Solar-Assisted Space Heating and Small Pond-Assisted Space Cooling of a Highly Insulated Energy Efficient House

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Abstract: For three weeks in October 2009, the U.S. Department of Energy hosted the Solar Decathlon Competition in which 20 teams of college and university students competed to design, build, and operate their own version of a solar-powered house. Team North's mission was to deliver North House, a compelling, marketable solar powered home for people with active lifestyles, while building Canada's next generation of leaders in sustainable engineering, business and design. This paper deals with a solar-assisted space heating system that was studied as a potential design for the competition. Among several other conclusions, it was found that using a solar-assisted in-floor heating system can decrease the energy consumption to only 8% of the case without the in-floor loop.

Key words: Net-zero energy house, TRNSYS software, energy modeling.

1. Introduction

In October 2009, Team North, a team consisting of students from three Canadian universities, headed to compete in the 2009 Solar Decathlon, which was hosted by the U.S. DOE (Department of Energy). The Solar Decathlon is a biennial competition where 20 teams, consisting of college and university students, will design, build and operate their versions of the most attractive, effective, and energy-efficient solar powered house. The event is a public event where thousands of people are attracted to the National Mall in Washington, DC [1]. Team North gathered students from the University of Waterloo, Ryerson University and Simon Fraser University together to design and deliver a compelling, marketable solar powered home for mobile, sustainable lifestyles.

Radiant systems are widely used in residential building applications. However, air based systems are still the more popular option in North America. By analyzing the performance of both air based and radiant heating systems involving solar collectors, radiant floor systems were able to use more of the available solar energy to assist in meeting space heating demands [2]. The incorporation of solar thermal energy in the CIESOL (Center de investigacion de la energia solar) building of the University of Almeria, Spain reduced the energy consumption of the air-conditioning system and resulted in an annual reduction of 13 tons of CO₂ emissions [3]. In their proposed study, real data of an existing building were used to demonstrate the benefits of properly matching the passive and active solar techniques. The designed system was able to provide sufficient energy to supply an absorption machine during the summer, and sufficient to cover the whole heating demand [3].

Several comparisons of different solar collector types and their mounting orientations were considered

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for the solar-assisted space heating system. The two solar collector types that were studied were flat plate collectors and evacuated tube collectors. Sensitivity analyses were conducted to determine the optimal installation of the solar thermal system to maximize the solar thermal capture/utilization so as to reduce the overall space heating energy consumption of the house. The fluctuation of consumption for an electric heating element, as auxiliary heating, was analyzed according to the size of tanks, as well as according to the variation of the flow rate and the position of the auxiliary electrical backup heater in the tanks.

As per cooling demand of the house, a small pond connected to the in-floor slab of North House was implemented in TRNSYS [4] software. Early studies for the climate of Shiraz, Iran indicated that utilizing a roof pond can reduce the cooling demand by 79.0% and 58.1% for the cases of shaded-pond, and un-shaded pond respectively [5]. For the climate of Baghdad, Iraq, integrating an evaporative cooling system using a roof pond with the help of a mechanical ventilator for real-life conditions where the ratio of the roof area to exterior walls is reasonably large, the cooling load could be reduced by around 29% [6]. An alternative study showed that in an actual building the drop in cooling load for a single room is between 28% and 30% [7]. Studies done in various climates indicated that the pond in a shade (e.g., by a tree) works better than the shaded-pond (e.g., under the deck) [8, 9]. The reason given is that in the first case the pond water exchanges thermal radiation with the sky at night, whereas in the shaded pond, which is shaded both in day time and at night, water exchanges heat with the ambient temperature in the shade. The cold sky as a heat sink for radiating bodies was considered as a potential alternative to conventional cooling techniques [10, 11].

From previous literature it can be seen that it is beneficial to integrate a cooling pond to the overall system. The analyses were performed assuming the pond orientation to be on the north side of the house.

2. North House Building Envelope

The house was 62 m² in area and designed as a highly insulated and airtight house. The wall system had a nominal RSI-11 (R-64), and an actual RSI-8 (R-47) with studs. The floor had a little less insulation, with a nominal RSI-9 (R-51), and RSI-6 (R-36) with joists respectively, since it did not have any insulation outside of the sandwich panel. The details of the structure and envelope of the house can be found in the article by Lee et al. [12].

A highly IGU (insulated quad-layered krypton-filled glazing unit) which was able to harness passive solar heat from the sun with its relatively low center of glass U-value of 0.474 W/m²K (RSI-2.1 or R-12) yet relatively high SHGC (solar heat gain coefficient) of 0.404. The overall glazing unit insulation value was R-8. The House incorporated 90% glazing on the south façade and 40% on east and west.

One significant problem with buildings with highly glazed façades is overheating due to excessive solar gains. Therefore, an automated dynamic shading system was considered in order to block unwanted solar gains which helped to significantly reduce the cooling load of the house. The control of the dynamic shading system was coupled with the house's HVAC control system to maintain a high level of thermal comfort while using minimal energy.

Fig. 1 shows North House during the 2009 Solar Decathlon completion in Washington, DC.

3. Description of the Overall System

The mechanical system was described by separating it into four different loops. The energy acquisition loop, the heat exchanger loop, the in-floor loop, and the domestic hot water loop. The system is shown in Fig. 2. The first loop was the energy absorbing and collecting loop. It was made up of an array of solar collectors of 9 m² total surface area associated with a heat exchanger and with a preheat tank of 750 L of storage capacity. The collected solar energy was transferred to the water in the storage tank via the second loop. The water in the

Fig. 1 North House, Solar Decathlon Competition, Washington, DC.

Fig. 2 The schematic of the overall mechanical system design.

second loop was circulated through the tank and the heat exchanger. The third loop was made up of a heat exchanger coil inside the preheat tank connected to in-floor radiant loops. In order to study the effect of the in-floor heating system more precisely, in-floor heating was modeled for all the zones in the house, including washroom and change room. Also a one-ton ASHP (air source heat pump) acted as the main back-up heating for this system. The fourth loop was used for production of hot water. It was made up of an auxiliary tank of 300 L equipped with two auxiliary heaters that could provide 2 kW of heating each. The temperature was maintained at 55°C or above to be able to have the possibility of taking three showers of 15min length each, consecutively in the morning, as required by the competition rules [1]. A waste heat recovery heat exchanger was placed at the drain to recover part of the energy back to the inlet city tap water before going into the preheat hot water tank.

In this study the focus was mainly on the first and second loops, but the third loop was simulated as well to allow the model to be more similar to how this system would perform in the competition.

The analyses for the cooling application were performed assuming the pond orientation to be on the north side of the house. The pond dimensions were defined to be 2.2 m wide, 0.3 m deep and a length of 12.3 m due to the land restriction. To utilize the pond as a heat sink, the pond was equipped with a single-pass coil (one loop) with the outer diameter of 0.016 m inside the pond, and it was also connected to the in-floor radiant loops. Sensitivity analyses were conducted to determine the reasonable length of spool, the diameter of the pipe and various flow rates. It was designed to be covered during the day and be exposed to the sky at night.

A proportional controller was integrated in the simulation model to adjust the external shading to manage solar gains and keep the inside temperature between 22°C to 24°C.

4. Heating Simulation Scenarios

A comparison between flat plate and evacuated tube collectors (vertical, horizontal and 10-degree tilt angle) was reported as the first part of the study. The installation was studied based on the preheat tank average temperature. For each case three different flow rates through the collector were considered, namely 0.3, 0.5 and 0.8 L/s. For the second part of the study, the main focus was on the performance of the evacuated tubes integrated in the overall system.

For the evacuated tube collector, the simulations were run for:

- 550, 650 and 750 L water preheat tank sizes;
- L/s and 0.2 L/s in-floor loop flow rate;
- with/without in-floor system.

The installation was optimized to reduce the overall energy consumption which was mainly by the heat pump. The simulation time step was one minute and the simulation was run over one year (8,760 hr) of operation. Smaller simulation time steps increased the simulation time significantly while there was no additional information provided. On the other hand, the ASHP module did not produce consistent results when the time step was larger than 2.5 minutes due to the part load performance issues. The selected tilt of 10 degrees was to conform to the competition rules regarding the allowed total height of the structure.

The electricity consumption of the heat pump was analyzed while the size of the tanks was changed, as well as when there was a change in flow rate. Two flow rates of 0.1 and 0.2 L/s were used in the simulations. These flow rates were determined based on the preliminary test runs to determine an optimum flow rate range that minimized the pressure drop while yielding a good heat transfer coefficient. Also a flow rate of zero was simulated to allow for a comparison of heat pump consumption in the various cases. The zero flow rate to the in-floor loop represented the case where there was no in-floor heating.

5. Cooling Simulation Scenarios

A comparison between various coil diameters and tube lengths were performed while different flow rates were taken into consideration. Simulations were run for the cooling season, defined to start from May 1 to October 15, when the house needed to be cooled down. Therefore, the simulation time period was considered to be from 2,880 hr to 7,032 hr. The purpose of the study was to reduce the overall energy consumption by identifying the best case. Simulations were conducted for:

(1) different coil tube diameters:

- 0.016 m OD, 0.014 m ID;
- 0.022 m OD, 0.0199 m ID;
- 0.029 m OD, 0.027 m ID;

(2) different tube (spool) lengths:

- 5 m;
- 10 m;
- 15 m;

(3) different flow rates:

- 0.14 L/s;
- 0.28 L/s;
- 0.56 L/s;
- 0.70 L/s.

The results for each case were compared with the house with the pond not being integrated in the overall system. The pressure drop in the pipe was calculated per scenario. Furthermore the electricity consumption of the pump located in the pond loop and the heat pump were simulated to allow the comparison of the various cases. Fig. 3 shows the TRNSYS model layout of the combined system.

Fig. 3 TRNSYS model layout of the proposed system.

6. Results

6.1 Heating Season

The results are presented in Figs. 4 and 5 for the heating season. Based on the obtained results, evacuated tube collectors maintained the highest temperature inside the preheat tank. The study of different types of collectors, evacuated tube and flat plate, for the city of Toronto, confirmed that utilizing evacuated tubes results in a higher preheat tank temperature leading to a reduction in the heat pump consumption.

From the analyses of all the scenarios studied in the second part of study where the performance of evacuated tube collectors was investigated, it was seen that the house temperatures were maintained above the required temperature of 22°C for the heating season. This allowed the team to confirm that the annual heating demand was met by all the scenarios for both Toronto and Baltimore. The temperature of the preheat tank ranges from 20°C to 70°C over the year. The useful energy gained from solar thermal collectors was around 3700 kWh/year for Toronto. Using these results the analysis was carried on with utilizing only

evacuated tube collectors. Although the difference was small, a collector loop flow rate of 0.3 L/s was found to offer higher maximum temperature. Based on this and the fact that low flow rate requires less pumping power, it was concluded that the optimum flow rate through the collector was 0.3 L/s. All subsequent analyses were performed at a collector-loop flow rate of 0.3 L/s.

Figs. 6 and 7 show the varying heat pump consumption for different tank sizes and flow rates with the vacuum tube collector system, consecutively. The study was performed for Toronto having heating degree days based on 65°F (18.3°C) equal to 7,306 and cooling degree days based on 50°F (10°C) equal to 2,370 (HDD65 = 7,306, CDD50 = 2,370) and Baltimore (HDD65 = 4,707, CDD50 = 3,709).

From these results, the scenario where the flow rate was at 0.2 L/s and the preheat tank size was 750 L indicated the lowest energy consumption of the ASHP for both Baltimore and Toronto. It was worth noting that for Baltimore, if the flow rate to the in-floor slab was low (0.1 L/s), increasing tank size would not decrease consumption, whereas for Toronto, regardless of flow rate, a larger storage tank proved to be better.

Fig. 4 Comparison between horizontal flat-plate and 20-degree tilted vacuum tube collectors based on the preheat tank temperature for Toronto.

Fig. 5 Comparison between vertical flat-plate and vertical vacuum tube collectors based on the preheat tank temperature for Toronto.

Fig. 6 Tank size vs. ASHP consumption for different flow rates (evacuated tube collector system, Toronto, ON).

Fig. 7 Tank size vs. ASHP consumptions for different flow rates (evacuated tube collector system, Baltimore, MD).

Without the in-floor heating system, the ASHP consumption increased drastically. The simulations showed that for Baltimore, the in-floor heating system was capable of meeting most of the annual heating demand, and in Toronto, the ASHP was required, but consumption of the ASHP was reduced to 8% of consumption required if only the ASHP was utilized.

Utilizing evacuated tube collectors, Tables 1 and 2 show the change in heat pump consumption along with the consumption of the heat pump when the in-floor heating was not utilized. Zhai et al. [13] calculated an average solar COP (coefficient of performance) of 0.4 for their solar-only in-floor heating system. The daily solar COP in their study was defined as in Eq. (1):

$$COP_{solar} = \frac{\int_{D_2}^2 Q_h dt}{(A_{hp} + A_u) \int_{D_3}^3 I dt} \quad (1)$$

where, D_2 is the duration of floor heating system operation in seconds, D_3 is the duration of sunshine in seconds, Q_h is the amount of heat delivered in kW, A_{hp}

is the heat-pipe evacuated tube collector area in m^2 , A_u is the U-type evacuated tube solar collector area in m^2 , and I is the solar radiation intensity in W/m [13].

6.2 Cooling Season

From the analyses, it was seen that the lowest pressure drop could be achieved by having the flow rate of 500 kg/hr which was the lowest flow rate used in the simulations as expected. The outside coil tube diameter of 0.029 m and inside of 0.027 m for the case of Baltimore and 0.022 m, 0.0199 m for Toronto were found to be more efficient when having flow rate of 500 kg/hr. All simulations were performed considering that the house temperature was maintained below the required temperature of 24°C and above 22°C. Comparing the scenarios between different tube lengths and diameters resulted in the minimum total pump consumption of 211 kWh for Toronto and 271 kWh for Baltimore as shown in Table 3.

Table 1 Toronto evacuated tube simulation results with different tank sizes and flow rates to compare ASHP consumption.

Toronto			Flow rate into the in-floor loop	Heat pump consumption
Collector	In-floor	Tank		
		(L)	(L/s)	(kWh)
Evacuated tube collector 9 m ²	With	550	0.1	325.3
Tilt 10 degree			0.2	336.0
Orientation: fixed south		650	0.1	315.8
0.3 L/s flow rate			0.2	302.9
		750	0.1	253.6
			0.2	200.9
		Without flow	-	2417.6

Table 2 Baltimore evacuated tube simulation results with different tank sizes and flow rates to compare ASHP consumption.

Baltimore			Flow rate into the in-floor loop	Heat pump consumption
Collector	In-floor	Tank		
		(L)	(L/s)	(kWh)
Evacuated tube collector 9 m ²	With	550	0.1	8.5
Tilt 10 degree			0.2	10.5
Orientation: fixed south		650	0.1	9.1
0.3 L/s flow rate			0.2	8.7
		750	0.1	9.0
			0.2	6.3
	Without flow		-	1453.0

Table 3 Cooling pond results from different scenarios.

	Coil tube diameter (m)	Tube length (m)	Flow rate (L/s)	Pressure drop (m)	ASHP consumption (kWh)
Toronto	0.022 OD, 0.0199 ID	15	0.14	0.22	211
Baltimore	0.029 OD, 0.027 ID	10	0.14	0.033	271

A study of the pond pump consumption along with ASHP (air source heat pump) consumption over the cooling period indicated the pond cooling capacity met the cooling demand of the house. For the case of Baltimore the heat pump consumption is more. It could be explained by studying the outside temperature profile of both cities since the cooling capacity of the pond decreases with increasing ambient temperature and relative humidity. Fig. 8 shows the temperature profile of the two cities. While there is no dramatic difference between the humidity profiles of the two mentioned cities, Fig. 8 shows that Toronto is on average roughly 5°C colder than Baltimore.

As indicated in Figs. 9 and 10, the house temperature remained below 24°C during the cooling season. It is important to reiterate the effect of the smart shading in controlling the temperature and lowering the cooling load significantly. The left axis indicates the house temperature (°C) and the right axis shows the cooling power demand (kW). The green-colored plots summarize the cooling demands of 1,055 kWh for Toronto and 4,062 kWh for Baltimore. Several occasions were detected for Toronto with zero cooling demand.

The study of the house temperature for the case without the pond identified the time when cooling was not yet turned on but the house required to be cooled down. In order to measure the extra cooling power, simulations were conducted having the time extended from 2,000 hr to 8,000 hr. The data gathered revealed a need for 835.37 kWh and 647.96 kWh of extra cooling demand for the city of Toronto and Baltimore respectively.

Table 4 summarizes the ASHP consumption for the two cities for the cases with and without the pond. The combination of the cooling pond and the smart shading has shown to maintain the temperature of the house below the set temperature of 24°C. When comparing the results for the cases without the pond, the heat pump consumption increases drastically for the city of Baltimore; whereas, the simulation carried out for Toronto showed a minor increase in the ASHP consumption. According to the obtained results indicated in Table 4, it was more beneficial to use the cooling pond for the city of Baltimore. The total energy consumption of 271 kWh for the case with the pond was estimated to be half of the case without the

Fig. 8 Outside temperature profile of Baltimore and Toronto.

Fig. 9 House temperature and ASHP demand profiles for Toronto.

Fig. 10 House temperature and ASHP demand profiles for Baltimore.

Table 4 Comparison between ASHP consumption and the energy consumption of pond's pump.

	With pond		Without pond
	HP consumption in cooling mode (kWh)	Pond pump consumption (kWh)	HP consumption in cooling mode (kWh)
Toronto	0	211	67
Baltimore	0	271	406

pond, which was around 406 kWh. In Toronto, the heat pump consumption was calculated to be 67 kWh, which was less than the pond pump consumption of 211 kWh.

7. Conclusions

From the heating season simulations, it was concluded that it was more beneficial to use the

evacuated tube collectors over the flat plate collectors. The calculations demonstrated that with the higher flow rate of 0.2 L/s, the 750 L tank was the best choice in terms of minimizing heat pump consumption. In Toronto, by using solar-assisted in-floor heating, the ASHP's energy consumption can be reduced to 8% of the consumption for the case when the in-floor system is not utilized. Furthermore, the solar-assisted in-floor system is able to meet almost all of the heating demand in Baltimore, and only about 6 kWh of electricity is required by the ASHP to meet the demand for the entire heating season. Although the solar assisted in-floor system met most of the heating demand for both Toronto and Baltimore, the use of heat pump was still necessary when the weather was at an extreme temperature (cold or hot temperature) or when no solar energy is available.

As per cooling season simulations, it was concluded that it was more beneficial to use the cooling pond for the city of Baltimore. For the city of Toronto, utilizing the pond may not be as beneficial as the case of Baltimore. Furthermore, more analyses were conducted to determine the appropriate dimension for the pipe and the flow rate in order to maximize the heat dissipation through the pipe. For each demonstration, the pressure drop was calculated. For the city of Baltimore a pipe with 0.028 m diameter, spool length of 10m and a flow rate of 500 kg/hr were used. For Toronto the best case was the diameter of 0.022 m, a length of 15 m and a flow rate of 500 kg/hr. Each configuration results in a pressure drop of 0.033 mH₂O and 0.22 mH₂O while having the minimum energy consumption of 211 kWh and 271 kWh for the case of Toronto and Baltimore, respectively.

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