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ABSTRACT

A long term monitoring system has been implemented in the *TRCA (Toronto and Region Conservation Authority) Archetype Sustainable House* to comprehensively monitor the energy performance of the archetype twin-houses and to investigate the effectiveness and efficiency of the mechanical systems. Two different sets of HVAC systems were installed in each of these twin houses: current practices and technologies in House-A, and sustainable technologies for future practices in House-B. Instrumentation of the monitoring system in House-B has been completed. Yet partial installation remains to be done in House-A. This paper describes some of the preliminary results of monitoring data of energy recovery ventilator (ERV), radiant in-floor heating system, total electrical energy consumption and Photovoltaic (PV) system. The sensible and latent heat recovery of the ERV increased with the increase of indoor-outdoor temperature difference and specific humidity difference, respectively. Higher radiant in-floor heating demand is observed on the 3rd floor. Seven months data of the 4.08 kWp photovoltaic (PV) system has been collected and its full year extrapolated result shows that annual electricity generation is 4563 kWh.

1. INTRODUCTION

The Sustainable Archetype House was built in 2008 at Kortright Conservation Centre of Toronto and Region Conservation Authority (TRCA) in Vaughan, Ontario, Canada. The Archetype House has two semi-detached houses: House-A is designed to demonstrate practices and technologies that are currently available and House-B is designed for sustainable technologies that will be practiced in the near future. Figure 1 shows the south side view of the Archetype Housing with House A on the left hand side. Both houses are R-2000 and LEED Platinum certified. The Archetype House is intended for sustainable technology demonstration, education, training and research purpose.

The objective of the monitoring system is to evaluate the performance of equipments and assessing the energy benchmarking of the HVAC systems with reference to the local climate, such as temperature and degree-day (DD), through long term monitoring.

Figure 1: South view of the TRCA Archetype twin houses

Similar, but different studies have been conducted in Canada. Located in Ottawa, the Canadian Centre for Housing Technology (CCHT) house is one of its kinds. This project consists of two side-by-side identical houses built in 1998. One is the reference house and another one is the test house. Both houses are two storeys and each one has a total floor area of 210 m^2 (2260 ft^2). To evaluate the performance of these two R-2000 certified houses, a comprehensive monitoring system was employed and more than 300 sensors were implemented. Simulated occupancy of 4 (four) family members was used in the houses. The long term monitoring results have been used in the model benchmarking which are being used to predict residential energy performance for different locations across Canada (Swinton *et al.*, 2001).

Another similar study is the Mattamy homes project in Milton, Ontario. This project consists of two houses built in 2005: one house is known as "The Wellington" and the other is known as "The Standbury". Both houses are equipped with solar thermal collectors and grey water heat exchanger to recover drain water heat. The Wellington house has a solar thermal collector integrated ground source heat pump for space heating and cooling and photovoltaic (PV) system for power generation. The Standbury house uses a two-stage high efficiency natural gas furnace with ECM motor and SEER 14 central A/C for space heating and cooling. Hot water is produced by the solar thermal collectors with natural gas mini boiler as backup (Cohen, 2010).

A short study has been conducted in the Factor-9 home in Regina, Canada. This is a one-storey R-2000 certified single family house. This house has a floor area of 301 m^2 (3239 ft^2) where 4 occupants are living. Passive solar systems are employed for space heating and ground source energy is used for space cooling. The energy performance of this house was monitored for only one year from June 1, 2007 to May 31, 2008 (Dumont, 2008).

2. HOUSE DESCRIPTION

2.1 House-A

This is a 3-storey south facing house which has a total (excluding basement) floor area of 261 m^2 (2808 ft^2). All windows are double glazed with U-value of 2.19 W/m^2 K (0.39 $Btu/ft^{2o}F$) with total window area of 37.68 m^2 (405.4 ft^2). Roxul fibre batt and 3" Styrofoam are used in the above grade walls with an overall resistance of RSI-5.31 (R-30), and Durisol blocks of RSI-3.54 (R-20) is used for the basement wall/foundation. The roof uses Structurally Insulated Panel (SIP) with RSI-7 (R-40).

The designed heating load of House A is 7.91 kW (27 MBH) when outdoor and indoor temperatures are -22^{o}C (-7.6^{o}F) and 22^{o}C (71.6^{o}F), respectively, and cooling load is 4.92 kW (16.8 MBH) when outdoor and indoor temperatures are 31^{o}C (87.8^{o}F) and 24^{o}C (75.2^{o}F), respectively.

The mechanical and hydronic systems of this house are featured with a one-tank hot water system with the capacity of 300 litres (79 USG). This tank has two coils: one is connected to a 2.32 m^2 (25 ft^2) flat plate solar collector and the other is connected to the wall mounted 18.5 kW (63 MBH) mini boiler for backup supply. A 10.5 kW (3 ton) two-stage air-to-air source heat pump is used to supply warm/cold air for space heating/cooling. The air source heat pump is connected to the air handling unit (AHU), which has a variable speed fan and supplies forced air to the zones above basement. If the heat pump cannot supply sufficient heat to the space during low outdoor temperature, mini boiler will start to supply hot water to the heating coil of the AHU for supplementary heat to the zone. The return warm water will circulate in the radiant in-floor heating system for basement space heating. In the mechanical ventilation system a heat recovery ventilator (HRV) is used for heat recovery from the stale air. A 0.91 m (36") long grey water heat exchanger was installed to recover heat from waste water (Barua *et al.*, 2009).

2.2 House-B

This is a 3-storey south facing house which has a floor area of 317 m^2 (3412 ft^2). All windows are triple glazed with U-value of 1.59 $W/m^{2o}K$ (0.28 $Btu/ft^{2o}F$) with total window area of 46.37 m^2 (499 ft^2). Heat-lock Soya Polyurethane Foam and/or Icynene spray Foam and 3" Styrofoam are used in the above grade basement wall with an overall resistance of RSI-5.31 (R-30) and Durisol blocks is used for the basement wall/foundation with combined resistance of RSI-3.54 (R-20). The roof uses Structurally Insulated Panel (SIP) with RSI-7 (R-40). This house has a 6.7 m × 3.81 m (22'×12.5') In-law Suite above the garage which has the same envelope features as the main house.

The designed heating load of House B is 7.94 kW (27.1 MBH) when outdoor and indoor temperatures are -22°C (-7.6°F) and 22°C (71.6°F), respectively and cooling load is 6.18 kW (21.1 MBH) when outdoor and indoor temperatures are 31°C (87.8°F) and 26°C (78.8°F), respectively.

More advanced HVAC systems are used in this house. A two-tank system was adopted for hot water production. One is a 300 litres (79 USG) preheat tank and the other is a 175 litre (50 USG) time-of-use (TOU) tank. The preheat tank is heated by a 2 m^2 (21.52 ft^2) evacuated tube solar collector and the TOU tank has a 6 kW (20.48 MBH) electric coil for back up hot water generation. The radiant in-floor heating system is used for space heating in each floor. A ground source heat pump (GSHP) with the capacity of 13.3 kW (45.4 MBH) is connected to two 152.3 m (500 ft) horizontal loops in the yard. In the cooling season, the GSHP supplies chilled water to the multi-zone AHU. A Stirling engine based micro combined heat and power (CHP) unit was also set up in substitute of the GSHP. This CHP unit can generate 1 kW electricity and 7 kW (24 MBH) equivalent thermal power. A buffer tank is used in between the GSHP/CHP and the infloor system/AHU to minimize equipment cycling. The roof-top PV system has the capacity of 4.08 kW and 2.4 kW for the wind turbine. An energy recovery ventilator (ERV) was installed in the mechanical ventilation system. A 0.91 m (36") long grey water heat exchanger was installed for grey water heat recovery. There is a 10 m^3 (2642 USG) underground cistern in the field that collects rain water for toilet flushing and gardening (Barua *et al*., 2009).

3. MONITORING SYSTEM

In any monitoring project the following activities are involved (ASHRAE, 1999a)

- Projects planning
- Installation of sensors and data acquisition equipments
- Calibration, ongoing data collection, and verification
- Data analysis and reporting

To implement the monitoring system of this project above activities are being followed.

In order to evaluate the performance of individual equipments, necessary equations are incorporated and based on these equations relevant sensors are selected. Common input parameters of these equations are air temperature, relative humidity (RH), air flow rate/velocity, water temperature, water flow rate, energy consumption and generation, soil temperature and moisture content as well as solar radiation. These inputs are useful to determine the energy balance of the house and the efficiency of each mechanical component. In order to evaluate the performance of each component as well as the energy performance of the house 9 different kinds and more than 300 sensors are installed. All sensors, except the solar irradiance sensors and gas flow meters, are field calibrated. Calibration of sensors is an ongoing routine process to ensure data quality. To capture the sensors signal National Instrument (NI) LabVIEW software and Data Acquisition (DAQ) hardware are being used where all data is saved in the SQL database.

4. DATA ANALYSIS

No occupant will live in the twin houses due to the nature of the project. However, the houses are open to the public for visit, and staff can work inside during the day. Therefore, both houses have occupants in the weekdays. The real time data being collected is similar to that in the typical family environment except household activities such as cooking, bath and laundry. Simulated occupancy system will be implemented later on to simulate typical residential conditions.

The following factors are considered for system performance analysis (EVO, 2007):

- outdoor temperature
- time intervals in seconds, hours or days

4.1 Energy Recovery Ventilator (ERV)

A tight building envelope system is often used in modern houses for energy conservation. Due to the reduction of infiltration in the air tight house, proper mechanical ventilation system is essential for adequate indoor air quality and human comfort. The ASHRAE standard 62.2 (ASHRAE, 1999b) recommends the minimum ventilation rate through the introduction of air-to-air heat recovery system. Typical air heat recovery systems are Heat Recovery Ventilator (HRV) and Energy Recovery Ventilator (ERV), which can filter fresh air, increase or decrease air temperature and/or humidity. Figure 2 shows the daily average indoor/outdoor temperatures and relative humidity during January 6-25, 2010. It was found that the average outdoor RH was 71% when the average temperature was -4.05°C (24.71°F). The absolute amount of moisture or water vapour in this cold air was only 2.59 g/m^3 (1.62×10^{-4} lb/ft^3). If the ERV were not installed, the incoming air would be extremely dry with only 13% RH at the room temperature. With the ERV, moisture from the exhaust air was transferred to the incoming low moisture fresh air, and the RH value rose to 27%.

According to ASHRAE Standard 62.2-2007, Walker *et al.* (2007a) showed that the minimum ventilation rate can be determined from the following equation:

$$Q(cfm) = 0.01A_{floor}\left(ft^2\right) + 7.5(N+1) \quad (1)$$

Where, A_{floor} is the house floor area and N is the number of bedrooms. From equation (1), the ventilation rate for this 3-bedroom residential house should not be less than 64 cfm (30 L/s) and the optimum humidity range for human comfort should be 30%-60% (ASHRAE, 2000). However, as shown in Figure 2, indoor RH remains below 30% for that period. The possible reasons of low RH value can be attributed to: a) high air exchange rate at low outdoor temperature, and b) low internal moisture generation (Walker *et al*., 2007b). It is worth noting that the ventilation rate through the variable speed ERV was kept at 148 cfm (70 L/s) during that period, which is high for a non-occupied house. The light human activity inside the house cannot provide sufficient moisture generation. Figures 3 and 4 show the sensible/latent heat recovery with respect to the indoor-outdoor conditions. As can be seen, the sensible heat recovery increases linearly as the dry bulb temperature difference increases. The latent heat recovery shows similar trend with respect to the specific humidity difference, although small discrepancy was observed.

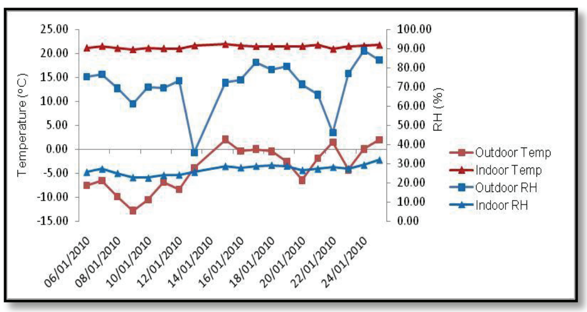

Figure 2 Daily average indoor-outdoor temperature and relative humidity during January 6-25, 2010

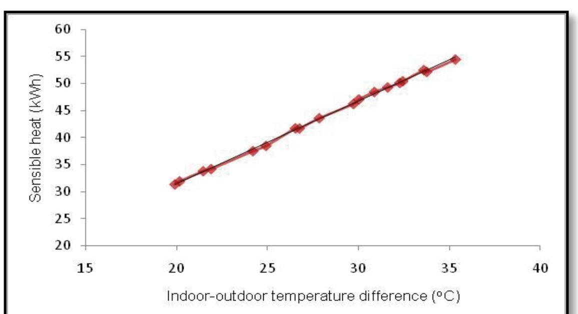

Figure 3 Sensible heat recoveries via ERV vs. daily average indoor-outdoor temperature difference from December 23, 2009 to January 11, 2010

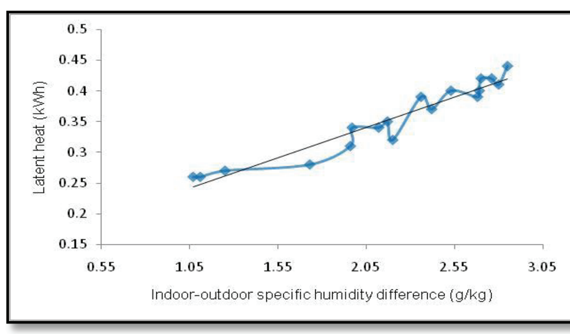

Figure 4 Latent heat recoveries via ERV vs. daily average indoor-outdoor specific humidity difference from December 23, 2009 to January 11, 2010

4.2 In-floor radiant heating

Figure 5 shows the "thin slab over frame floor" system was used on 1st, 2nd and 3rd floor of House B. A set of 1.25 cm (0.5 inch) diameter tubing was stapled on the plywood subfloor at 23 cm (9.05 inch) center to center distance under the 6.5 cm (2.56 inch) thick cement slab. On top of the cement slab, 1.5 cm (0.59 inch) thick finished wood floor was installed. Figure 6 show that the in-floor radiant heating system maintained indoor temperature at around 20 °C (68°F). This is controlled by the actuator, which has a series of valves that control the hot water flow from the buffer tank to different zones as required. The actuator is operated by the controller, following a demand from the thermostat which makes decision based on the indoor-outdoor temperature difference. The buffer tank holds warm water at constant temperature around 40°C (105°F) during the heating season.

As shown in Figure 7, the space heating increases with the increase of indoor-outdoor temperature difference. Figure 8 shows that there is higher heating demand on the 3rd floor. Possible reasons can be attributed to the larger exposed surface area and the higher ceiling, where the highest level is 4.98 m (16 ft) away to the floor. Elovitz (2001) shows that radiant in-floor heating system is popular in residential and light commercial buildings where the ceiling height is in the range of 2.4 m (8 ft) to 2.7 m (9 ft).

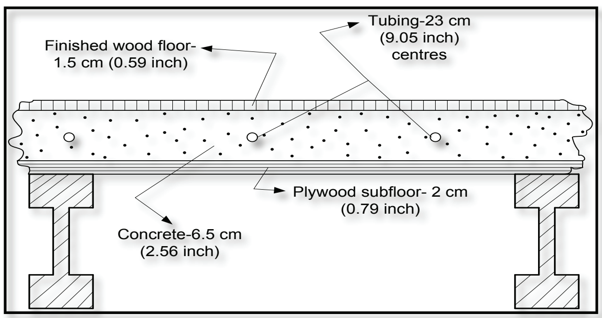

Figure 5 Radiant in-floor heating of "thin slab over frame floor" system

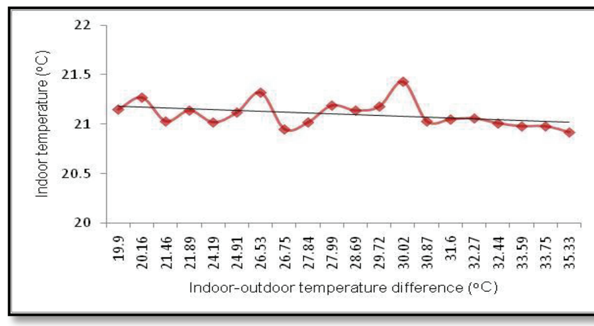

Figure 6 Daily average indoor temperature from December 23, 2009 to January 11, 2010

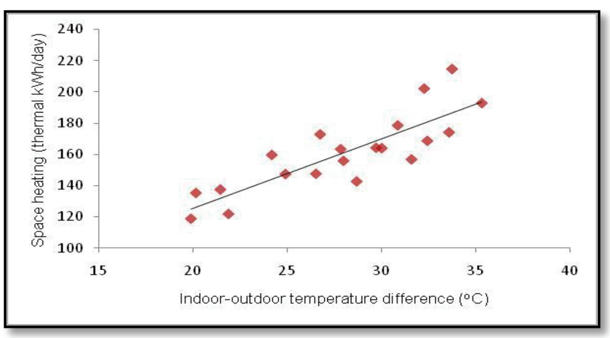

Figure 7 Space heating vs. daily average indoor-outdoor temperature difference from December 23, 2009 to January 11, 2010

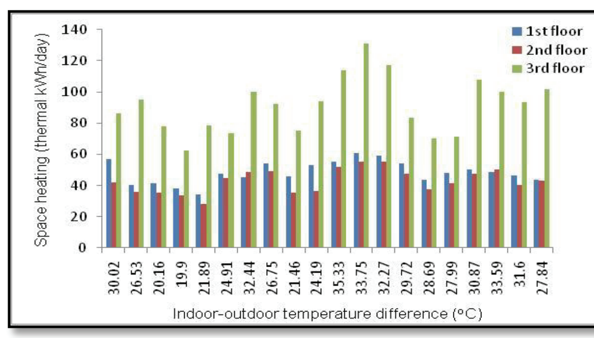

Figure 8 Daily space heating at different floors from December 23, 2009 to January 11, 2010

4.3 Total electricity consumption

Roth and Brodrick (2008) showed that occupant behaviour has a major impact on the building energy consumption. In the archetype houses, most of the appliances are not utilised in full capacity due to the absence of occupants. However, all mechanical and hydronic systems are operated in partial or full load capacity. Figures 9 and 10 show the total electricity consumption is mainly influenced by indoor-outdoor temperature difference, indicating that the space heating is the major factor for electricity consumption in the heating season.

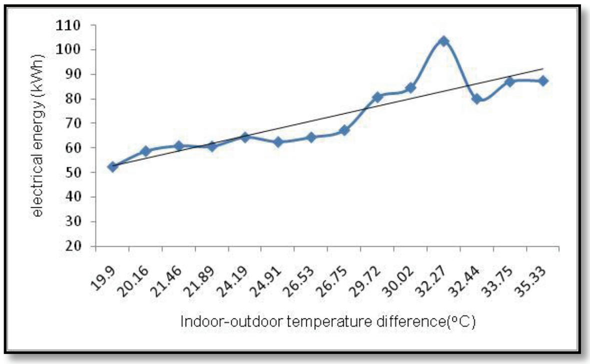

Figure 9 Total electricity consumption vs. daily average indoor-outdoor temperature difference from December 23, 2009 to January 5, 2010

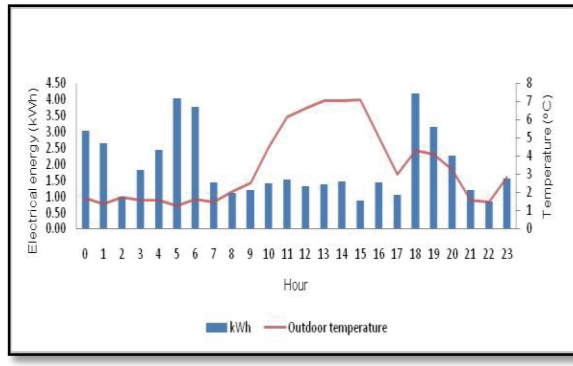

Figure 10: Outdoor temperature vs. electricity consumption on Tuesday, Dec 01, 2009

4.4 Photovoltaic (PV) system

The monocrystalline photovoltaic system composed of 48 modules was installed on the roof of House-B. Each module has a capacity of 85 W. The total cell area of all modules is 31.1 m^2 (334.34 ft^2) with combined generation capacity of 4.08 kWp. Under standard test condition, the maximum efficiency of this PV system is 13.12%. Out of 48 modules, 16 modules were installed on the roof at a tilt angle of 9.46^o, 24 modules at an angle of 11.77^o and the rest 8 modules at an angle of 33.69^o. All modules were grouped in 3 strings of 16 modules each which were connected to a 5 kW single inverter. This inverter's efficiency is 95.5%. To determine the PV output at different angles, the generation capacity of 4.08 kWp is distributed according to the ratio of total cell area: 1.36 kWp at angle 9.46^o, 2.04 kWp at angle 11.77^o and 0.68 kWp at angle 33.69^o. Seven months of PV data from September 2009 to March 2010 was collected at Kortright Centre. The evaluation of yearly PV performance has been conducted with RETScreen. Solar radiation of 20 years averaged data at Pearson International Airport (PIA) weather station was used in the RETScreen analysis. This solar radiation data was compared with the available data at University of Waterloo weather station, which is the closest station to both PIA and Kortright Centre. It shows that the solar radiation of the 7 months data at University of Waterloo weather station is 1.23% higher than the 20-year average data at PIA using RETScreen.

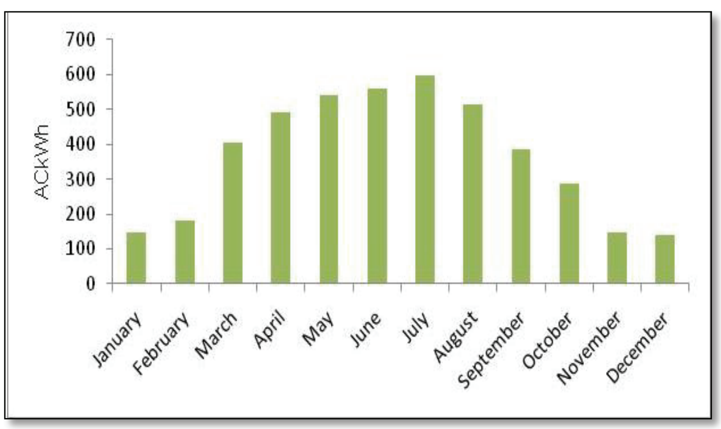

Figure 11 Yearly electricity generations by the 4.08 kWp roof top grid connected PV array

In RETScreen analysis, losses of the PV system were set to be zero. The results show that yearly electricity generation is 4970 kWh in RETScreen. During this 7 months period, PV generated 1726 kWh electricity, which is 10 % less than the RETScreen prediction. Possible reasons for underproduction are: a) dirt accumulation on the PV surface in the no-rain period, b) snow accumulation on the array during winter period (SolarCity, 2009a), c) more miscellaneous losses of array and inverter, d) actual radiation is different on site from the RETScreen database. Pyranometers were recently installed at the site to obtain the actual solar radiation. Figure 11 shows a full year PV electricity generation from September 2009 to August 2010. The PV generation from April to August 2010 was extrapolated based on the ratio of actual data to RETScreen output of the 7 month period. The total yearly PV generation was estimated to be 4563 kWh. This amount of energy can reduce 0.89 MT of GHG emission based on hourly average GHG emission factors (Gordon and Fung, 2009). The rule of thumb for Toronto's solar resources shows that each kW PV system can generate 1100 kWh/yr electricity (SolarCity, 2009b). According to this rule, the existing 4.08 kW PV system can generate approximately 4500 kWh/yr electricity, which is only 1% less than the extrapolated result.

5. CONCLUSION

A monitoring system has been implemented in the Archetype Houses at Kortright Centre. Preliminary analysis shows that indoor-outdoor temperature difference is the primary factor influencing the ERV performance, in-floor radiant heating and total electricity demand.

The sensible and latent heat recovery of the ERV increased with the increase of indoor-outdoor temperature difference and specific humidity difference, respectively. In the in-floor radiant heating system, higher heating demand was observed on the 3rd floor. Indoor temperature was maintained constant at 21^{o}C regardless of the indoor-outdoor temperature difference. Space heating demand and total electricity consumption increased linearly with the increase of indoor-outdoor temperature difference. Seven months data of the 4.08 kWp photovoltaic (PV) system has been collected. The measured seven months output is 10% less than the RETScreen analysis, excluding the consideration of PV losses. Nevertheless, the yearly extrapolated data is only 1% less than the prediction based on the rule of thumb of Toronto's solar resources.

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