Component sequence and thermal mass effects on the transient thermal performance of concrete walls

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Abstract. The increased requirements of buildings to reduce energy use have highlighted the importance of accounting for all factors that influence energy use in buildings. One consideration that requires further study in the envelope design of concrete-based wall assemblies is the placement of the thermal mass layer. In this study, two thermally massive walls, Insulated Concrete Form (ICF) and tilt-up walls, with the same thermal resistance but different sequencing of layers are investigated. In addition, a wall made of a homogeneous insulation layer with an identical thermal resistance was considered to further investigate the thermal mass effect on the potential for energy savings. Results of the numerical simulations performed using COMSOL Multiphysics® software indicate that, for the transient scenarios investigated, thermal mass can contribute to shifting and dampening peak heating and cooling loads, as well as saving energy. Also, less intense fluctuations were observed in the heat fluxes when considering the ICF wall. Energy savings during the primary seasons (i.e. winters in Montreal and summers in Miami) are found to be marginal but the existence of a thermally massive layer considerably reduced the demands during secondary seasons i.e. summers in Montreal and winters in Miami.

1. Introduction

Recently, a framework has been developed by the Canadian government regarding clean growth and climate change with the objective to reduce 50% Green House Gas (GHG) emissions by 2030 as compared to the amount emitted in 2005 [1]. Buildings’ heating, cooling, and lighting account for nearly 30% of the total energy consumption and 17% of GHG emissions in Canada [2]. These factors, as well as the rising costs of energy, have led to growing attention towards constructing more energy-efficient buildings. One of the factors whose potential for energy savings should be investigated is the effect of thermal mass. Buildings can take advantage of the thermally massive assemblies if they are properly designed and coupled with appropriately sized Heating, Ventilation, and Air Conditioning (HVAC) systems.

"Insulated Concrete Form" (ICF) and tilt-up walls are two concrete wall types that are commonly used in North American construction. Reduced construction time, increased durability, improved thermal performance due to better airtightness, high thermal insulation levels, existence of the concrete as a thermally massive element, and consequently reduced HVAC system sizes are some of the advantages of these assemblies [3]. The core of the ICF wall is a concrete layer sandwiched between two insulation layers. Interior and exterior finishes can then be applied to complete the construction of these walls. On the other hand, tilt-up walls are prefab panels, which comprise an insulation layer...
sandwiched between two concrete layers. These panels are constructed in the factory and shipped to the site, which then can be connected to each other to build the entire wall.

Different studies have investigated the potential benefits of ICF and tilt-up wall systems by simulating the total heating and cooling demands of case study buildings. For example, two similar studies conducted by Kosny et al. [4] and Doebber and Elis [5] investigated the effects of thermal mass and reduced air-infiltration on the total energy demand of a single-storey ranch house using whole-building energy simulation software. Kosny et al. considered an ICF and 10 wood-frame walls while Doebber and Elis compared a waffle Precast Concrete Panel (PCP), sandwich PCP, conventional wood-frame, highly-insulated wood-frame, and ICF wall assemblies. Both papers took annual weather conditions of a dominantly cold and a dominantly hot climate locations for their studies. They assumed lower infiltration rates for the concrete walls and studied the consequences on the overall energy demand of the case study building. It was concluded that the effect of thermal mass and infiltration rate on energy saving is dependent on the climate conditions and that heating and cooling loads as a result of air leakage can be determinative.

Saber et al. [3] numerically and experimentally studied the transient hygrothermal performance of a west-facing ICF wall. A 1.2 m × 2.4 m ICF wall specimen was tested in a field facility for a duration of 161.66 days starting from October 13th, with their exterior surface being exposed to Ottawa weather conditions and the interior surface being ASHRAE-specified indoor conditions. Meanwhile, they simulated the hygrothermal performance for the same wall using NRC-IRC's hygrothermal model, which utilizes COMSOL Multiphysics as its solver. Two case study walls were simulated, namely the existing ICF wall and an ICF wall without its concrete layer (only an insulation layer). They concluded that the thermal mass can dampen the fluctuations in the heat dissipated to the outside during the heating season while shifting the peak heat fluxes, which in turn leads to smaller-sized mechanical heating system requirements. In addition, the thermally massive wall consumed 6% less energy during the heating period. However, the thermal mass effect was more evident in the cooling seasons, during which the cooling loads were minimized. Annual accumulative heat gain for the case of ICF wall was 2 W.day/m² while it was 37 W.day/m² for the insulation wall case.

Using the sinusoidal outside sol-air temperature fluctuating between 0°C and 1°C as the outdoor boundary condition and 0.5°C as constant indoor temperature condition, Asan [6] showed that distributing half of the insulation at the inside and the other half at the outside of the walls with wood and brick as their thermally massive components leads to the maximum efficiency. Ciampi et al. [7] conducted cases studies to evaluate the effect of resistance-capacitance distribution within the wall assemblies on the peak building plant loads. They concluded that even distribution of thermal resistance and capacitance in the wall can lead to lower fluctuations in building plant power outputs to maintain the indoor temperature at a constant value. On the other hand, Al-Sanea et al. [8] investigated the effects of masonry types, solar absorptivity, and thermal mass placement within two case study concrete walls using hourly weather data for Riyadh, Saudi Arabia (highly cooling demand location). They showed that using solid concrete blocks at the inside could maximize the energy saving in hot climates. However, it should be noted that the exterior weather conditions can highly affect the conclusions of such studies.

Although the energy performance of ICF and tilt-up wall technologies were evaluated in various studies, due to the fact that many parameters contribute to the total energy consumption, the sole effect of concrete layer placement in concrete walls on the overall thermal performance of the assemblies has not been investigated to the best of the authors' knowledge. In this paper, the effect of material sequence on the overall transient thermal performance of sandwich concrete walls was investigated considering three wall assemblies, namely an ICF wall, a tilt-up wall, and a wall with a homogeneous Expanded Polystyrene board (EPS) layer having identical thermal resistance. COMSOL Multiphysics® 5.5 software was used to perform the simulations. Heat transfer through these wall assemblies due to the indoor/outdoor temperature difference was calculated and the possibility of saving energy, as well as shifting and dampening peak heating and cooling demands, was investigated. In the following sections, governing equations, simulation specifications, model boundary conditions, and results will be presented.
2. Methodology

2.1. Governing equations
The main governing equation for evaluating the thermal performance of the case studies is the heat conduction across each of these walls. Because it was assumed that the materials simulated for this study have isotropic material properties and that there is no anomaly in the geometries, the heat is only conducted across the walls in the direction normal to the wall surfaces. One-dimensional heat transfer equation can be described as follows [2]:

\[
\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) = \rho c_p \frac{\partial T}{\partial t} \tag{1}
\]

As mentioned earlier, one of the objectives of this study is to compare the thermal performance of ICF and tilt-up walls under Montreal and Miami temperature conditions using the sol-air equivalent temperature. The sol-air temperature is calculated as the combined effect of both the ambient temperature and the incident solar radiation on the building surface [10]. Solar absorptance was assumed to be 0.8 for all cases. Beam normal, diffuse, and total horizontal solar irradiances can be found in the Typical Meteorological Year (TMY) data for each city from the EnergyPlus website [11]. Then, sol-air temperature (in °C) can be calculated using the equation presented in the ASHRAE Fundamentals handbook [9].

2.2. Geometry
As mentioned above, this study compares the thermal performances of an ICF wall, a tilt-up wall, and a thermally light wall with the same thermal resistance. The ICF wall has a six-inch concrete layer sandwiched between two three-inch insulation layers. The tilt-up wall is comprised of a six-inch insulation layer sandwiched between two three-inch concrete layers. Two-dimensional schematics of these assemblies are illustrated in Figure 1. Although ICF walls usually have interior and exterior finishes, for the sake of consistency and equal thermal resistances, these layers were not taken into account. Also, with the aim of isolating the effects of thermal mass, another geometry made up of only one layer of EPS insulation was investigated. The thickness was adjusted such that its overall thermal resistance was equal to that of the ICF and tilt-up walls. The required thickness of the EPS layer was found to be 6.17 in. Also, the thermal capacitance of the ICF and tilt-up walls is 311 kJ/m².K while the thermal capacitance of the EPS wall is 2.6 kJ/m².K.

2.3. Materials, boundary conditions, and solver configurations
Material properties of the EPS and concrete are presented in table 1. As for the boundary conditions, the indoor temperature is maintained at 20°C throughout the simulation and the convection coefficient was assumed to be 8.33 W/m².K. Initially, two different sinusoidal outside temperature scenarios were assumed: (a) An outside sinusoidal temperature profile fluctuating between -20°C and -8°C (heating season) and (b) An outside sinusoidal temperature profile fluctuating between 20°C and 32°C (cooling season) throughout the day. The minimum and maximum values of these profiles occur at 3 A.M. and 3 P.M., respectively. Simulations started from midnight with the initial temperatures being -18.24°C and 21.76°C for the first and second scenarios, respectively. The number of days each wall requires to reach pseudo steady-state conditions was taken as a parameter to show the thermal mass effect. Finally, sol-air temperature conditions of Montreal (as a case study heating-dominated city) and Miami (as a cooling-dominated region) for a TMY were considered as exterior boundary conditions. Convection coefficients for all exterior boundaries were 33.33 W/m².K [9]. The initial conditions for Montreal and Miami correspond to those of December 31st. Also, the effects of night-time cooling were ignored in the sol-air boundary condition in each location. All these walls were assumed to be south-oriented.
Figure 1. Schematics of (a) the ICF; and (b) the tilt-up walls.

| Material | Thermal conductivity (W/m.K) | Density (kg/m³) | Thermal capacity (J/kg.K) |
|----------|-----------------------------|----------------|----------------------------|
| EPS      | 0.05                        | 11.5           | 1450                       |
| Concrete | 1.8                         | 2300           | 880                        |

3. Results and discussion

Firstly, steady-state simulations at the initial boundary temperatures were performed, and then these results were used as initial conditions for the transient heat transfer simulations. The resultant R-value of the assemblies was 3.13 m².K/W. Figure 2 shows the energy flux (W/m²) through the interior surface for the ICF, EPS, and tilt-up walls considering the first sinusoidal outside temperature scenario. Because the indoor temperature is maintained at 20°C throughout the duration, integrated heat fluxes for a full cycle are the same for all three cases, and the effects of thermal mass are restricted to the time lag, peak demand shifting, and the time required for each wall to reach quasi-steady state i.e. the situation that indoor heat fluxes have a constant daily variation profile. The temperature profile is also illustrated in the same graphs. It can be observed that it takes 7 days for the ICF wall to reach pseudo steady-state conditions while the tilt-up wall requires only one day to reach stabilized conditions. On the other hand, transient thermal response of the EPS wall follows the trend of outside temperature conditions almost from the starting point. This is due to the fact that the concrete layer of the ICF wall is placed between the insulation layers; as a result, any change in the temperature conditions will be dampened by the insulation layer and then the layer with high thermal mass will regulate the response of the wall. Whereas, the concrete layers of the tilt-up wall are directly exposed to the boundary temperature conditions; thus, the exposed exterior concrete layer responds rapidly to the temperature variations, and because the exterior boundary conditions are periodically stable, the thermal response of tilt-up wall will stabilize faster. On the contrary, as the EPS wall has a very low thermal mass (value), any change in boundary temperature conditions has a more direct impact on the thermal response of this wall. Positive values in these graphs refer to the case of heating energy demand while cooling energy demands are shown by negative values. Another effect of thermal mass is peak demand shifting. It is evident from Figure 2 that there is a time lag of nearly 7 hours between the daily maximum heat flux transferred from the interior surface of the ICF wall and the daily minimum outside temperature. This time lag is approximately 6.5 hours for the tilt-up wall while a minimal time lag between the response of the EPS wall and outside temperature profile was observed. Considering the fact that the amplitude and the phase of the second exterior temperature scenario are the same compared to those of the first scenario, and that thermal properties are not assumed to be temperature-dependent, same trends were found, with the only difference being the scale of the resultant heat fluxes.
Next, the ICF, tilt-up, and EPS walls were simulated using the sol-air temperature conditions of Montreal and Miami as the exterior boundary conditions. Figure 3 and Figure 4 show the annual interior heat fluxes, as well as annual heating and cooling demands, for the Montreal (heating-dominated) and Miami (cooling-dominated) cases, respectively. Comparing the performances of the ICF and tilt-up assemblies, the energy fluxes for the tilt-up case tend to fluctuate more widely because its concrete layers are directly in contact with the exterior and conditioned interior boundaries. As an example, the minimum and maximum values, as well as amplitudes of the heat fluxes on February 1st for the Montreal case, are presented in Table 2. The resultant heat flux amplitudes for the ICF, tilt-up, and EPS wall cases under Montreal TMY sol-air temperature conditions were 0.43 W/m², 2.00 W/m², and 4.64 W/m², respectively. As expected, these fluctuations are more evident for the interior surface of the EPS assembly due to the lack of thermal mass. The integrated heat fluxes for the case study walls are shown in Table 3. As the indoor temperature is set at 20°C throughout the year, for each city, the overall integrated heat fluxes were the same for all case study walls (within 0.3% difference). However, it does not necessarily mean that the heating demands or the cooling demands for all three cases are the same because the amount of heat stored in the thermally massive layer can contribute to the energy demands. As shown in Table 3, compared to the EPS wall, the ICF wall had 7.7% less heating energy demand in Montreal. While the ICF wall required 1.10 kWh/m² cooling energy in Montreal to compensate the heat gains through the assembly, EPS wall required 3.81 kWh/m². On the other hand, the ICF wall, compared to the EPS wall, demanded 6.5% less cooling energy in Miami while the heating demands for the ICF and EPS walls in Miami were 0.04 kWh/m² and 1.28 kWh/m², respectively. Comparing these two specific walls, although there are wide deviations between the heating energy demands in Miami and cooling energy demands in Montreal, it should be noted that they account for small portions of the total energy demands in the case study cities. It also can be observed that the heating demand of the EPS wall is 5.7% higher than that of the tilt-up wall in Montreal. The cooling energy demand of the tilt-up wall in Montreal was 1.99 kWh/m². Also, the EPS wall required 3.8% more cooling energy in Miami compared to the tilt-up wall. The heating energy demand of the tilt-up wall in Miami was 0.59 kWh/m². As a result, it can be concluded that the benefits of the thermal mass in terms of energy savings are more evident during the secondary seasons for each city.

**Figure 2.** Heat fluxes transferred over the interior surface under the first assumed sinusoidal exterior temperature profile (heating scenario) for the ICF, tilt-up, and EPS walls.

**Table 2.** Max. and min. values and amplitudes of the heat fluxes on February 1st for the Montreal case.

| Walls  | Maximum heat flux (W/m²) | Minimum heat flux (W/m²) | Amplitude (W/m²) |
|--------|--------------------------|--------------------------|------------------|
| ICF    | 8.88                     | 8.02                     | 0.43             |
| Tilt-up| 8.39                     | 4.40                     | 2.00             |
| EPS    | 10.11                    | 0.83                     | 4.64             |
Table 3. Integrated heat fluxes for ICF, tilt-up, and EPS wall assemblies under Montreal and Miami TMY sol-air temperature conditions.

| Wall  | Heating (kW/m²) | Montreal Heating (kW/m²) | Integrated heat flux (kW/m²) | Miami Heating (kW/m²) | Cooling (kW/m²) | Integrated heat flux (kW/m²) |
|-------|-----------------|--------------------------|-----------------------------|-----------------------|----------------|-----------------------------|
| ICF   | 32.06           | 1.10                     | 30.96                       | 0.04                  | 19.46          | -19.42                      |
| Tilt-up| 32.86           | 1.99                     | 30.87                       | 0.59                  | 19.98          | -19.39                      |
| EPS   | 34.74           | 3.81                     | 30.93                       | 1.28                  | 20.73          | -19.45                      |

Figure 3. (a) Interior surface energy fluxes and (b) heating and cooling energy demands for the ICF and tilt-up assemblies under Montreal TMY sol-air temperature conditions.

In order to better understand the effect of thermal mass placement within concrete walls, energy demands of the ICF and tilt-up walls were compared. The ICF wall in Montreal needed 2.5% less heating energy. Also, the difference between the cooling energy demands of the ICF and tilt-up walls in Miami was 2.6%. Thus, based on the cases studied, the thermally massive layers can benefit the buildings in terms of energy saving if they are not directly exposed to the exterior conditions. Finally, the minimum indoor surface temperatures for each wall assembly were also calculated for each location. In Montreal, the minimum surface temperatures were 18.7°C, 18.4°C, and 18.1°C for the ICF, Tilt-up wall, and EPS, respectively. In Miami, the maximum surface temperatures were 20.4°C, 20.6°C, and 21.0°C for the ICF, Tilt-up wall, and EPS cases, respectively.
4. Conclusion

In this study, using COMSOL Multiphysics® heat transfer simulation software, transient thermal performance of three wall assemblies, namely an ICF wall, a tilt-up wall, and an EPS wall, were compared. Firstly, two sinusoidal temperature profiles representative of heating and cooling seasons accounted for the outside boundary conditions. It was observed that the time lag between the outside temperature profile and the thermal responses of the ICF and tilt-up assemblies were 7 hours and 6.5 hours, respectively. EPS wall was found to have minimal peak-demand shifting due to the lack of thermal mass. Also, thermal response of the ICF wall had a smaller amplitude as compared to those of the tilt-up and EPS walls. Next, sol-air temperatures based on TMY data provided for Montreal and Miami were calculated and considered as outside boundary conditions. Indoor surface heat fluxes and total energy demands due to the heat loss/gain through the wall assemblies were compared for the case study walls. Maximum heat losses for ICF, tilt-up, and EPS walls were 10.95 W/m², 13.67 W/m², and 15.61 W/m² for the Montreal case, respectively. Also, maximum heat gains in Miami were 3.63 W/m², 5.15 W/m², and 8.27 W/m² for these walls, respectively. Thus, the heat fluxes of the ICF wall tend to fluctuate less compared to the tilt-up and EPS walls. Based on the heating and cooling loads for Miami and Montreal, it was concluded that the thermal mass effect is more evident during the secondary season for both locations. Also, the ICF wall required 2.5% and 2.6% less energy in comparison with the EPS wall for compensating heat losses/gains through the opaque wall during the primary seasons in Montreal and Miami, respectively. Regarding the indoor surface temperatures, it was observed that the fluctuations in interior surface temperatures are less for the ICF wall. Overall, it was concluded that based on the case studies of our interest, ICF walls can shift and dampen the peak loads and reduce the energy usage in buildings better than tilt-up walls.

Thermal mass benefits will be more evident when the indoor temperature is allowed to be changed or variable thermostat setpoint temperatures are intended because during the heating season, for example, heat can be stored in the thermally massive layer, which can be released back to the conditioned space at a lower setpoint temperature. This can contribute to the amount of heat required to maintain the conditioned zone at the desired temperature. Also, it should be mentioned that because the thermal properties of the concrete are moisture-dependent, performing hygrothermal simulations can provide a
better insight into the problem. However, it is out of the scope of the current study. As a result, these two points of consideration can be potentially beneficial future works.

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