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RINNAI MODULATING DV WALL FURNACE HEATING SYSTEM
IN-SITU PERFORMANCE TESTING
AT THE CANADIAN CENTRE FOR HOUSING TECHNOLOGY

A Joint Government/Industry Technology Assessment
Gas Technology Institute
and
CanmetEnergy Research Centre-Natural Resources Canada
Canadian Centre for Housing Technology

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Canadian Centre for Housing Technology (CCHT)

Built in 1998, the Canadian Centre for Housing Technology (CCHT) is jointly operated by the National Research Council, Natural Resources Canada, and Canada Mortgage and Housing Corporation. CCHT's mission is to accelerate the development of new technologies and their acceptance in the marketplace.

The Canadian Centre for Housing Technology features twin research houses to evaluate the whole-house performance of new technologies in side-by-side testing. The twin houses offer an intensively monitored real-world environment with simulated occupancy to assess the performance of the residential energy technologies in secure premises. This facility was designed to provide a stepping-stone for manufacturers and developers to test innovative technologies prior to full field trials in occupied houses.

As well, CCHT has an information centre, the InfoCentre, which features a showroom, high-tech meeting room, and the CMHC award winning FlexHouse™ design, shown at CCHT as a demo home. The InfoCentre also features functioning state-of-the art equipment, and demo solar photovoltaic panels. There are over 50 meetings and tours at CCHT annually, with presentations and visits occurring with national and international visitors on a regular basis

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EXECUTIVE SUMMARY

In early 2011, Gas Technology Institute (GTI) established a research project with CanmetENERGY's Renewables and Integrated Energy Systems Laboratory (RIES) to assess the energy performance of a modulating propane-fired direct vent (DV) wall furnace system. DV wall furnaces and room-to-room air ventilators were installed in the single detached house at the Canadian Centre for Housing Technologies (CCHT) and their energy performance was compared to the performance of condensing central furnace in the identical house next door.

Two propane-fired DV wall furnaces were installed in the CCHT Experimental research house. The first DV furnace with a high firing input of 36500 Btu/hr was installed on the first floor in the living room area while the second DV furnace with a high firing input of 20700 Btu/hr was installed on the second floor in the master bedroom. In addition, two room-to-room air ventilation units, or air share units, were installed on the second floor to assist with warm air distribution between bedrooms. The reference condensing central base case system installed in the Control House was a propane-fired condensing central furnace with input of 50000 Btu/hr.

The DV wall furnaces were commissioned on February 9, 2011 and operated in the Experimental House for 5 consecutive weeks to develop a comparison between the DV wall furnaces and reference base case system. The furnaces performance parameters as well as house energy consumption, weather conditions and other valuable parameters were monitored, recorded and analysed.

The following main conclusions can be drawn from the present work:

- During the testing period, the DV furnace system met all space heating loads of the Experimental House and provided a better comfort than the reference system in the Control House. The units operated reliably without any interruptions or faults during the testing period and under various outdoor temperatures ranging from -0.4 ^{o}F to 54.0 ^{o}F (-17.5 ^{o}C to 12.2 ^{o}C).

- In general, propane gas consumption of the DV furnaces was higher by 5 % on average to the condensing central furnace.

- The DV wall furnaces operating with two bedroom doors closed resulted in an overall net increase of 10.8 MJ/day (3.7%) in total energy consumption (propane and electricity), when compared to a condensing central furnace. The propane consumption increase by the DV systems was 9.7 % during the same period.

- The DV wall furnace system (including the air share units) electrical consumption averaged 4.3 kWh/day compared to 3.5-7.5 kWh/day for the condensing central furnace system. The DV wall furnace system provided about a 76 % reduction in electrical consumption compared to the condensing central furnace system. Approximately 55 to 65 % of the 4.3 kWh/day consumption of the DV wall furnace system was attributable to the operation of the air share units. The electrical consumption of the DV wall furnaces without the air share units averaged 1.5 kWh/day. With doors open and air share units off, the electrical savings of the DV system were even more substantial, close to 88 %. Total energy consumption of the DV wall furnace system was on average 0.5 % lower than the condensing central furnace system.

- In general, during testing the DV wall furnace system operated more frequently and with longer daily on-time cycles than the condensing central furnace.

- Throughout the experiment, the DV wall furnace system maintained temperatures at/or above the 68 °F (20 °C) 2006 IRC requirement in all measured locations but the two closed off bedrooms of the house.

- In general, the DV wall furnace system maintained room air temperatures the same or warmer than the condensing central furnace system. However, in the closed off rooms, temperatures were either identical or warmer than those expected with the condensing central furnace system.

- During the experiment and benchmark, the supply ducts and return duct in the basement were sealed (making it an unconditioned space). Heat losses to the basement from the condensing central furnace (baseline system) were substantial, keeping the Control House basement air temperature approximately 2 °C warmer than the Experimental House basement air temperature.

- The lowest daily outdoor temperature experienced during the experiment was 12.6 °F (7 °C). The developed energy consumption trends during the testing indicate more potential energy savings by the DV furnaces in colder weather.

NOMENCLATURE

A/C	*Air conditioning*
AFUE	*Annual Fuel Efficiency*
AHRI	*Air-conditioning, Heating and Refrigeration Institute*
ARC	*International Residential Code*
BTU	*British Thermal Unit*
CCHT	*Canadian Centre for Housing Technology*
CLD	*Chemiluminescence*
DV	*Direct-vent*
ECM	*Electronically Commutated Motor*
EPA	*Environmental Protection Agency (U.S.)*
GTI	*Gas Technology Institute*
HHV	*Higher Heating Value*
NDIR	*Non-dispersive infra-red*
NO	*Nitric oxide*
NO_x	*Nitrogen oxides*
NRC	*National Research Council Canada*
NRCan	*Natural Resources Canada*
PERC	*Propane and Education Research Council*
PSC	*Permanent split capacitor*
RIESL	*Renewables and Integrated Energy Systems Laboratory*
SH	*Space heater*

1. INTRODUCTION

In this project, the feasibility of using modulating direct-vent (DV) wall furnaces for home heating was performed. The DV wall furnace system, including both DV wall furnaces and room-to-room ventilators evaluated is by Rinnai. Gas Technology Institute (GTI) contracted CanmetEnergy's Renewables & Integrated Energy Systems Laboratory (RIESL) to evaluate the DV wall furnaces as a system and compare their performance to a condensing central furnace system.

The report presents the results of in-situ performance testing and the effect of operating and outdoor conditions on the system performance. The DV wall furnace heating system and the condensing central furnace system are compared in direct side-by-side testing under the same space heating, water heating and ventilation loads.

Testing was carried out at the Canadian Centre for Housing Technology's (CCHT) side-by-side research houses. The DV space heating system was run for five weeks of testing; this allowed collecting enough data under various outdoor conditions for complete analysis of the system performance in comparison to the base case condensing furnace heating system.

The project objective was to provide GTI with third-party test data in establishing the performance of the DV Wall furnace.

The report includes six main sections. In the next three sections, an introduction, project objectives and the methodology are first presented in some details. Then the detailed analysis of the in-situ test results follows in Section 5. The last section provides the main conclusions of the work with some recommendations regarding the improvement of the DV wall furnace systems operability and performance.

The appendices found in an accompanying but separate document contain information on the DV wall furnaces, the room-to-room air ventilators, condensing furnace specifications, details of the monitoring protocol, and additional test results and analysis.

2. PROJECT OBJECTIVES AND APPROACH

In this project, the performance of a DV wall furnace system was compared to the base-case system - a condensing central furnace. The project objective was to evaluate the DV wall furnace system and compare its dynamics response and performance to a condensing central furnace system over a range of outdoor conditions. The ultimate objective of the study is to provide PERC and Rinnai with third-party test data in establishing the performance of the DV Wall Furnace System.

This project was executed in five main tasks:

- Development of detailed test plan and schedule;
- Equipment installation at CCHT, commissioning, and debugging;
- DV wall system start-up and operation;
- Monitoring, test data processing and analysis;
- Performance assessment and final reporting.

3. BACKGROUND

3.1. CCHT Twin House Facility

Built in 1998, the Canadian Centre for Housing Technology (CCHT) (www.ccht-cctr.gc.ca) is jointly operated by National Research Council (NRC), Natural Resources Canada (NRCan), and Canada Mortgage and Housing Corporation (CMHC). CCHT's mission is to accelerate the development of new technologies and their acceptance in the marketplace. The Canadian Centre for Housing Technology features twin research houses to evaluate the whole-house performance of new technologies in side-by-side testing. The houses were designed and built by a local builder to the R-2000 Standard (R-2000). R-2000 is voluntary standard administered by NRCan that defines technical performance for energy efficiency, indoor air tightness quality, and environmental responsibility in home construction. The houses feature a popular model currently on the market in the Ottawa region, and were built with the same crews and techniques normally used by the builder. The CCHT twin houses are fully instrumented and are unoccupied. To simulate the normal internal heat gains of lived-in houses, these houses feature identical 'simulated occupancies'.

3.2. DV Wall Furnace Heating System

The heating system installed at CCHT operated on propane gas and consisted of Rinnai direct-vent (DV) wall modulating furnaces with room-to room air ventilators, as an alternative to a central ducted heating system with condensing furnace. The DV wall furnaces are able to extract up to 83 % AFUE efficiency using a unique stainless steel heat exchanger, modulating gas valve and variable speed blowers. There are two primary applications for this technology:

- Total heating solution as a ductless furnace:
    - Uses "Comfortable Heat" to heat entire house;
    - Ductless;
    - Either with no A/C system or "Mini-Split" ductless A/C system.

- Zone heating solution as a zone heat source used for:
    - Small spaces;
    - Hard-to-heat spaces;
    - Eliminating cold spots;
    - Supplementing conventional ducted system;
    - Supplementing heat pump systems.

The employed modulating technology allows the DV units to follow the heating demand to optimize operation resulting in lower propane gas usage and higher levels of delivered heat. The feedback comes from a temperature-sensing thermistor that constantly monitors room temperature and accurately detects temperature changes. The DV wall furnace begins to heat the room at low fan speed. It increases fan speed and energy output if necessary to achieve the desired temperature. Once the desired temperature is achieved, the furnace goes into standby mode. As the temperature of the room gradually drops, the wall furnace restarts and gradually warms the room back to the desired temperature. If there is a sudden injection of cold air, the furnace automatically adjusts fan speed and heat to quickly restore the set temperature.

The DV wall furnace equipment description is provided in Appendix A [1].

4. METHODOLOGY

4.1. Side-by-side Testing Procedure

The DV wall furnace system was evaluated using a side-by-side testing procedure. First, the CCHT twin houses were compared in identical configuration to establish a benchmark. Periods of benchmarking were spread throughout the heating season to establish consumption and temperature relationships between the two houses over a range of outdoor conditions. Following benchmarking, one house remained unchanged, referred to as the “Control House”, and the DV wall furnace system was installed in the second house, referred to as the “Experimental House”. The differences between the operations of the Experimental House with the DV furnace heating system were then quantified, using the Control House as a reference. Following the experiment, the houses were returned to benchmarking conditions to ensure that no changes occurred to the house setup during testing. The details on the operating conditions and the test results for the benchmark are documented in Section 5.2.

4.2. Installation

This section describes the various steps taken to install equipment and monitoring devices at the CCHT. The log of events highlighting the installation steps is provided in Appendix B.

4.2.1. Benchmark Set-up

Both houses Control and Experimental (Figure 1) used propane-fired condensing furnaces and central forced air sheet-metal ductwork for the distribution of warm air during the heating season.

Figure 1: Photograph of Exterior View of Houses Showing Experimental House Propane Tank (May 2011)

The ductwork is typical of current Canadian practice. Warm air supply registers are located in each room at floor level under or near exterior windows and doors. Return air registers are located near the ceiling in each of the four bedrooms located on the second floor. Two larger returns are located centrally on first floor near floor level. Appendix C presents the floor plan of the three floors with the DV wall furnace heating systems, the air share units and the position of the 2-foot-3-foot thermocouples.

The basements are full height insulated spaces; they have been left un-finished and are currently not deemed liveable/habitable areas. If intended for full time use by occupants additional heating and finishing would be required, the basement temperatures are normally lower than upstairs.

Three warm air supply ducts and one return duct terminate at the ceiling level of the basements. During Benchmarking and the Experimental phase of the project these four duct openings were closed and sealed. No direct furnace air connection to the basement was intended. However due to the presence of the ductwork in the basement and un-intentional duct leakage via gaps in the ductwork, some heat would escape into the basements. The basement door remained open in both houses throughout testing.

Three warm air supply and one return duct also terminate in an under floor space in the master bedroom above the ground level attached garage. This feature is employed to warm the floor, which is directly above an unheated garage.

For this project, two new propane-fired forced air condensing furnaces were installed by Superior Propane, one in each house. Details on the specifications of these furnaces can be found in Section 4.3.

Because the research houses are built to the R-2000 standard they include a continuous mechanical ventilation strategy, using a Heat Recovery Ventilator (HRV). The fresh air is supplied to the return duct of the forced air distribution system and the furnace blower runs continuously at low speed. This function was disabled during the project. The fresh air from the HRV would therefore enter the house at the same flow rate as before but the circulation to rooms via the ductwork was limited to periods when the space heating was activated. At all other times fresh air would still enter the building but not be directed to each room, and most of the fresh air would presumably exit out of the first floor return air grills. Stale air from the house is picked up in the kitchen and from the 3 bathrooms continuously via high wall intake grilles and drawn back to the exhaust side of the HRV.

Two second floor bedroom doors Bedroom 2 and 4, were kept closed during Benchmarking, and also during the experiment. These two doors were undercut at the bottom so when closed some air could move under the doorway. The space is about 1.5 inches.
Figure 2 shows a photograph of undercut of two bedroom doors to allow 1.5 inches of space. During the experiment, these doors were opened for a few days in both houses to study the impact on heat movement to those rooms. All other interior bedroom, bathroom and laundry doors were kept open.

Figure 2: Photograph of Undercut of Bedroom Door

The houses are equipped with numerous temperature sensors with additional sensors being added to specific locations for this project. These temperatures are recorded and saved continuously by a data acquisition system.

Closing the doors in Bedroom 2 and Bedroom 4 provided an excellent opportunity to study the temperature differences that occur in a closed south facing and north facing bedroom.

Figure 3 shows a photograph of Bedroom 2 location of 2 foot 3 foot thermocouple on metal pipe stand near outside wall. Per the 2006 International Residential Code, a heating system must maintain temperatures above at/or above 68 °F (20 °C) at location 2 foot from an outside wall and three feet above floor. Also shown is centre of room thermocouple stand, which provided validation of overall room temperatures.

Figure 3: Photographs of Bedroom 2 Location of Thermocouples on Metal Pipe Stands

During Benchmarking the data collected from numerous sensors documented temperatures in each room as well as characteristics of the heating equipment. Additional basement temperature sensors were added to capture the possible change in temperature of the basement space. It was assumed that during the experimental phase of the project the ducted furnace in the Control House would loss additional heat from the large amount of ductwork present in the space as compared to the Experimental House, which had no space heating in the basement.

In conclusion, shutting two bedroom doors, sealing the four duct openings in the basement and running the circulating furnace blowers only during heating cycles, were the three major elements in the Benchmarking phase of the project. Under these benchmark operating conditions both houses provided a good baseline understanding of the strengths and limitations of a forced air system in a typical two-story building.

4.2.2. Experimental Set-up

For the Experimental portion of the project the Control House remained the same as in the Benchmark configuration, and the Experimental House was reconfigured. Two DV propane-fired wall furnaces were added; one in the family room on the first floor and one in the master bedroom on the second floor (refer to Appendix C for floor plan).

The Rinnai ES38P (Figure 4) and the Rinnai EX22CP (Figure 5) units were installed on the first and second floors respectively. Each unit sits on the floor and is fastened to the exterior wall. Details on the specifications of the DV wall furnaces can be found in Section 4.3.

Figure 4: Photograph of First Floor DV Unit in the Family Room Location against East Facing Exterior Wall

Figure 5: Photograph of Second Floor DV Unit in Master Bedroom against East Facing Exterior Wall

The furnace in the basement was turned off; all ductwork terminations in rooms were taped shut (except one return) to not allow any flow of air between spaces. The HRV continued to operate on continuous circulation and the return air register on the first floor below the house thermostat was left open to allow fresh air to and from the HRV to enter the first floor. Distribution of the fresh air to other areas of the house would be reduced, but the overall amount of HRV ventilation exchange to the house remained the same.

The locations of the DV units were chosen to provide optimal air flow to the rest of the rooms on each floor for heat distribution. The locations on the eastern exterior wall also provided ease of installation for concentric venting and access to the propane tanks outside.

On the first floor, there are no doors except for the small bathroom door near the garage and the front door. This door was kept open throughout the project in both houses. The airflow vanes on the DV unit were adjusted from a straight position to a position, which split the flow to the right and the left of the kitchen island. This step assisted somewhat in moving airflow from the unit to the dining room behind the kitchen and to the front of the house and the living room.

The venting of the DV units was very straight forward because of the compact adjustable design of the vent. A hole was made in the interior drywall from the room side and then a pilot hole was drilled thru the exterior brick to indicate the proper location. A suitable hole was drilled in the brick from outside, the vent was installed partial from both sides of the wall and sealed. The venting installation took only 15 minutes after the holes were made (Figure 6).

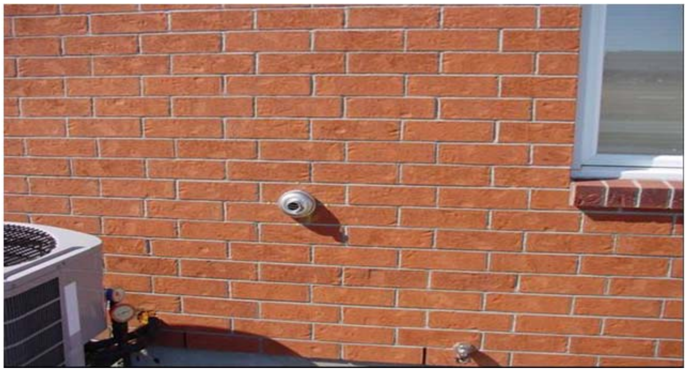


Figure 6: Photograph of Concentric Vent Kit Connected to First Floor Family Room Showing Exterior Termination

Also included in the Experimental House with the DV units were two through-the-wall room-to-room air ventilation blowers, commonly referred as air share units. These units were installed in second story walls between the Master Bedroom and the two bedrooms 2 and 4, which had their doors closed. The function of these units as their name implies was to move air from one space to another. The units were mounted in the stud cavity high on the wall to capture warm air and blow it down the stud space to the termination exit located close to the floor in the bedroom opposite. Figure 7 shows photographs of location of an air share intake unit in the Master Bedroom; high on wall and output low in same wall stud cavity in Bedroom 4. Figure 8 shows location of air share intake unit in Master Bathroom; high on wall and output low in same wall stud cavity in Bedroom 2.

Figure 7: Photographs Showing Location of Air Share Intake Unit in Master Bedroom and Stud cavity in Bedroom 4

Figure 8: Photographs Showing Location of Air Share and Stud Cavity in Bedroom 2

The intention was to provide heated air from the Master bedroom with the DV unit to rooms that had no heater and their doors closed. The project team wanted to use Bedroom 2 as a closed bedroom because it provided a south facing window. The compromise was that the air share unit was positioned further than optimum from the DV wall furnace heat source in the Master bedroom. In a real house a bathroom would not be an appropriate room to mount the air share unit for several reasons. But for the experiment this was deemed a suitable compromise to gather the required data. If the bathroom was a walk-in closet it would be more suitable.

Bedroom 4, the other closed bedroom door has a north facing window and provides a different challenge for the DV wall furnace/air share heating system.

Bedrooms 2 and 4 have different window sizes, exterior wall surface areas, and furnace ductwork issues that were well suited to use for a realistic experiment comparing the DV wall furnace/air share heating system to a centrally-ducted condensing furnace system. The side-by-side identical houses at CCHT provided good real world situations for this type of evaluation.

The operation of the air share units was achieved by using 120-volt thermostat controllers (Figure 9).

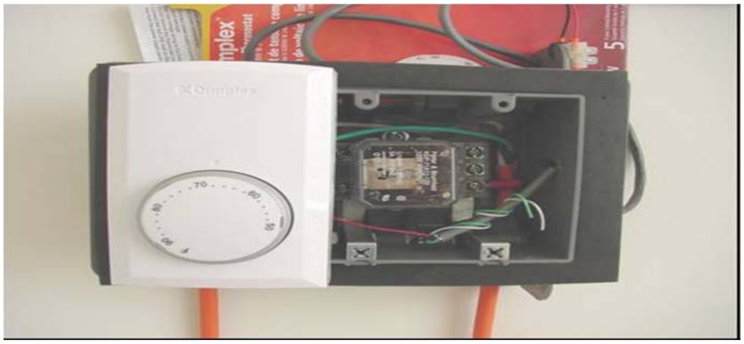


Figure 9: Photograph of 120-volt Thermostat Control for Air Share Units and Status Relay Connected to CR3000 DAS

Installation of the air share units had two notable issues which were somewhat addressed in the instruction manual. The interior wall stud space at CCHT was 24 inches rather than the normal 16 inches; this required the blocking of the extra space around the Air share unit so that air would not bypass the intended flow path. And secondly, one stud space had an electrical wire and a plumbing pipe installed in the space with oversized openings in the wooden studs. These gaps would have allowed air to escape into unintended areas. The gaps were sealed, by opening up access to the stud space.

Figure 10 shows a photograph of Bedroom 2 stud space openings around electrical wire and ABS plastic plumbing pipe sealed with mastic. The white metal scoop at the bottom exits the air from the air share blower unit installed above. Once installed, the stud space was later closed with drywall and tape.

Figure 10: Photograph of Bedroom 2 Stud Space Openings around Electrical Wire

Figure 11 shows the air share blower installed for Bedroom 4. The air share grill is partially removed; the blower is positioned to blow downwards into its stud space.

Figure 11: Picture Showing Air Share Grille Partially Removed

4.3. Condensing and DV Wall Furnace Specifications

The two new forced-air condensing furnaces installed by Superior Propane were furnaces manufactured by International Comfort Products, Keeprite, model number N9MP2050B12C2, 90 % AFUE, serial number A103559978, and 8683, input 50000 btu/hr, Conversion kit number 1172598.

Superior Propane installers converted the furnaces from natural gas to propane on site. The Benchmark configuration uses these two Keeprite furnaces and the fuel is propane. The main floor thermostat connected to the furnaces is set 71.6 ^{o}F (to 22 ^{o}C). The system specifications of the condensing furnaces are provided in Appendix D.

Figure 12: Photographs of Propane Furnace in Basement Connected to Existing Ductwork

The heating systems tested at the CCHT Experimental House consisted of two DV wall furnaces, ES38P and EX22CP, 83 % AFUE installed on the first and second floors with input high-firing rating of 36500 and 20700 Btu/hr, respectively. Each unit sits on the floor and is fastened to the exterior wall. The system specifications of the DV wall furnaces are provided in Appendix D. To assist with air movement between bedrooms on the second floor two through-the-wall room-to-room air ventilation blowers were installed.

Figure 13 shows a schematic of the DV wall furnace heating system installed at the CCHT Experimental House. The system specifications for the DV wall and condensing furnaces are provided in Appendix B.

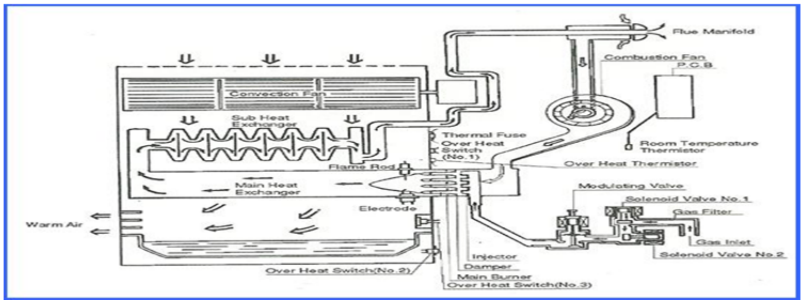


Figure 13: Schematic of the DV Wall Ductless Furnace Heating System [1]

4.4. Propane Gas Supply

Both DV wall and condensing furnaces were operated using propane gas. This later was supplied by tanks at a normal test pressure immediately ahead of all controls at 11 to 13 inches of water column (2.75 to 3.25 kPa). This was a requirement for using the diaphragm natural gas meters without correction to the reading volumes. Exterior propane tanks were placed at suitable locations near each house and a single propane gas line was installed to the basements to supply the furnaces. For the Experimental house, two additional propane lines were located on the outside brick work and run to locations one on the first and one on the second floor on the east side of the building.

The propane used during the project had a heating value of 2504 Btu/ft^3 (93.3 MJ/m^3).

Figure 14 presents a photograph of the Experiment House exterior showing propane tank and flexible yellow coloured gas tubing.

Figure 14: Photograph of Experiment House Exterior showing Propane Tank and Gas Tubing

Refilling of tanks was done as required (Table 1).

Table 1: Refiling Propane Tanks for the Control and Experimental Houses

	CCHT Control House	CCHT Experimental House

	24 B Building	24 C Building
Date	**Propane Volume (Litres)**	
28-Jan-11	306	318
21-Feb-11	304	323
14-Mar-11	257	245
15-Apr-11	247	224

4.5. Data Acquisition System and Monitoring

4.5.1. Data Acquisition System

Two portable Campbell Scientific CR3000 data loggers were used one in each house to supplement the data collected from the main CCHT data acquisition system (DAS). Several duplicate sensors/meters were also connected to both DAS, in order to provide security of data collection and ensure accuracy of results (Figure 15).

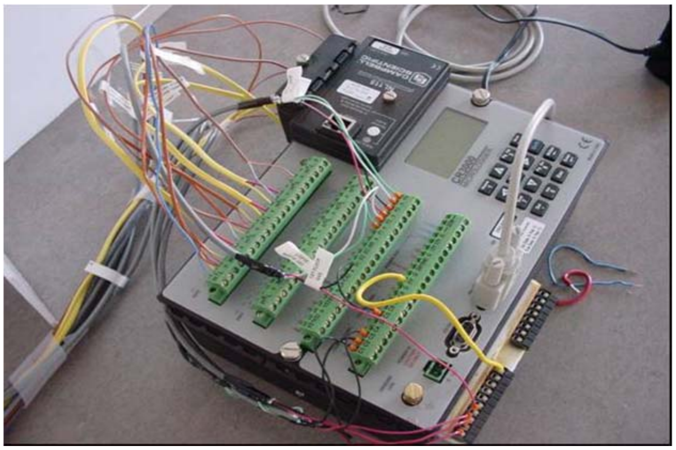


Figure 15: Photograph of Campbell Scientific CR3000 Connected to Sensors Monitoring both the DV Wall Furnace and the Two Air Share Units

As already specified, the propane-fired DV wall and condensing furnace heating systems were well instrumented to continuously monitor the propane gas usage, the electrical consumption, as well as the temperatures throughout the house and the furnace heating systems. The furnaces were fitted with inlet and outlet plenums, and are instrumented with thermocouples for incoming and outgoing air, condensate collection for the condensing central furnace, electric power consumption, fuel consumption and flue gas emissions measurement. Additionally four thermocouples were located to monitor the temperature of the room air entering and heated air leaving the DV wall furnace, as well as combustion air supplied to the unit from outside and exhaust gases leaving the DV unit to outdoors. The sensors were connected to the Campbell Scientific CR3000 data loggers.

The measurement of these temperatures was done with calibrated K and T thermocouples, with accuracy of 0.5 % over the tested temperature range.

The thermostat setting on the 2 DV units was set to 72 °F (22.2 °C) to somewhat match the setting of the Honeywell thermostat controlling the furnace in the Control house (22 °C).

The weather conditions and the solar radiation on a south-facing vertical plane were monitored with a weather station and a pyranometer.

Each DV unit was connected to a 120-volt electrical supply and the power usage was logged.

Normally the DV wall furnace thermistor is factory installed behind the unit at a height close to the floor. The DV wall furnace installation team relocated the moveable thermistors for both DV units to a position just outside of the units' enclosure and somewhat higher off the floor to adjust for the potential of cool air from the unconditioned space directly below the first flow unit and to allow for two monitoring thermocouples to be placed alongside the thermistor to document the temperature of air at this location. In the Control House thermocouples were also placed at these locations even though DV units were not placed in that house. Figure 6 shows a photograph of the location of thermistor (black wire end) and monitoring thermocouples (brown wire ends).

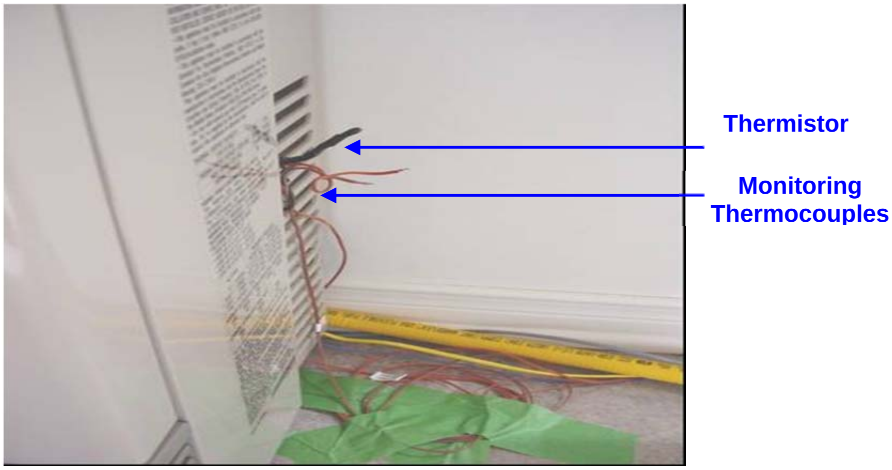


Figure 16: Photograph of Location of Thermistor and Monitoring Thermocouples

Propane gas flow was measured accurately using two pulse-generating utility gas meters with a resolution of 0.05 ft^3/pulse. The propane gas pressure was regulated and checked to a value of 10-13 inches water column for all experiments, which is a required pressure for the propane gas. The heating system electrical consumption (on 120 V) was measured using a pulse-generating kWh meters of 1 pulse/0.0006 kWh.

Propane usage was measured using 2 meters, at the DV units indoors (Figure 4 and Figure 5).

The DV wall furnace on-time values were calculated based on trigged propane gas flow.

The air share units on-time signals operating on thermostat set to 68 °F (20 °C) were recorded for all the air share units installed in the second floor of the bedroom 2 (South-West), bedroom 3 (North-West) and bedroom 4 (North-East).

The condensate from the condensing furnace exhaust was recorded using a pulse output from rainfall-type tipping scale of 1 pulse/0.01111 litres.

Figures C.1-C.3 in Appendix E describes the locations of the instrumentation on the DV wall furnace heating system that were monitored and recorded in the Experimental House.

4.5.2. Monitoring Protocol

The monitoring protocol was developed and approved by all parties involved prior to the start of the project. The CR3000 data logger was programmed to scan all sensors every 5 second-scans and to save all measured and calculated values in five-minute and one-minute intervals. Refer to Table E.1 in Appendix E for details. Three tables were generated for the five-minute and one-minute recorded data for the DV wall furnaces installed in first and second floors. The furnace on-time was trigged by furnace propane flow and was recorded in the one-minute data file. The DV wall furnace cycles were calculated using the on-off cycles one-minute post-data processing.

4.5.3. Flue Gas Emissions Measurement

The concentrations of carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxide (NO_x) and oxygen (O_2) were measured both in the raw exhaust with a Horiba PG-250 portable multi-gas analyser at steady state conditions. The PG-250 can simultaneously measure up to five separate gas components using the measurement methods recommended by the EPA. The Horiba PG-250 utilizes the same measurement principles as a CEMS (continuous emissions monitoring system). These include:

- Nondispersive infrared absorption (NDIR, pneumatic) for CO and SO_2;
- Nondispersive infrared absorption (NDIR) (pyrosensor) for CO_2;
- Chemiluminescence (CLD, crossflow modulation) for measurement of NO plus an NO_2-NO converter. The CLD comprises a reaction chamber with a solid-state photodetector, ozoniser and a converter for NO_x measurement.
- Galvanic oxygen analyser for measurement of O_2.

The signal output of the instrument was interfaced directly with a laptop computer through an RS-232C interface to record measured values. Major features of the PG-250 include a built-in sample conditioning system with sample pump, filters, and a thermoelectric cooler. Mounted behind a blank panel is the type refrigeration unit to cool a chamber through which the sample gas is passed. It removes condensate from the sample prior to its entering the NDIR, paramagnetic and chemiluminescent analysers [2].

Figure 17 shows the emissions measurement setup and the sampling lines through the gas vents of the DV wall and condensing furnaces.

Figure 17: Flue Gas Emissions Measurement Set-up and the Sampling Lines of the DV Wall and Condensing Furnaces Installed in the Experimental and Control Houses

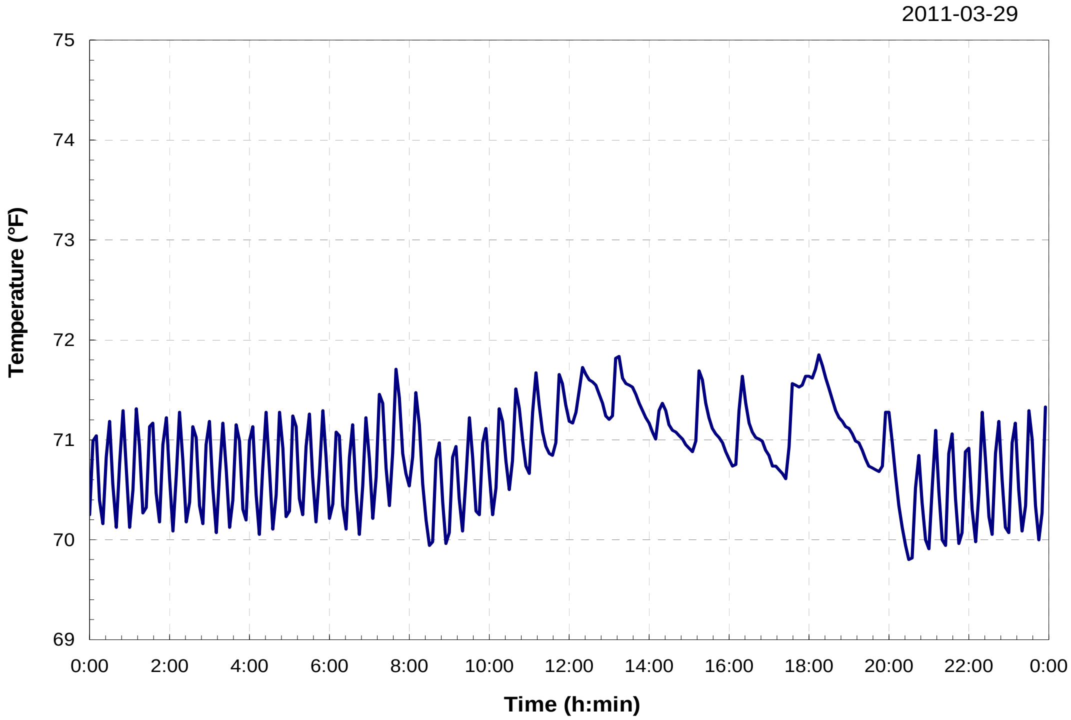
5. TEST RESULTS AND ANALYSIS

5.1. DV Wall Furnace Performance

In this Section, the test results obtained with the DV wall furnace heating system installed in the Experimental House in comparison to the condensing central furnace installed in the Control House during the test period are presented in detail. The events log listed in Appendix B, provides the testing periods, and the daily minimum, average and maximum outdoor temperatures and the total vertical solar gain values are given in Appendix F.

5.1.1. DV Wall and Condensing Furnaces: Typical Daily Operation Profiles

Shown in Figures 18-20 are the typical daily operation temperature and energy consumption of the DV modulating wall furnace heating system. Figure 21 and Figure 22 show the thermostat temperature profiles for the Experimental and Control houses heated with the DV wall furnaces and condensing furnace respectively.



It can be seen from Figure 18 and Figure 19 that the Experimental house first-floor DV wall furnace supply air daily temperature profiles are more stable than the second floor profiles due to its continuous operation compared to the frequent cycling of the second floor unit. Further, the supply temperature by the DV units in the Experimental House is higher than the one in Control House heated by the condensing furnace. As shown in Figure 21 and Figure 22, the DV wall furnaces thermostat temperatures have a smoother profile compared to the condensing central furnace thermostat temperature in the Control house due to the thermistor's narrow deadband of 0.2 °F.

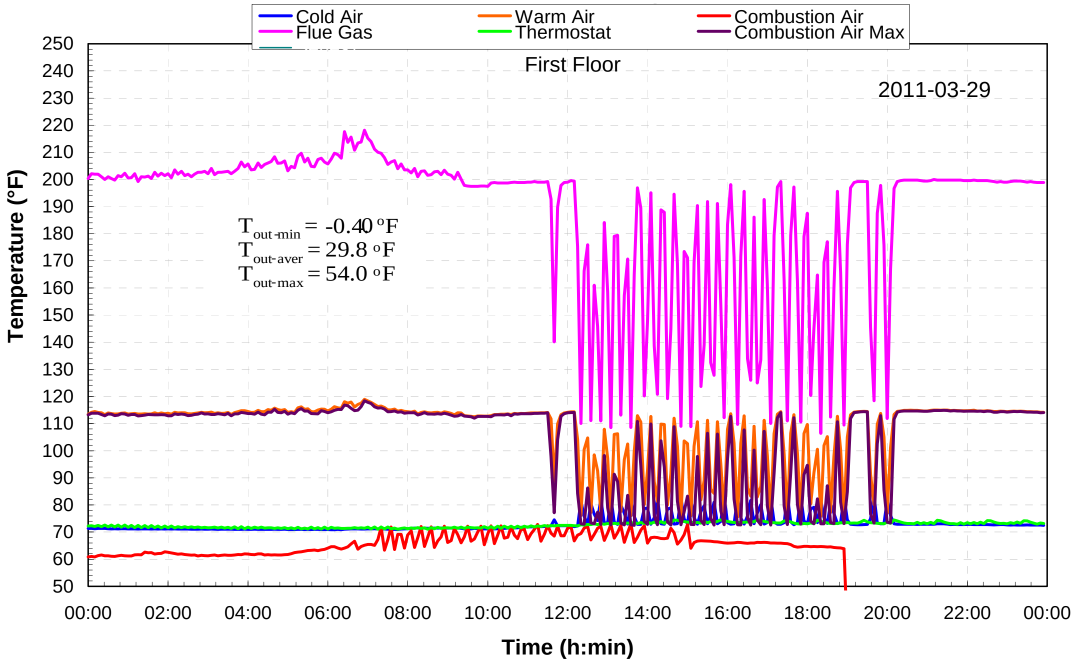


Figure 18: DV Wall Furnace Daily Typical First-floor Temperature Profile

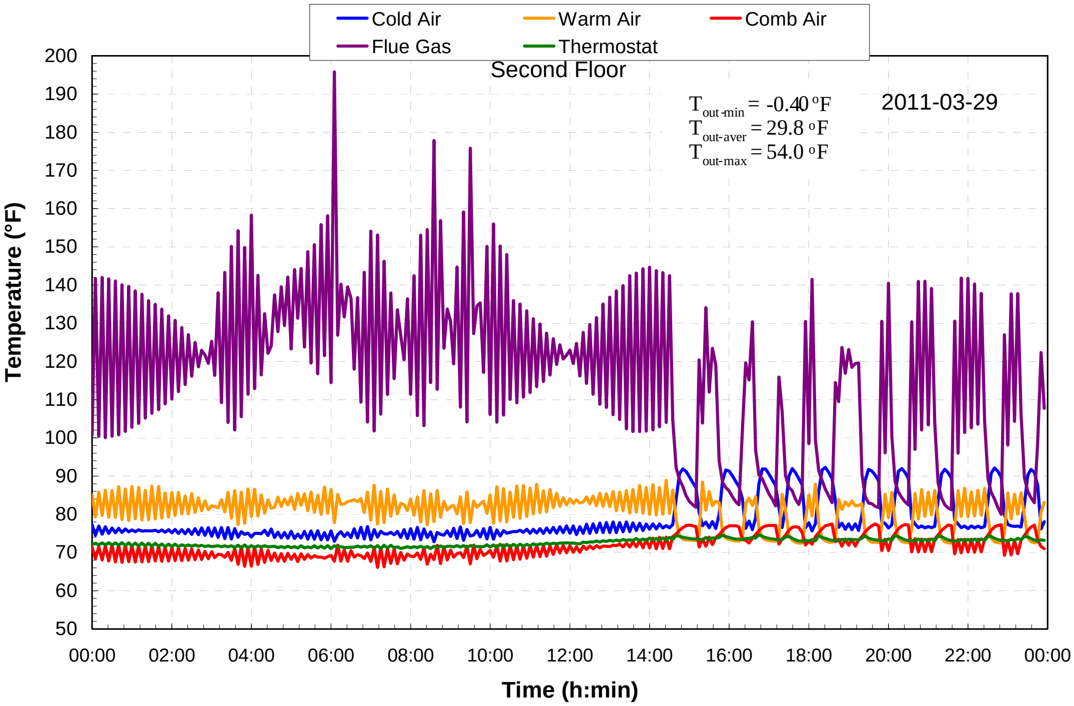


Figure 19: DV Wall Furnace Daily Typical Second-floor Temperature Profile

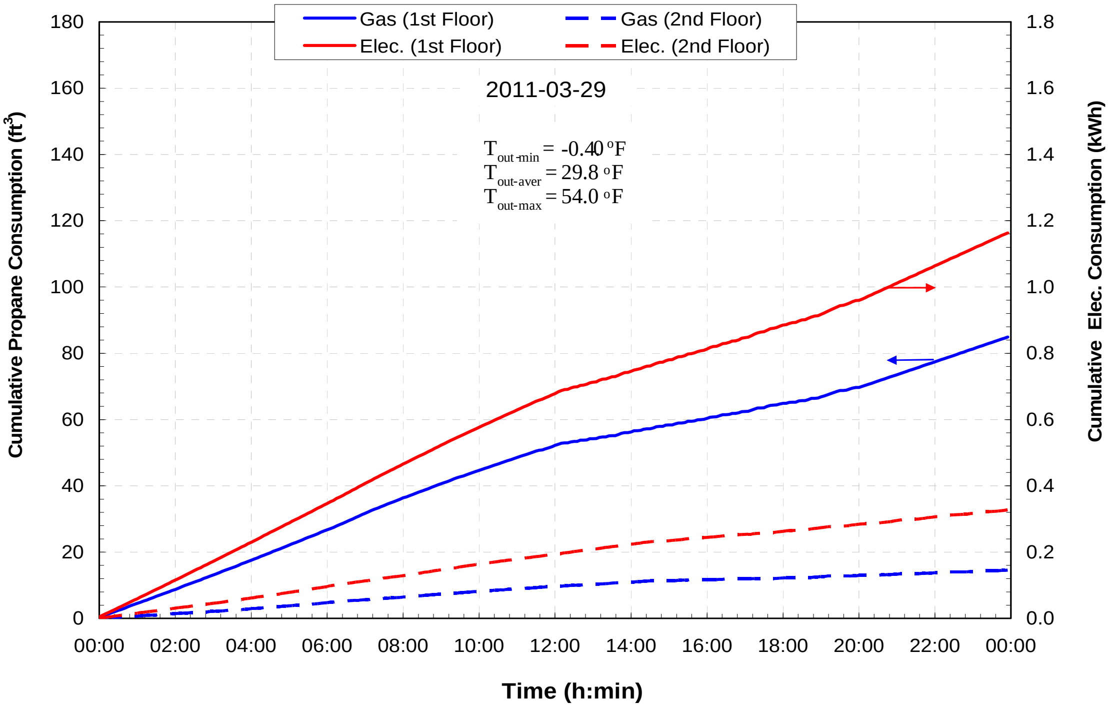


Figure 20: DV Wall Furnace Typical Daily Propane and Electrical Consumptions

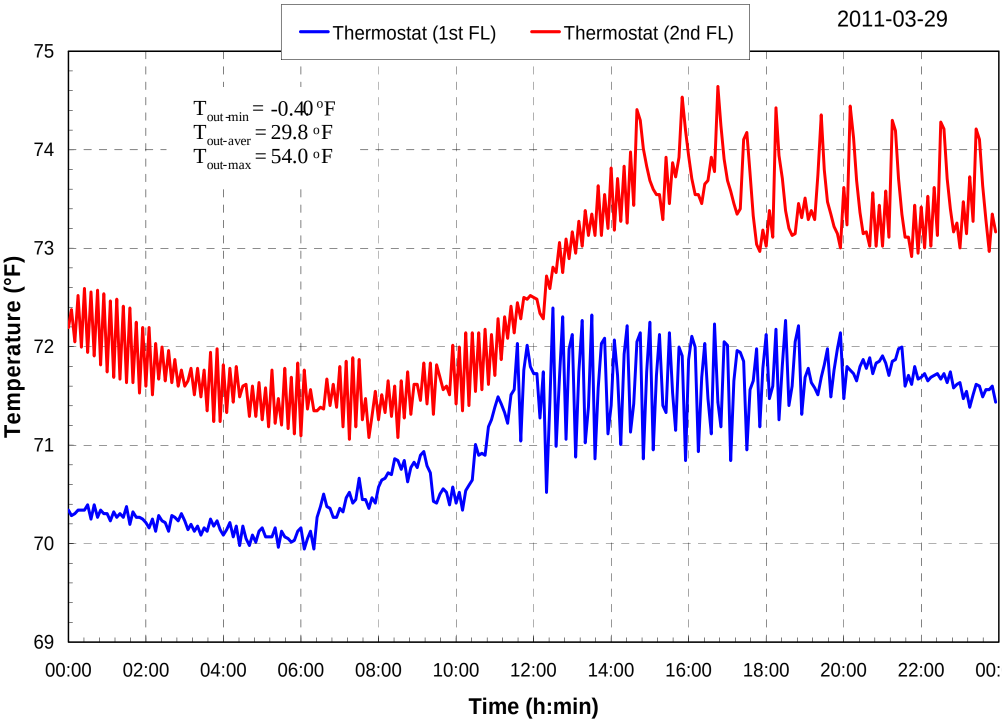


Figure 21: DV Wall Furnace First- and Second-Floor Thermostat Temperature Profiles

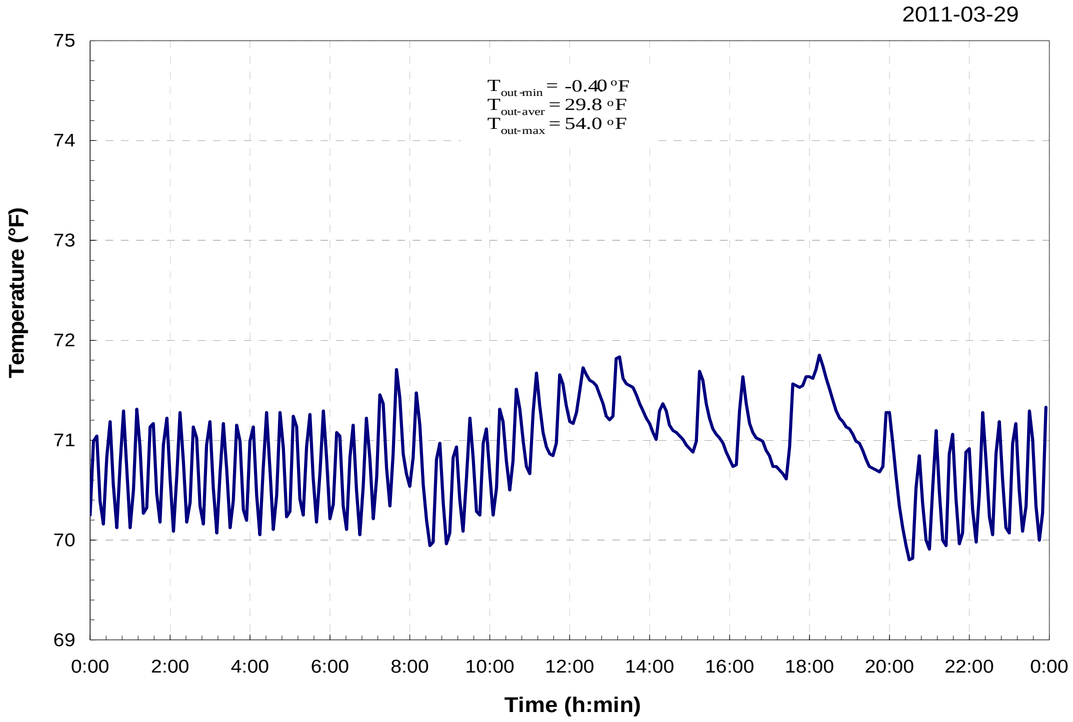


Figure 22: Condensing Furnace Daily Thermostat Temperature Profile

5.1.2. DV Wall and Condensing Furnaces: Daily On-time and Cycles

The frequency of operation (number and length of the cycles) of the DV wall and condensing furnaces during the testing period are presented in Figure 23 and Figure 24.

Figure 23 shows the daily on-time cycles comparison between the DV wall furnaces and the condensing central furnace. The DV wall furnace in the first floor operated practically continuously, while the unit on the second floor cycled frequently, between 60 and 140 cycles with daily on-time operation between 1.5 and 7 hours, as depicted in Figure 24. The on-off condensing furnace operated daily in average on-time between 4 and 8 hours with average outdoor temperatures ranging between 11.7 and 45.7 ^{o}F (-11.3 and 7.6 ^{o}C). It can be seen that the furnace on-time and cycles are a function of the outdoor ambient temperature and solar gain.

In general, during the test period, the DV wall furnaces experienced a higher number of daily cycles with longer on-time operation compared to the on-off condensing furnace.

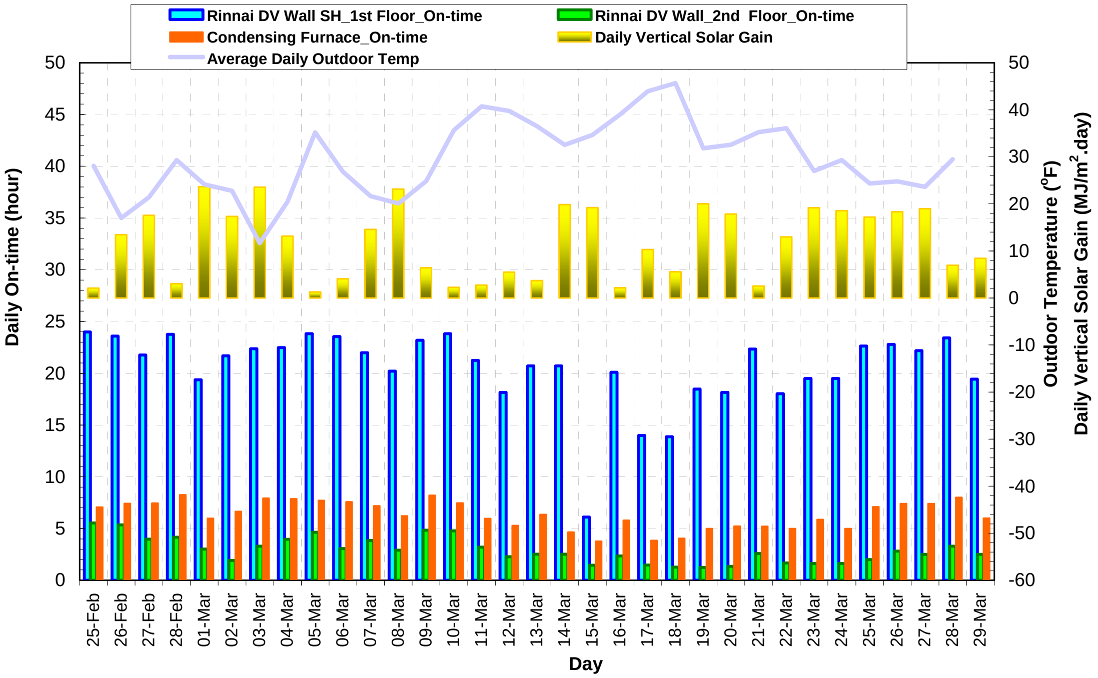


Figure 23: DV Wall Furnace Daily On-time as a Function of Average Outdoor Temperature and Vertical Solar Gain

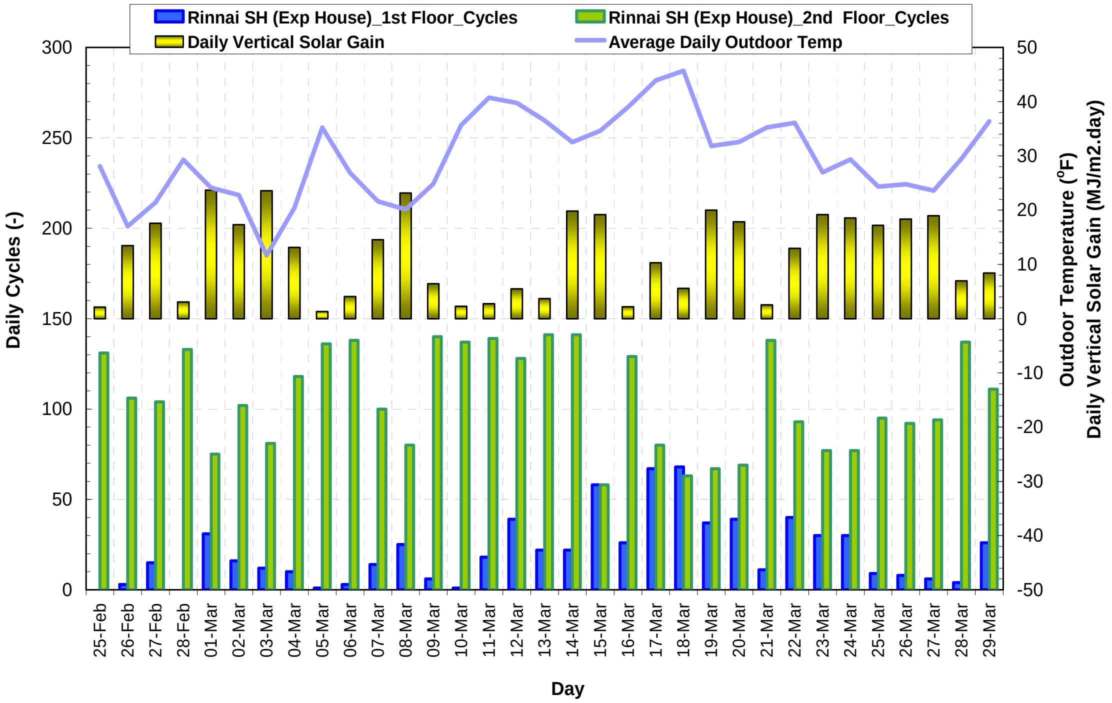


Figure 24: DV Wall Furnace Daily Cycles as a Function of Average Outdoor Temperature and Vertical Solar Gain

5.1.3. Electric and Propane Gas Consumption Test Results

5.1.3.1. Electric Consumption

A comparison between the electrical consumption of the DV wall furnaces in the Experimental House and the condensing furnace in the Control House is presented in Figure 25. It can be seen that the DV wall furnaces (with and without air share units) consume much less electricity than the condensing furnace. The electric consumption of the DV wall furnace alone averaged 1.5 kWh during the testing period. The DV wall furnace system (including the air share units) electrical consumption averaged 4.3 kWh during testing. The condensing central furnace system electric consumption ranged from 3.5 to 7.5 kWh, with an average of 5 kWh. The effect of the outdoor ambient air temperature on the electrical consumption for both DV wall and condensing furnaces is depicted in Appendix G. It can be seen than the furnace electric consumption depends on the weather conditions such as solar radiation and the house thermal status and operating conditions.

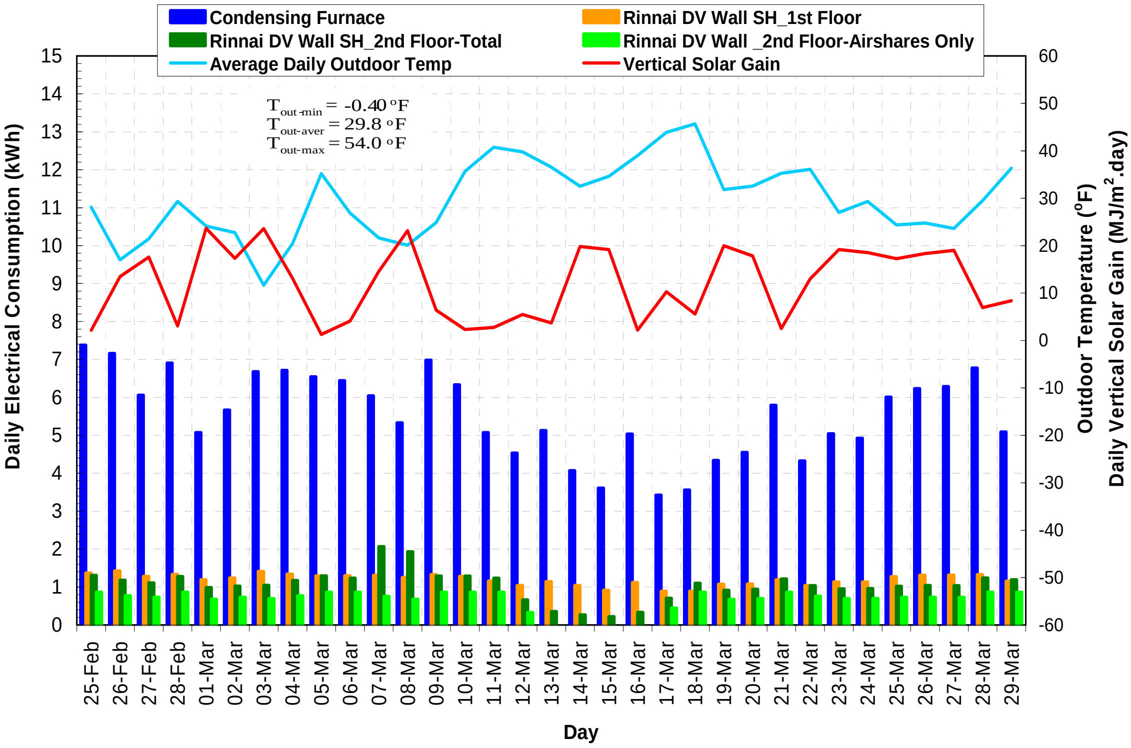


Figure 25: DV Wall Furnace Daily Cycles as a Function of Average Outdoor Temperature and Vertical Solar Gain

5.1.3.2. Propane Consumption

Figures 26-29 (Figure 26, Figure 27, Figure 28, and Figure 29) present a comparison in propane consumption between the DV wall furnaces in the Experiment House and condensing central furnace in the Control House. As shown in the figures, the DV wall furnaces propane consumption is in the same order as that of the condensing central furnace. The DV wall furnaces daily propane consumption during the test period averaged 2.4 gallons or 89 ft^3 (First-Floor Unit), 0.4 gallons or 15 ft^3 (Second-Floor Unit), and 2.8 gallons or 104 ft^3 (First- and Second-Floor Units Combined). The daily propane consumption for the condensing central furnace was in average of 2.7 gallons or 99 ft^3, for the same period which is about 5 % lower than the DV wall furnaces consumption. This is illustrated in Figure 29, showing the propane consumption differences profiled during the five weeks of testing. Note that in general, the Experimental House heated by the DV wall furnaces was warmer than the Control House, by about 1-3 ^oF as illustrated in a typical daily temperature control profile in Section 5.1. This in part could explain the difference in propane consumption. Note that additional information and explanation of the difference in propane consumption is given in the House Performance section, Section 5.2. As for the electric consumption, the effect of the outdoor ambient air temperature on the propane consumption for both DV wall and condensing central furnaces is shown in Appendix G. Similar to the electric consumption; the propane consumption follows the same trend.

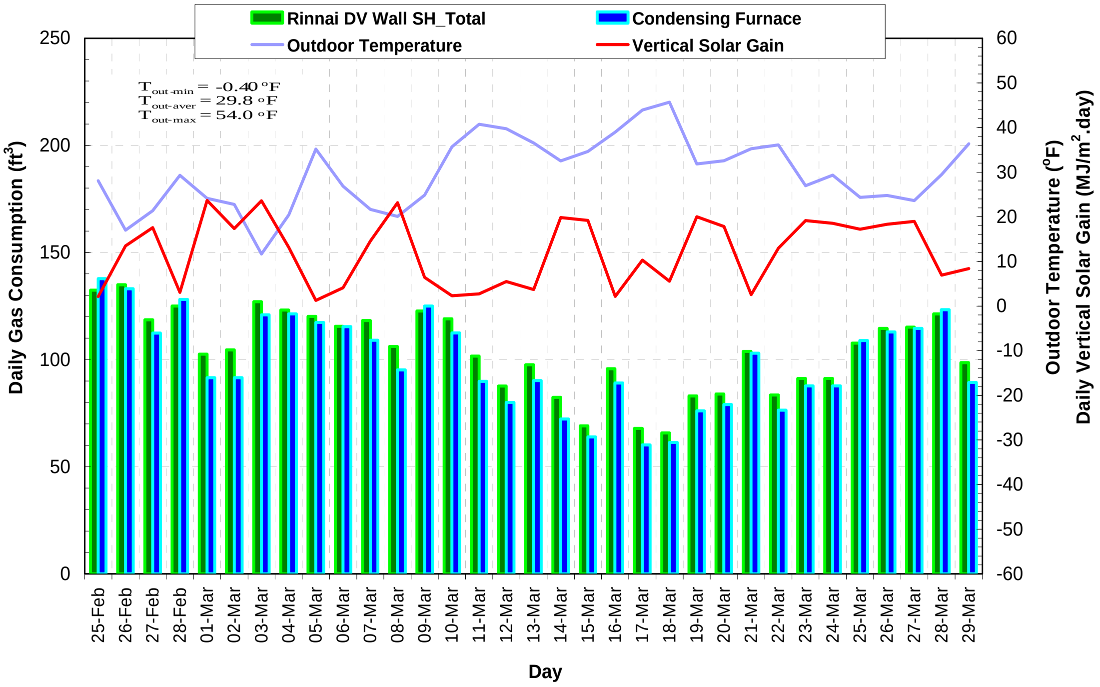


Figure 26: DV Wall Furnace Daily Propane Consumption (ft³) as a Function of Average Outdoor Temperature and Vertical Solar Gain

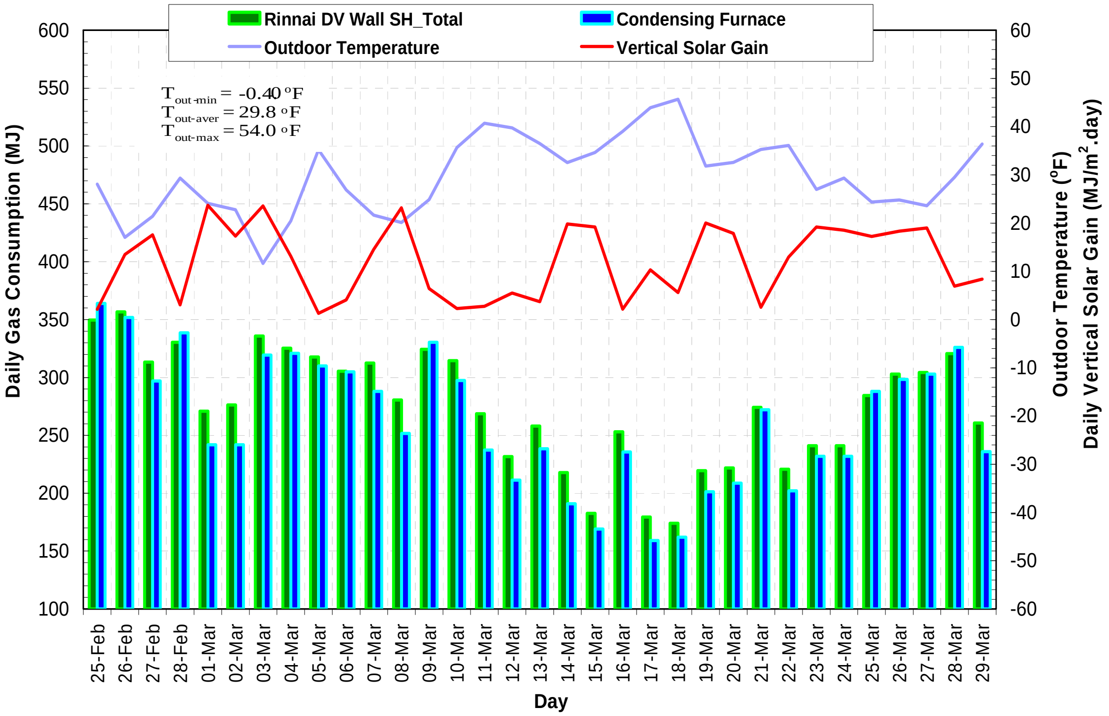


Figure 27: DV Wall Furnace Daily Propane Consumption (MJ) as a Function of Average Outdoor Temperature and Vertical Solar Gain

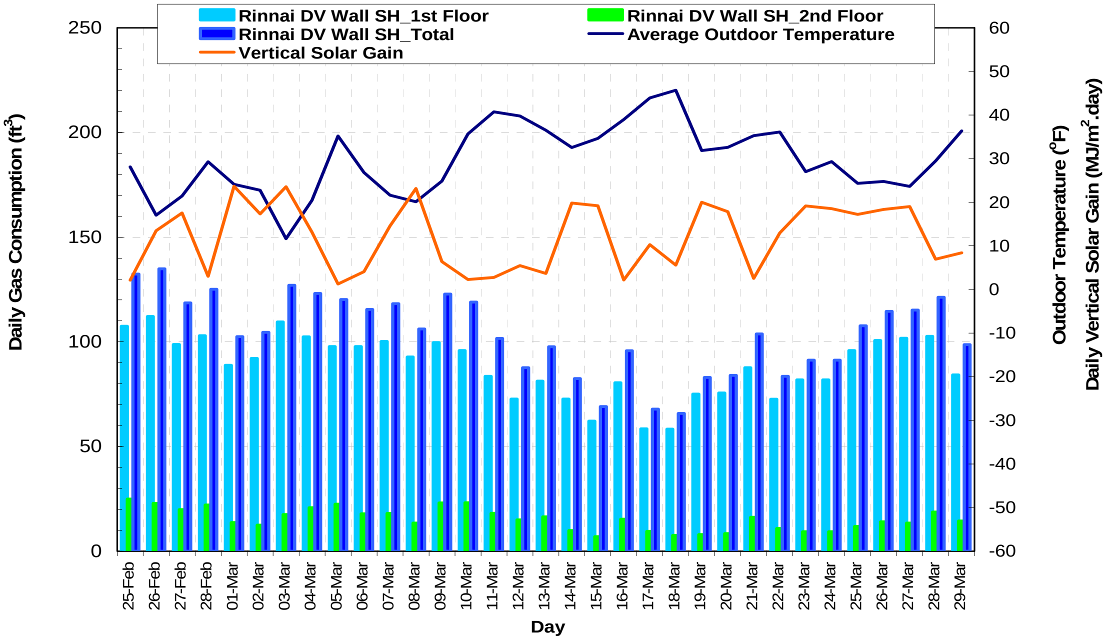


Figure 28: Daily Propane Consumption Comparison between DV Wall and Condensing Furnaces as a Function of Average Outdoor Temperature and Vertical Solar Gain

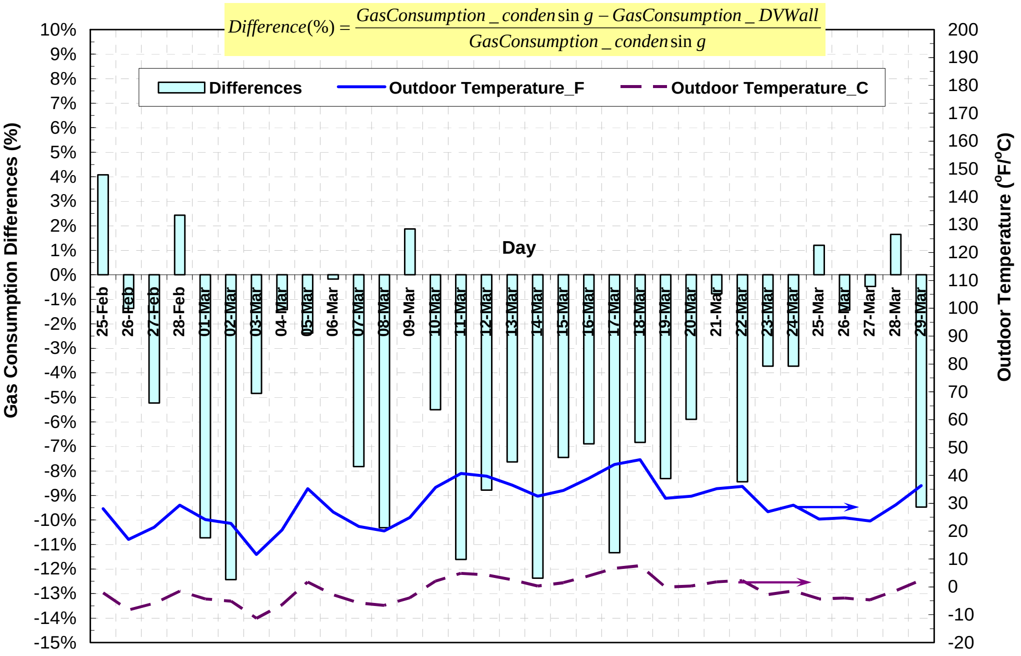


Figure 29: Daily Propane Consumption Differences Comparison between DV Wall and Condensing Furnaces as a Function of Average Outdoor Temperature

Notes for Figures 28 and 29: bedroom doors in the second floor, Experimental House open between 12 and 17 March

5.1.3.3. Total Energy Consumption

A comparison between the daily total energy consumption (propane plus electricity) for the DV wall furnace system in the Experiment House and for the condensing central furnace system in the Control House is shown in Figure 30 and Figure 31. It is that the DV wall furnace system daily total energy consumption is in the same order as the total consumption of the condensing central furnace system. Based on the fact that the electrical consumption of the DV wall furnace system is on average 78 % lower than the condensing central furnace, the DV wall furnace system total energy consumption during the testing period was on average 279 MJ/day, compared to 282 MJ/day for the condensing central furnace system, or 0.5 % higher than the DV wall furnace system's total energy consumption. This is well illustrated in Figure 31, Figures G.3-G.5 (Appendix G), where the effect of the outdoor ambient air temperature and the temperature difference between the indoor and outdoor temperature on the daily total energy consumption for the DV wall and condensing central furnace systems are presented. A detailed comparison between both systems is presented in Appendix G.

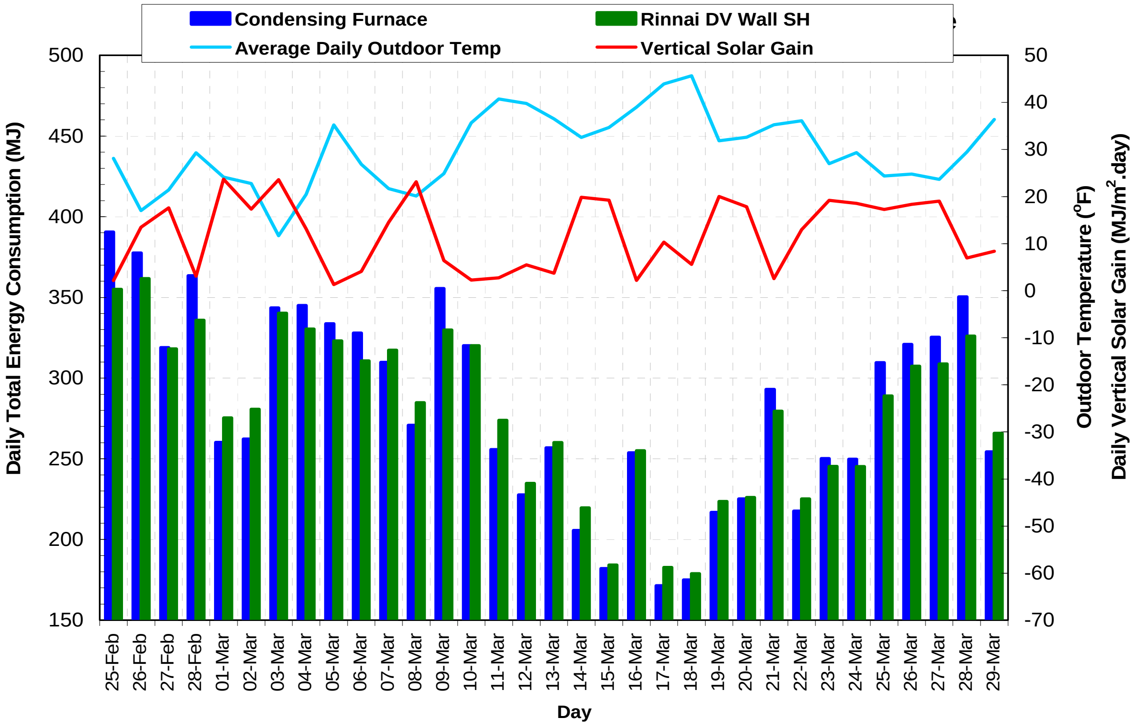


Figure 30: Daily Total Energy Consumption Comparison between DV Wall and Condensing Central Furnace System as a Function of Average Outdoor Temperature and Vertical Solar Gain

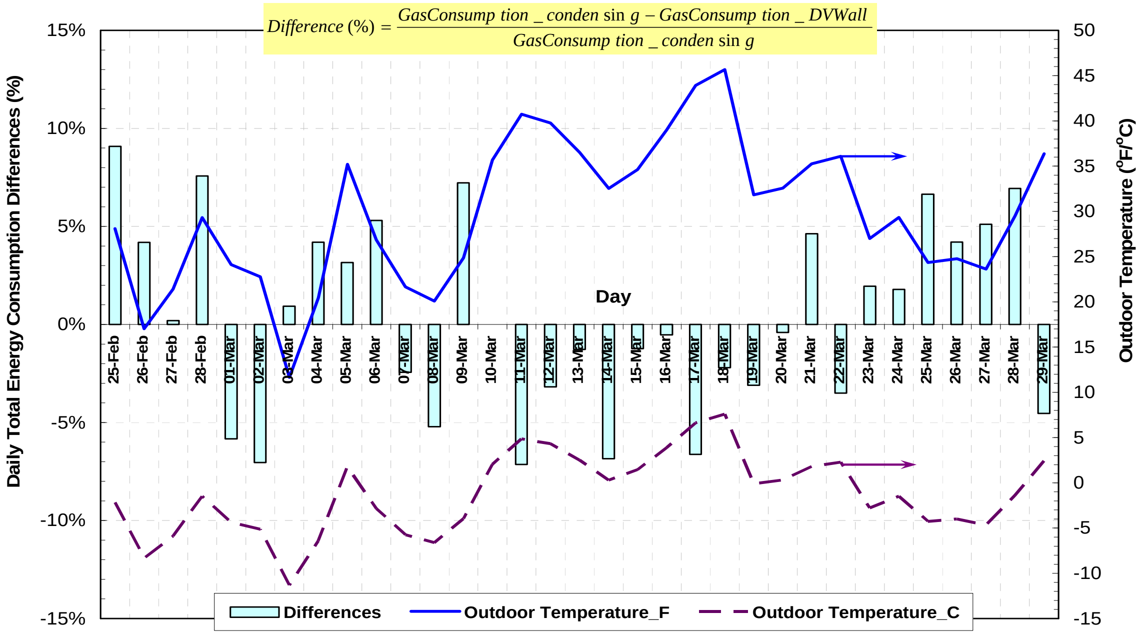


Figure 31: Daily Propane Consumption Differences Comparison between DV Wall and Condensing Central Furnace Systems as a Function of Average Outdoor Temperature

5.1.3.4. *DV Wall Furnaces Heat Input*

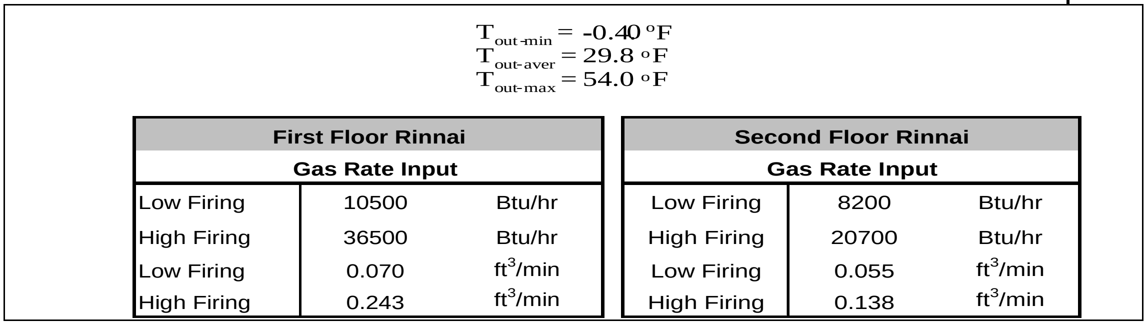
Table 2, Figure 32, and Figure 32, present the propane energy inputs for the DV wall furnaces installed in the first and second floors. These are calculated based on the on-time firing data presented in Figure 23 and an HHV of 2504 Btu/ft^3.

It can be seen that for an average outdoor temperature of 30 ^oF (-1.1 ^oC), the average propane gas energy inputs during the testing period were 10587, 13745 and 24332 Btu/hr for the first floor, second floor and entire house, respectively. This represents 29 %, 66 % and 48 % of the DV furnaces average energy input of rated maximum.

Table 2: Propane Gas Energy Input for DV Wall Furnaces

	DV Wall Furnace Propane Gas Energy Input					
	First Floor		Second Floor		First and Second Floor	
	(Btu/hr)	(%)	(Btu/hr)	(%)	(Btu/hr)	(%)
Average	10587	29%	13745	66%	24332	48%
Minimum	7782	21%	9688	47%	18471	35%
Maximum	12257	34%	16397	79%	26957	54%

Notes:



$T_{out\text{-}min} = -0.40\ ^oF$
$T_{out\text{-}aver} = 29.8\ ^oF$
$T_{out\text{-}max} = 54.0\ ^oF$

First Floor Rinnai Gas Rate Input		
Low Firing	10500	Btu/hr
High Firing	36500	Btu/hr
Low Firing	0.070	ft^3/min
High Firing	0.243	ft^3/min

Second Floor Rinnai Gas Rate Input		
Low Firing	8200	Btu/hr
High Firing	20700	Btu/hr
Low Firing	0.055	ft^3/min
High Firing	0.138	ft^3/min

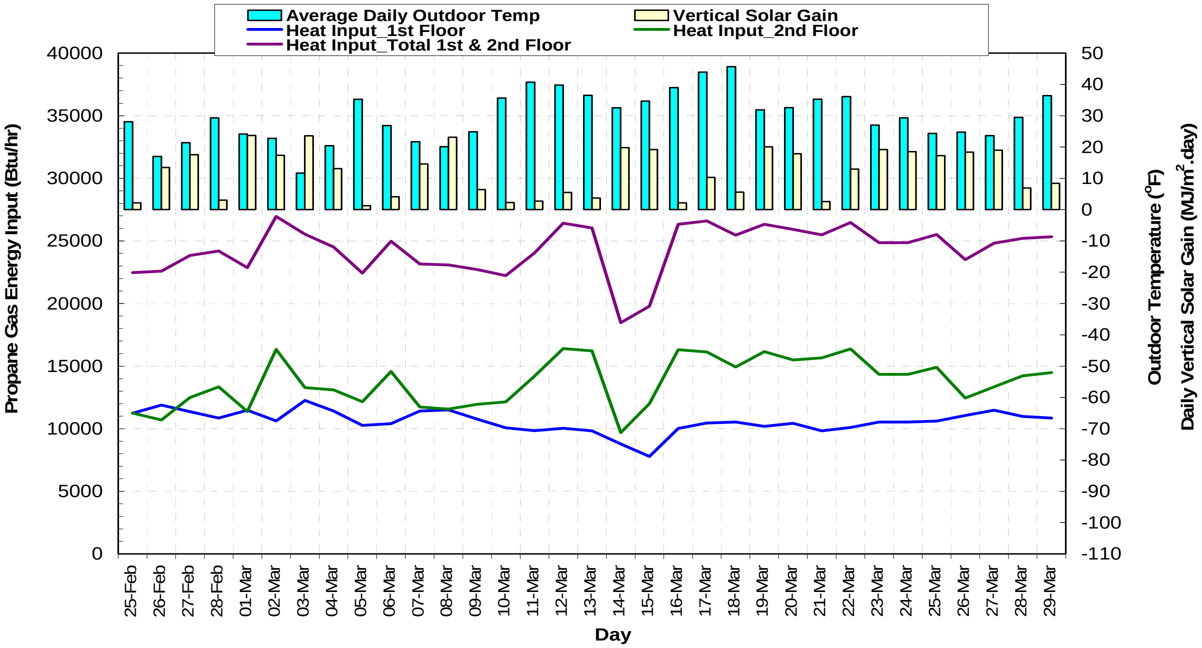


Figure 32: Heat Input (Btu/hr) for DV Wall Furnaces as a Function of Outdoor Temperature and Vertical Solar Gain

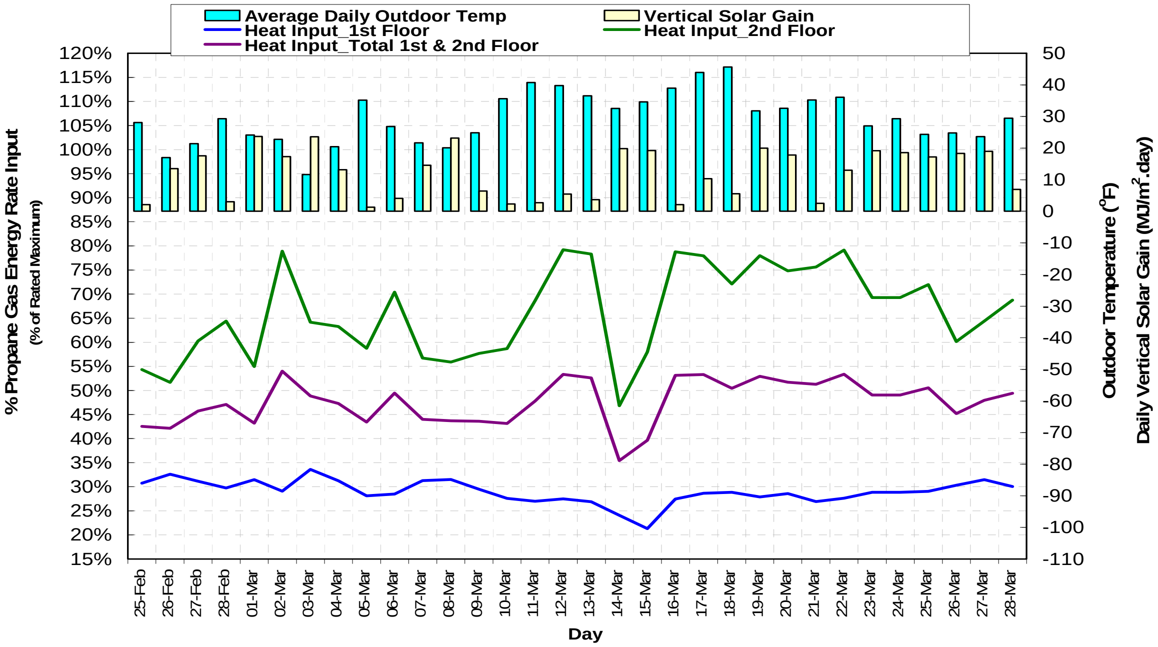


Figure 33: Heat Input (% of Rated Maximum) for DV Wall Furnaces as a Function of Outdoor Temperature and Vertical Solar Gain

5.1.4. Flue Gas Emissions Test Results

The flue gas emissions of the DV wall and condensing central furnaces were measured at the end of the testing period. The concentrations of gases in the exhaust gas were measured with a Horiba PG-250 portable multi-gas analyser at steady state conditions. The measurement results are summarised in Table 3. Details of the emissions test results are provided in Appendix H.

Table 3: DV Wall and Condensing Furnace Flue Gas Emissions

Furnace	**House**	**% of Rated Maximum**	**Flue Gas Emissions**			
			NO_x (ppm)	**CO (ppm)**	**CO_2 (%)**	**O_2 (%)**
DV Wall Furnace	Experimental First Floor	96.0	75.2	4.1	7.05	10.05
		93.9	76.4	3.9	7.09	9.98
DV Wall Furnace	Experimental Second Floor	96.4	97.3	2.8	7.06	10.04
		89.0	92.0	3.3	6.90	10.80
Condensing Furnace	Control	84.1	54.1	7.1	6.9	10.0
Condensing Furnace	Experimental	85.1	43.0	4.5	5.8	11.7

As shown in Table 3, the DV wall furnace NO_x emissions are on average 42 % higher than those obtained on the condensing central furnaces. On the other hand, the CO emissions from the DV wall furnaces are in average 65 % lower than those produced from the condensing furnaces. This could be explained by the fact that the DV wall furnaces are operated at a higher temperature than the condensing furnaces resulting in higher NO_x and lower CO emissions.

5.2. House Performance Test Results and Analysis

5.2.1. Weather Conditions

The minimum, maximum and average outdoor air temperatures for the benchmark and experiment periods are provided in Table 4. A table listing daily values of outdoor air temperature and global solar radiation during the experiment period is also included in Appendix F. Notably, the benchmarking period and experiment period with doors closed experienced similar minimum outdoor temperatures. However, these minimum temperatures were still warmer than the design temperature for Ottawa, -13°F (-25°C). The short four-day experiment period with doors open did not reach the same minimum outdoor temperature as the doors closed portion of the experiment, with the outdoor temperature dropping to only 24.3°F (-4.3°C).

Table 4: Outdoor Air Temperature

	Dates	**Min °F (°C)**	**Max °F (°C)**	**Average °F (°C)**
Benchmarking	10-Feb-11 to 20-Feb-11 and 3-Apr-11 to 18-Apr-11	1.2 (-17.1)	77.2 (25.1)	35.6 (2.0)
Experiment Doors Closed	25-Feb-11 to 11-Mar-11 and 18-Mar-11 to 29-Mar-11	-0.4 (-18.0)	54.0 (12.2)	28.0 (-2.2)
Experiment Doors Open	13-Mar-11 to 16-Mar-11	24.3 (-4.3)	45.7 (7.6)	35.6 (2.0)

5.2.2. Energy Consumption

5.2.2.1. *Total Heating System Energy Consumption*

The impact of the DV wall furnace system on energy consumption can be evaluated on a daily basis.

Figure 34 compares total energy consumption (propane and electricity) of the condensing central furnace system in the Control House, and both the condensing central furnace system during benchmarking and the DV wall furnace system during the experiment in the Experimental House.

The Control House daily consumption is plotted on the x-axis. The Experimental House daily consumption is plotted on the y-axis. Each data point represents a single day of consumption. If the houses were completely identical, the resulting benchmark trend would have a perfect slope of 1 (a 45-degree angle) with an intercept of 0. The condensing central furnace benchmark data (shown in black) has a slope of 0.955 and intercept of 3.55. The fact that the benchmark is not perfect is the result of small differences in the houses – if the houses were identical, there would be no reason to benchmark. The differences in benchmarking are accounted for in the savings calculation method. Refer to Appendix I for a description of this method.

Results from the DV wall furnace system operation with bedroom doors closed are plotted in pink. Most experiment points lie above the benchmark line – an indication of an increase in overall heating system energy consumption. However, a few points fall below the benchmark line, particularly during high heating loads. This may be an indication of the DV wall furnace system showing savings at colder temperatures. More cold weather data is required to further explore this phenomenon, and to verify the DV wall furnace system trend.

The experiment portion with doors open is plotted as blue diamonds, with transition days to and from doors-open plotted in green. The doors open total consumption data fall within the scatter of the data collected during the experiment period with doors closed.

The average increase in heating system consumption for the test period (doors closed) was 10.8 MJ/day (3.7 %). Change in consumption due to the DV wall furnace system ranged from -14.5 (savings) to 33.8 (increase) MJ/day, -3.9 % to 14 %.

Daily consumption data and savings calculations are provided in Appendix J.

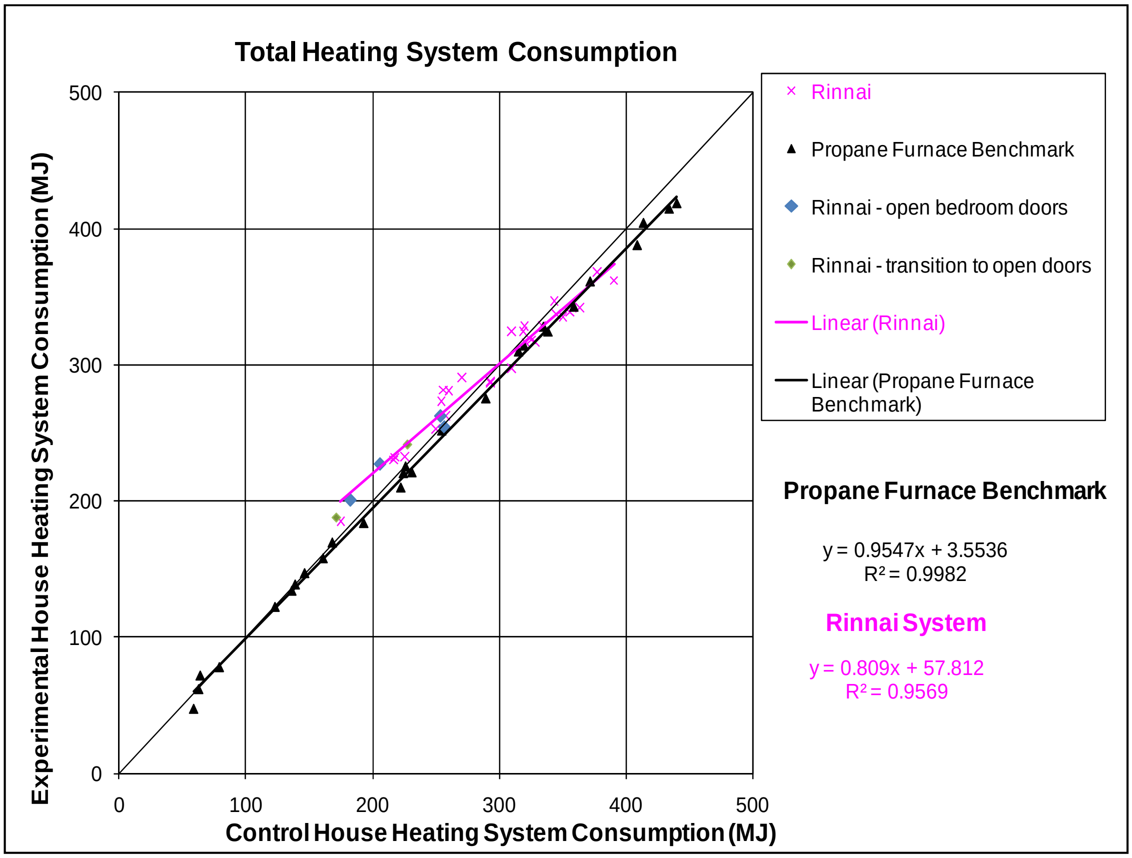


Figure 34: Daily Total Heating System Energy Consumption (Propane and Electricity)

5.2.2.2. Heating System Propane Consumption

The total heating energy consumption in the previous section is composed of both propane and electricity consumption. A similar analysis can be performed for propane consumption alone. The daily propane consumption trends are shown for the Benchmark and DV wall furnace experiment in Figure 35.

All the points from the DV wall furnace experiment lie above the benchmark line, indicating an increase in propane consumption. For the experiment period with doors closed, the average increase in propane consumption was 26.1 MJ/day (10 %). The increase in consumption ranged from 5.5 to 46.1 MJ/day (1.6 % to 20 %).

A daily breakdown of propane consumption is included in Appendix J.

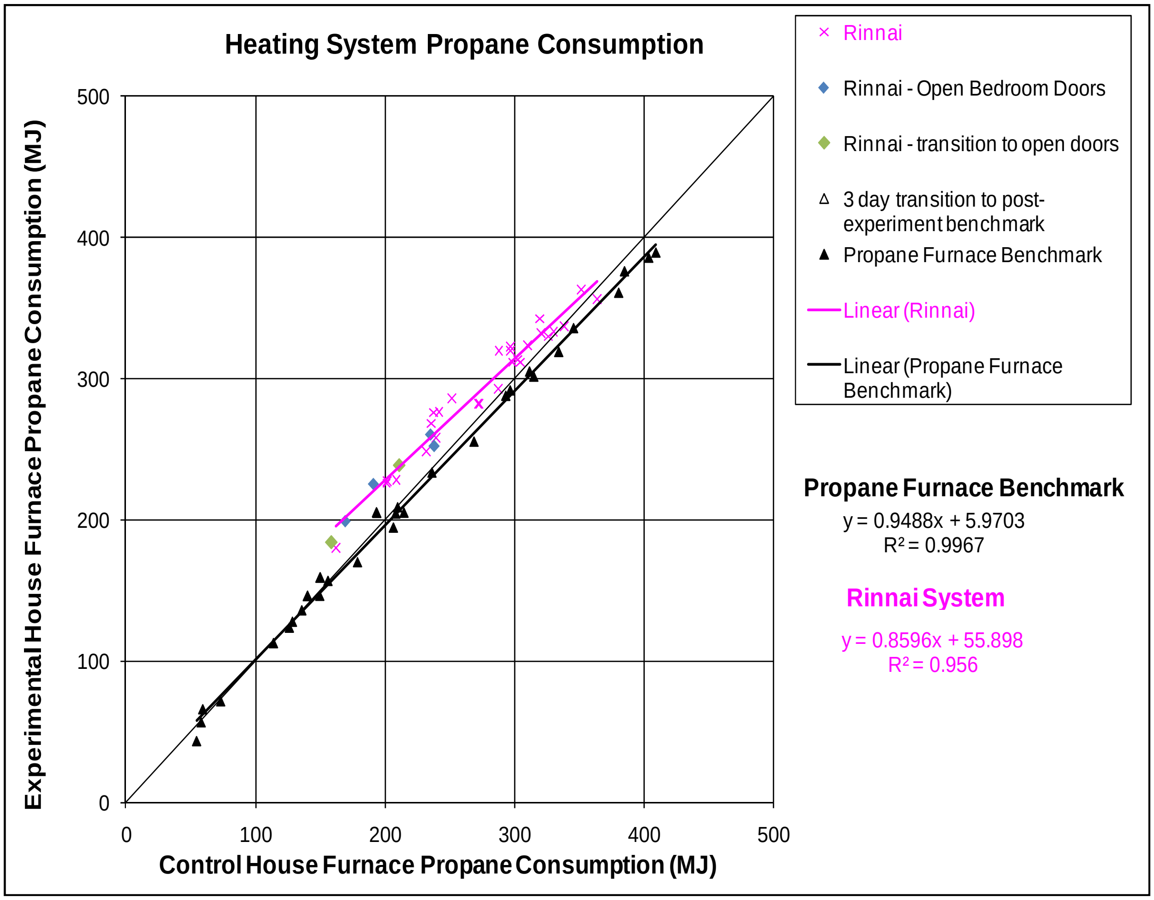


Figure 35: Daily Total Heating System Propane Consumption

5.2.2.3. Heating System Electrical Consumption

Daily heating system electrical consumption is plotted in Figure 36. The DV wall furnace experiment trend line (doors closed) is well below the benchmark line, indicating significant energy savings. The average decrease in heating system electrical consumption for the test period (doors closed) was 4.3 kWh/day (76 %). Savings ranged from 2.1 to 5.5 kWh/day, 62 % to 80 %.

During the four-day experiment period with the doors open (plotted as blue diamonds), the air share units were shut off. As a result, the electrical savings during this period were ever more substantial – ranging from 87 to 89 %.

During the experiment with doors closed, the two air share units were responsible for between 55 to 65 % of the total daily electrical consumption of the DV wall furnace System.

The breakdown of daily electrical consumption and savings are provided in Appendix J.

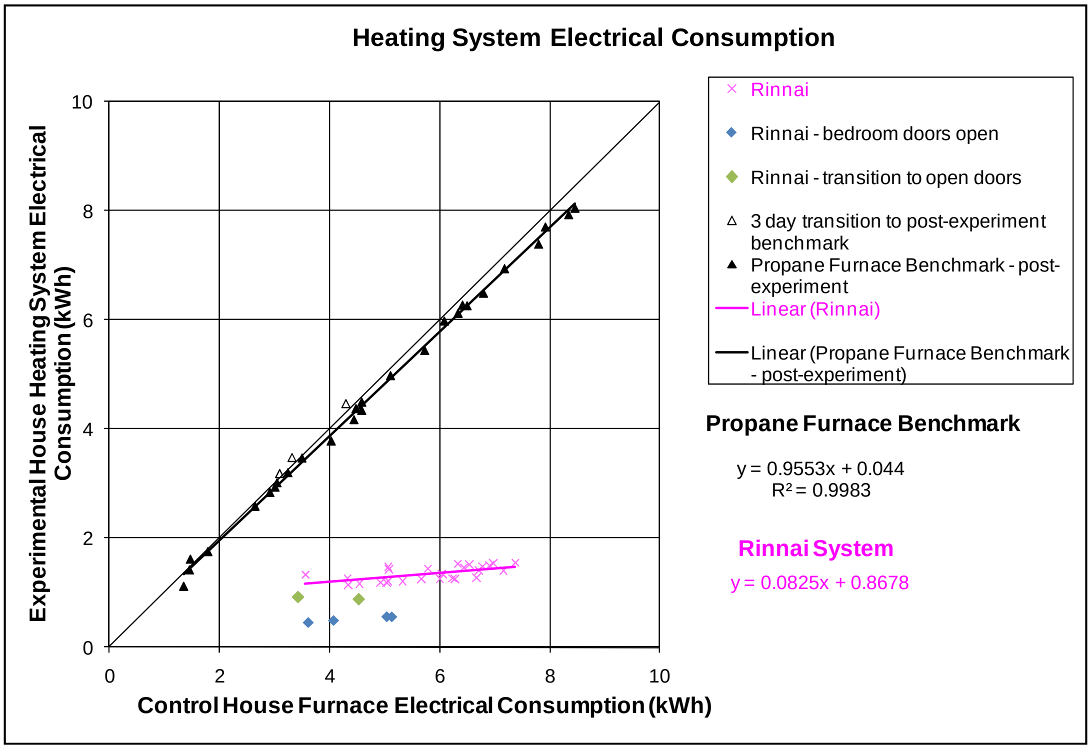


Figure 36: Daily Total Heating System Electrical Consumption

5.2.3. House Temperatures

5.2.3.1. Basement Temperature

During the experiment, the basement temperatures of the two houses differed. Despite the three basement supply ducts and one basement return duct being shut off during propane furnace operation, heat losses from the duct work and duct air leakage likely still contributed to warming the basement space. During the benchmarking period prior to the experiment (with propane furnaces operating in both houses), the basement air temperature was between 60.8 and 64.4 °F (16 and 18 °C). During the experiment, the temperature in the Experimental House with the DV wall furnace System dropped to approximately 57.2 °F (14°C). The air temperature measurement shown in the graph was taken ~2 ft (60 cm) out from the North basement wall, at a height of ~2 ft (60 cm) (Figure 37).

The basement wall temperature was also affected. Prior to the experiment, the Experimental House concrete wall surface temperature, measured near the base of the wall behind batt insulation, was slightly warmer than the Control House wall. During the Experiment, the reverse was true – with the Experimental House wall slightly cooler than the Control House wall. As a result, there was a lingering impact on the benchmark energy consumption following the experiment period, as the mass of concrete in the Experimental House basement warmed up. Official post-experiment benchmarking was delayed 3 days until the daily energy consumption trend returned to the benchmark line.

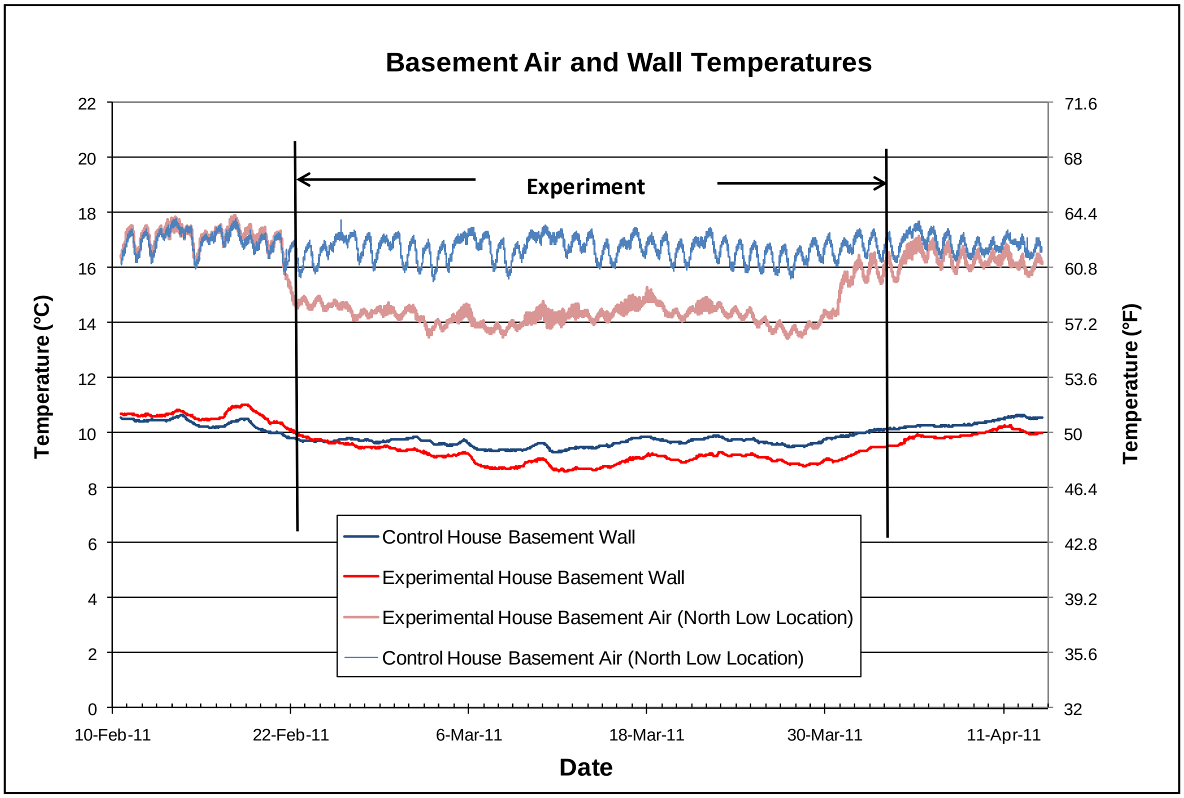


Figure 37: Basement Air and Wall Surface Temperatures

5.2.3.2. Main Floor Temperatures

Temperature results show that throughout the experiment period, the DV wall furnace system maintained the air temperature in all main floor rooms above 68°F (20°C) at a location 2 ft in from an outside wall and 3 ft up. Thus, temperature performance met the requirements of the 2006 International Residential Code. In all measured locations, the main floor room temperatures were in fact warmer due to DV wall furnace system operation, compared to the benchmark condensing central furnace reference system.

This section contains detailed room temperature analysis from the benchmark and experiment periods. All graphs contain temperature data from the benchmark period (plotted in black), the transition periods (plotted in grey), the DV wall furnace experiment with doors open (plotted in pink), and with doors closed (plotted in blue).

Two graphs are provided for each room: one graph for the Control House – featuring the propane furnace heating system, and one for the Experimental House – featuring the propane furnace heating system during benchmarking, and the DV wall furnace system during the experiment.

Graphs of individual sample benchmark and experiment days from each room are provided in Appendix K.

Family Room

The air temperatures in the Control House and Experimental House family room are plotted in Figure 38 and Figure 39, respectively. This temperature was measured at a location 2 ft in from an outside wall and 3 ft up. The family room is located in the northeast corner of the main floor of the home, and is also the location of the main floor DV wall furnace heater. In the Control House the temperature is regulated by a centrally located thermostat. In this house, the room temperature occasionally dips below the 68 °F (20 °C) IRC requirement, both during the benchmark period and the experiment period (Figure 38). The same is true during the benchmark period in the Experimental House – when the propane furnace was providing heat. However, during the experiment, the temperature at the measurement location was approximately 3.6 °F (2 °C) warmer in the Experimental House than in the Control House, well above the 68 °F (20 °C) threshold.

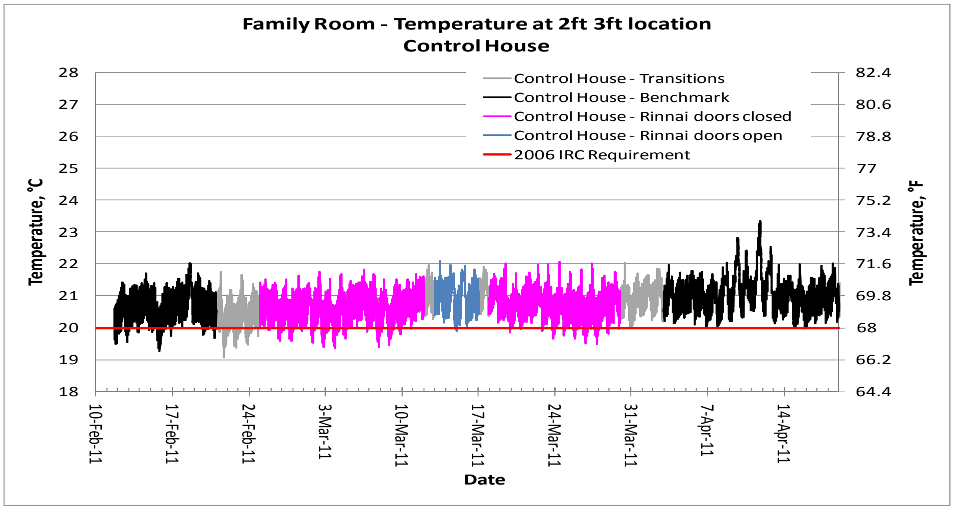


Figure 38: Family Room Temperature in the Control House

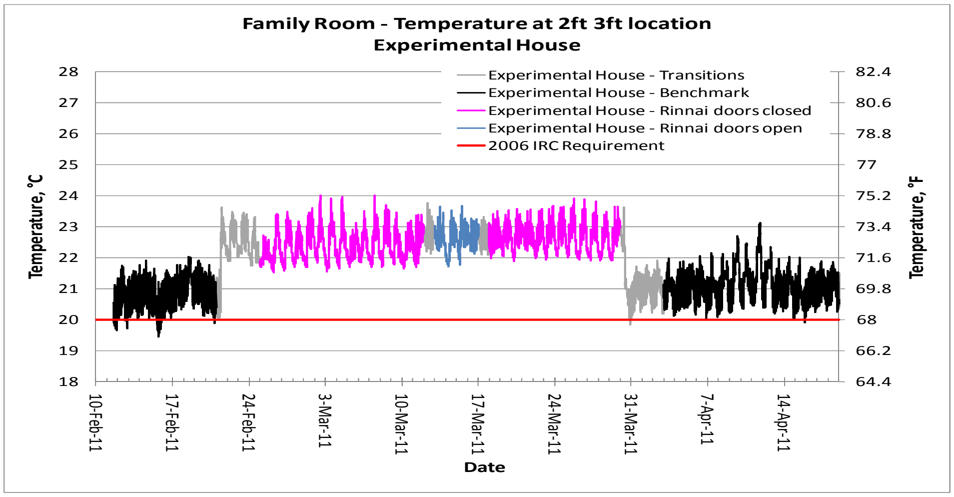


Figure 39: Family Room temperature in the Experimental House

Dining Room

The air temperatures in the Control House and Experimental House dining room are plotted in Figure 40 and Figure 41 respectively. This temperature was measured at a location 2 ft in from an outside wall and 3 ft up. The dining room is located in the northwest corner of the main floor of the home. In the Control House, the propane furnace maintained the air temperature at this location above 20 °C (68 °F) for most of the benchmark and experiment period. Temperatures were similar in the two houses during benchmarking. During the experiment, the Experimental House temperature was warmer than the Control House temperature, and varied between 21°C (69.8 °F) and 23 °C (73.4 °F).

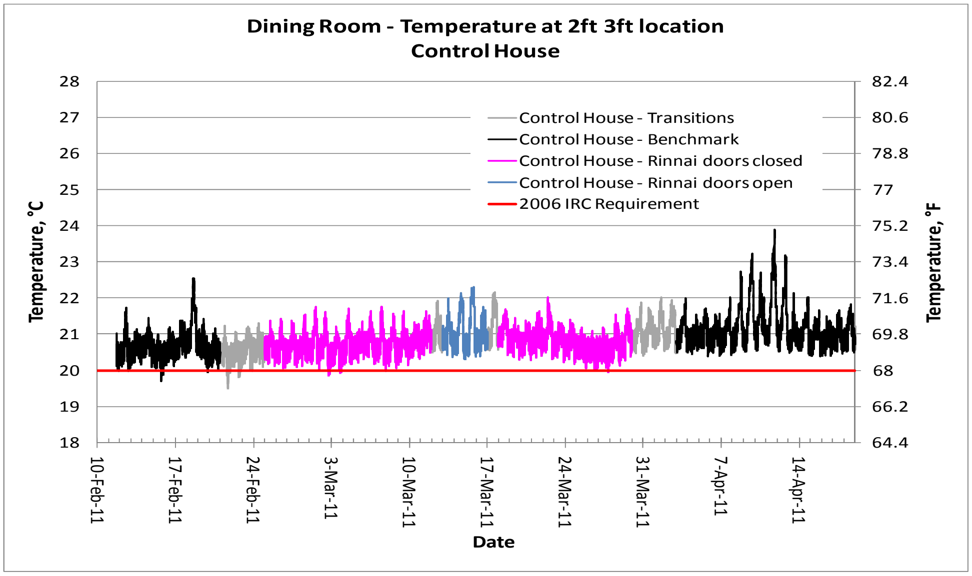


Figure 40: Dining Room Temperature in the Control House

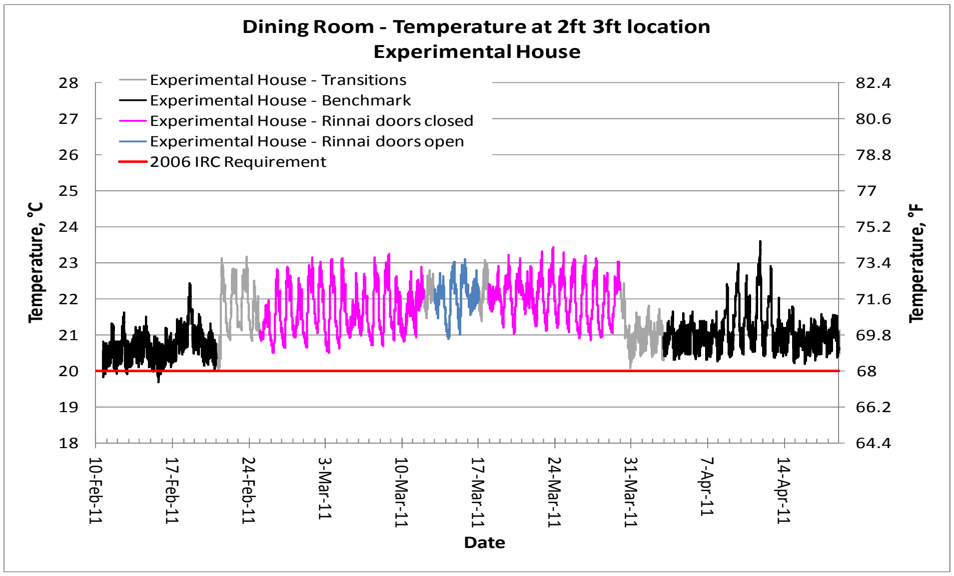


Figure 41: Dining Room Temperature in the Experimental House

Living Room

The air temperatures in the Control House and Experimental House living room are plotted in Figure 42 and Figure 43, respectively. This temperature was measured at a location 2 ft in from an outside wall and 3 ft up. The living room is located in the southwest corner of the main floor of the home. Daily temperature spikes are seen in both houses due to solar gains through this room's large south facing window, and local heating of the thermocouple due to these gains. During the experiment, the living room temperature in the Experimental House was maintained above the 20 °C (68 °F) threshold, and was again warmer than the temperature in the Control house.

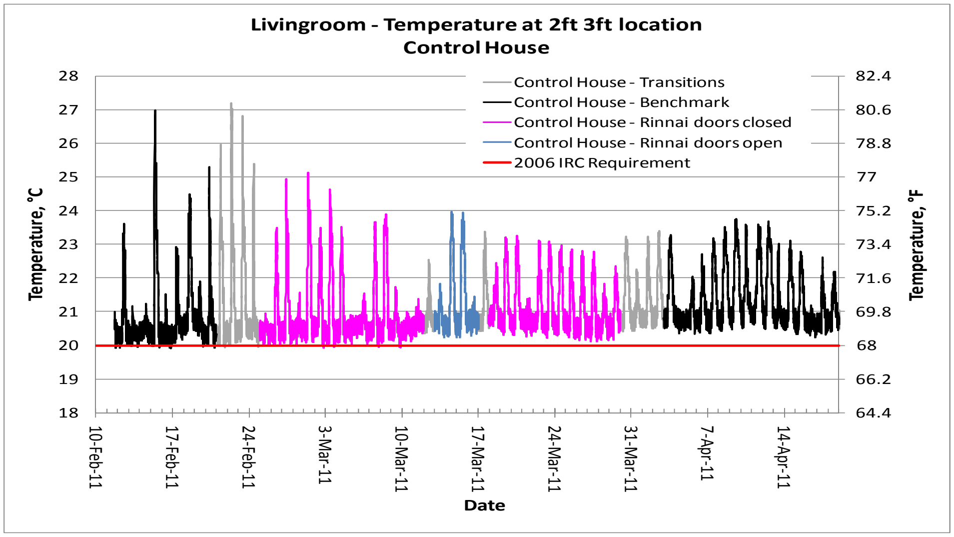


Figure 42: Living room Temperature in the Control House

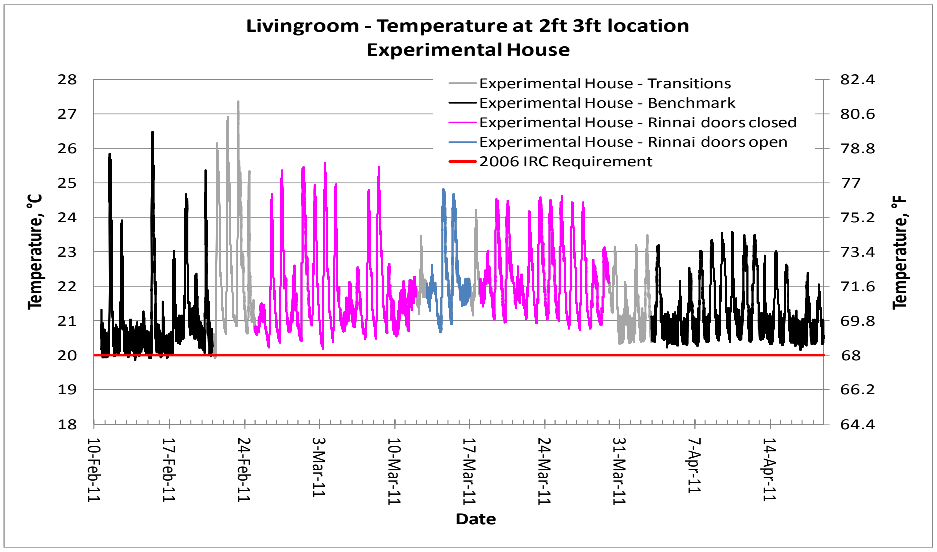


Figure 43: Living room Temperature in the Experimental House

Powder Room

The air temperatures in the Control House and Experimental House powder room are plotted in Figure 44 and Figure 45, respectively. This temperature was measured at a central location 39.4 in. (1 m) above the floor. The powder room is located near the entrance on the main floor of the home. There is no clear view of the DV unit from this room, and hot air must pass through the hallway and around two corners to reach the room. Despite this challenging layout, heat successfully reached the powder room. The powder room temperature in the Experimental House was maintained above the 68 °F (20 °C) threshold.

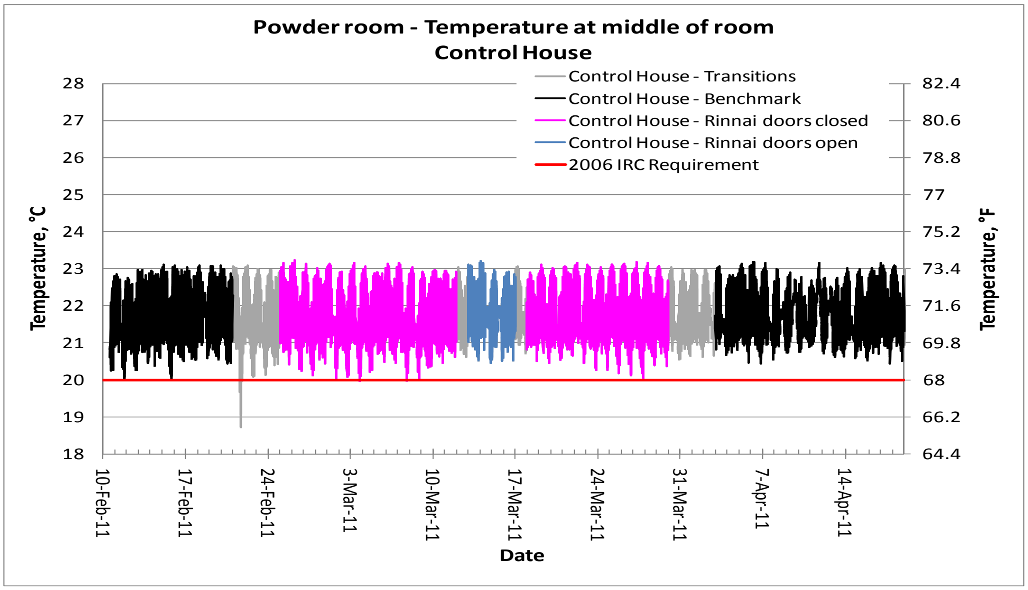


Figure 44: Powder Room Temperature in the Control House

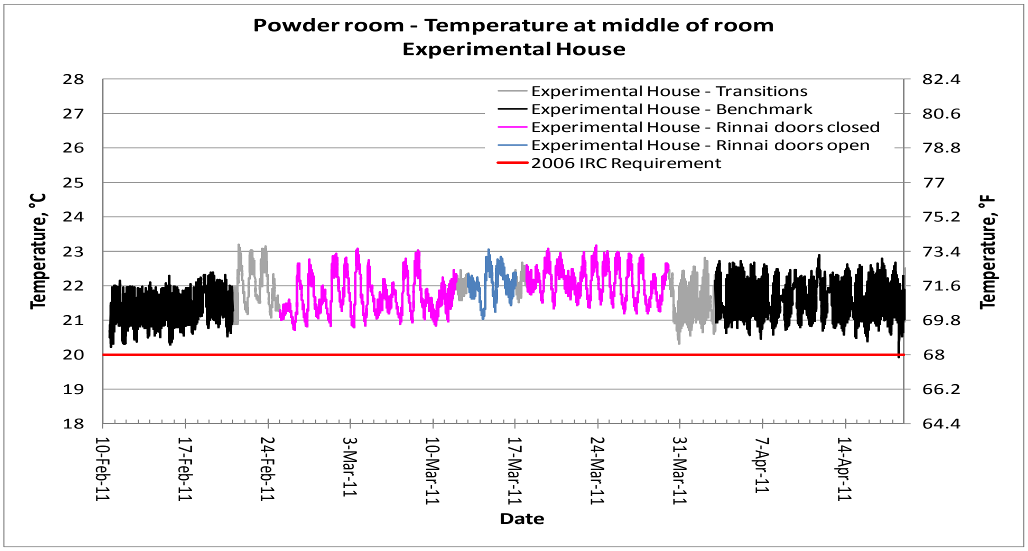


Figure 45: Powder Room Temperature in the Experimental House

5.2.3.3. Second Floor Temperatures

Second floor temperature results show that the DV wall furnace system maintained temperatures above the requirements of the 2006 International Residential Code in all rooms with open doors. In the two rooms with closed doors, the temperatures were at times cooler than the 68 °F (20 °C) threshold. However, the air temperatures in the Experimental House with the DV wall furnace system were either the same or warmer than temperatures in the Control House using the condensing central furnace.

This section contains detailed room temperature analysis from the benchmark and experiment period. All graphs contain temperature data from the benchmark period (plotted in black), the transition periods (plotted in grey), the DV wall furnace experiment with doors open (plotted in pink), and with doors closed (plotted in blue).

Two graphs are provided for each room: one graph for the Control House – featuring the propane furnace heating system, and one for the Experimental House – featuring the propane furnace heating system during benchmarking, and the DV wall furnace system during the experiment.

Master Bedroom

The air temperatures in the Control House and Experimental House master bedroom are plotted in
Figure 46 and
Figure 47, respectively. This temperature was measured at a location 2 ft in from an outside wall and 3 ft up. The master bedroom is located in the southeast corner of the second floor and is also the location of the second floor DV wall heater.

Temperature spikes are seen in the both houses, when the solar radiation caused spikes in thermocouple temperature. In the Control House, and during benchmarking in the Experimental House, temperatures on the second floor were not held within the same tight deadband as temperatures on the main floor. The central forced-air distribution system has only a single thermostat control, located centrally on the main floor, allowing temperatures on the second floor to drift freely. By contrast, the DV wall furnace system in the Experimental House maintained the Master Bedroom temperature within a ~3.6 °F (2 °C) of the set point temperature (with the exception of solar gains). The DV wall furnace system also maintained temperatures during the experimental period above the 68°F (20°C) IRC threshold, whereas, temperatures in the Control House, or in the Experimental House during the benchmark period dipped on occasion below the 68°F (20°C) IRC threshold requirement.

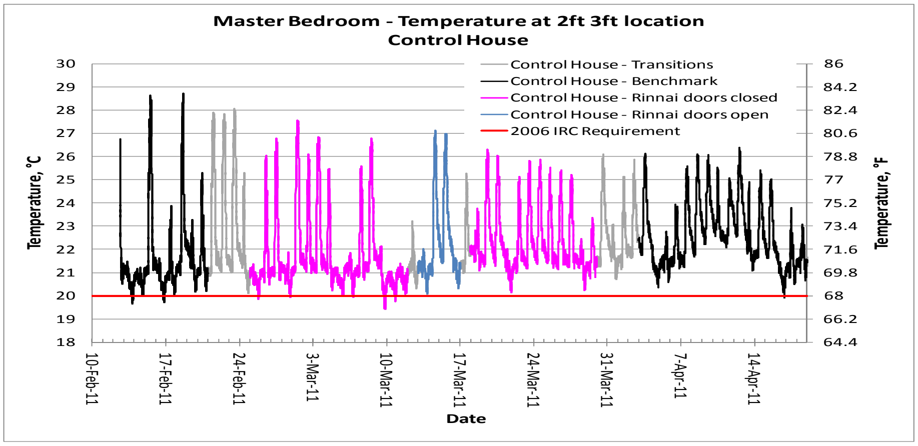


Figure 46: Master Bedroom Temperature in the Control House

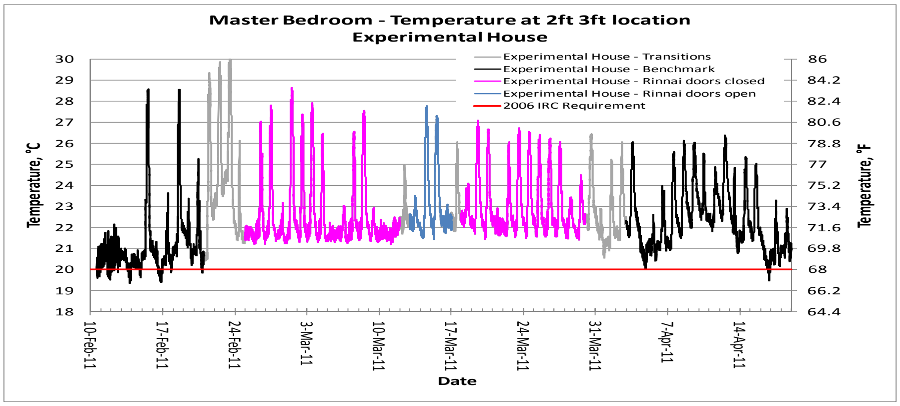


Figure 47: Master Bedroom temperature in the Experimental House

Bedroom 4 (Northeast)

The air temperatures in the Control House and Experimental House Bedroom 4 (northeast bedroom) are plotted in
Figure 48 and
Figure 49, respectively. This temperature was measured at a location 2 ft in from an outside wall and 3 ft up. Bedroom 4 is located in the northeast corner of the second floor. The door to this room was closed in both houses throughout benchmarking and the experiment (with the exception of the "doors open" period).

Air temperatures in Bedroom 4 were often below the IRC temperature requirement in the Control House. This is likely due to the fact that this room is fed by the longest run of ductwork in the house – as it is further away from the central propane furnace. With the doors closed, warm air from other rooms does not easily reach Bedroom 4. During the short experiment period with doors open, temperatures in the Control House room were above the 20°C (68°F) mark. However, this effect could also be partially attributable to warmer outdoor temperatures.

During the Benchmark period in the Experimental House – the propane furnace operation resulted in similar cool temperatures in Bedroom 4. During the experiment period, temperatures were warmer – but still dipped below 68 °F (20 °C).

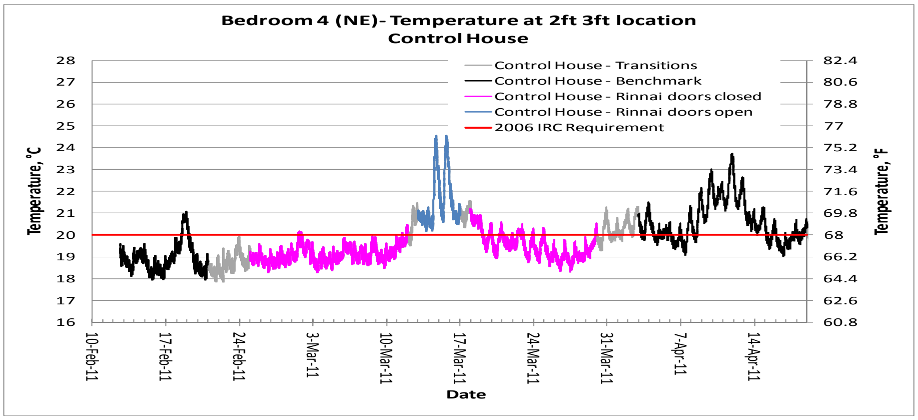


Figure 48: Bedroom 4 (Northeast) Temperature in the Control House

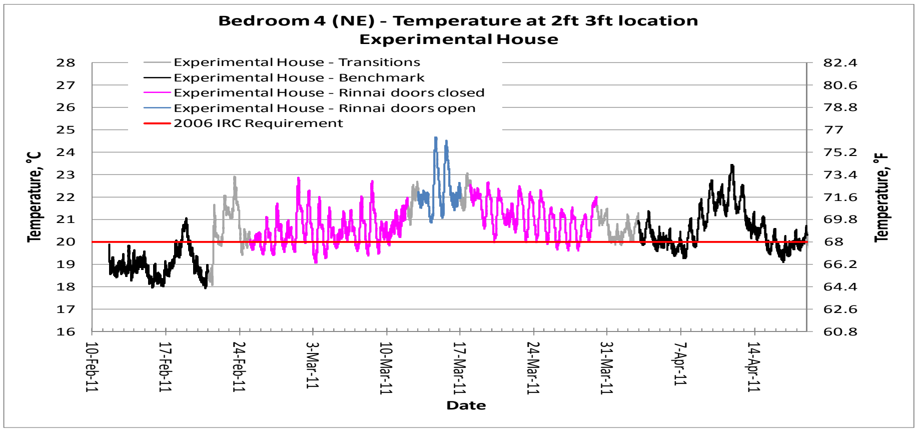


Figure 49: Bedroom 4 (Northeast) Temperature in the Experimental House

A statistical analysis of this temperature effect is presented in Figure 50. These graphs present the cumulative frequency curves for the 5-minute temperature data from the benchmark period and from the experiment period with doors closed. In each graph, the Control House temperature data for Bedroom 4 is plotted in red, and the Experimental House temperature data is plotted in blue.

The cumulative frequency curve shows the percentage of time during the period spent below a given temperature.

For example, in the Benchmark graph, the temperature in Bedroom 4 of both houses was below the IRC requirement of 68 °F (20 °C) ~54 % of the time, as given by the dashed red line.

During the experiment period with doors closed, the Bedroom 4 temperature in the Control House was below 20°C (68°F) ~91 % of the time – an indication that the experiment period was cooler on average than the benchmark period. However, despite these cooler conditions, the Bedroom 4 temperature in the Experimental House dropped below the IRC requirement for only ~23 % of the experiment period.

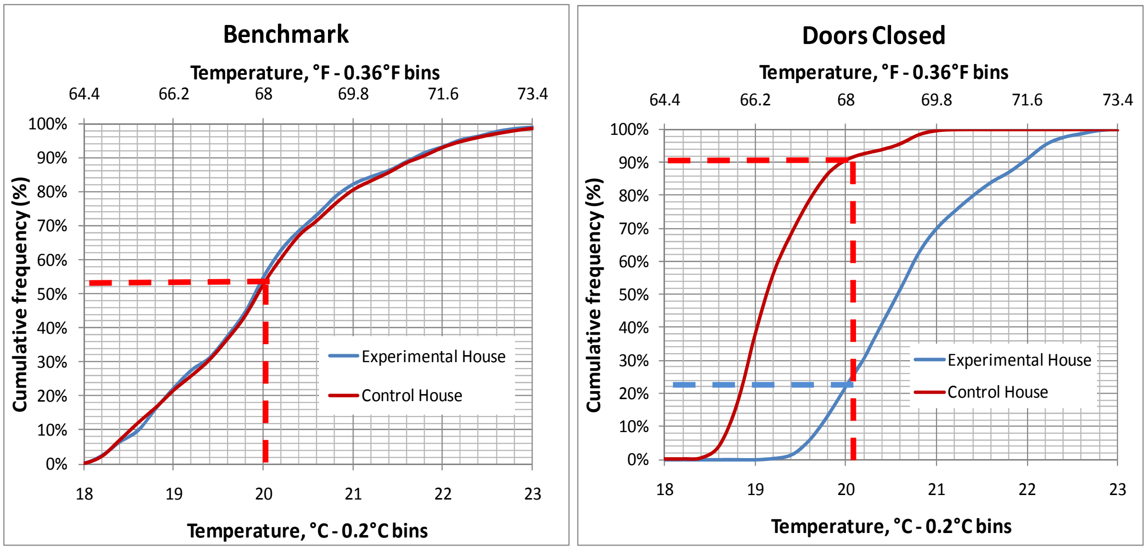


Figure 50: Cumulative Frequency Diagram of the Bedroom 4 (Northeast) temperature at the 2 ft 3 ft Location during Benchmarking and the Experiment with Doors Closed

Bedroom 3 (Northwest)

The air temperatures in the Control House and Experimental House Bedroom 3 are plotted in Figure 51 and Figure 52, respectively. This temperature was measured at a location 2 ft in from an outside wall and 3 ft up. Bedroom 3 is located in the northwest corner of the second floor. The door to this bedroom remained open throughout benchmarking and the experiment.

Both houses experiences peaks in air temperature during sunny days. This is due to overheating on the second floor, from solar gains through the large south facing windows of Bedroom 2 and the Master Bedroom. The Bedroom 3 temperature in the Control House dipped slightly below the 20°C (68°F) threshold line only occasionally during the benchmarking and experiment periods. In the Experimental House, the DV wall furnace system maintained the temperature in this room above 20°C (68°F) throughout the experiment period.

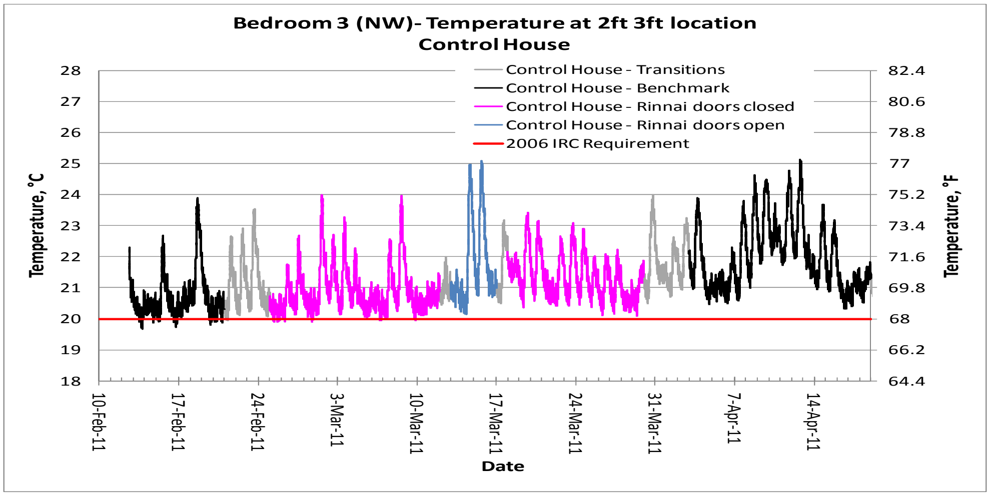


Figure 51: Bedroom 3 (Northwest) Temperature in the Control House

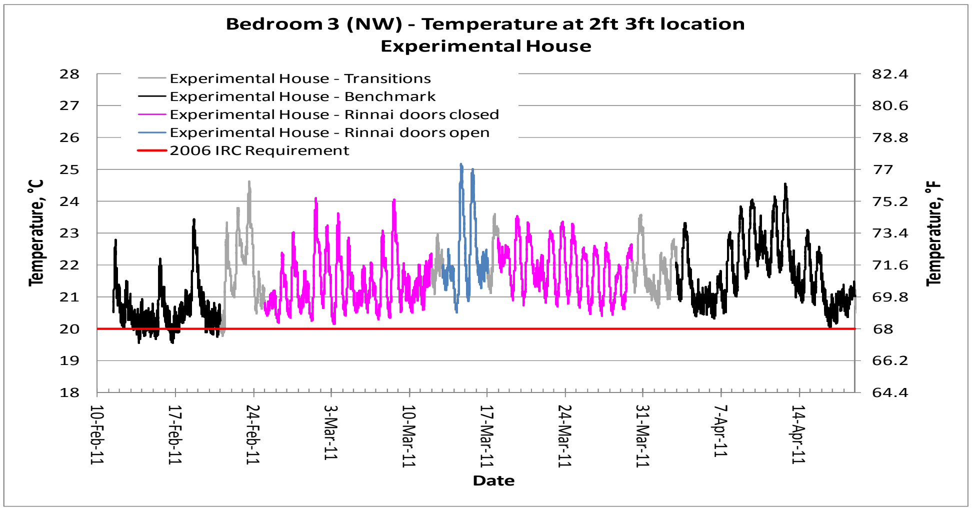


Figure 52: Bedroom 3 (Northwest) Temperature in the Experimental House

Bedroom 2 (Southwest)

The air temperatures in the Control House and Experimental House Bedroom 2 are plotted in Figure 53 and Figure 54 respectively. This temperature was measured at a location 2 ft in from an outside wall and 3 ft up. Bedroom 2 is located in the southwest corner of the second floor. The door to this bedroom remained closed throughout benchmarking and the experiment (except during the short experiment portion with doors open – indicated in blue).

The large windows in this room pose a challenge to temperature control. Both houses experience temperature spikes on sunny days, due to high solar gains through the south facing windows. Additionally, the temperature in the room drops at night as low as 18 °C on many occasions – likely due in part to heat losses through the same windows. The Bedroom 2 temperature in both houses dropped below the 68 °F (20 °C) threshold during both the benchmarking and experiment with doors closed phases.

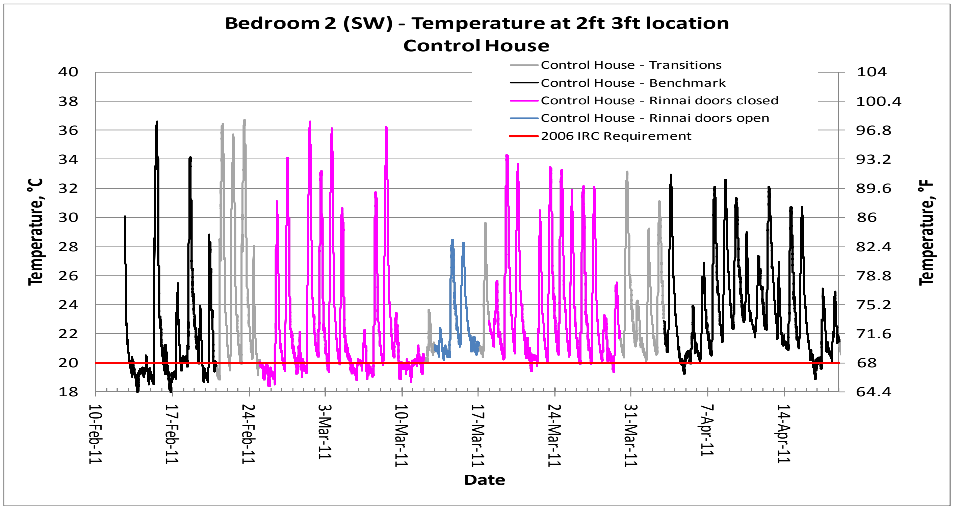


Figure 53: Bedroom 2 (Southwest) Temperature in the Control House

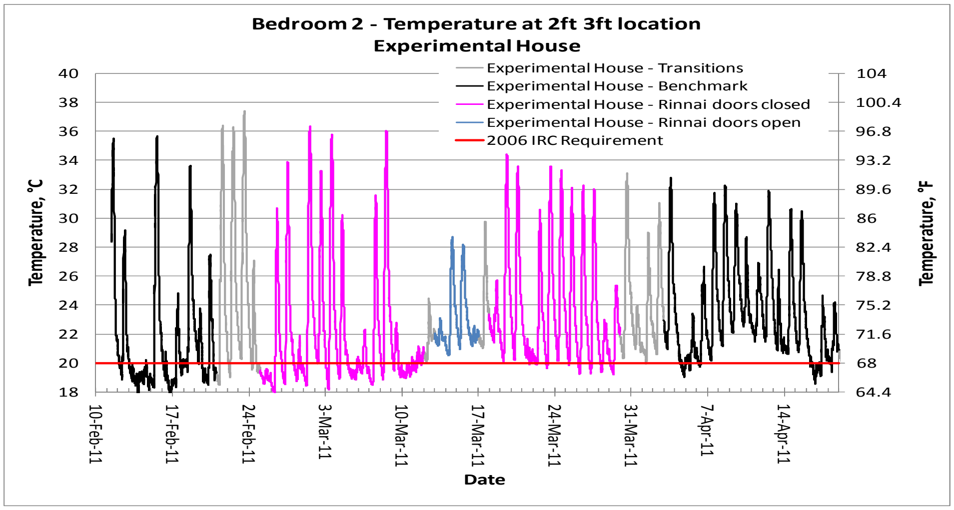


Figure 54: Bedroom 2 (Southwest) Temperature in the Experimental House

A statistical comparison of temperatures is required to determine the impact of the DV wall furnace System on room temperature. The cumulative frequency diagrams of Bedroom 2 temperature are presented in Figure 55.

During the benchmark period, the Experimental House was slightly cooler than the Control House, spending 27 % of the time during the benchmark period below 68 °F (20 °C). The Control house spent only 19 % of the benchmark period below this threshold. The 8 percentage point difference is due to slight differences between the houses, which may include differences in duct balancing and heat losses from the room.

Room temperatures during the experiment period with doors closed were cooler in both houses. During this period, the Control House Bedroom 2 air temperature was below the 20°C (68°F) threshold 42% of the time, while the Experimental House Bedroom 2 air temperature was below this threshold 32% of the time. This is a ten percentage point difference compared to eight percentage points during Benchmarking. This two point change in the difference between the houses due to the DV wall furnace system is minimal.

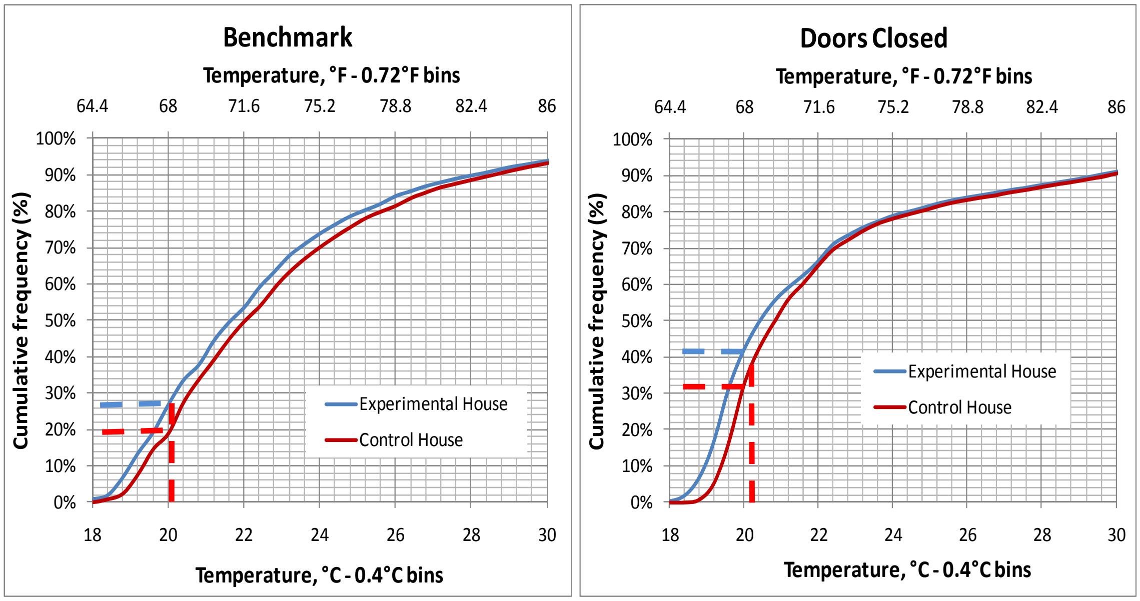


Figure 55: Cumulative Frequency Diagram of the Bedroom 2 (Southwest) Temperature at the 2 ft 3 ft Location during Benchmarking and the Experiment with Doors Closed

5.2.4. Discussion

The energy consumption results from this experiment resemble those of the electronic commutated motor (ECM) experiment [3]. In this CCHT twin house experiment, the performance of a furnace with ECM fan motor was compared to the performance of a furnace with a traditional PSC motor. Results showed a substantial reduction in electrical consumption thanks to the high efficiency of the ECM motor. However, the same efficient motor released less heat to the house, and the furnace had to compensate by running more often in heating mode and consumed more natural gas. The low electrical consumption of the DV wall furnace system also likely results in less heat losses to the home, contributing to an increase in heating load and propane consumption.

Other factors contributing to the difference in net energy consumption of the two systems include: the DV wall furnaces have lower efficiencies than the condensing furnaces, and thus would be expected to consume more energy to supply the same amount of heat; the condensing central furnace system had substantial heat losses to the basement, that would result in added furnace energy consumption; and most room temperatures with the DV wall furnace system were substantially warmer 1.8 to 3.6 °F (1 to 2 °C) than temperatures with the condensing central furnace system, requiring additional energy consumption from the DV wall furnace system to maintain these elevated temperatures.

6. CONCLUSIONS AND RECOMMENDATIONS

This report presented the feasibility of using modulating direct-vent (DV) Wall furnaces for home heating. The DV wall furnaces and the condensing central furnace heating systems were compared in direct side-by-side testing with virtually identical space heating, water heating and ventilation loads during the winter of 2011. The in-situ testing was carried out at the Canadian Centre for Housing Technology's (CCHT) side-by-side research houses. The DV wall furnace heating system was run during five weeks of testing. This allowed enough data to be collected under various outdoor conditions for complete analysis of the system performance in comparison to the base case condensing central furnace heating system.

The following main conclusions can be drawn from the present work:

- During the testing period, the DV wall furnace system met all space heating loads of the Experimental House and provided a better comfort than the system in the Control House. The units operated reliably without any interruptions or faults during the testing period and under various outdoor temperature ranging from -0.4 ^oF to 54.0 ^oF (-17.5 ^oC to 12.2 ^oC).

- The DV wall furnace system operation with two bedroom doors closed resulted in an overall net increase of 10.8 MJ/day (3.7%) in total energy consumption (propane and electricity), when compared to a condensing central furnace system. The propane consumption increase by the DV system was 9.7 % during this period.

- The propane consumption comparison between the DV wall furnaces and the condensing central furnaces in both houses showed that the DV wall furnaces were comparable to the condensing furnaces. In general, the propane gas consumption of the DV wall furnaces was higher by 5 % on average.

- The DV wall furnace system (including the air share units) electrical consumption averaged 4.3 kWh/day compared to 3.5-7.5 kWh/day for the condensing central furnace system. The DV wall furnace system provided about a 76 % reduction in electrical consumption compared to the condensing central furnace system. Approximately 55 to 65 % of the 4.3 kWh/day consumption of the DV wall furnace system was attributable to the operation of the air share units. The electrical consumption of the DV wall furnaces without the air share units averaged 1.5 kWh/day. With doors open and air share units off, the electrical savings of the DV system were even more substantial, close to 88 %. Total energy consumption of the DV wall furnace system was on average 0.5 % lower than the condensing central furnace system.

- In general, during the testing the DV wall furnace system operated more frequently and with longer daily on-time cycles than the condensing central furnace system.

- Throughout the experiment, the DV wall furnace maintained temperatures at/or above the 68 °F (20 °C) 2006 IRC requirement in all but the two closed off bedrooms in the Experimental House. However, temperatures in the closed off bedrooms were either identical or warmer to those closed off bedrooms in the Control House being heated by the condensing central furnace system. In general, the DV wall furnace system maintained room air temperatures the same or warmer than the condensing central furnace system.

- During the experiment and benchmark, the supply ducts and return duct in the basement were sealed (making it an unconditioned space). Heat losses to the basement from the reference system (propane furnace) were substantial, keeping the Control House basement air temperature approximately 2 °C warmer than the Experimental House basement air temperature during the experiment period.

- The lowest daily outdoor temperature experienced during the experiment was 12.6 °F (7 °C). The developed energy consumption trends during the testing indicate more potential energy savings by the DV wall furnaces in colder weather.

Identified below are some areas for further investigation:

- Improved controls strategies and distributed wireless thermostats for optimal operation that could result in energy consumption reduction and improved comfort level. The DV wall furnace heating system would likely benefit from remotely located thermostats. With remotely located thermostats, the DV wall furnaces could maintain temperatures in locations far from the heat source without overshooting the desired thermostat set point. These thermostats would result in an optimized control system, and likely reduced energy consumption.

- Additional modelling for proper sizing of DV wall furnaces if more than one furnace is installed in the house.

- Additional testing in colder weather would be of interest to determine performance at the design temperature, and also to confirm the energy consumption trends for high heating load conditions.

7. REFERENCES

[1] Rinnai America Corporation, "Ductless Furnace 101 Manual, A Complete Training and Sales Guide for Rinnai's Line Direct Vent, Ductless, Wall Furnace Heating Systems", 3/2007.

[2] Horiba Ltd., "Portable Gas Analyser PG-250 User Manual", 5th Edition, July 1998.

[3] Gusdorf, J. Swinton, M.C. Simpson, C. Entchev, E. Hayden, S. Castellan, B. Final Report on the Project to Measure the Effects of ECM Furnace Motors on Gas Use at the CCHT Research Facility. Canadian Centre for Housing Technology. Ottawa, Canada. 2003. Available Online: http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc38500/nrcc38500.pdf

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