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SOLAR-ASSISTED SPACE HEATING 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 an a potential design for the competition. It shows which component must be used to have a better efficiency by comparing several simulation models used to improve the electrical consumption as well as comfort in the building.

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. Department of Energy (DOE). The Solar Decathlon is a byannual 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 widely public event where thousands of people are attracted to the National Mall in Washington D.C. (U.S. DOE, 2009)

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 covering space heating demands (Haddad et al., 2007). The incorporation of solar thermal energy in the CIESOL[1] building reduced the energy consumption of the air-conditioning system and resulted in an annual reduction of 13 tons of CO_2 emissions (Rosiek and Battlles, 2009). 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 (Rosiek and Battlles, 2009).

Several comparisons of different solar collector types and their mounting orientations were considered for the solar-assisted space heating system. The two solar collector types that were studied were flat plate collectors and vacuum 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.

The results of the installation when it is connected to the house are presented for the cities of Toronto and Baltimore, which is the closest available weather data to Washington, D.C. in TRNSYS 16(Klein et al. 2004)

2. THE SMALL POND SYSTEM DESCRIPTION

2.1 Description of the Overall System

The mechanical system was described by separating it into three different loops: the energy acquisition loop, the heat exchanger loop, and the domestic hot water loop.

The first loop was the energy absorbing and collecting loop. It was made up of an array of solar collectors of 9m² total surface area associated with a heat exchanger and with a preheat tank of 750L of storage capacity. The second loop was made up of a heat exchanger inside the preheat tank connected to infloor radiant loops. In order to study the effect of the infloor heating system more precisely, infloor heating was modeled for all the zones in the house, including washroom and change room. Also a one-ton air source heat pump (ASHP) acted as the main back-up heating for this system.

The third loop was used for the production of hot water. It was made up of an auxiliary tank of 300L equipped with two auxiliary heaters that could provide 2kW of heating each. The temperature was maintained at 50ºC 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. 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 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. Figure 1 illustrates the overall schematic of the system.

[1] CIESOL (CENTER DE INVESTIGACION DE LA ENERGIA SOLAR) Center of Investigation of the Solar Energy, University of Almeria, Spain

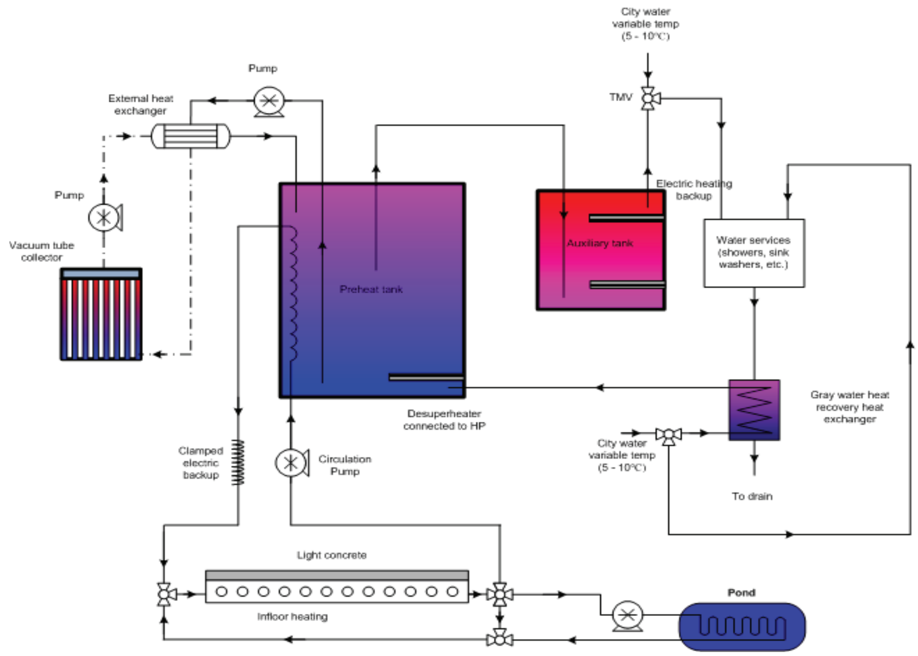

Figure 1: The schematic of the overall design

2. METHODOLOGY

TRNSYS is a simulation environment for the simulation of systems, including multi-zone buildings. It is used for validating new energy concepts, from simple domestic hot water systems to the design and simulation of buildings and their equipment. TRNSYS is also able to simulate the control strategies, occupant behavior, alternative energy systems (wind, solar, photovoltaic, hydrogen systems) that can be added to the buildings (Klein et al. 2004).

The house was designed as a highly insulated and airtight house that minimizes heating and cooling loads while making the most of passive solar gain through its large glazing area. The details of the structure and envelope of the house can be found in the paper by Lee *et al.,* (2010). The wall system had a nominal RSI of 11 (R-64), and an actual RSI of 8 (R-47) with studs. The floor had a little less insulation, with a nominal RSI of 9 (R-51), and 6 (R-36) with the curtain wall facades featuring a quadruple pane glazing unit at about R-12(RSI 2.1). The quadruple-glazed windows were located on the south, east, and west sides. 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.

2.1 Simulation Scenarios

A comparison between flat plate and vacuum tube collectors was reported based on the heat pump consumption. Then, the main focus was the performance of the vacuum tubes integrated in the overall system. The installation was optimized to reduce the overall energy consumption, which was mainly by the heat pump.

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

- 550, 650 and 750L water preheat tank
- 0.1L/s and 0.2L/s flow rate
- With/Without infloor 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. 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. 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 preliminary test runs to find 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 infloor loop represented the case that there was no infloor heating. Figure 2 shows the layout and the different components of the simulation model created in TRNSYS.

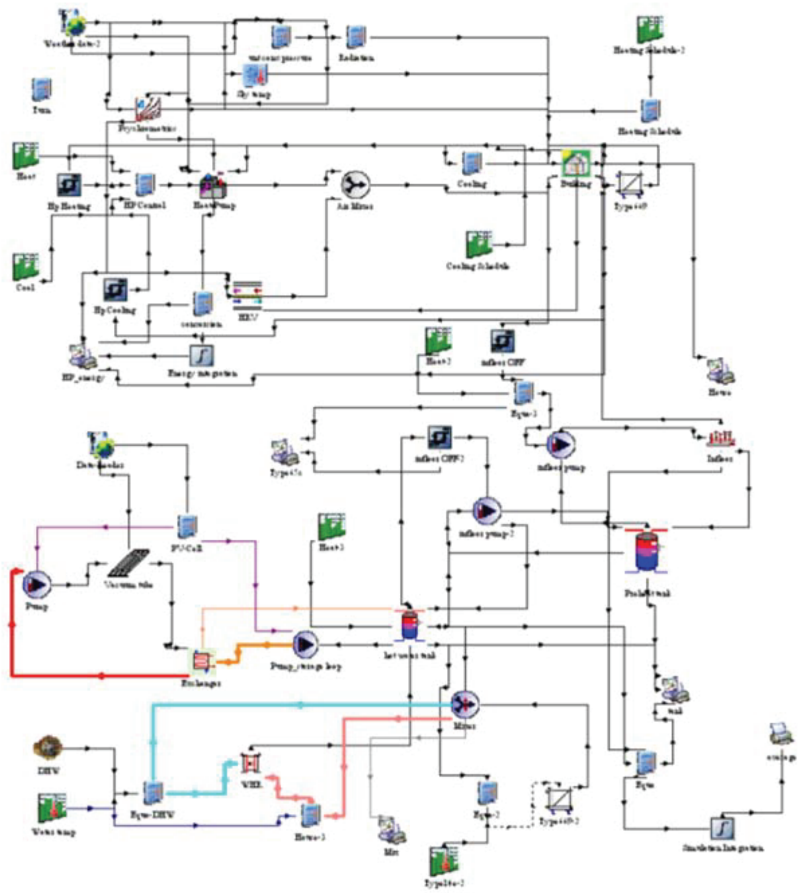

Figure 2: Design layout in TRNSYS simulation studio

3. RESULTS

The study of different types of collectors, vacuum tube and flat plate, for the city of Toronto, confirmed that utilizing vacuum tubes results in a higher preheat tank temperature leading to a reduction in the heat pump power consumption.

From the analyses of all the scenarios, 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 to 70˚C over the year. Useful energy gained from solar thermal collectors was around 3700kWh/year for Toronto.

Comparing the scenarios between the flat plate collectors and vacuum tube collectors, the vacuum tube collectors showed better results. There was a higher reduction in the one-ton ASHP's energy consumption. Figures 3 and 4 show the varying heat pump consumption for different tank sizes and flow rates with the vacuum tube collector system, consecutively.

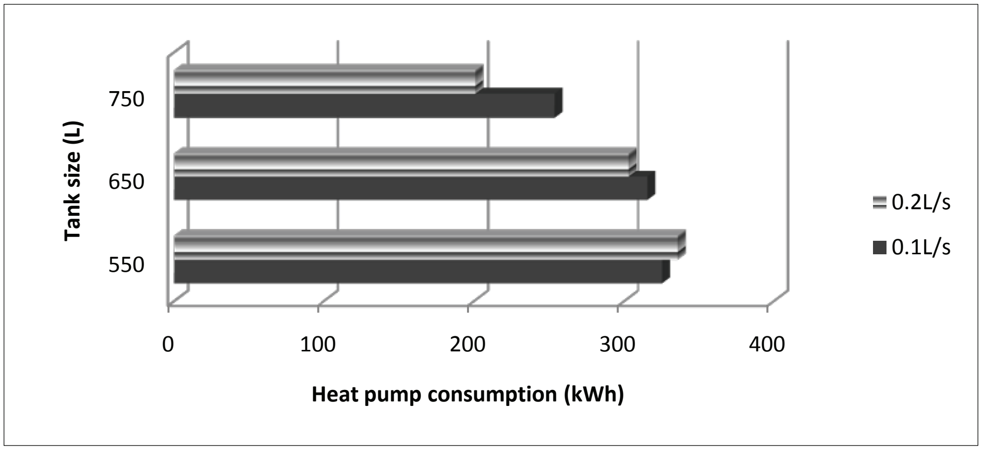

Figure 3: Various tank sizes vs. ASHP consumption for different flow rates (vacuum tube system, Toronto)

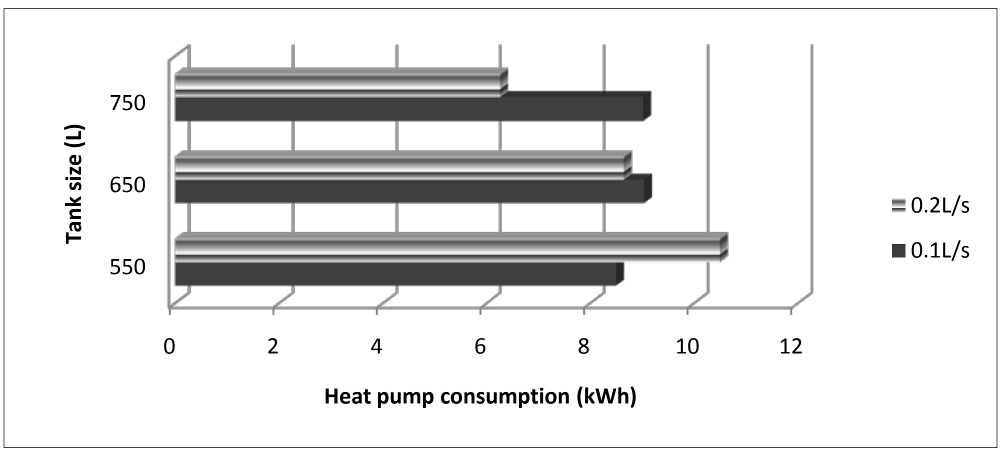

Figure 4: Various tank sizes vs. ASHP consumptions for different flow rates (vacuum tube system, Baltimore)

From these results, the scenario where the flow rate was at 0.2L/s and the preheat tank size was 750L 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 infloor slab was low (0.1L/s), increasing tank size would not decrease consumption, whereas for Toronto, regardless of flow rate, a larger storage tank proved to be better.

Without the infloor heating system, the ASHP consumption increased drastically. The simulations showed that for Baltimore, the infloor 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.

Figure 5 indicates that the heat pump consumption increased when the vacuum tube system was replaced with the flat plate.

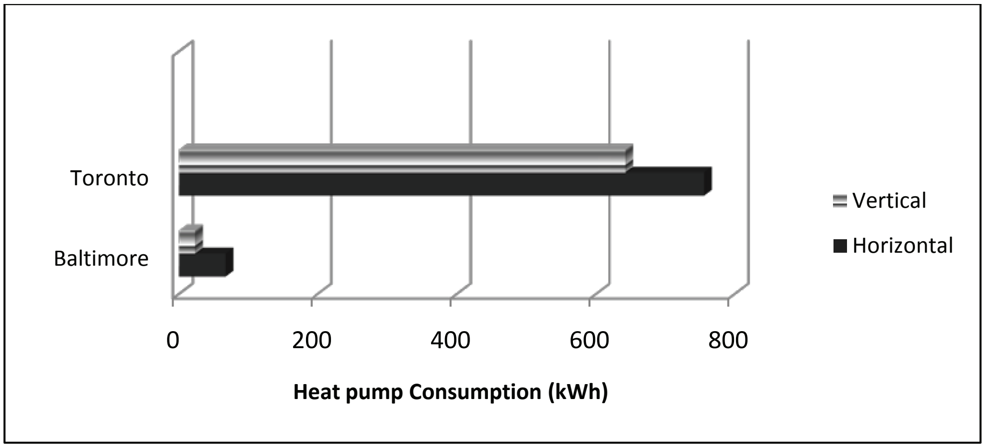

Figure 5: Comparison of the heat pump consumption for different cities when flat plate was utilized

Utilizing Vacuum Tube Collectors (VTC), Tables 1 and 2 show the change in heat pump consumption along with the consumption of the heat pump when the infloor heating was not utilized.

Table 1: Comparison of HP consumption for different tank sizes and flow rates when VTC was utilized (Toronto)

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

Table 2: Comparison of HP consumption for different tank sizes and flow rates when VTC was utilized (Baltimore)

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

The calculations demonstrated that with the higher flow rate of 0.2L/s, the 750L tank was the best choice in terms of heat pump consumption. Although the infloor system met most of the heating demand for Toronto and Baltimore both, the use of a heat pump was still necessary when the weather was at an extreme temperature (cold or hot temperature) or when no solar energy is available. The heat pump energy consumption for Baltimore was found to be lower than that of Toronto due to the milder climate.

4. CONCLUSION

From the simulations, it was seen that it is more beneficial to use the vacuum tube collectors over the flat plate collectors. Even if the 750L tank is the largest of the three, the calculations have demonstrated that with the appropriated flow rate of 0.2L/s, this tank is the best choice in terms of heat pump consumption and to have a higher quantity of available water. For the infloor system, it seems to be the most efficient in terms of heating, but we must keep in mind that we have to keep the heat pump when the weather is at an extreme temperature (cold or hot temperature). The same remarks are made for Baltimore due to the heating part of this subject even if the power consumption is lower because of higher temperature. The infloor radiant heating system is able to meet almost all of the heating demand required in both Toronto and Baltimore. In Toronto, the ASHP's energy consumption can be reduced to 8% of the consumption for the case when the infloor system is not utilized. And the infloor system is able to meet almost the all of the heating demand, and only about 6 kWh of heating is required from the ASHP to meet the demand all the time.

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