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Temperature, Relative Humidity, and Carbon-Dioxide Modulation in a Near-Zero Energy Efficient Retrofit House

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ABSTRACT

The concept of Net Zero Energy Buildings (NZEB) has reached a phase where countries all around the world are encouraging its implementation into mainstream construction. In the United States, both private and public sector buildings are incorporating energy efficient technologies to reduce their environmental impact, while increasing the productivity and comfort of its occupants. A Net Zero Energy Building (NZEB) performs as expected only when the building's envelope, HVAC and other mechanical/electrical systems work in unison. Subsequently, once these buildings are occupied, the behavior of its occupants significantly influences the buildings energy performance. The authors have captured the modulation of temperature, relative humidity, and carbon-dioxide within a home retrofit to near Net Zero Energy Building conditions during the heating season. This house is a Deep-Energy Retrofit Home completed as a marketing and demonstration home for a joint neighborhood stabilization project and U.S. Department of Energy funded community-wide retrofit grant program. The house includes an internet based real-time home energy monitoring system, which facilitates reviewing the changes in the houses energy consumption as a consequence of fluctuating internal temperature settings and external climate conditions. Post retrofit blower-door test result conform that the house has been made fairly air-tight during the retrofit. Hence ventilation of the house is achieved via an Energy Recovery Ventilator (ERV) with multiple stages of operation. To this end, the paper is an exploratory examination of the inter-relationships between occupancy, interior temperature, relative humidity, carbon-dioxide levels and energy consumption within a Near-Zero Energy Building.

1. INTRODUCTION

Development in building technology has helped in reducing air infiltration within modern homes, hence reducing unwanted energy loss through uncontrolled air exchange. Energy star rated equipment installed in these modern homes are highly energy efficient, and contribute in reducing the overall energy consumption RECS (Residential Energy Consumption Survey, 2011). EIA's 2011 survey found that over 40 million householders in America (35 percent) have used caulking or weather-stripping to seal cracks and air leakages around their house and 26 million (23 percent) had added some form of insulation to their existing homes.

Houses with lower air infiltration consume considerably less energy for space heating and air-conditioning. However, as a result of reducing the infiltration of fresh outside air to very low levels, residents of modern residential building may run a risk of less than recommended ventilation rates or Air Change Rates (ACR) within their homes. For any building a ventilation rate of 20cfm per person is recommended for maintaining optimum level of Indoor Air Quality (IAQ) (ANSI/ASHRAE Standard 62-1999, Ventilation for Acceptable Indoor Air Quality). Occupant health and perceived IAQ will usually be improved by avoiding ventilation rates below 20 cfm (9 L/s) per occupant and further improvements in health and perceived IAQ will sometimes result from higher ventilation rates up to 40 cfm (18 L/s) per person. (O. Seppänen, W.J. Fisk, M.J. Mendell, 2002)

The primary reason behind making a house airtight is to reduce energy consumption with the additional benefit of increased occupant comfort. Comparing the average energy consumption of modern homes, with the ones built before 2000 reveals that the way residential buildings in the United States consume energy has changed drastically over the past few decades. Homes built in the 2000s accounted for 14% of the total occupied housing units in 2009 and these new homes consumed 21% less energy than older homes for space heating. Energy use units in 2009 and these new homes consumed 21% less energy than older homes for space heating. Energy use per household for the year 2005 was 95 million British Thermal Units (BTUs) compared with 138 million BTUs per household in the year 1978 (RECS, 2009), a drop of 31 percent.

Increasing energy costs, strict building codes and reduced cost of energy efficient alternatives are some explanations for this decrease in the energy consumption of residential buildings. The RECS 2009 survey has identified space heating and household appliances as the two main end-uses that consume the most energy within residential buildings in the United States. With this knowledge, making a house airtight appears to be a logical step for homeowners who want to reduce their energy bills.

2. DEEP ENERGY RETROFIT HOME

Taking the concept of reducing energy consumption to the next level, some modern buildings are designed and constructed to be a Net Zero Energy Building (NZEB). A NZEB is defined as a building with very high energy performance, when the primary energy that it produces and feeds-in to the grid or any other network is equal to total energy that is delivered to the building by the grid and all other sources. It is important that the annual energy balance of energy exchanged must be 0 BTU/sf.

These modern buildings are capable of providing more comfortable interior environments than traditional homes at a fraction of its energy cost. The operation and maintenance of such energy efficient building is just as important as their design and construction. This is especially important in a residential setting, where the home owners largely do not have sufficient knowledge of all the installed systems. These buildings perform as predicted only if all the components of the house work in unison.

Providing a high quality and comfortable interior environment is desirable for all residential buildings. Over the past two decades, the scientific community has shown increased concern for indoor air quality (IAQ) and the effect of interior air on the health of occupants. As mentioned earlier, modern homes are more airtight than older homes, these modern homes use more synthetic materials that generate Volatile Organic Compounds (VOCs) into indoor air. Whilst these improvements have led to more comfortable buildings with lower running costs, they also provide indoor environments in which contaminants are readily produced and may build up to a much higher concentration than are found outside. (Jones, 1999)

Purdue University participated in the Lafayette Energy Assistance Program (LEAP) and guided the technical development of the program as well as the design and retrofit of a Near-Zero Energy demonstration retrofit home. As a retrofit of an existing home it was not able to achieve the full goal of a NZEB, but far exceeded the energy performance of both new and existing homes in the community in which it is located. The demonstration home was completed to provide visibility to attract LEAP program participation and to provide opportunities for homeowner education within the community where it was located. The Energy Conservation Measures (ECM's) for the retrofit house listed in Table 1 were carefully chosen and recommended to the builder competing the retrofit and the Neighborhood Stabilization Program (NSP) program manager. Alternative energy production through roof-mounted solar panels was used on the demonstration home to attract attention. All other ECMs were selected to reduce energy consumption in addition to the following decision criteria:

- Appropriate for homes found in the project communities
- Easy for local building trades to understand and install
- Available through traditional supply channels without delay
- Assessed from a whole-building energy performance viewpoint
- Expected to provide near-term potential for positive payback, but with no specific cut-off
- Appropriate to or related to energy retrofits that could be funded by LEAP program grants
- A contributor to energy conservation first with introduction of alternative energy sources only when energy consumption had been minimized

Table 1: Energy Conservation Measures

ECM	Description
Windows	R-5.56 triple glazed casement
Sun Tube	One in each bath with dimmer to provide daylight illumination and control
Exterior Doors	Insulated steel, thermal break frame, magnetic weather-strip, polyurethane core R-8.3
Crawl Space	Damp Proof w/ sealed 20 mil poly floor cover
Attic Access	R-40 insulated, weather-stripped attic closure system
Air Seal Attic	Air seal all top plates and ceiling penetrations with closed cell foam
Air Seal Walls	Expanding foam seal all exterior wall penetrations
Insulate Attic	R-60 Loose Fill Cellulose with 3" closed cell foam - 3' wide at roof edge (R-20+)
Insl. Crawl Space	Conditioned crawl, 2" closed cell foam on interior of crawl wall and band joist (R-13+)
Insulate Ext. Walls	R-11 batts @ 2x3 wall cavity plus 4" (R-20) extruded polystyrene sheathing (2 layers of 2" foam with lapped and taped joints)
South Overhang	Extend to 16" for summer shading and add continuous vent
Hot Water	Heat Pump Water Heater with min. COP rating of 2.0 or greater
Solar Energy	Nominal 4 KW Solar PV System
Furnace & AC	Multi-speed air handler, min. 25,000 BTU gas furnace, 1 ton AC
Ductwork - Supply	Within conditioned space, Mastic seal all ductwork
Ductwork - Return	Within conditioned space were possible, Attic runs min. R- 20 insulation, Mastic seal all duct
ERV	Energy Recovery Ventilator min. 60% heat recovery, installed in conditioned space
Thermostat	7-Day Setback
Washer	Front Load – Energy Star Rated
Dryer	Electric – Energy Star Rated
Refrigerator	Top Freezer, No water and ice through door, Energy Star Rated
Dishwasher	Energy Star Rated
Electrical	44 circuit eMonitor® energy monitor, real-time internet energy use dashboard
Lighting	All lighting CFL or T-8 florescent except LED kitchen task lighting
Window Coverings Air-Tightness	Living Room Insulating Cellular Shades with air sealing tracks Infiltration post-retrofit 2.28 air changes/hour @ 50 pcal pressure (blower door)

Significant care was exercised in use of caulk, air barriers and spray foam to provide an airtight envelope. After the completion of retrofits, a blower door test was conducted to measure the infiltration post-retrofit. The test results indicated that the house was highly air tight, with 2.28 air changes per hour under 50 pcal of pressure. Achieving this level of air tightness was an important step towards creating the highly energy efficient home reflected in the HERS certification rating of 17 (Figure 1).

3. METHODOLOGY

For the purpose of this study, the authors started with identifying some measurable parameters within the retrofit house which provide basic information about the house's HVAC system performance. Temperature and relative humidity were the two obvious parameters that were chosen to be monitored for this purpose. It was predicted that these readings would allow the authors to study the occupants comfort preference and also let the authors monitor how the house performed in meeting these needs. Indoor carbon-dioxide levels correlate reasonably well with perceived odor and levels of human bio effluents. Thus, interior carbon-dioxide concentrations are often used to judge the acceptability of indoor air. Its concentration is an indicator that may be used to identify pollutant sources, determine building and heating, ventilating, and air conditioning (HVAC) system deficiencies, verify corrective actions, and correlate occupant symptoms to IAQ. (Batterman &Peng, 1995). Therefore, the third parameter chosen to be monitored for this study was in-door concentration of carbon-dioxide as it would provide the authors valuable information about effect of air-tightness of the retrofit house on the indoor air quality.

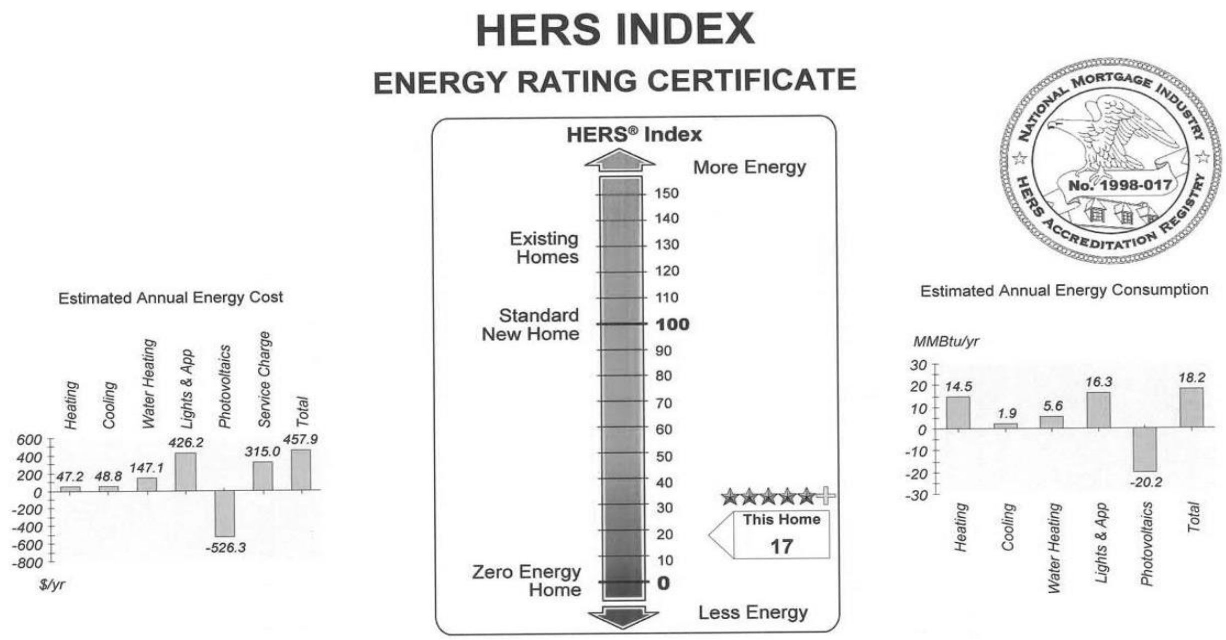

Figure 1: Demonstration Home HERS Rating Certificate

ASHRAE recommends carbon-dioxide concentration between 1000ppm – 1200ppm for spaces housing sedentary people, in this case the retrofit house. As per guidelines in ASHRAE Standard 62.1-2013, "Ventilation for Acceptable Indoor Air Quality" carbon-dioxide concentration greater than 5000 ppm within indoor environments can pose health risks.

For this experiment the authors used Fluke 975 AirMeter, this device was capable of recording and recording the concentration of carbon-dioxide, relative humidity and interior temperature continuously for 99 hours within the retrofit house. Three sets of 99 hour readings were collected between 7th February 2016 and 2nd March 2016 for this study. The first set of readings was recorded in the living room of the house. During this time the measuring device was placed at the floor level (6 inches above the floor level). The second set was recorded in the master bedroom of the retrofit house. This time the measuring device was placed at a height of 3 feet above the floor level. The third set was recorded in the kitchen and the meter was placed just 1 foot below the ceiling level. The authors placed the meter at different levels for all the three readings to study the stratification of indoor air-temperature within the retrofit house. The retrofit house is occupied by a single resident. The authors interviewed the occupant before starting data collection to learn about the occupant's comfort preferences and knowledge of the installed systems. Since the occupant did not know the advantages and procedure of operation of the setback thermostat, the authors informed the owner about some advantages of using this system, and how it can be operated. The authors also encouraged the resident to use the setback thermostat of house during the course of this study. The use of setback thermostat caused the indoor temperatures to fluctuate, indoor carbon-dioxide concentrations and relative humidity levels also reacted to the changing indoor temperatures. The next section presents these findings in detail.

4. ANALYSIS OF DATA

Comfort criteria due to odors with respect to human bio effluents are likely to be satisfied if the ventilation results in indoor carbon-dioxide concentrations are less than 700 PPM above the outdoor air concentration. (ASHRAE 62-2001). This reference to a carbon-dioxide concentration of 700 PPM over outdoor air is not an upper limit for acceptable IAQ, rather a recommendation for comfort. The concentration of carbon-dioxide within the retrofit house measured during the study was between 200 PPM -3333 PPM. Although typical outdoor CO_2 concentrations are approximately 380 ppm, outdoor levels in urban areas as high as 500 ppm have been reported (Persily 1997). Hence indoor carbon-dioxide concentrations recorded during the study were higher than ASHRAE recommendations. Prior research has documented direct health effects of carbon-dioxide on humans, but only at concentrations much higher than those found in normal indoor settings. Carbon-dioxide concentrations greater than 20,000 ppm cause deepened breathing; levels of 40,000 ppm increases respiration markedly; 100,000 ppm levels cause visual disturbances and tremors and has been associated with loss of consciousness; and at 250,000 ppm carbon-dioxide (a 25% concentration) can cause death (Lipsett et al. 1994). Maximum recommended occupational exposure limits for an 8-hr workday are 5,000 ppm as a time weighted average, for the Occupational Safety and Health Administration (OSHA 2012) and the American Conference of Government Industrial Hygienists (ACGIH 2011). The ASHRAE 62-2001 standard recommends maintaining a maximum 60% humidity during the summer and at least 25–45% during the winter. ASHRAE Standard 62.1-2013 recommends that relative humidity in occupied spaces be controlled to less than 65% to reduce the likelihood of conditions that can lead to microbial growth. The recorded humidity readings within the retrofit house were within acceptable range, with a low of 40 %RH and a high of 58.8%RH.

Through an internet connected energy monitor the authors have access to minute-by-minute, real-time and past electricity usage of all major appliances and circuits within the retrofit house. The retrofit house uses natural gas furnace for space heating, but the air handler runs on electricity. The house is billed monthly for gas with no other gas consumption monitoring so its real-time consumption was not available. The authors used the real-time electricity consumption from the air handler unit to monitor the operation of the furnace.

Figure 2, Figure 3 and Figure 4 exhibit the modulation of outside temperature, and indoor temperature of the retrofit house in the living room (7th Feb- 11th Feb), bedroom (14th Feb – 18th Feb) and kitchen (26th Feb – 2nd March) as well as energy used by the air handler unit circuit which includes the ERV. All three graphs present 99 data points representing each hour the Fluke AirMeter was recording. The indoor temperature reading was collected by the Fluke meter, while outdoor temperature and electricity used by the air hander was recorded by the real-time energy monitoring system.

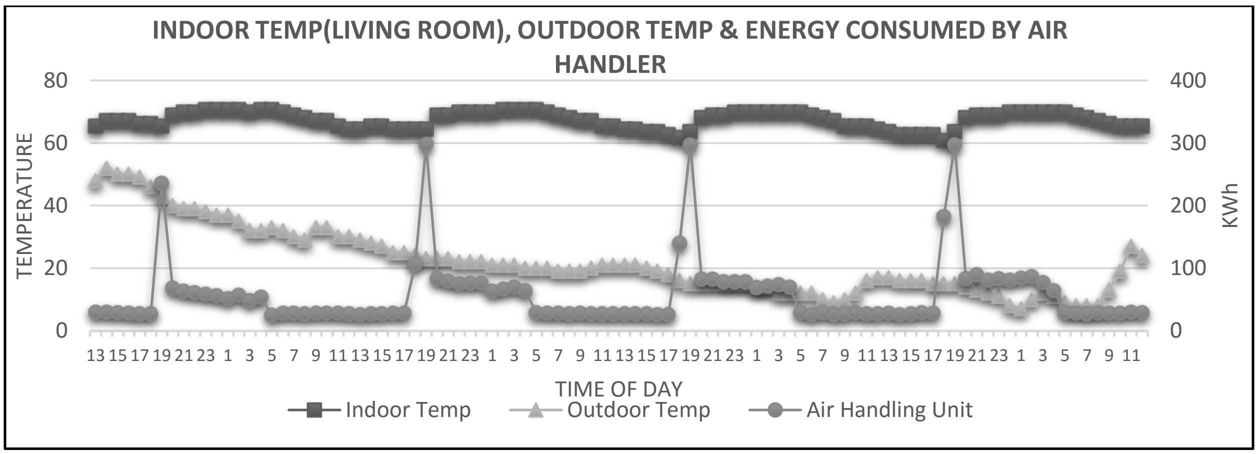

Figure 2: Indoor Temperature in the Living Room, Outdoor Temperature & Energy Consumed by Air Handler

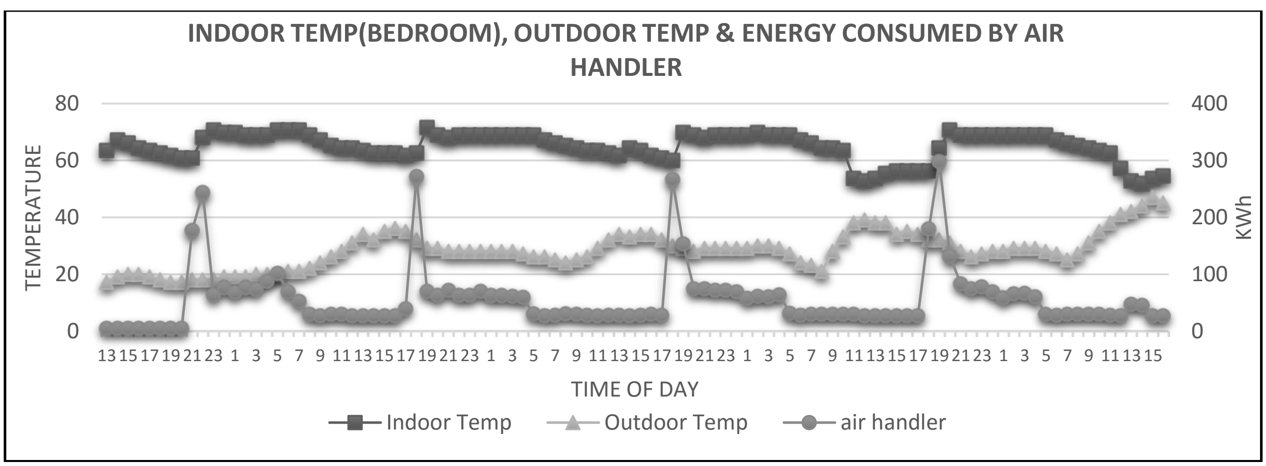

Figure 3: Indoor Temperature in the Bedroom, Outdoor Temperature & Energy Consumed by Air Handler

In the brief interview with the occupant prior to beginning the indoor air measurements they mentioned the setback capable thermostat was programmed to maintain the interior temperature of the house at 70 degree Fahrenheit from 7PM to 5 AM. Figure 1 and Figure 2 shows that every day at 7PM the house starts consuming energy and brings the interior temperature back to 70 degree Fahrenheit. ASHRAE Standard 55-2013, Thermal Environmental Conditions for Human Occupancy, notes that for thermal comfort purposes, indoor temperature could range from between approximately 67 and 82 °F. The data indicates that the HVAC system as controlled by the occupant's settings of the setback thermostat successfully controlled indoor temperature and humidity at acceptable comfort levels". During this study, the outdoor temperature was an average of 22.19 °F in the first set of readings (7th Feb- 11th Feb) in Figure 1 and an average of 28.38 °F in the second set of readings (14th Feb – 18th Feb) as seen in Figure 2. The occupant also mentioned that the house was allowed to cool down to a minimum of 50 °F when it was un-occupied between 5AM and 7PM which allowed maximum energy savings without any compromises in comfort.

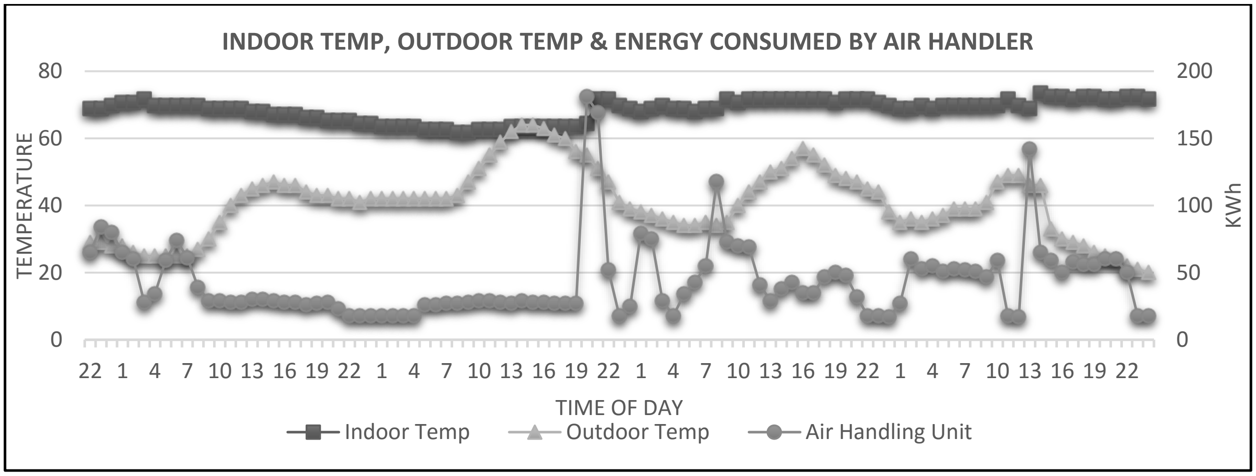

Figure 4: Indoor Temperature in the Kitchen, Outdoor Temperature & Energy Consumed by Air Handler

Figure 4 shows the modulation of indoor temperature, outdoor temperature and energy consumed by air handler in the last set of recorded data (26th Feb – 2nd March). In this data set the average outdoor temperature was 40.9 °F, which was highest in all the three sets. Also, in this data set it was observed that the house did not use any heat between 3PM on 27th Feb. to 10PM on the 28th of February. During this time the house was unoccupied and the occupant had turned off the heating system.

Most people spend 70-90 % of their time indoors, with a large percentage of this time spent within one's own residence. Some pollutants found in outside air find their way indoors, and indoors the home's occupants release toxins further creating the possibility of higher indoor pollutant concentrations. As a result, it is acknowledged that inhalation of indoor air is the major determinant of human exposure to many pollutants (Samet et al., 1987, 1988). Although not considered a pollutant itself, carbon-dioxide concentration is often used as a simple and inexpensive method to indicate effective ventilation levels.

Figure 5, Figure 6 and Figure 7 show that the carbon-dioxide concentrations within the retrofit house varied between 200 PPM to 3333 PPM. The average carbon-dioxide concentration recorded in the living room was 1915 PPM, in the bedroom the average concentration of carbon-dioxide was 1934 PPM and in the kitchen the concentration of carbon-dioxide was an average of 1979 PPM. Since average outdoor concentration of carbon-dioxide varies ranges from 380 PPM to 500 PPM, the difference in concentration between indoor and outdoor concentration of carbon-dioxide suggested the building needs additional ventilation.

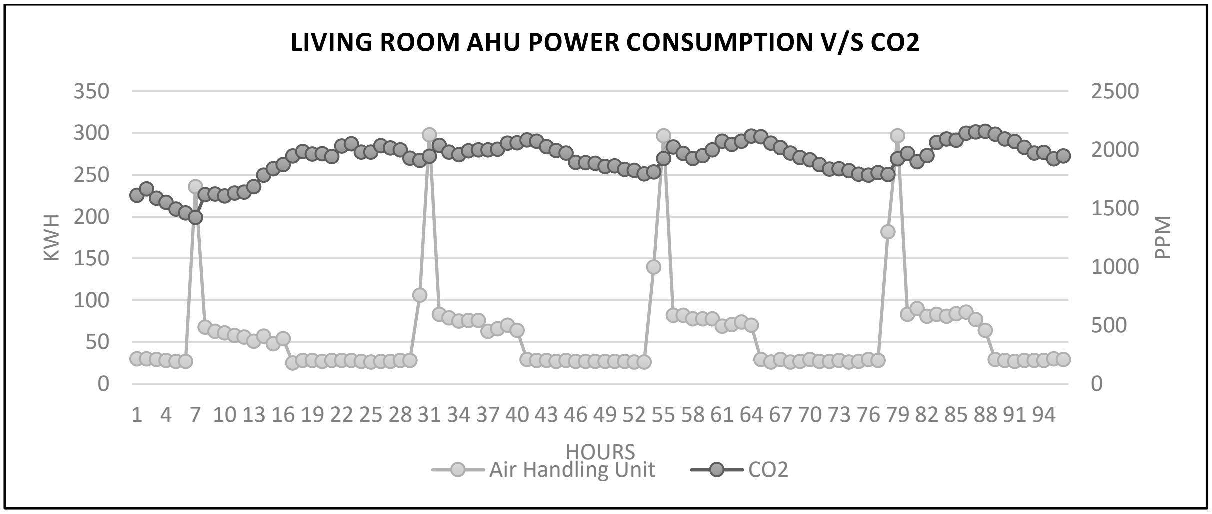

Figure 5: Modulation of Carbon-Dioxide in the Living Room

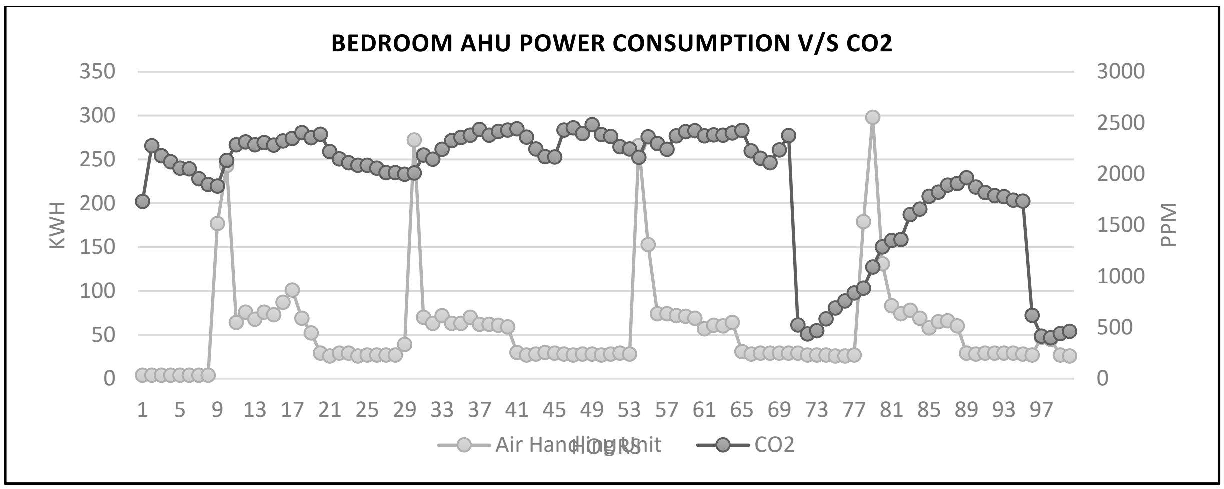

Figure 6: Modulation of Carbon-Dioxide in the Bed-Room

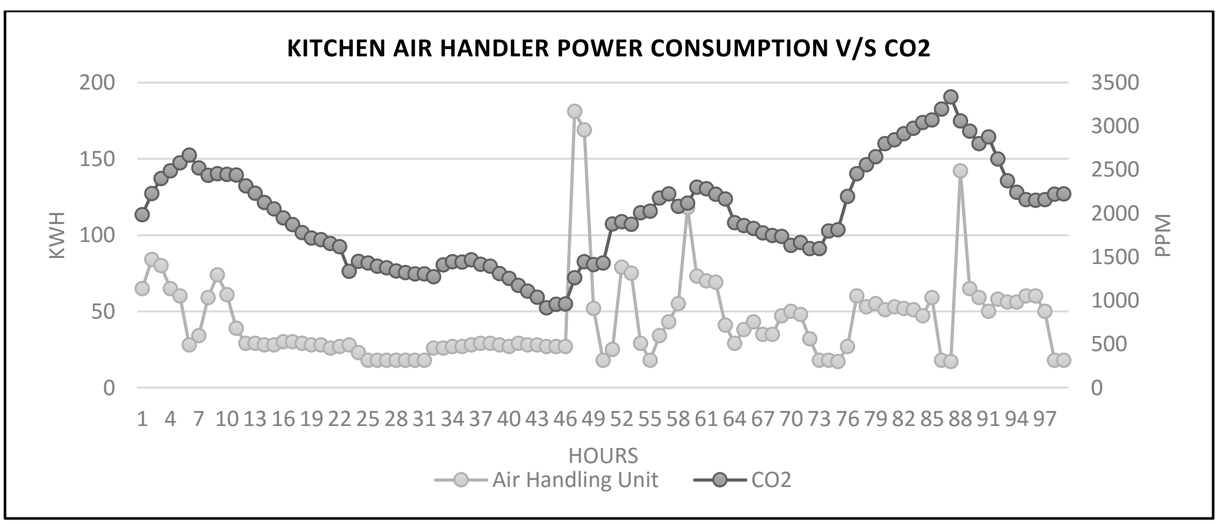

Figure 7: Modulation of Carbon-Dioxide in the Kitchen

A closer look at the modulation of carbon-dioxide appears to show that the concentration of carbon-dioxide increases with when AHU is in operation. The authors hypothesize that this increase in the concentration of carbon-dioxide is not an actual increase but an apparent increase, captured by the meter as a result of increased air flow through the registers which creates air drafts within the house. To study the correlation between the concentration of carbon-dioxide and AHU operation, the authors performed a Pearson Product Moment correlation (Pearson's r test). In this case the tests measured the linear correlation between two variables X (carbon-dioxide concentration) and Y (AHU energy usage), giving a value between +1 and −1 inclusive, where 1 is total positive correlation, 0 is no correlation, and −1 is total negative correlation.

Overall, the Pearson's coefficient of correlation between carbon-dioxide concentration and AHU operation for the first and second set of data were -0.04 and 0.00 respectively, which meant that there was absolutely no correlation. However, for the third data set, the coefficient of correlation was 0.27, showing a slight positive correlation and some possibility that the concentration of carbon-dioxide increased with AHU operation.

Figure 8, Figure 9 and Figure 10 are graphs that show the modulation of relative humidity with operation of AHU. To study the correlation of relative humidity with AHU operation, the authors again performed the Pearson's r test. In this case the tests measured the linear correlation between two variables X (Relative humidity) and Y (AHU energy usage). In the first set of data (Figure 8), Pearson's coefficient was 0.20 which suggested that there was slight correlation, and there was a slight chance that RH increased with AHU operation. In the second set of data (Figure 9), the coefficient was – 0.24, which suggested that there was a slight chance that RH decreased with AHU operation. Finally, for the third data set (Figure 10), Pearson's coefficient was 0.31, suggesting a slight correlation of increased RH with AHU operation.

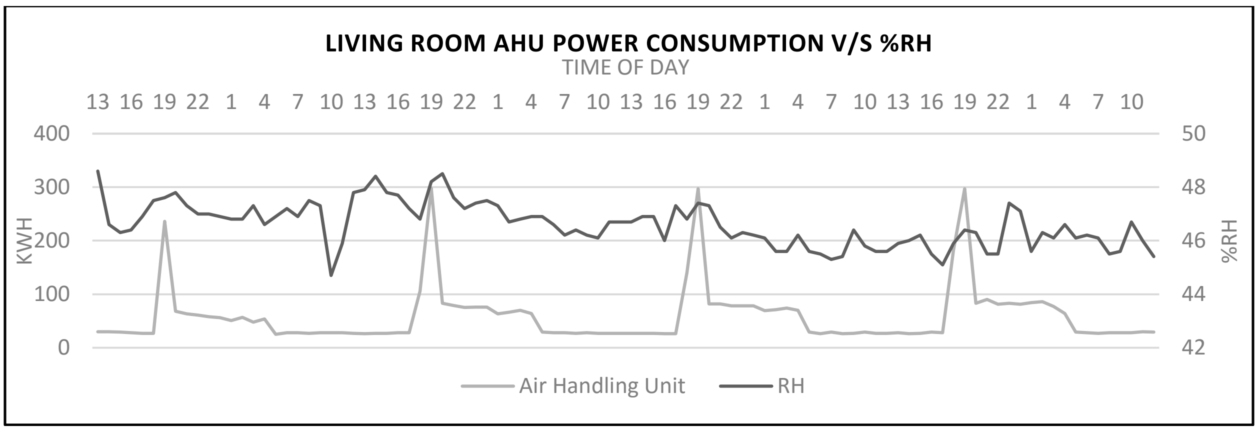

Figure 8: Modulation of Relative Humidity in the Living Room

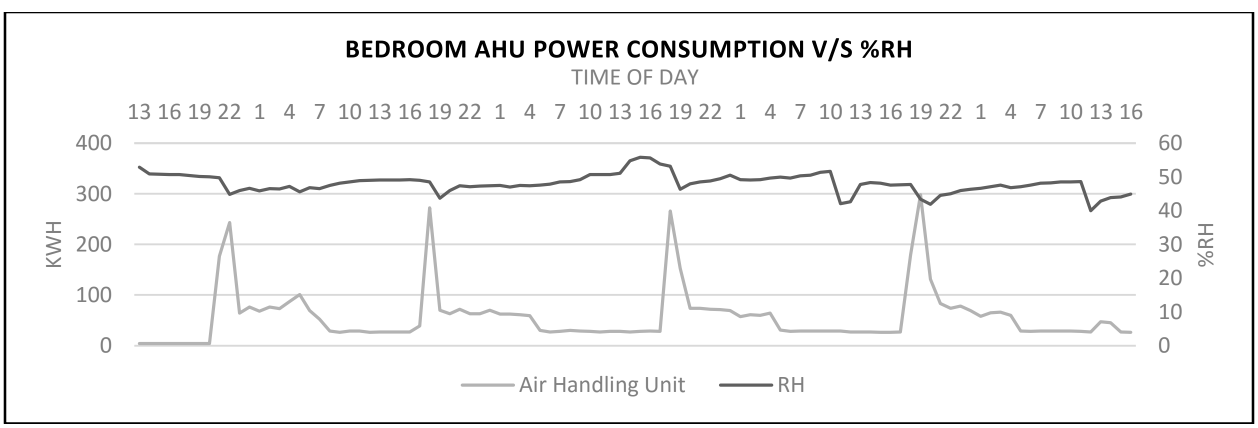

Figure 9: Modulation of Relative Humidity in the Bedroom

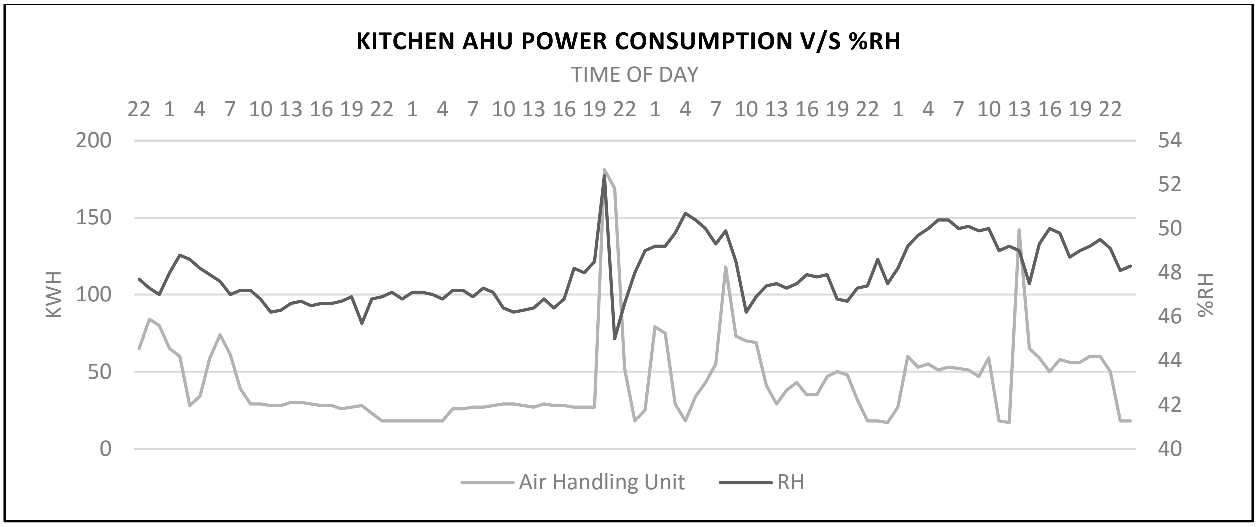

Figure 10: Modulation of Relative Humidity in the Kitchen

5. CONCLUSION

This study compared the effect of operation and control of the HVAC system of a home retrofit for low air infiltration on various interior air parameters. During the course of this study, authors measured interior concentrations of carbon-dioxide higher than ASHRAE's recommendation for the retrofit house. The house being highly airtight and the occupant's preference for having all windows and doors closed are some primary explanations for this phenomenon. In a questionnaire the occupant revealed that the ERV was at its highest setting throughout the heating season. Hence it can be concluded that the ERV is not able to providing adequate ventilation for the retrofit house under the present conditions. While the elevated carbon-dioxide levels are not an indication of unhealthy air quality, they do indicate that adequate ventilation may not be available for odor control. The relative humidity and indoor temperature readings from the retrofit house did not show any unusual patterns, and overall it can be concluded that the operation of furnace with the setback capable thermostat allows the occupant to reduce energy consumption, while maintaining a comfortable interior environment during hours of occupancy.

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