thermal mass in a cold climate such as that found in Canada. The simulations showed that, for colder climates, thermal mass can replace some of the insulation and still provide superior results. Also the impact of thermal mass was found to be more significant during the winter season than summer for Toronto.

INTRODUCTION

Buildings are responsible for more than 30% of the total energy consumed in Canada [*SBRN, 2007*]. As the price of energy increases and concerns for sustainability and conservation grow, it has becomes essential to devise ways of reducing the overall energy use in buildings. The use of thermal mass incorporated into the building envelope has been found to be an effective way to reduce the heating and cooling loads. Furthermore, in climates where a large daily temperature fluctuation exists, the use of thermal mass has contributed to the lowering of the indoor temperature peaks and smoothing of the temperature fluctuations, thereby contributing significantly to the occupant comfort [*Kalogirou et al*., 2002].

Thermal mass is defined as any building material having a high heat storage capacity that can be integrated into the structural fabric of the building to effectively utilize the passive solar energy for the purposes of heating and cooling. Some of the commonly used materials include concrete slabs, bricks and ceramic blocks [*Shaw et al*., 1994]. The selection of a particular material to function as thermal mass depends on a variety of factors such as a high density (ρ), a high specific heat capacity (C_p) and the ability to delay the time taken to release the heat [*Kalogirou et al*., 2002]. The time lag for some common building materials with a thickness of 305 mm is 10 hours for common brick, 6 hours for face brick, 8 hours for heavyweight concrete and 20 hours for wood [*Balaras*, 1996]. The selection of a particular material depends upon the desired indoor thermal characteristics and the structural properties of the building envelope.

Most of the buildings and homes constructed in cold environments such as Canada and parts in the North East of the United States, are highly insulated and of a light construction with very little thermal mass. This is in contrast to buildings in Africa and Asia that are primarily designed for use in a hot climate and have concrete and other heavy materials as part of the building envelope [*Gregory et al.,* 2008]. Thus most buildings in Canada and the US are prone to extreme temperature fluctuations and uncomfortable indoor conditions especially during the fall and spring seasons, when the heating and cooling is not in operation.

One aspect by which thermal mass proves to be more effective when compared to conventional insulation is its ability to delay the peak loads during the winter and summer seasons. In winter, any excess solar radiation that is stored by the building mass during the daytime is progressively released later during the evening, when the heating load can be significant. This can have a significant impact on the overall heating load of the building. *Kalogirou et al*. (2002) have shown a total reduction in heating load of 47% through the application of thermal mass in a south facing wall using TRNSYS. During the summer, the use of thermal mass can provide a significant improvement in the overall occupant comfort by the reducing the possibility of indoor overheating. The peak air-conditioning load which occurs during the afternoon can also be drastically reduced by incorporating south facing walls with thermal mass. *Ruud et al*. (1990) demonstrated through the use of test chamber in Florida, the impact of using thermal mass causing a reduction of 18% in the cooling load during the day time. *Brown* (1990) conducted detailed simulations on an office building to determine the effect of varying the thermal mass. It was concluded that that an increase in thermal mass from 21 to 201 kg/m^2 of floor area, in closed and ventilated buildings, can reduce the peak indoor temperature by between 1°C and 2°C. *Ogoli* (2003), in tests conducted in Nairobi, Kenya, showed that thermal mass in the form of heavy concrete tile and timber panelling was able to maintain the indoor temperature within the comfort zone of around 25°C, when the outdoor temperature hovered around 33°C. The location of thermal mass within the building envelope is also very important. *Balaras* (1996) has determined that it is more effective when the thermal mass is placed in between the insulation. It can also be placed on the outside of the building envelope thus providing direct exposure to the solar radiation Furthermore, the orientation of the thermal mass within the building is essential ,as it dictates the time delay of the temperature peaks. North and east facing building envelopes have little need for a time delay. For the building envelopes facing the south and west directions respectively, an 8h time lag is sufficient to delay heat transfer from midday until the evening hour [*Ogoli,* 2003].

MODEL/METHODOLOGY

In order to conduct detailed simulations and analyses of the impact of using thermal mass, a detailed model of the Net Zero House located in the downtown area of Toronto, ON is developed in TRNSYS. The concept behind a Net Zero or Low Energy house is the design of thermal and structural systems for a residential unit in a manner that minimizes the energy consumption with the aim of making the house energy self sufficient . This is achieved through the use of high quality insulation materials and the utilization of renewable energy technologies such as PV and Geothermal for production of energy. The townhouse has a covered area of 210 m^2 and the orientation of the house is 37° West of South. The orientation and location of the houses have optimized to ensure that a maximum amount of solar energy can be captured to operate the Photovoltaic and PV Thermal panels for the generation of electricity and hot water respectively for the house. A ground source heat pump is also utilized during the winter to provide a reliable and efficient source of heating. Figure 1 shows a computer generated 3-D model of the house. The building envelope of the Net Zero House is designed with the intention of minimizing the heat transfer to the outside.

Figure 1: 3-D Computer representation of one of the three identical Toronto Net Zero Energy Houses.

The external walls have been insulated with sprayed polyisocynurate foam insulation, which provides an overall insulation value of R-60. Roof assembly consists of drywall on 19 x 19 mm furring and 0.15 mm polyethylene vapour retarder attached to the bottom of the 294 mm pre-engineered I-joists. Sprayed polyisocyanurate foam is applied between joists as roof insulation. The roof has an insulation value of R-76. Table 1 shows the various layers used within the building envelope. The windows used have low emissivity are argon filled with a fibreglass frame have an insulation value of R-4 value. Walls below grade are of the insulating concrete form and have a 2.5 in of rigid polystyrene board with a waterproof membrane. The overall insulation value of the below grade wall is R-35.

Table 1: Layers for all the exterior walls used with the house.

Gypsum Board (Dry Wall), 13mm
19 x 19mm Furring
Polyethylene Vapour Retarder, 0.15mm
(2x6) Wood Studs at 600mm (24") O.C
Sprayed Polyisocyanurate closed cell foam 139mm RSI-6.5
OSB Structural Sheathing with STO Gold Coat 13mm
Rigid insulation-Extruded Polystyrene 100mm RSI 3.48
Air space 25mm
Face Brick 100mm

Figure 2 shows the model of the Net Zero Energy House developed in TRNSYS.

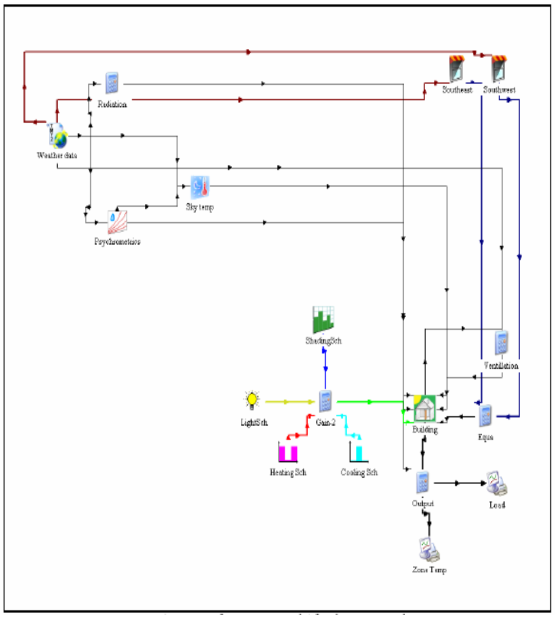

Figure 2: Layout of the Net Zero Energy House in TRNSYS

SIMULATION PARAMETERS

A variety of simulations are conducted in TRNSYS to illustrate the impact of using thermal mass with the Net Zero house. TRNSYS is a modular simulation program, based on the FORTRAN programming language. It utilizes standalone components and mathematical modules for a wide variety of applications such as Heat Pumps and PVs etc in a user-friendly graphical interface. Each of these components can be connected together and represents the flow of information during the simulation. The TRNSYS engine calls the system components based on the input file and iterates at each time-step until the system of equations is solved. Weather data is needed to perform the simulations with TRNSYS. TRNSYS runs through hourly values of various weather parameters included in a typical meteorological year (TMY) file. The weather file included with TRNSYS contains detailed weather data for thousands of locations around the world [*Klein et al.,* 1998].

For the particular case study on the Net Zero house, the weather data for the city of Toronto is used. For each of the different scenarios, the simulations are run for one year with a time step of one hour to ensure that the results are accurate. The simulations are run with the house unconditioned, which means that other than the solar gain and heat loss, there is no artificial heating or cooling of the house. This is to ensure that the there is no interference with the thermal mass effect provided by the building envelope. The house consists of 5 zones which represent the garage, 1st floor, 2nd floor, 3rd floor and mezzanine. As a means of comparison all of the results are shown for either the 2nd floor or the 3rd floor or the mezzanine, since these are locations where the temperature peaks and fluctuations are expected to be the greatest.

SIMULATION/ RESULTS

Figure 3 provides a comparison of the yearly indoor temperature profile for the 2nd floor, with and without thermal mass. A 6 inch concrete slab is used as the thermal mass and layered next to the gypsum board when considered from the indoor surface of the wall.

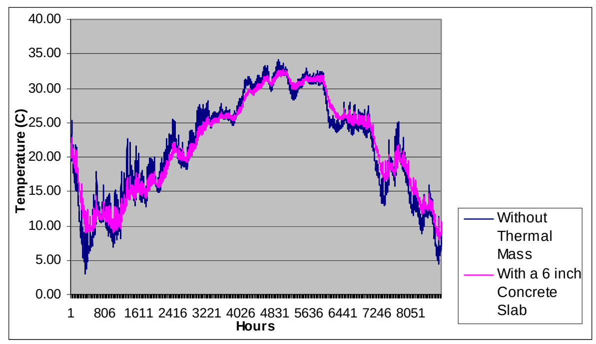

Figure 3: Yearly temperature profile of the 2nd floor of the Net Zero Energy House.

Figure 4 shows a comparison of the temperature profile for the mezzanine floor, with and without thermal mass for a typical winter day in Toronto. A 6 inch concrete slab is used as the thermal mass.

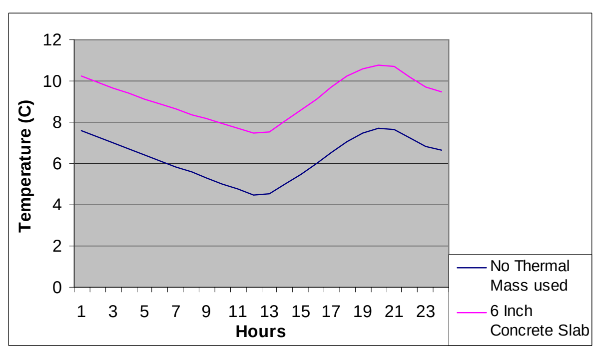

Figure 4: Temperature profile of the 2nd floor of the Net Zero Energy House for a typical winter day in Toronto.

Figure 5 shows a comparison of the temperature profile for the mezzanine floor, with and without thermal mass for a typical summer day in Toronto. A 6 inch concrete slab is used as the thermal mass.

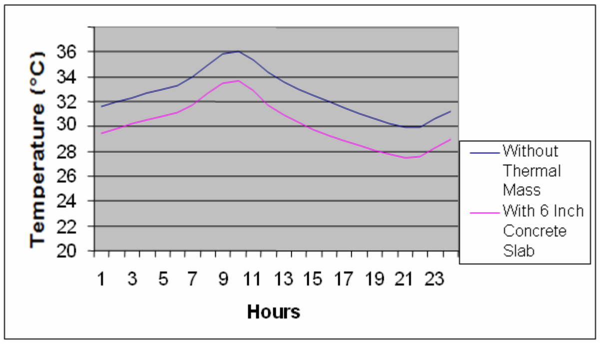

Figure 5: Temperature profile of the 2nd floor of the Net Zero Energy House for a typical summer day in Toronto.

The location of the thermal mass within the building envelope is extremely important in determining its effectiveness. It can either be attached to the outside surface of the walls to directly absorb the solar radiation or it can be placed within the interior walls, right next to the gypsum board [*Brown*, 1990].

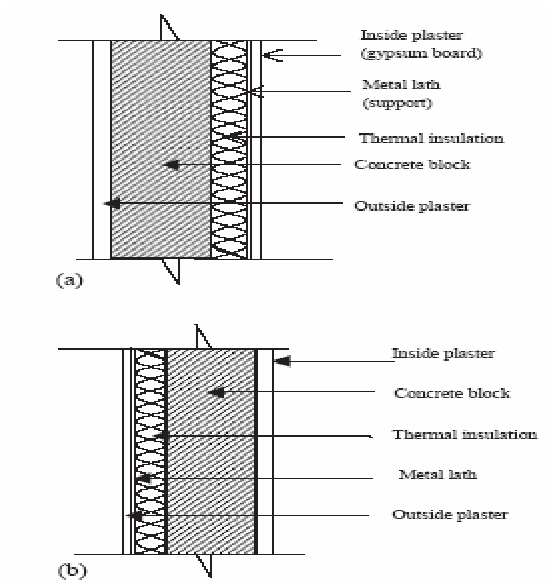

Figure 6: Possible Locations of Thermal Mass within the building envelope [Al-Homoud, 2005]

Result of the simulation conducted to determine the effectiveness of thermal when placed at different locations within the building envelope is given below. In this scenario, the thermal mass was placed at three different locations; right next to the inside plaster, corresponding to scenario (a) in Figure 6, right next to the outside plaster, which corresponds to scenario (b) in Figure 6 and at the middle of the building envelope next to the insulation. Figures 7 and 8 show the temperature profile of the mezzanine floor as a result of this analysis. The location of the thermal mass within the building envelope would be denoted by the variable, *x*, where *x* represents the thickness of the building envelope at the point where the thermal mass is placed. The variable *x* can be defined as:

$$0m \le x \le 0.384m$$

Where the total thickness of the thermal mass is 0.384m and *x* has a value of 0 m at the indoor wall surface. Figure 7 shows the temperature profile for a typical winter day in Toronto when the 6 inch concrete slab is placed within the building envelope at different locations.

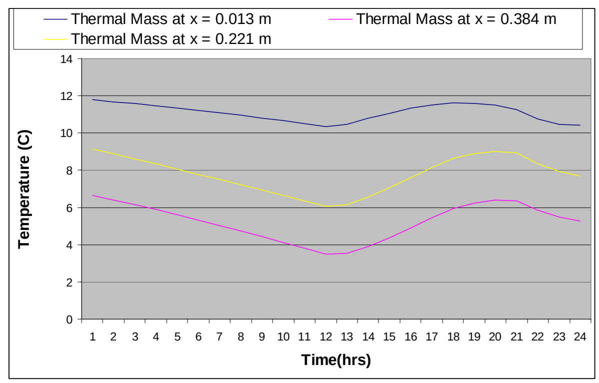

Figure 7: Thermal mass placed at different locations within the building envelope for a typical winter day in Toronto.

Figure 8 shows the temperature profile for a typical summer day in Toronto when the 6 inch concrete slab is placed within the building envelope at different locations.

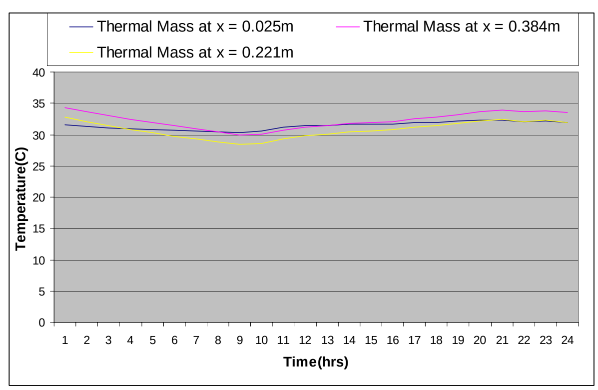

Figure 8: Thermal mass placed at different locations within the building envelope for a typical summer day in Toronto.

The effect of varying the thickness of the thermal mass is also an important parameter, which would enable the determination of the optimum thickness and would provide the best return in terms of energy savings. Simulations were performed to see the impact of varying the thickness of the concrete slab from 2 inches up to 8 inches. Figures 9 and 10 detail the results of the simulation. Figure 9 illustrates the temperature profile of the mezzanine floor when the thermal mass in form of a concrete slab is varied in thickness from 2 in to 8 in. These simulations are run for a typical winter day in Toronto.

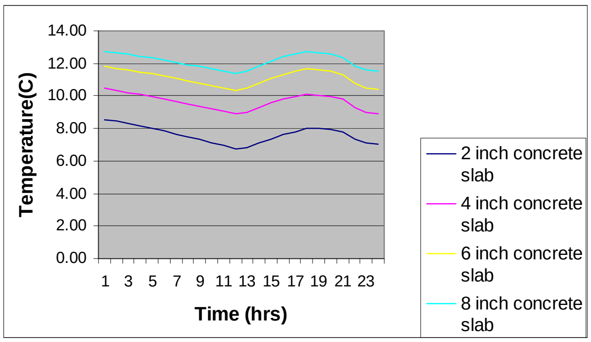

Figure 9: Effect of varying the thermal mass of the Net Zero Energy house for a typical winter day in Toronto.

Figure 10 illustrates the temperature profile of the mezzanine floor when the thermal mass in form of a concrete slab is varied in thickness from 2 in to 8 in. These simulations are run for a typical summer day in Toronto.

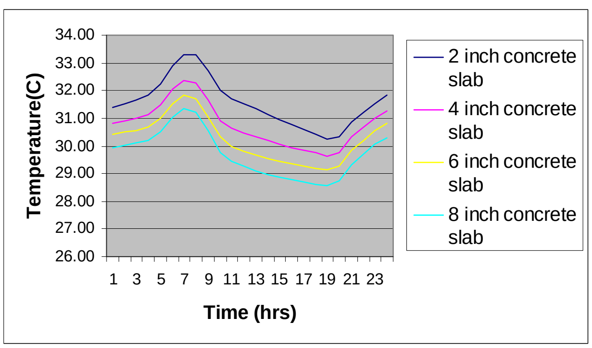

Figure 10: Effect of varying the thermal mass of the Net Zero Energy house for a typical summer day in Toronto.

The interaction between insulation materials and thermal mass within a building envelope is complex and depends upon the structure of the building and the climatic conditions. In cold climates such as Canada, an emphasis is placed on the use of high resistance, low mass insulation, so that the heat loss could be minimized. Little attention is directed towards the use of making the building thermally massive. One of the disadvantages of this approach is wide indoor temperature fluctuation and higher energy consumption. A simulation is conducted to illustrate the fact that excellent temperature stability can be obtained even when thermal mass replaces some of the insulation in a house. Figure 11 shows the yearly indoor temperature profile of the mezzanine floor in the Net Zero Energy house, with the Polyisocynature foam replaced with a 6 inch concrete slab. It is clear from the figure that replacing the Polyisocynature foam with the concrete slab reduces the temperature peaks during the summer and winter seasons, while at the same time providing a superior insulation effect. It is interesting to note that even though the U-value of the modified building envelope (with thermal mass) increases to 0.198W/m^{2}K from 0.093 W/m^{2}K, no negative impact is noted in the temperature profiles.

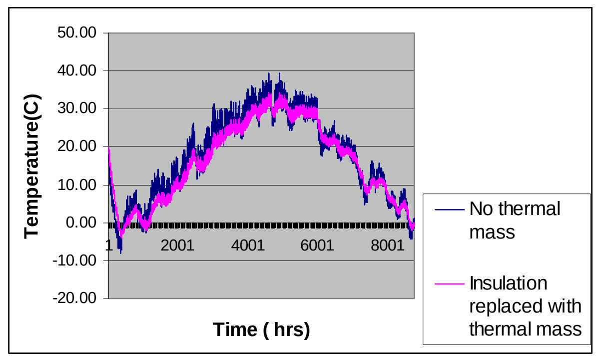

Figure 11: Impact of replacing the Polyisocynature with a 6 inch concrete slab.

ANALYSIS

A variety of simulations were conducted illustrating the impact of using thermal mass with the Net Zero Energy house in Toronto. A key characteristic of using thermal mass with the building envelope is a reduction in the indoor temperature fluctuations and the peak temperature during the winter and summer seasons respectively. Analyzing Figure 3, it is seen that for the 2nd floor of the Net Zero Energy house, during the winter season, the use of thermal mass prevents the indoor temperature from dropping below 9°C, while it drops below 3°C when no thermal mass is present. The results for the summer season are reasonable but not as dramatic as for the winter, with indoor temperatures lower by 3°C - 4°C when the thermal mass is used. This can be explained by the full utilization of the thermal storage capacity of the thermal mass due to the excessive solar radiation during the summer. Once the concrete slabs are fully charged (All thermal storage capacity used), any additional solar radiation translates into an increase in the indoor temperature.

The location of the thermal mass within the building envelope is an important consideration that has a significant impact on the overall effectiveness of the thermal mass. A variety of simulations were conducted to determine the optimal location within the building envelope that the thermal mass can be placed. Figure 7 shows the temperature profiles obtained as a result of applying thermal mass to three locations within the building envelope of the Net Zero Energy house. It was found that for the winter season only, the location where the concrete slab was attached had a large impact on the indoor temperatures. Best results were obtained when the thermal mass was placed right next to the gypsum board, which forms the interior wall in the house. The effectiveness of this configuration depends on the fact that heat transfer with the surroundings has to pass through the thick layers of insulation thus slowing down the flow. For the summer season, the results were not as good, with the lowest indoor temperature achieved when the insulation was placed in the middle of the building envelope. This result is illustrated by Figure 8.

The thickness of the thermal mass within the building envelope is a critical parameter. Although an extremely thick concrete slab would prove to very effective as a thermal mass, it might not conform to the structural requirement of the buildings. Thus it is essential that a compromise between the amounts of thermal mass used and architectural specifications. It was found from the analysis conducted that the 6 inch concrete slab during the winter, and the 4 inch concrete slab provided the best return in terms of temperature reduction and dimensions. It is also obvious that increasing the thickness of the slab generates diminishing returns in terms of the temperature reduction potential.

Results from Figure 11 emphasize the importance of including thermal mass as a component of every building envelope so that a proper balance can be achieved between the indoor temperature and its fluctuations during the various seasons. Although the removal of a portion of insulation decreases the overall resistance value, the thermal diffusivity of the building envelope is increased. With less insulation, any solar gains incident on the exterior walls, move through the various building layers faster to charge the thermal mass and store heat faster. By replacing a portion of the insulation with thermal mass, significant costs savings and occupant comfort can be achieved.

CONCLUSIONS

The use of thermal mass with the Net Zero Energy house in Toronto provides excellent results in terms of the reductions in the daily indoor temperature fluctuations and throughout the winter and summer, a reduction of the temperature extremes. The impact of the thermal mass during the winter was found to be more significant when compared with summer. This could be due to the unique construction and orientation of the Net Zero Energy House. The optimum thickness of the concrete slab (thermal mass) was found to be 6 inch for the winter season and 4 inch for summer. Optimum location for the placement of the thermal mass was also determined and found to be right next to the gypsum wallboard, which forms the interior part of the wall. Finally, the importance of using thermal mass was demonstrated by replacing a significant portion of the insulation with a 6 inch concrete slab, with superior results and very little adverse effects. Analyzing the impact of thermal mass on the Net Zero Energy house from a broader context of energy conservation and occupant comfort, the positive and synergistic aspects are quite obvious.

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