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COLD THERMAL ENERGY STORAGE FOR BUILDINGS: A FEASIBILITY STUDY

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Abstract:
In this study, we examined the feasibility of using cold ice as a medium to store the cold energy in the cold season and use it during the hot season in locations which experience both cold and hot seasons. We studied a cylindrical storage tank, two meters in diameter and two meters in length, wrapped with conventional insulation providing R-50. We assumed that the contained ice reaches -25 ℃ during the winter time and it was assumed to be exposed to the warm temperature of 18 ℃ for six months prior to being required for cooling. We used COMSOL Multiphysics to model the heat transfer in a three dimensional configuration. The results showed that 40 percent of the stored cold energy would be depleted during the six month period prior to the hot season. It would take 43 days for the ice in the tank to reach the melting point. after consuming the sensible stored cold, and the melting process begins after that. The remaining energy is able to provide the cooling energy for almost full 24 days for an R-2000 2-story detached house located in Ottawa, Ontario.
Keywords:
Cold storage, Cooling, Building, Climate change, Overheating, Feasibility study

1. Introduction

It is anticipated that in the coming 50 years, Canadian homes will be increasingly exposed to extreme overheating caused by global warming and urban heat island effects. Overheating of building interior spaces has been identified as a major concern to the comfort and health of vulnerable people, overloading of building HVAC systems, and straining the electric and water utility infrastructure. Prolonged exposure to extreme heat induces heat stress in people and may lead to severe health issues or even death. In urban settings, extreme heat events combined with air pollution were found to increase morbidity (sickness), mortality (loss of life), and insurance claims (particularly in North America). The extent of this effect varies from climate to climate, region to region, and city to city. In Canada and the USA, the number of excess mortalities due to extreme heat events is higher than any other natural hazard event such as storms and floods (ICLR, 2018; Bertko et al., 2014). Studies on climate change adaptations at a building (or individual) level have been, however, very limited in the Canadian context due to the lack of information on exposure to elevated indoor temperatures. Given the expected risk of Canadian homes overheating in the future as a result of the effects of climate change, there is a need to mitigate these effects by providing emergency cooling to homes when an overheating event occurs.

Since the occurrence of such events may require only a few days of additional cooling to prevent overheating in homes and thereby maintain a minimum level of comfort for its occupants, it is hypothesized that the cooling load may be provided from seasonally stored cooling energy located within the home. Seasonally stored cooling energy would be captured during the cold winter months through exchange of a storage fluid with the outdoor air. The cold storage would be maintained throughout the winter and subsequent summer months by means of a highly insulated storage tank.

As shown in Figure 1, thermal energy storage (TES) systems store energy using three types of technologies: (1) Sensible heat thermal energy storage (SHTES); (2) Latent heat thermal energy storage (LHTES); and (3) Chemical Reaction/Thermochemical storage (TCS).

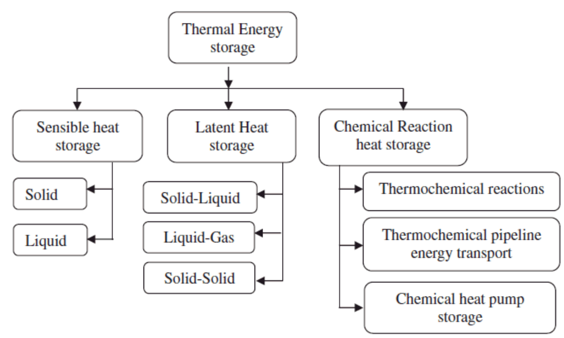

Figure 1: Classification of thermal energy storage (source: Raam Dheep & Sreekumar, 2014)

In latent heat thermal energy storage (LHTES) systems the energy is stored and released at a molecular level in a medium that has the capability to absorb and release heat during the phase change transformation (e.g. solid to liquid; liquid to gas; solid to gas; or solid to solid from one crystalline form to another). The term "Phase Change Material" (PCM) is commonly used in the literature to describe materials that absorb or release relatively large amounts of latent heat at a relatively constant temperature when solidifying or liquefying. The majority of PCMs used in TES systems are solid-liquid transition materials (Nazir et al., 2019). Energy enters or leaves the system without causing a temperature change in the system and the amount of heat stored depends on the mass and the capability of the PCM to absorb and release heat during its phase transition. The large amount of energy required to go through a change in phase between solids and liquids (i.e., amount of energy needed to melt a given mass of a solid at its melting point temperature, or the amount of energy released when a given mass of liquid solidifies) is referred to as the latent heat of fusion, which for water at 0°C is ~334 joules/gram or ~80 calories/gram. Figure 2 shows the classification of PCMs used for cold thermal energy storage. Organic PCMs are carbon based compounds; Inorganic PCMs are usually metallic and hydrated salts; Eutectic PCMs are mixtures of two or more PCMs developed to achieve a certain melting point, which is a key criterion for cold storage applications. A comprehensive overview of PCMs for cold thermal energy storage (and their thermal characteristics) is available in the review article by Veerakumar & Sreekumar (2016). Recent PCM developments for TES are also available in Nazir et al. (2019), which lists 38 international organisations commercializing at present time PCMs for various TES applications. Lizana et al. (2017) found that at present time there are more than 250 commercially available organic and inorganic latent heat storage materials and provided a detailed review of their thermal properties and characteristics.

In this feasibility study we studied liquid-solid latent heat storage. A cylindrical tank of two meters in diameter and height was studied for storing ice. The tank was insulated using conventional insulation (e.g. EPS, XPS or fiberglass). COMSOL Multiphysics was employed to examine the cold storage depreciation through time.

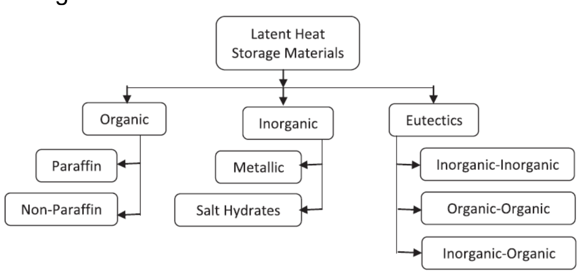

Figure 2: Classification of phase change materials (or latent heat storage materials) for cold thermal energy storage (source: Raam Dheep & Sreekumar, 2014).

2. Methodology

We studied liquid-solid latent heat storage. A cylindrical tank of two meters in diameter and height with flat ends was studied for storing ice. The tank was assumed to be insulated using conventional insulation (e.g. EPS, XPS or fiberglass). COMSOL Multiphysics was employed to examine the cold storage depreciation through time.

The following assumptions were made for the modeling of the cold storage tank in COMSOL Multiphysics:

- A two dimensional axisymmetric model was used to reduce the calculation time by taking advantage of the symmetry of the geometry.
- R-50 insulation around the tank was achieved using conventional insulation (340 mm of EPS). The temperature dependence of the insulation R-value was neglected.
- The initial ice temperature in the tank was set to -25 ℃ and the tank was placed in an indoor environment having a constant ambient temperature of 18 ℃.
- Convective heat transfer in the storage liquid was not considered.
- Time steps of 60 seconds, 30 seconds and 15 seconds were used to examine the time step dependency of the results. The sensitivity analysis showed that one minute time steps may predict the results properly thereby significantly reducing the computation time.
- The transient thermal behavior of the system was studied for 180 days (6 months).
- The tank shell was assumed to have negligible thermal mass and hence did not affect the storage capacity and transient behavior of the tank.

3. Results and discussions

Figure 3 shows the temperature and phase index contours after 45 days of being exposed to an ambient temperature of 18°C. The units in the graphs are adjusted according to the minimum and maximum values occurring in the system. Phase indicator shows the phase change of the ice. The phase indicator value of "0" as the minimum indicates full solid and "1" as the maximum value indicates full liquid. Values between the extremes indicate that the storage substance is undergoing the phase change and is in a mushy region. As it can be seen, after 45 days only the sensible cold in the system was used and no melting of the ice was observed.

Figure 4 depicts the temperature and phase indicator contours after 90 days (3 months). Melting at the surface of the ice has started and the latent heat portion of the stored energy is contributing to the heat transfer process; hence, the temperature remains constant at the edges. As it can be seen the minimum temperature in the system has risen to -1.38 ℃ from -6.16 ℃ on the 45th day.

Figure 5 shows the temperature and phase indicator contours after 135 days (4.5 months) of storage. The minimum temperature in the system has not changed since the 90th day which indicates that only the latent energy in the system has been used during this period. Also as it can be seen from the phase indicator graph more melting has happened especially around the corners.

Figure 6 illustrates the temperature and phase indicator contours after 180 days (6 months). There is still a significant amount of cold energy stored in the storage medium and the minimum temperature of the system has not changed, which means that the cold energy was only provided from the latent heat of fusion.

To better understand the heat transfer inside the tank, we also plotted the total heat flux magnitude (W) and the temperature (℃) on the tank wall and insulation wall, as shown in Figures 7 and 8, respectively. The heat fluxes begin at a very high rate (more than 100 Watts) when the temperature difference between the insulation surface and the ambient temperature is the largest, and then reaches an equilibrium when the melting begins after 43 days. The total heat fluxes should be exactly the same at each time, due to the assumption of negligible thermal mass in the insulation; however, as it can be seen after the beginning of melting, the total heat.

We calculated the total energy available in the storage tank and how much energy remained after 180 days based on the simulation results. The total initial energy stored in the tank is expressed as follows.

$$Q = \left[\rho V C_{p,ice}\left(T_i - T_{phase\ change}\right) + \rho V L_{ice}\right]_{ice} = (58.277 + 1{,}929{,}718.4)\ kJ = 1{,}929{,}777\ kJ \quad \textit{(Eq. 1)}$$

where

ρ	=	Ice density
V	=	Ice volume
C_p	=	heat capacity
T_i	=	Initial temperature of ice
L_{ice}	=	Latent heat of ice

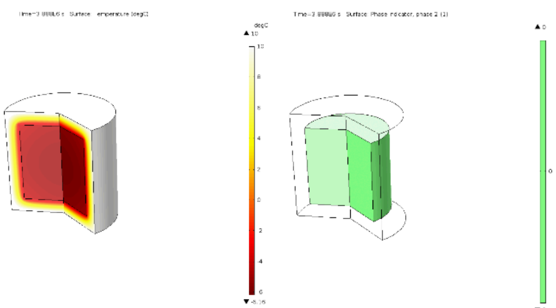

Figure 3. Temperature contours (left) and phase indicator contours (right) after 45 days of being exposed to the ambient temperature

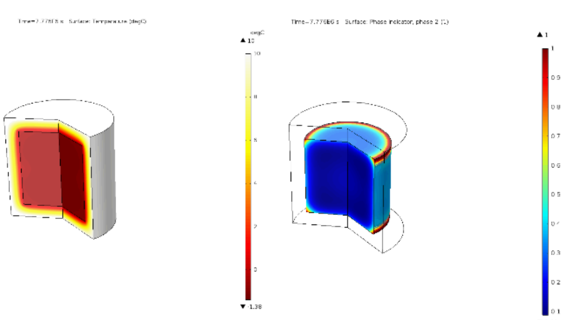

Figure 4. Temperature contours (left) and phase indicator contours (right) after 90 days of being exposed to the ambient temperature

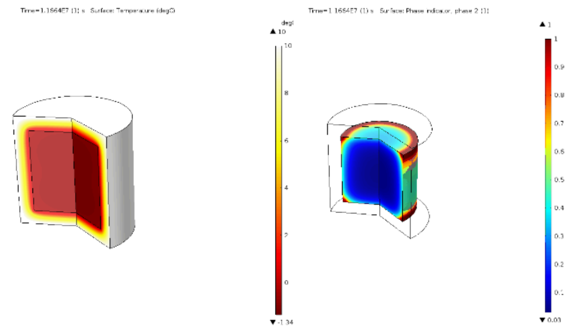

Figure 5. Temperature contours (left) and phase indicator contours (right) after 135 days of being exposed to the ambient temperature

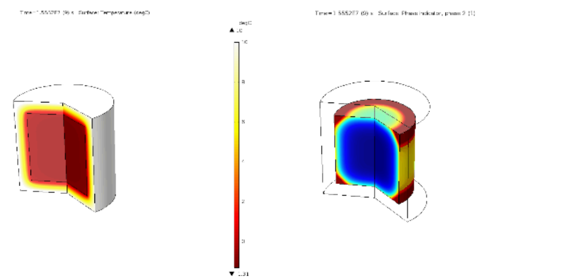

Figure 6. Temperature contours (left) and phase indicator contours (right) after 180 days of being exposed to the ambient temperature

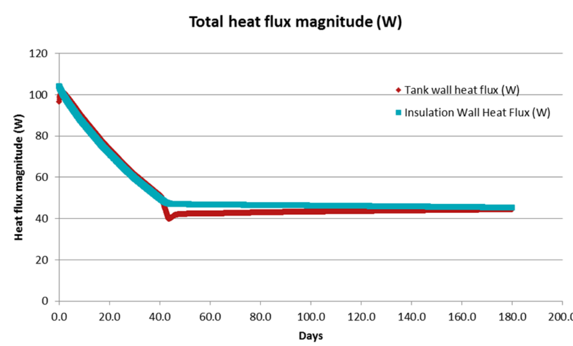

Figure 7. Total heat flux magnitude (W) on the tank wall surface and on the insulation surface

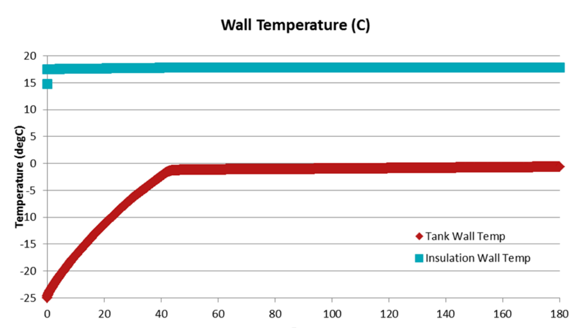

Figure 8. Wall temperature of tank and insulation

The first portion of the above equation shows the sensible heat of the ice, the second part is the latent heat. It can be seen that the latent heat is the main part of the cold storage in the system and the sensible part is negligible (below 0.003%). The energy calculation for this cold storage system is summarized in Table 1. Also, using the values for total heat flux at each time step, as shown in Figure 6, we calculated the total heat lost by the system over 180 days. The remaining energy was assumed to be available to provide the required cold energy for space cooling of a typical residential 2-storey house. According to Laouadi (2010), the cooling energy used by a typical R-2000 house (including 250 m^2 of livable space; double-glazed low-e windows; interior venetian blinds) over the cooling season is 33,500 KJ, with a typical peak cooling demand of 1.5 kW. As such, the storage tank system proposed in this study could provide the cooling demand of the entire house for almost 23.5 days, or 35% of the cooling energy demand of the entire cooling season. Given that extreme heat waves may last a few days to a few weeks in the summer, the proposed storage system may easily fulfill the space cooling requirements of the house over an extreme heat wave event.

Table 1. The energy calculation of the cold storage system

Parameter	Value
Total cold energy stored	1,930,000 KJ
Heat loss to the surrounding environment	764,053 KJ
Net remaining energy for space cooling	1,165,947 KJ
Peak cooling demand of a typical R-2000 house in Ottawa	1.528 KW
Average daily cooling energy demand (at 9h/day)	49,507 KJ
Cooling energy use of a typical R-2000 house in Ottawa	3,358,800 KJ
Cold storage satisfies the cooling energy use of R-2000 house by	35%
Number of days provided by the cold energy tank	23.5 days

4. Conclusions and outlook

The feasibility of using ice as a medium for cold storage in the Canadian climate was investigated. A cylindrical tank, two (2) meters in diameter and height, wrapped with conventional insulation to provide R-50 of insulation to the cold storage tank was considered. The tank contained ice at -25 ℃ during the winter time and it was assumed to be exposed to warm interior temperatures of 18 ℃ for six months. COMSOL Multiphysics was employed to examine the amount of heat that transferred to the system and whether the sensible and latent cold energy stored in the ice could withstand the heat transfer process. It was found that 40 % of the stored cold energy was lost during the six months leading to the hot season, and the remaining 60% could provide the cooling energy of an R-2000 residential 2-storey house located in Ottawa for almost 24 days based on the required daily cooling energy demand of the building. The melting process begins after 43 days and the high value of latent heat capacity of ice maintains the ice temperature at 0 ℃.

Further studies on the topic are required to examine other dimensions of the storage tank and its insulation values, geometry and boundary conditions. The charging feasibility of the cold storage considering the dimensions and heat losses of the heat exchanger located inside the storage tank as well as outdoors, should also be investigated. Additionally, the convective heat transfer of the liquid should be considered in the COMSOL model. The tank size can also be further optimized based on the cold energy demand according to the cooling load of either residential or commercial buildings. Also other geometries can be studied to determine the optimum geometry to minimize heat transfer, energy storage and the type and installation of different insulation products. Different boundary conditions such as an isothermal situation (e.g. should the tank be stored beneath ground level or on the roof of a building) can be considered to establish the most suitable location to install the tank.

Acknowledgements

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