2014

Annual Performance Of A Solar Assisted Heat Pump Using Ice Slurry As A Latent Storage Material

Justin Tamasauskas
Natural Resources Canada/CanmetENERGY, Canada, jtamasau@nrcan.gc.ca

Michel Poirier
Natural Resources Canada/CanmetENERGY, Canada, mpoirier@nrcan.gc.ca

Radu Zmeureanu
Department of Building, Civil and Environmental Engineering, Concordia University, Canada, zmeur@bcee.concordia.ca

Martin Kegel
Natural Resources Canada/CanmetENERGY, Canada, mkegel@nrcan.gc.ca

Roberto Sunye
Natural Resources Canada/CanmetENERGY, Canada, rsunye@nrcan.gc.ca

Annual Performance of a Solar Assisted Heat Pump Using Ice Slurry as a Latent Storage Material

Justin TAMASAUSKAS[1]*, Michel POIRIER[1], Radu ZMEUREANU[2], Martin KEGEL[1], Roberto SUNYE[1]

[1]CanmetENERGY, Natural Resources Canada,
Varennes, Quebec, Quebec
Tel.: 450-652-4822 E-mail:jtamasau@rncan-nrcan.gc.ca

[2]Concordia University, Department of Building, Civil and Environmental Engineering,
Montreal, Quebec, Canada

* Corresponding Author

ABSTRACT

This paper presents a novel solar heat pump system operating using ice slurry as a latent storage material. The new system builds upon previous ice-based thermal storage systems through the addition of a new cooling mode using the ice tank as a cool storage reservoir. Cooling operations are split between distinct day and night modes, allowing for improved heat pump performance and potential peak load reductions. The proposed system is integrated with a detailed single family housing model in Montreal, Toronto, and Vancouver to investigate the potential of the system throughout Canada. Results demonstrate annual energy savings over 50% in all three regions.

1. INTRODUCTION

The Canadian residential sector accounts for approximately 16% of all secondary energy use, with over 80% of this total directed towards space heating, cooling and domestic hot water (DHW) (OEE, 2010). Heat pumps represent a critical design element in the development of lower energy homes, as they facilitate the integration of renewable energy sources into the building. In particular, the combination of solar thermal and heat pump systems has demonstrated the potential to significantly reduce energy use in buildings (Freeman *et al.*, 1978). However, these systems face a number of challenges including appropriate storage capacity and degraded system performance during the winter months. This paper seeks to address some of these issues through a novel combination of solar thermal, heat pump, and ice based thermal storage technologies integrated into a single family Canadian home.

Latent storage has been previously recognized as an effective method of bridging the discrepancy in time between the thermal demands of the building and available solar radiation. In particular, the use of ice/water as a latent storage material offers a number of unique benefits, especially when combined with solar thermal and heat pump technologies. These benefits include:

i. High energy storage densities. The latent heat of ice (333 kJ/kg) is higher than for a number of other latent storage materials (Hawes *et al.*, 1993). This allows for higher energy storage densities, and smaller tank sizes.
ii. Stable heat pump source temperatures. The phase change temperature of ice places a lower limit on the source temperature for the heat pump evaporator. This allows for more stable heat pump operations, especially in comparison to an air-source unit
iii. Improved solar collector efficiencies. Using ice storage allows a cold temperature fluid to be circulated in the collector loop. Figure 1 demonstrates the improvement in solar collector efficiency offered by ice storage (Assumed ambient temperature -5°C). This is particularly attractive in heating dominated climates,

where ice storage allows for increased thermal gains and extended collector utilization periods during the winter months when building thermal demands are highest.

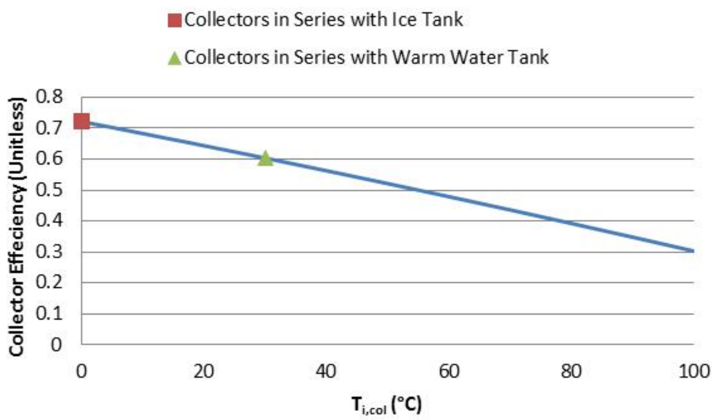

Figure 1: Impact of ice storage on solar collector efficiency

Combining ice storage with heat pump systems has demonstrated significant energy savings potential in heating mode. Trinkl *et al.* (2009) studied a solar assisted heat pump in which ice was generated using an in-tank heat exchanger, with the authors reporting a seasonal performance factor (SPF) of 4.6 for a high performance home in Germany. Tamasauskas *et al*. (2012a) examined a solar assisted heat pump using ice slurry (a mixture of small diameter ice particles and water) as a latent storage material. The seasonal system performance factor was 8.22 for a high performance home in Montreal, operating with a system sized to achieve the maximum possible energy savings.

The objective of this paper is to build upon the system presented by Tamasauskas *et al.* (2012a) via the addition of an innovative new cooling mode. First, the new proposed system is presented from an operations and control perspective. The overall modelling approach is then discussed for three distinct climate regions in Canada. Finally, the performance of the new heat pump system is examined on a system and component level to determine the energy savings potential of the new design.

2. SYSTEM DESCRIPTION

The proposed system combines solar thermal, heat pump, and ice thermal storage technologies. A system schematic is provided in Figure 2. Two distinct solar loops allow the system to operate in its most energy efficient configuration:

i. Solar Loop A. The collectors operate in series with the ice storage tank. This offers improved solar collector efficiencies, increased thermal gains and extended collector utilization periods in the winter months when solar radiation and ambient temperatures are lower.
ii. Solar Loop B. The collectors operate in series with the warm water tank. This minimizes heat pump operations when ambient conditions allow the collectors to directly meet building thermal demands.

During heating mode the heat pump links the ice tank with the warm water tank, upgrading the energy obtained from Solar Loop A for use within the building. The warm water tank itself acts as the primary heat distribution point for the home. Water is drawn from the top of the tank to serve a radiant floor network meeting the heating demands of the first and second floors. Domestic hot water (DHW) loads are partially met by passing incoming water through a vertical coiled heat exchanger located internal to the warm water tank. Additional heating capacity is provided to the building using electric water heaters in the radiant floor and DHW loops, and electric baseboards in the basement of the home.

The new proposed cooling mode builds on heating operations by using the ice tank as a source of cool thermal energy for a central cooling coil during the summer months. Cooling operations are divided into day (6 AM to 10 PM) and night (10 PM to 6 AM) modes of operation. During the day Solar Loop B is used to meet the DHW load of the building, with the heat pump operated only as needed to maintain a minimum temperature at the top of the warm tank. During the night, the heat pump is operated continuously in order to build up cooling capacity within the tank. Thermal energy from the heat pump condenser is rejected to either (i) the warm water tank provided that there is sufficient capacity, or (ii) the ambient air via a remote air-cooled condenser. This method of system operations offers several benefits including potential peak demand reductions related to the separation of cooling energy use and productions, improved heat pump performance resulting from cooler ambient air temperatures during the nighttime hours, and improved part load performance as the heat pump does not need to frequently cycle on/off throughout the day.

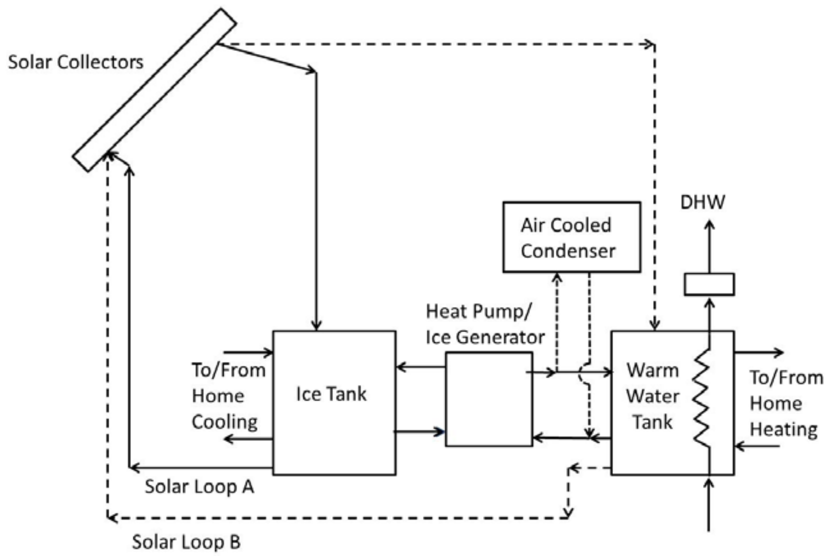

Figure 2: Schematic of Solar Heat Pump System

2.1 System Control

Overall control of the system can be examined in terms of the solar loop, heat pump loop, and heating/cooling distribution loops.

Solar Loop Control

Control of the solar loop is dependent on three separate control parameters:

i. Tank Fluid Temperatures. Both the ice tank and warm water tank have defined maximum fluid temperatures to avoid potential operational issues. The maximum ice tank temperature ($T_{Ice,Max}$) is set to 13°C (the maximum inlet temperature allowable to the heat pump evaporator), while the maximum temperature at the top of the warm water tank ($T_{WT,Max}$) is set at 60°C.
ii. Useful Solar Gains. Each solar loop is operated only when useful thermal gains are available from the solar collectors. In this study, a fluid temperature rise of 3°C is required for either solar loop to become operational.
iii. Ice Mass. The ice mass in the ice tank is used to select the appropriate solar loop. In this system, the maximum ice mass ($m_{ice,max}$) was set to 40% of the fluid mass of the ice tank, based on experimental results from the CanmetENERGY ice slurry test bench. In heating mode, the allowable ice mass is set at 50% of the ice capacity of the tank ($0.5*m_{ice,max}$). In cooling mode this value is set to 100% ($1*m_{ice,max}$). The overall objective of this rule is to allow the heat pump to operate when needed by storing sufficient thermal energy in the ice tank (When ice is at its maximum, no thermal energy is available in the ice tank and all heating and DHW must be met with auxiliary elements).

All three control signals are examined to determine which solar loop (if any) to operate. In heating mode, Solar Loop A operates when:

$$T_{fluid}<13°C,\ \Delta T_{col,LoopA}>3°C,\ m_{ice}\geq 0.5m_{ice,max}\ \underline{\text{or}}\ T_{WT}\geq 60°C \tag{1}$$

Loop B is then used when:

$$T_{WT}<60°C,\ \Delta T_{col,LoopB}>3°C,\ m_{ice}<0.5m_{ice,max} \tag{2}$$

In cooling mode, Loop A is used when:

$$T_{fluid}<13°C,\ \Delta T_{col,LoopA}>3°C,\ m_{ice}=m_{ice,max} \tag{3}$$

Loop B is then used when:

$$T_{WT}<60°C,\ \Delta T_{col,LoopB}>3°C,\ m_{ice}<m_{ice,max} \tag{4}$$

The collector flow rate is fixed and set proportional to the total collector area.

Heat Pump Loop Control

Heat pump loop operations are primarily based on the ice mass (m_{ice}) and fluid temperature at the top of the warm tank (T_{WT}). In heating mode, the heat pump is allowed to operate whenever (i) the ice mass is below its maximum value, and (ii) the temperature at the top of the warm tank is below 40°C. In cooling mode, these control signals are combined with an ice charging sequence. During the daytime, the heat pump operates in an identical manner to the heating mode in order to maintain a minimum 40°C temperature in the warm tank. At night time (10 PM to 6 AM), the heat pump operates continuously until the ice mass reaches 50% of the maximum ice capacity ($0.5*m_{ice,max}$). Heat is rejected to the warm tank if fluid temperatures are below 40°C, or to the ambient in all other cases.

Mathematically, the heat pump operates in heating when:

$$m_{ice}<m_{ice,max},\ T_{WT}<40°C \tag{5}$$

The heat pump then operates in cooling when:

$$m_{ice}<m_{ice,max},\ T_{WT}<40°C\ ,\ 6\text{ AM}<t<10\text{ PM}\quad \underline{\text{or}} \tag{6}$$

$$m_{ice}<0.5m_{ice,max},\ 10\text{ PM}\leq t\leq 6\text{ AM} \tag{7}$$

Heat/Cool Distribution Loop Control

Heating energy is supplied to the home via a radiant floor system. Radiant flooring is divided into first and second floor loops, each served with a dedicated variable speed pump. The flow rate through each pump is varied using a PID controller in order to maintain an operative temperature of 20°C in each zone. An outside air reset control is also incorporated to vary the supply fluid temperature according to the formula:

$$T_{\sup} = -0.3659T_{outdoor} + 31.59 \qquad\qquad 25°C \leq T_{\sup} \leq 40°C \tag{8}$$

Cooling is distributed to the home using a fan coil unit located in the stairwell of the home. An on/off control on both the fan and pump is used to maintain a setpoint of 23°C on the upper floor.

3. MODELING APPROACH

TRNSYS v.17 (Klein *et al.*, 2010) was selected to develop an energy model of the proposed system. The large library of solar thermal and heat pump components provided an important degree of flexibility in modelling the complex system presented in this paper. The developed energy model combined both standard and custom component models in order to properly assess the proposed system.

3.1 Housing Design

Housing models were developed for three distinct regions in Canada (Montreal, Toronto, and Vancouver) in order to assess the impact that various climates had on the performance of the system. The shell of each home was based on the Canadian Center for Housing Technology test home in Ottawa, Ontario (Swinton *et al.*, 2003). The home was built to represent a typical single family Canadian home, with a total floor area of 210 m^2 split between two above ground floors and a basement. This shell was then used in each region to define a net-zero ready home, which can be defined as a home which has the infrastructure and building envelope required to make the addition of onsite renewable energy generation cost effective (Parekh, 2010). For this study, a net zero ready home was defined as a home meeting ERS-86 on the EnerGuide Rating Scale (OEE, 2005). Further details on the development of each housing model can be found in Kegel *et al.* (2012). Table 1 summarizes key housing characteristics in each region.

Table 1: Key Housing Characteristics

	Montreal	**Toronto**	**Vancouver**
Roof RSI	8.93 m^2°C/W	8.93 m^2°C/W	8.93 m^2°C/W
Wall RSI	5.46 m^2°C/W	5.46 m^2°C/W	4.48 m^2°C/W
Basement Wall RSI	4.95 m^2°C/W	4.95 m^2°C/W	4.95 m^2°C/W
Basement Slab RSI	2.58 m^2°C/W	2.58 m^2°C/W	1.86 m^2°C/W
Window U-Value	1.35 m^2°C/W	1.35 m^2°C/W	1.35 m^2°C/W
Infiltration	0.75 ACH @ 50Pa	0.60 ACH @ 50Pa	1.0 ACH @ 50Pa

In order to properly assess the energy savings potential of the solar heat pump system, it was also important to define a base case mechanical system for each home. Table 2 provides details of each system by housing region. All mechanical systems were electrically based to easily facilitate the integration of onsite renewable energy generation (e.g. PV) in the future.

Table 2: Base Mechanical System Characteristics

	All Regions
Heating System	Electric Baseboard
Cooling System	Split System Rated COP = 3.45
Ventilation	HRV, 0.84 effectiveness
DHW	Electric Conventional Tank

3.2 Solar Collectors

Glazed flat plate collectors were selected for this system because of their improved efficiency at the low inlet collector temperatures anticipated (ASHRAE, 2006). The collector array was sized to meet the full south facing roof area, with a total array area of 27.9 m^2, an azimuth of 0°, and a slope angle of 40° (equal to the roof angle). Collector performance was calculated using a standard TRNSYS type based on the semi-empirical expression (Duffie and Beckman, 2006):

$$\eta = a_0 - a_1 \frac{\left(T_{i,col} - T_{outdoor}\right)}{G} - a_2 \frac{\left(T_{i,col} - T_{outdoor}\right)^2}{G} \quad (9)$$

Where a_0=0.740, a_1=3.76 (W/m^2·°C), and a_2=0.00356 W/(m^2·°C^2) based on manufacturer supplied data (Silicon Solar, 2013). The collector specific flow rate was set at 50 kg/(h·m^2), with each collector having an area of 1.99 m^2.

3.3 Ice Tank
A custom component model was developed to simulate the ice tank. The model assumed that the ice and water separated into two distinct control volumes at each time step. Energy balances were then applied to each control volume and solved simultaneously to determine the ice mass and tank fluid temperature at the end of a time step. Further details regarding the development and validation of this model can be found in Tamasauskas *et al.* (2012b). For this study, the total tank volume was set to 5 m^3 as a balance between storage capacity and space constraints within the home.

3.4 Warm Water Tank
The warm water tank was modelled as a stratified storage device, with the tank divided into four isothermal nodes as a balance between computational efficiency and simulation accuracy on a seasonal basis (Arias *et al.*, 2008). The total tank volume was set to 1.5 m^3 to provide a buffer between thermal supply and demand in heating mode.

3.5 Heat Pump/Ice Generator
The heat pump/ice generator was simulated using a water-water heat pump component model modified to account for the ice slurry generator. Performance was based on the ice slurry heat pump/generator operating at the CanmetENERGY facility. The unit had a rated COP of 3.6 at a design condition defined by an inlet evaporator fluid temperature of 0°C and an inlet condenser fluid temperature of 25°C.

4. Results and Discussion

Performance was examined on both a system and component level in order to fully assess the potential of the system in the Canadian climate.

4.1 System Performance
Table 3 compares the energy use of the base case and solar heat pump systems for each region.

Table 3: Energy Performance of Solar Heat Pump System by Region

	Montreal		Toronto		Vancouver	
	Base	**Ice Slurry HP**	**Base**	**Ice Slurry HP**	**Base**	**Ice Slurry HP**
Heat + DHW (kWh)	13042	4201	12099	3876	11010	3994
Cool (kWh)	819	1269	768	1211	586	971
Fans+Pumps (kWh)	1222	1371	1222	1360	1222	1316
Total Mechanical (kWh)	15082	6841	14089	6448	12818	6280

An analysis of the results highlights the strong energy savings potential of the solar heat pump system in all three regions. Total energy savings for the mechanical system (heating, cooling, DHW and distribution) range from a high of 55% in Montreal and Toronto to a low of 51% in Vancouver. A closer examination reveals the true strength of the system is in reducing the energy used for heating and DHW, with peak energy savings of up to 65% in Montreal and Toronto, and 61% in Vancouver. Implementation of the new cooling system results in an increase in cooling energy use relative to the base case, primarily due to the energy intensive nature of the ice generation process. Despite this increase, the shift of cooling use and production has important implications for peak demand reductions, and could potentially result in utility cost savings compared to the base case in regions where time of use rates are in effect. Future work will further examine this aspect of the design, in addition to reducing cooling energy use through new charging cycles and more advanced controls.

In order to more fully assess system performance, a seasonal performance factor (SPF) was calculated for each region and mode of operation. The SPF was defined as the thermal load (heating and DHW, cooling, or both) divided by the energy inputs required to meet this load (including the heat pump, pumps, fans, and auxiliary equipment). System SPFs are summarized in Table 4.

Table 4: SPF of Solar Heat Pump System by Region

	Montreal	Toronto	Vancouver
SPF Heat+ DHW	2.86	2.85	2.55
SPF Cool	2.57	2.58	2.63
SPF System	2.79	2.79	2.57

The solar heat pump system offers a significant improvement in SPF for all three regions in comparison to a base case of electrical heating and DHW (SPF=1). SPFs in heating mode are higher for Montreal and Toronto, primarily due to the greater abundance of solar radiation (and resulting collector gains). This trend is reversed in cooling mode, where the cooler ambient conditions in Vancouver during the summer months allow for improved heat pump performance during heat rejection. Overall system SPFs demonstrate the ability of the heat pump system to integrate renewable energy for heating, cooling, and DHW. While these values are lower than the SPF of 8.22 described in Tamasauskas *et al.* (2012a), it is important to note that system sizing is significantly different. The system presented in this paper is designed to be suitable for the average Canadian home, with a collector area 56% smaller and an ice tank volume 85% less than the previous design iteration.

4.2 Component Level Performance

The performance of individual components was also examined in order to fully assess system operations. For brevity within this paper, component performance is presented for the Montreal case only.

Ice Tank Performance

Figure 3 shows the variation in ice mass over the entire year. In general, the system appears to be sufficiently sized to make significant use of the ice capacity of the tank without frequently reaching the defined maximum ice mass. The ice capacity of the tank is used most extensively in December and January when available solar radiation is lower and the thermal demands of the home are highest. The maximum ice capacity is reached for several periods in January, limiting heat pump operations and necessitating the use of auxiliary heating elements.

The significant peaks in ice mass during the summer months relate to the charging cycle during cooling. In general, each charge to a 50% ice capacity satisfied the cooling load for several days. Further work will look at the impact of different charging levels and control strategies.

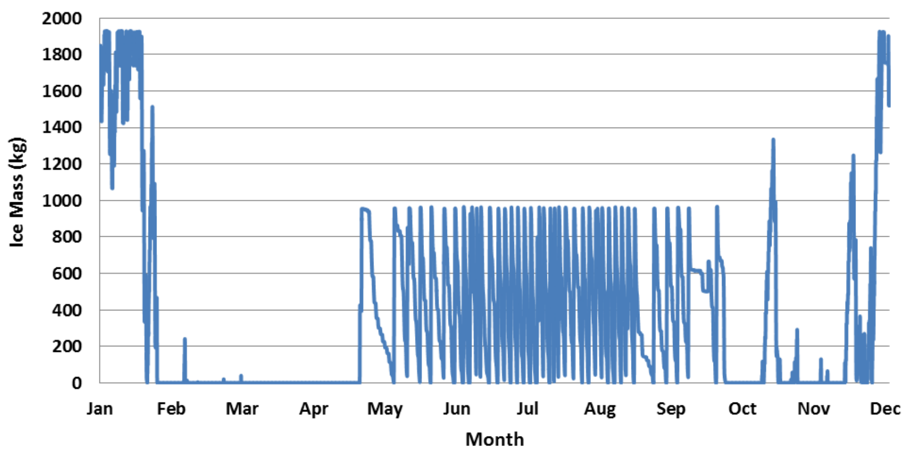

Figure 3: Ice Mass in Ice Tank for Montreal Region

Figure 4 shows the average fluid temperature in the ice tank by month. Tank temperatures stay relatively low throughout the early and middle portions of the winter, allowing for improved collector performance. The low temperatures from May to September confirm the ability of the ice tank to provide sufficient capacity to the cooling loop.

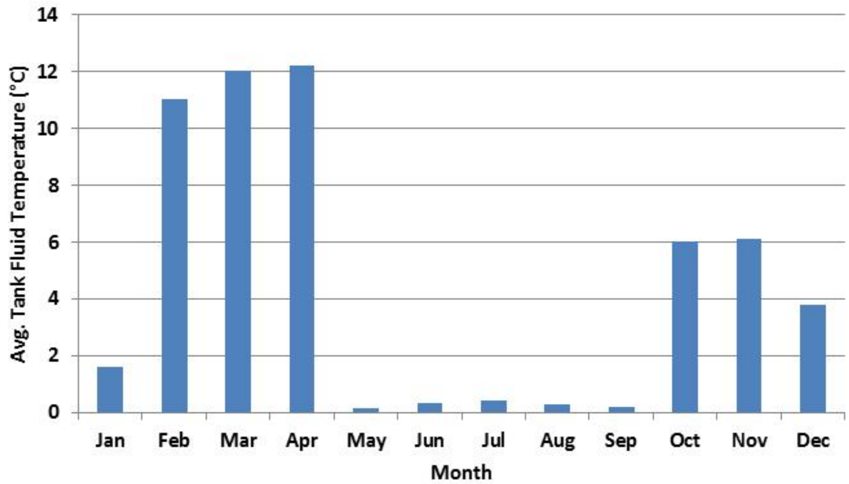

Figure 4: Fluid Temperatures in Ice Tank for Montreal Region

Solar Collector Performance

Figure 5 shows the efficiency of the solar collectors by month and on an annual basis. The impact of ice storage is clear, with Solar Loop A achieving a consistently higher solar collector efficiency throughout the year. Efficiencies are highest in October and November, when a combination of warmer outdoor temperatures and relatively cold fluid temperatures in the ice tank minimize collector losses to the ambient. The annual overall collector efficiency is 0.50, which represents a significant improvement over flat plate collectors operating in series with a warm water tank (Hugo, 2008).

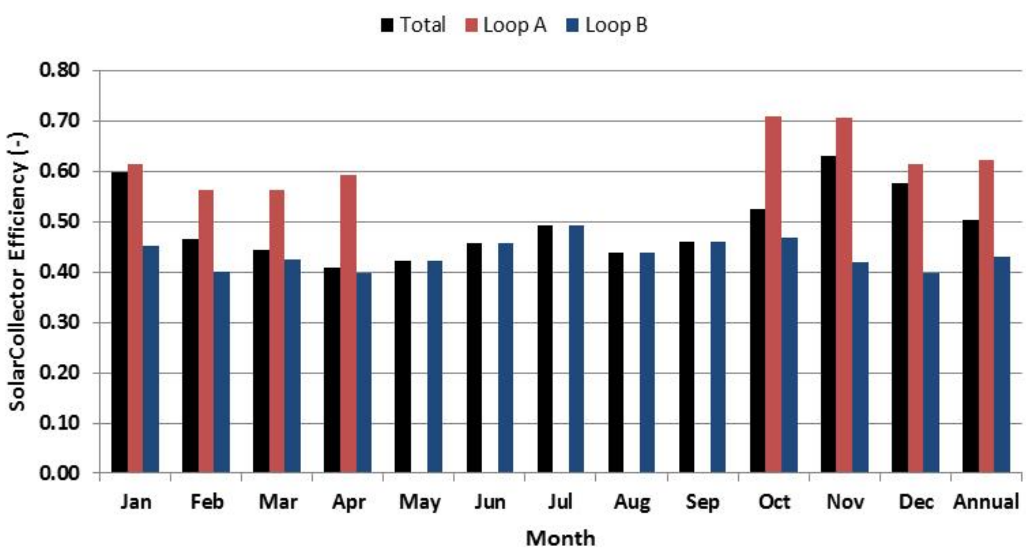

Figure 5: Performance of Solar Collectors in Montreal Region

5. CONCLUSIONS

A new solar assisted heat pump concept has been developed using ice slurry as a latent storage material. This work builds on previous studies by incorporating an innovative new cooling mode which uses the ice tank as a cool storage reservoir for the building. Cooling system operations are split between day and night modes, allowing for improved heat pump performance and potential peak load reductions.

The new heat pump system is combined with a detailed single family housing model in three different regions in Canada (Montreal, Toronto, and Vancouver). Results at the system level show strong energy savings potential in all regions, with an up to 65% reduction in heating and DHW energy use and an up to 55% reduction in the annual energy use for heating, cooling, and DHW. An examination of performance at a component level shows a significant use of ice storage capacity throughout the heating season. The impact of ice storage on solar collector performance is also clearly evident, with an estimated annual overall collector efficiency of 0.50.

NOMENCLATURE

a_0	optical efficiency	-
a_1	1st order efficiency	$W/m^2{}^\circ C$
a_2	2nd order efficiency	$W/m^2{}^\circ C^2$
DHW	domestic hot water	
G	Solar radiation	W/m^2
m	mass	kg
SPF	Seasonal performance factor	-
T	temperature	Celsius
t	time	h
Δ	Difference	-
η	Collector efficiency	-

Subscript

col	solar collector
fluid	fluid in ice tank
i	inlet
ice	ice in ice tank
LoopA	solar Loop A
LoopB	solar Loop B
max	maximum
outdoor	outdoor
sup	radiant floor supply
WT	warm tank

REFERENCES

Arias, D., McMahan, A., Klein, S., 2008. Sensitivity of long-term performance simulations of solar energy systems to the degree of stratification in the thermal storage unit. *Int. J. Energ. Res*, vol. 32, no. 3: p. 242-254.

ASHRAE, 2006, ASHRAE GreenGuide (2nd ed.), Elsevier, New York, 416 p.

Duffie, J., Beckman, W., 2006, *Solar Engineering of Thermal Process (3rd ed.)*, John Wiley and Sons, New York, 919 p.

Freeman, T.L., Mitchell, J.W., Audit, T.E., 1978, Performance of combined solar-heat pump systems, *Sol. Energy*, vol. 22, no. 2, p. 125-135.

Hawes, D.W., Feldman, D., Banu, D., 1993. Latent heat storage in building materials. *Energ. Buildings*, vol. 20, no. 1: p. 77-86.

Hugo, A., 2008, *Computer Simulation and Life Cycle Analysis of a Seasonal Thermal Storage System in a Residential Building*, M.A.Sc thesis, Concordia University, Montreal, 174 p.

Kegel, M., Sunye, R., Tamasauskas, J., 2012, Lifecycle Cost Comparison and Optimisation of Different Heat Pump Systems in the Canadian Climate, *Proceedings of eSim 2012*, IBPSA Canada: p.492-505.

Klein S. A., et al., 2010, *TRNSYS 17 – A TRaNsient SYstem Simulation program user manual*, University of Wisconsin-Madison Solar Energy Laboratory, Madison, 88 p.

Office of Energy Efficiency (OEE), 2005, *EnerGuide for New Houses: Administrative and Technical Procedures*, NRCan, Ottawa, 64 p.

Office of Energy Efficiency (OEE), 2010, *Energy efficiency trends in Canada 1990 to 2007*, NRCan, Ottawa, 54 p.

Parekh, A, 2010, *Path to Net Zero Energy Homes*, NRCan, Ottawa <http://www.mb-bec.ca> [Accessed Dec. 2011]

Silicon Solar, 2010, *TitanPowerPlus SU-2 Solar Flat Plate Collector*, <http://www.siliconsolar.com > [Accessed Mar. 2013].

Swinton, M.C., Entchev, E., Szadkowski, F., Marchand, R., 2003, *Benchmarking twin houses and assessment of the energy performance of two gas combo heating systems,* Canadian Centre for Housing Tech., Ottawa, 18 p.

Tamasauskas, J., Poirier, M., Zmeureanu, R., Sunye, R., 2012a, Modeling and optimization of a solar assisted heat pump using ice slurry as a latent storage material, *Sol. Energy*, vol. 86, no. 11: p. 3316-3325.

Tamasauskas, J., Poirier, M., Zmeureanu, R., Sunye, R., 2012b, Development of a mathematical model for the simulation of a non-agitated ice slurry storage tank, *Proceedings of eSim 2012*, IBPSA Canada: p. 380-392.

Trinkl, C., Zorner, W., Hanby, V., 2009, Simulation study on a Domestic Solar/Heat Pump Heating System Incorporating Latent and Stratified Thermal Storage, *J. Sol. Energ.-T. ASME*, vol. 131, no.4: p. 041008-1 to 041008-8.

ACKNOWLEDGEMENT

The authors acknowledge the financial support provided by Natural Resources Canada through the Program of Energy Research and Development (PERD) built environment heat pumps program.