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Thermal Analysis of Insulated Concrete Form (ICF) Walls

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Abstract

A three dimensional numerical model of a PVC water pipe embedded inside an insulated concrete form wall was numerically developed. Different wall thickness sizes and optimal distance between pipes were analyzed. Three inlet temperature and four inlet velocity for each set have been studied. Thermal behavior of the concrete was investigated in a transient mode. This study focused on storing thermal energy inside the wall and using it when there is a demand rather than transferring heat for space conditioning. Predicted heat transfer rate and potential thermal energy storage were tabulated. In general, this study helps designers to gain detail understanding of heat transmission between water pipe and concrete.

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Keywords: Thermal Energy Storage (TES), Insulated Concrete Form (ICF), Integrated BITES, Heat Transfer in Concrete

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1. Introduction

There are potentials for the short term thermal energy storage in buildings. Utilizing the buildings thermal mass is a common way of storing thermal energy for short term. The idea of using building's walls as thermal energy storage has been discussed for many years. Integrating the phase change material (PCM) into walls has been vastly studied in the literature [1, 2, 3]. However, the feasibility of using wall itself (without PCM) has not been studied in detail yet. For instance, an Insulated Concrete Form (ICF) wall is a potential sensible Thermal Energy Storage (TES) that its thermal properties, behaviour, and benefits have not been investigated in details.

Sensible TES stores thermal energy as an internal energy and increases the medium's temperature. Among all possible mediums, water and air are the most commonly used options but oil, rock, brick, sand, and soil are also well known mediums for sensible TES [4, 5]. Water due to its low cost, availability, and high specific heat is the first choice of many designers for TES systems and heat transport purposes [6, 7]. Although tanks and underground storages are potential options for the short term TES, implementing concrete wall/floor of buildings as TES could be more economically viable. Additionally, replacing a tank with building thermal mass saves more space inside the building. There is interest in using ICF walls or concrete floor as TES. To date there has been limited studies on this subject, rather the objective of other researches are providing comfort heating via embedded pipes inside the floor/wall [8]. This study numerically investigates the thermal behaviour and temperature distribution inside a concrete wall.

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2. Motivation

The energy consumption in building could be more efficiently managed if a thermal energy storage system is integrated into the whole mechanical system. Building integrated thermal energy storage (BITES) systems require to be investigated in more details. Effectiveness of BITES in different areas are highly recommended in the literature. Rad et al. [9] and Wang et al. [10] have shown that solar thermal energy storage in the ground could reduce the length of ground heat exchanger by 15%. Chen et al. [11] designed and modeled a building integrated photovoltaic/thermal (BIPV/T) system in a near zero energy building in cold climate of Canada. Accordingly, they have studied the effect of integrating a ventilated concrete slab (VCS) with BIPV/T system as an active TES system. Since most of the times temperature output from the BIPV/T is not high enough to be fed into the VCS, it is recommended by Chen et al. to consider and include an air source heat pump in the integrated system. Moreover, Kamel and Fung [12, 13] studied a BIPV/T system integrated with air source heat pump. It has been shown that the combined system will enhance the performance of the overall system and it is recommended that an appropriate BITES system will increase the overall efficiency of the entire integrated system further [12, 13]. Accordingly, Ekrami et al, [14] showed how effective an integrated concrete based BITES could be.

In order to investigate the effect of a BITES on the overall performance of the integrated system, a full scale (30ft × 25ft) test hut is designed and planned to be built at Toronto and Region Conservation Authority (TRCA) Kortright Center. The test hut will be equipped with an Air Source Heat Pump (ASHP), which is integrated with roof based BIPV/T panels to improve the performance of the system [15]. The ASHP can produce hot air/water. All ICF walls and the concrete floor are designed to be used as Building Integrated Thermal Energy Storage (BITES). Stored thermal energy can be used later for space heating and/or domestic hot water use. This configuration is expected to enhance the overall performance of the integrated system by implementing the TES.

3. Methodology

Besides the structural function of a concrete wall, it can also serve as actively charged thermal mass to store thermal energy and then passively release it to assist space heating. However, in this study the objective of using an ICF wall as TES is not to discharge the thermal energy to the space directly, rather to re-use it as an input of another mechanical system such as heat pump or re-use it through the hydronic forced air or infloor heating. The ICF walls are designed to be charged with heated water provided by the heat pump when the sun is available and the solar assisted heat pump works very efficiently [12, 13]. Stored thermal energy inside the concrete can be used to heat up the water in a later time when there is a demand.

A bigger thermal storage requires more space and more cost. Therefore a reasonable ratio between surface/volume and thermal capacity/volume is recommended [4]. In order to find a practical approach for finding optimal volume of concrete in ICF walls a numerical model has been developed. An embedded pipe inside the body of concrete with a unit length was thermally analyized. In this model a ½ inch pipe with 0.66 inch inside diameter, 0.84 inch outside diameter (0.09 inch thickness) and thermal properties of a Schedule 40 PVC pipe was employed to circulate the water. The concrete wall thickness was 6 inches. Each side of the wall assumed to be perfectly insulated with the foam (adiabatic). Different temperature and velocity senarios were tested and maximum distance between parallel pipes for a uniform thermal destribution and efficient use of concrete found to be 20 inches. The schematic of the model is shown in Figure 1a.

Density and specific heat of materials along with their volume are directly proportional to the heat storage capacity of TES [16]. However, performance of TES and volume of the substance depend on density and specific heat of the material [17]. A high performance thermal storage uses a dense medium with high specific heat. The medium requires to have a high convective heat transfer rate (for liquid), and be highly diffusive (for solid) [7]. Although liquids are better to exchange thermal energy, stratification is easier in solid mediums [7]. In this study a medium weigth concrete with the density of 2000 kg/m^3, specific heat capacity of 1000 J/kg.K, and thermal conductivity of 1.13 W/m.K was used for the simulated model.

Short term TES systems usually work in low temperature range which depends on being active or passive. Most of the passive short term TES systems work within 20 to 60 °C while active system's temperature can be up to 95 °C [4]. Accordingly, different temperature settings were tested to better understand the effect of water temperature in the overall heat transfer process. Also, the temperature change of concrete was studied in a transient mode to find the charging cycle duration. Both laminar and turbulent flows were considered and studied in the model.

4. Numerical Simulation

Flow Simulation module of Solidworks program was used to simulate the fluid and heat transfer phenomena for the ICF wall configuration. This model helps to gain a better understanding of effects and relation between different variables such as; inlet temperature, inlet velocity, heat transfer rate inside the pipe, etc. A simplified three dimensional model of the ICF wall was created. Pipes are assumed to be straight with no fittings and a unit length of PVC pipe was used for the model. Therefore, all heat transfer calculations and results are presented based on one meter length of the pipe. All pipes are parallel to each other and located in a fixed distance of 20 inches. Insulations were assumed to be perfect. Hence, boundary conditions for the side walls were defined as adiabatic. In order to study the effect of inlet into the ICF wall, the entry side of the concrete was defined based on initial concrete temperature of 20°C and the exit as symmetry. Also, the PVC pipe properties was defined by the density of 1379 kg/m^3, specific heat capacity of 1004 J/kg.K, and thermal conductivity of 0.16 W/m.K.

At the beginning a mesh independency test had been performed and as previously mentioned the optimum distance between pipes had been estimated. Since the inlet velocity plays an important role in the heat transfer rate between water and concrete around the pipe, the simulated model has been run for different inlet velocity ranges. Initially, variety of velocity ranges were examined and it has been noted that four velocities of 0.01, 0.1, 0.5, 1 m/s are the best cases for demonstration of heat transmission between water and concrete. The lowest inlet velocity which is 0.01 m/s represents laminar flow with the Reynolds number of 463 and all other three velocities fall in the range of turbulent flows.

Furthurmore, different water temperature were also tested to address the associated changes in the heat transfer rate and temperature destribution in concrete. The selection of water inlet temperature range was based on possible options of heat sources for hot water production in the test facility. Hence, inlet water temperature of 40°C, 45°C, and 50°C were tested in the simulated model. For all cases initial temperature of the concrete was set at 20°C to be close to the room temperature. In general, testing three different temperature setting and four different velocites for each set, provided a detail understanding of heat transfer process between water and concrete in the ICF wall.

A 2D temperature destribution sample in the concrete alongside the pipe for half a meter is shown in Figure 1b. The "Z" value indicates the distance from the inlet parallel to the pipe, which represents the height while temperature contours across the graph are scaled to represent temperature destribution half way through two parallel pipes, which is equal to 10 inches. The inlet temperature and velocity of water in this particular case, that has been shown in Figure 1b, are respectively 40°C and 0.01 m/s to show the concrete temperature after 24 hours charging process.

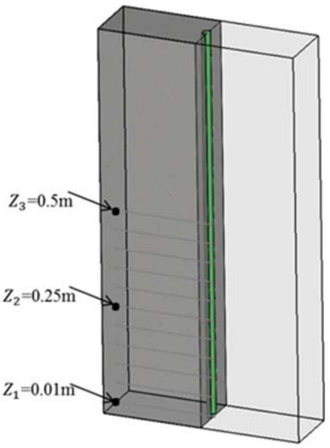

Figure 1a- Schematic of the ICF wall and embedded pipe

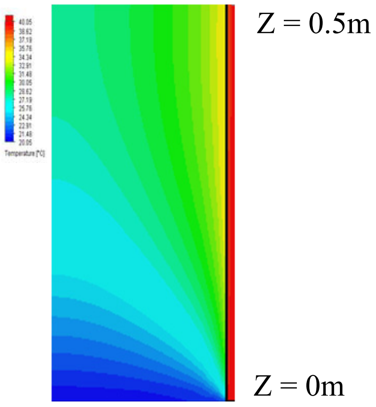

Figure 1b - Temperature contours inside concrete

Accordingly, heat transfer in concrete has been further analyzed in detail. In order to be consistent Figure 2 was developed with the same inlet temperature and velocity of 40°C and 0.01 m/s after one day. The system seems to be thermally stable after this period of time. Figure 2 shows how temperature varies by location and distance from the thermal source. Eleven different lines are shown in bottom half left side of Figure 1a, which physically represent different Z elevations (discussed in Figure 2) from the inlet. As expected, temperature of concrete increases along the pipe starting by the highest temperature of 35 °C and has lower value when distance from the pipe increases. It has been found that the inlet effect on temperature distribution is between 0 to 0.5m for most of the temperature-velocity settings and the temperature is distributed uniformly after that point.

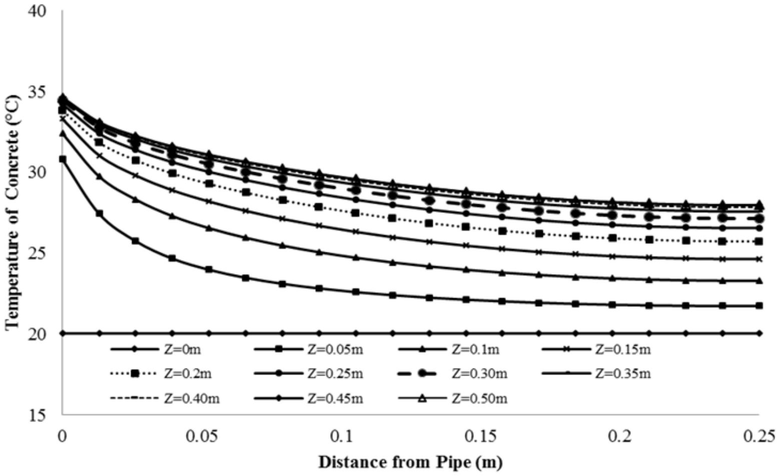

Figure 2 - Temperature of Concrete at different Z values and distances

Since the model has been tested in a transient mode, temperature change of concrete in different point at different times has been analyzed. Figure 3 shows temperature of three points in the concrete previously shown in Figure 1a under charging process for 24 hours. The same temperature-velocity setting as other figure is shown here as well. Figure 3 illustrates that the temperature at point 1 reaches to 35°C. Point 1 is located half way between two parallel pipes. Since point 1 is almost the location where entrance effects are neglegible, all other points with higher Z elevation have almost the same temperature trend.

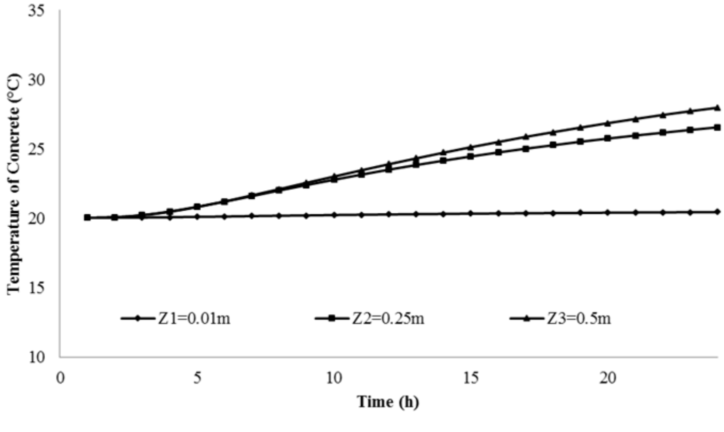

Figure 3 - Temperature Change inside Concrete by Time

Analyizing the overall performance of the system requires to investigate the heat transfer rate between the water and concrete for each of the temperature-velocity settings. Since the transient behavior of the system is important, heat transfer rate of the system was studied for each time step of the simulation for total

24 hours. Initialy, the heat transfer rate is higher for all the temperature-velocity settings. It is due to high temperature difference between the hot water and concrete. As time passes, the temperature inside the concrete increases and heat transfer rate decreases. A sample of calculated heat transfer rate for the temperature-velocity setting of 40°C and 0.01 m/s for 24 hours has been shown in Figure 4. In this particular setting the heat transfer rate decreases to 9 W per unit length of pipe (m) after the system is in a thermally stable condition. However, the average heat transfer for this period of time is higher (10.89 W).

The heat transfer rate for all twelve temperature-velocity settings has been analyzed. Additionally, total thermal energy transferred from hot water to the concrete was calculated for each separate settings. It has been shown that the heat transfer rate increases with higher inlet temperature and velocity. Therefore, associated transferred thermal energy increases accordingly. However, transfering more thermal energy does not necessary means a more efficient system. The percentage of recovered heat would be a better indicator for ranking efficiency of the system. The results of calculated transferred thermal energy and heat transfer rate after 24 hours are presented in Table 1.

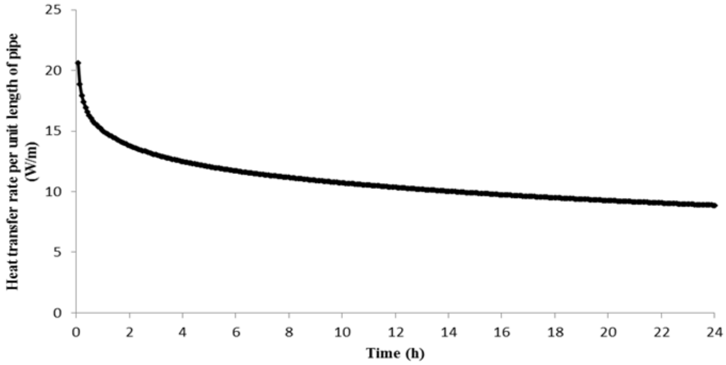

Figure 4 - Heat Transfer Rate vs Time

Table 1 - Simulated Results of Different Temperature-Velocity Settings for one meter length of Pipe

Temperature of the Fluid (°C)	Velocity of the fluid (m/s)	Total Transferred Thermal Energy after 24 hours (Wh)	Heat Transfer rate (W)
40	0.01 (Laminar)	260.35	10.89
	0.1 (Turbulent)	294.70	12.33
	0.5 (Turbulent)	308.15	12.89
	1 (Turbulent)	309.48	12.94
45	0.01 (Laminar)	325.63	13.62
	0.1 (Turbulent)	369.92	15.48
	0.5 (Turbulent)	385.3	16.12
	1 (Turbulent)	386.92	16.19
50	0.01 (Laminar)	390.96	16.35
	0.1 (Turbulent)	451.22	18.88
	0.5 (Turbulent)	462.46	19.35
	1 (Turbulent)	464.37	19.43

5. Remarks

Preliminary thermal analysis of the ICF walls shows that it could be a possible option to be integrated as a TES with BIPV/T+ASHP system. Additionally, the study helps designers to have a better understanding of thermal capability of each unit meter embedded pipes inside the concrete walls. The performance of the system changes if the initial condition varies with defined boundary conditions. However, provided temperature-velocity settings are close to real conditions. It has been found that temperature distribution is uniform when the distance from the inlet is more than half a meter. Also, change of heat transfer rate with time has been investigated for multiple temperature-velocity settings. The study of water-polyethylene Glycol solution as working fluid is also recommended, since part of the piping system may be exposed to outdoor environment and freeze in a cold climate area when the system is off. Furthermore, use of PCM material incorporated in concrete needs to be analyzed.

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Biography

Navid Ekrami is a PhD candidate in the Mechanical and Industrial Engineering Department at Ryerson University, Toronto, Canada. He received an Aerospace engineering degree from Azad, Science and Research University, Tehran, Iran, and a MASc degree in Mechanical engineering at Ryerson University. His research focus is on sustainable energy technologies and their applications in buildings.