Realtime Analysis of Carbon Dioxide Concentration Curves for Intelligent Ventilation Control

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Abstract

This thesis is an investigation into the intelligent control of on-demand ventilation systems using carbon dioxide concentrations to determine occupancy patterns, the building's natural infiltration rate and as a proxy for indoor air quality (IAQ). The suitability of using CO_2 sensors to continuously monitor concentration changes in a ventilation zone in order to determine occupancy and natural infiltration rate is investigated.

A heat recovery ventilator (HRV) was modified by replacing the factory electronics with a designed controller that enabled variable air flow rates and direct control of recirculation via direct computer control. Apparatus was built to centrally sample the incoming fresh air and outgoing exhaust flows for CO_2 which was measured using a non-dispersive infrared (NDIR) sensor. An additional controller was designed to select air streams for sampling, command the HRV and send data to a data acquisition system. Data was logged for several months into a database and analysed. CO_2 concentration decays that highly correlated with a theoretical decay curve using a moving

window technique were studied as an indicator of vacancy while the decay constants of the decay curves were used to calculate the natural infiltration rate.

The results demonstrate that building ventilation zone occupancy schedules and natural infiltration rates can be accurately determined via the analysis of CO_2 concentration decay curves. These techniques allow a control system to automatically adjust to changing usage patterns without manual reprogramming. The natural infiltration rate of a ventilation zone would normally be unknown, making prediction of future CO_2 concentrations difficult. These calculated parameters allow intelligent, predictive ventilation control schemes which have the potential to minimize ventilation energy losses to their theoretical limits.

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List of Symbols, Nomenclature or Abbreviations

ACH	Air exchanges per hour
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
CAD	computer aided design
CO_2	carbon dioxide
[CO_2]	concentration of carbon dioxide
dCO_2	time averaged indoor minus outdoor [CO_2]
DCV	demand controlled ventilation
EPA	United States Environmental Protection Agency
ERV	energy recovery ventilator
HRV	Heat recovery ventilator
IAQ	indoor air quality
kg	kilogram
TLV	threshold limit value
max	maximum
min.	minimum
min	minute
mg	milligram
mySQL	A structured query language database server owned by Oracle
NBC	National Building Code of Canada
NDIR	non dispersive infrared
PCB	electronic printed circuit board
PHP	PHP hypertext preprocessor, a computer language
PIC	microcontroller product line from Microchip Technology Inc.
PID	proportional integral derivative control method
PM	Particulate Matter
PM10	particulate matter less than 10um in length
PM2.5	particulate matter less than 2.5um in length
ppm	parts per million
ppb	parts per billion
SBS	sick building syndrome
SQL	Structured Query Language
TVOC	total volatile organic compound
UFP	ultra Fine Particles
μg	microgram
USB	universal serial bus
USEPA	United States Environmental Protection Agency
VAV	variable air volume ventilation
VBA	Visual Basic for Applications
VFD	variable frequency drive
$\sum$	sum

Chapter 1

Introduction and Literature Review

1.1 Introduction

Increases in energy prices since the 1970s has resulted in continuous pressure to reduce the cost of heating and cooling buildings. While significant reductions in energy demands are possible by increasing the thermal resistance of building envelops and the optimization of fenestration, potential savings in cold climates are ultimately limited by the need to maintain acceptable indoor air quality (IAQ). The 2010 National Building Code of Canada states that ventilation rates shall not be less than the rates required by ANSI/ASHRAE standard number 62.1, "Ventilation for Acceptable Indoor Air Quality". The outdoor air flow rates required by ASHRAE 62.1 are primarily functions of both average occupancy and floor area and yield large ventilation flows of outdoor air. In order to reduce the energy demand for tempering the incoming fresh air, heat must be recovered from the outgoing exhaust air by mechanical heat exchangers. ASHRAE 62.1 allows demand controlled ventilation (DCV) as an alternative to fixed formulas based on occupancy and area but their DVC requirement is still rigid. A purely scientific approach whereby IAQ is analysed in real-time and flow rates are controlled precisely to meet minimum IAQ targets would be superior although it can conflict with less sophisticated legal mandates.

1.2 Review of Building Code

It is possible to design a ventilation system that provides indoor air quality (IAQ) that is acceptable to more than 80% of occupants with no known pollutant exceeding accepted threshold value limits derived from biological studies while minimizing the energy costs of providing the required ventilation, but such systems will be non-compliant if they do not meet building code. Most building codes rely heavily on generalities so that they can be applied to all buildings and achieve the desired outcomes in aggregate across the entire building stock. Minimum ventilation rates based on the occupied floor area are designed to minimize pollutants due to sources such as volatile organic compounds (VOC) off-gassing of carpets and furniture finishes or radon gas emissions from granite tiles or soil gasses. For an individual building these fixed rates may make little sense, especially if sensors are installed to measure actual VOC, radon and CO_2 concentrations, or if it is known that the off-gassing is very low or potentially highly variable such as a showroom for new furniture with hundreds of fresh finishes of unknown composition. The review of construction codes that follows is intended to look at the specific regulations that can conflict with ventilation control decisions based on a scientific analysis.

1.2.1 ASHRAE standard 62.1-2013

ASHRAE standard 62.1-2013, "Ventilation for Acceptable Indoor Air Quality", is commonly incorporated by reference into building codes as one of the minimum ventilation standards that must be met. Section 5.16 of the standard sets up classifications of air and restricts recirculation. ASHRAE categorizes air streams into four quality categories. Class 1 air is defined as having low concentrations of pollutants, little odour and low capacity for human sensory-irritation. Class 2 air is mildly offensive or inappropriate to send to other areas, for example the odour of food is acceptable in a cafeteria but not appropriate to recirculate to a library. Class 3 has significant contamination with objectionable odours while class 4 is a health hazard.

When air is mixed during recirculation via common return ducts, its new classification is the highest numerical classification of its source components. Class 1 air can be recirculated anywhere, class 2 can be recirculated to areas

Room Examples	Air Class
Commercial kitchen grease hoods, laboratory fume hoods	4
Residential kitchen hoods, daycare sick room	3
Daycare, wood working shop, cafeteria, kitchens, art classrooms	2
Libraries, classrooms, residential spaces	1

Table 1.1: Examples of Room Types and their Air Class

of similar purpose or to a toilet area while class 3 air can be recirculated only within its own zone. Class 4 air may not be recirculated and must be directly vented outside. Section 5.9.2 requires that the minimum outdoor air intake exceeds the maximum exhaust air flow. This creates a small positive pressure difference of a few Pascals relative to outdoors that minimizes uncontrolled infiltration of untreated outdoor air.

Section 5.9.1 requires that relative humidity in occupied spaces be limited to 65% or less. The moisture content of building materials is proportional to the relative humidity with higher levels allowing the growth of mold and causing excessive condensation on windows when outside temperatures are below the interior dew point.

Section 6.2.2.1 defines the basic prescriptive formula for the breathing zone outdoor airflow as follows:

$$V_{bz} = R_p * P_z + R_a * A_z \tag{1.1}$$

where:

R_p is the required minimum air flow per person

R_a is the minimum air flow required per square meter of zone floor area

P_z is the peak human population of the zone under typical conditions

A_z is the floor area of the zone

If the zone population peaks are of short duration, an averaging period of T minutes can be used where:

$$T = 50 * v/V_{bz} \tag{1.2}$$

where:

v = volume of breathing zone (m^2)

V_{bz} is the breathing zone outdoor flow rate (L/s)

An Example:

A school classroom is typically designed to allow $2m^2$ of floor air per student with a maximum occupancy of 25 students and 2 teachers and a ceiling height of 3m therefore:

R_a is 0.6 $L/s * m^2$ (from ASHRAE 62.1-2013 table 6.2.2.1)

R_p is 5 L/s*person (from ASHRAE 62.1-2013 table 6.2.2.1)

P_z is 25+2 = 27 people

A_z is $50m^2$

V_z is 50 * 3 = $150m^3$

V_{bz} is (5*27) + (.6 *50) = 165 L/s

Averaging time T = 50 * 150/165 = 45 seconds

The flow rates specified by ASHRAE range from $0.3 L/s * m^2$ to $0.9 L/s * m^2$ and per person from 2.5 L/s to 5 L/s and examples are provided [2].

Using this prescriptive approach, there is nothing that an intelligent control system can improve as the minimum flow rate is legally fixed based on the intended use of the building.

Section 6.2.7.1 of the code allows a dynamic reset as conditions change, the most obvious being at the regular close of business when a building becomes unoccupied. During these conditions, the minimum breathing zone outdoor airflow rate that of the floor area component.

Section 6.3 allows the outdoor flow rate to be calculated based on mass balance equations to reduce the concentration of measured contaminates to acceptable levels, however this method can only be used to provide additional air flow over and above the rate required by prescriptive procedures. There is no provision for lower flow rates based on sensor data. When a building has multiple zones and the population moves between zones, such as students changing classrooms, the per person air flow requirement can be reduced by a diversity factor as follows:

$$D = P_s / \sum_{i=1}^{n} P_{z_i} \tag{1.3}$$

Where:

D is diversity factor

P_s is the entire population of the building

P_{z_i} is the peak population of zone i

n is the number of ventilation zones

The outdoor air flow rate for a building with n zones then becomes:

$$V_{bz} = D * \sum_{i=1}^{n} (R_{p_i} * P_{z_i}) + \sum_{i=1}^{n} (R_{a_i} * A_{z_i}) \tag{1.4}$$

Any control system that can detect occupant density or determine the occupancy schedule can utilize the optional demand reset concept to lower ventilation flows when the building is unoccupied. Until regulations are updated in future versions of the standard to allow intelligent pollutant sensor based control, the statutory minimum air flow requirements must be also the minimum flow rate for any control algorithm.

1.2.2 2009 International Residential Code for One and Two- Family Dwellings

Natural ventilation is dominant in the International Residential Code (IRC) [3] since all inhabitable rooms must have windows with an area not less than 8% of the floor area and the openable area must not be less than 4% of the floor area. If mechanical ventilation is provided in lieu of operable windows, it must provide 0.35 air exchanges per hour (ACH) in that room or 78 L/s of fresh air per occupant for the entire dwelling, assuming one bedroom has two occupants and all other bedrooms have a single occupant.

Bathrooms require 0.3 m^2 of glazing with half of it openable or a mechanical system providing 24 L/s on request, or 10 L/s continuous.

1.2.3 National Building Code of Canada - 2010

The National Building Code of Canada is a model code that is intended to be adopted by Canadian provinces and applies to all new buildings constructed in Canada and to the alteration of existing buildings.

Section 9.32 Ventilation, provides prescriptive ventilation requirements for residential occupancies. Natural ventilation is permitted provided the sizes of window openings meet code, otherwise mechanical ventilation is required. The ventilation rates are fixed by room types rather than a function of floor area.

The principal ventilation fan, or multiple fans working as a group are required

Room Type	Air exchange rate L/s
Basement	10
Bathroom or toilet room	5
Dining room	5
Family room	5
Kitchen	5
Laundry room	5
Living room	5
Master bedroom	10
Other bedrooms	5
Other habitable rooms	5
Recreation room	5
Utility room	5

Table 1.2: Room types and non-heating season air exchange rate from NBC Clause 9.32.2.3.(1)(a)

to provide an exhaust air flow based on the number of bedrooms.

	Air exchange rate L/s	
Number of Bedrooms	Min flow L/s	Max flow L/s
1	16	24
2	18	28
3	22	32
4	26	38
5	30	45
more than 5	System must comply with Clause 9.32.3.1.(1)(a)	

Table 1.3: Principal Exhaust Fan Capacity for heating season ventilation

The primary ventilation exhaust system is under user control with a manual switch that can be turned off and there is no requirement to ensure that a minimum flow rate is automatically provided. This switch must be capable of overriding any automated control system.

If a fan is used to introduce fresh air into the dwelling, its capacity must be adjusted and permanently fixed to be within 10% of the flow rate of the primary ventilation exhaust system. Both systems must operate simultaneously. Outdoor air must be tempered to at least 12 °C unless a heat recovery ventilator is installed. Each bedroom must have a fresh air supply as must each story of the dwelling.

Currently, the ventilation requirements of building codes require statutory minimum fresh air flow rates based on the intended occupancy for commercial buildings, but allow residential occupants to turn off their mechanical ventilation systems. Therefore, a control system for residential use is not hampered by regulation. Commercial control systems do have to comply with current regulations although this is also subject to change since some codes, notably the National Fire Protection Association (NFPA) standards, fully describe the intent of each consensus based rule and allow for other engineered solutions provided that it meets the underlying objective. As building systems become more complex, construction codes will be forced to become outcome based rather than prescriptive and allow any engineered alternative that achieves equivalent outcomes.

1.3 Indoor Air Quality

The ideal atmosphere for humans is free of particles and aerosols and contains water vapour to provide a relative humidity between 40% and 60% with a temperature of approximately 22 °C. This humidity range minimizes microbial growth while providing sufficient moisture to prevent the dehydration of skin and mucous membranes. Additionally, the ideal breathing atmosphere is free of volatile organic compounds, irritating gasses such as nitrogen oxides or ozone and contains nitrogen, oxygen, argon and carbon dioxide in a ratio closely approaching the composition of the current atmosphere of Earth. The mixture would therefore be odourless, moist and sterile.

Some attempts to quantify various aspects of indoor air quality (IAQ) have been proposed. Fanger [4] and [5] introduces the concept of the olf which is the emission rate of pollutants from a standard person or any other pollutant source that results in the same level of dissatisfaction. The decipol is defined as the concentration of pollution created by a person in a room with a ventilation rate of 10 L/s. The standard person was derived from a study of 1000 sedentary men and women with an average skin area of 1.8m^2, daily underwear changes, 80% using deodorant and averaging 0.7 baths per day. These types of metrics are not usable as inputs to ventilation control systems and while a sensor array could be developed to quantify human body odour, the system would not be able to rank other combinations of unknown pollutants as having the equivalent undesirability as perceived by humans.

A logarithmic scale is proposed to relate total volatile organic compounds (TVOC) and CO_2 to human perception of odours since the human olfactory response is not linear (Jokl, 2000) [6]. The odour thresholds, 485 ppm for CO_2 and 50 μg/m^3 for TVOC are defined as 0 decibels with the upper limits of 15,000 ppm for CO_2 and 25,000 μg/m^3 for TVOC set by toxicity limits and equal to 135 on the logarithmic scale. These scales allow comparison of the relative contribution of CO_2 and TVOC to occupant dissatisfaction.

An auditorium occupied by 109 women was judged to be acceptable to 80% of the male and female judges when entering the space at a steady state ventilation rate of 7 L/s per person (Berg-Munch et all, 1986) [7]. The occupants however become acclimatized with a constant 10% dissatisfaction rate even with flow rates as high as 20 L/s per person. This indicates that if the goal of a control system is the satisfaction of regular occupants then the flow rate can be significantly lower than if the goal was the satisfaction of visitors.

Perfect indoor air quality is seldom practical to achieve due to the expense of filtering particles, absorbing gaseous pollutants and recovering energy from the exhaust during the heating and cooling season. In practice, acceptable indoor air quality is anything that is satisfactory to 80% of the occupants provided that the concentrations of all known pollutants are below their safe limits as defined by the authorities having jurisdiction. Clearly, acceptable indoor quality from a legal perspective may be totally unacceptable to 20% of the population and even dangerous to a smaller subset of the population. Examples of unacceptable air quality, albeit legally acceptable, are mould spore concentrations sufficient to trigger asthma in susceptible individuals, or volatile organic compounds from fabric flame retardants that appear to be linked to various diseases.

The filtering requirements and minimum flow rates specified in ASHRAE 62.1

are intended to provide acceptable indoor air quality, however any control system utilizing sensors has the potential to significantly improve indoor air quality.

1.4 Pollutants

Human generated pollutants are proportional to the number of occupants and their level of activity. The maximum designed occupancy of a zone is the usual criteria to determine the minimum outdoor air ventilation rate. For non human sources, such as the off-gassing of furniture finishes, volatile organic compounds from paints, radon gas from granite counter tops, an arbitrary ventilation rate based on floor area is used. Since the incoming fresh air may have other undesirable properties, it may be filtered to reduce particulates, humidified and tempered.

The following sections look at particular pollutants, their measurement and control.

1.4.1 Particulate Matter

The Canada Wide Standard for Particulate Matter less than 2.5 um in size (PM2.5) is $30\mu g/m^3$ with 24 hour averaging [8]. Particulate matter ranges in size from large dust particles visible to the naked eye to respirable dust with lengths below 10 micrometers (PM10). Particles larger than 10 um are filter are generally filtered by the nose and while very small particles, under 0.1

um are exhaled. The principal methods of removal are mechanical filtration, electrostatic precipitation and cyclonic separation. If PM10 in outdoor air exceeds 120 μg/m3 annually or 120 μg/m3 daily (National Building Code of Canada (NBC) 6.2.1.7) then the air must be filtered. In maritime climates, sea salt can contribute approximately $4\mu g/m^3$ to PM_{10}, with approximately 35% of that fraction as PM2.5.

This can impact the design of an IAQ control system. If indoor PM10 is expected to exceed regulatory limits, the control strategy can use recirculation and filtration to reduce particulates as well providing sufficient air flow to keep particles in suspension to facilitate their removal by filtration.

Particulate limits for a single species of fungus are 50 colony forming units per cubic meter and 150 when multiple species are present [9]. Removing spores from incoming fresh air is worthwhile however, it the fruiting fungi are growing indoors, then source control is necessary and the underlying excess moisture issues must be resolved.

1.4.2 Volatile Organic Compounds

A volatile organic compound (VOC) is any organic chemical with a vapor pressure sufficient to allow significant evaporation. VOC are normally present in the indoor environment and can originate from building materials, paints and varnishes, cleaning chemicals, room deodorizers or fresheners, cooking and human occupants.

A mass spectrometer study of the VOCs in classroom air and the exhaled air of students [10] finds ethanol, acetone, isoprene, toluene, methylisobutylketone, and aromatic hydrocarbons. Ethanol is traced to a duplicating machine, while actone and isoprene are produced by the students. Methylisobutylketone is traced to felt tipped pens, while the toluene and aromatic hydrocarbons source is not determined.

A review of 67 peer reviewed research articles containing both data on total volatile organic compound (TVOC) concentration and observed health effects [11] finds inadequate evidence for the relevance of TVOC as an indicator of discomfort or health risks. Since TVOC cannot distinguish the contributions of harmless endogenous components such as isoprene from toxic or irritating VOCs such as formaldehyde, this conclusion is not unexpected.

Wargocki et al [12] measured 32 VOCs in a occupied room with and without extra building materials which included four year old linoleum with a surface area equal to the room floor and 16 meters of wooden shelves with books and paper. The emission rate of VOCs is 3612 μg/h with the extra office materials and 60% less without the added materials.

Forty seven homes built to the R-2000 energy efficient building standard are found to be operating between 25% and 128% of the regulatory ventilation standards due to operator intervention [13]. This indicates that actual ventilation rates are heavily influenced by occupants of residential homes because they are free to open windows or turn off the heat recover ventilation (HRV) unit to reduce heating costs. Experimental results indicate that reducing the air exchange rate at which R-2000 homes receive their energy certification, by 25% would result in 32% of the study homes with TVOC concentrations exceeding 1000 μg/m^3 and the percentage of homes exceeding the target level of 0.05 ppm of formaldehyde would increase from 1.7% to 4.7%.

Mayo [14] finds the TVOC in Canadian research homes range from 0.04 mg/m3 to 0.7 mg/m3 with higher levels seen after occupants moved in with new furniture.

VOCs can be detected with commonly available, inexpensive, metal oxide sensors but these sensors are non-specific. Much research has been done on arrays of sensors, either dissimilar or identical but operating at different temperatures to characterize odours. The output of the array can be used as a signature to identify combinations of VOCs such as a coffee or spice mixture and they have been successfully used to identify adulterations. However, these electronic noses are very crude compared to human noses and cannot uniquely identify specific indoor air contaminates. VOC sensors arrays could be incorporated into a control system to identify large changes in VOC levels or used to identify the signatures of cooking, a newly painted wall or the chemicals used to clean floors and temporarily increase the ventilation rate.

Wolkoff et al [15] questions whether testing for specific VOCs such as formaldehyde or TVOC is overly simplistic as a predictor of sick building syndrome or human discomfort. The threshold limit values of VOCs that cause irritation in humans are generally 10 to 1000 times higher than the levels encountered in indoor air with the exception of formaldehyde and acrolein. Oxidizing agents such as ozone, either introduced from outside air or generated by electrostatic sources such as air cleaners or photocopiers can react with unsaturated VOCs to create new chemicals that have lower TLVs. Additionally, chemicals adsorbed onto particulate matter be relevant to SBS.

Rim et al [16] find that ultra fine particles (UFP) ranging from 5 to 100 nm infiltrating into a house are reduced by a factor of three to five by keeping all windows closed. UFP may originate from automotive exhaust or atmospheric photochemical reactions, or from indoor sources such as gas burning appliances. Toxic chemicals such as polycyclic aromatic hydrocarbons can adsorb onto UFP and enter the human body via respiration.

1.4.3 Humidity and Temperature

Indoor relative humidity should be maintained between 40 and 60 percent [17]. While occupants can tolerate a larger range, low humidity dries out skin and mucous membranes and increase static electricity, while higher humidity levels increase the moisture content of building materials. If the non-heating season, the hard upper limit on humidity is approximately 90% where the moisture content of organic building materials exceeds approximately 25% percent allowing fungi to destroy wood and pollute indoor air with spores. In the heating season, the interior face of windows can be below the dew point and dehumidifies the air. This forces a compromise between lower humidity levels and dry windows openings.

Predictive models of the perceived thermal comfort for occupants engaged in sedentary activities using temperature, relative humidity and the insulation value of clothing statistically account for less than 6% [18] of the mean comfort score or percentage of participants dissatisfied. Human perception of thermal comfort is complex and is heavily influenced by non physical environmental factors such as cultural attitudes, dress code, physiological adaptation and individual fitness which cannot be adjusted by a ventilation control system. Therefore, the most profitable ventilation control strategy from an indoor temperature and energy perspective is to maintain the indoor temperature as close as practical to outdoor ambient temperature without exceeding generally accepted cultural limits for indoor air temperature.

1.4.4 Radon

Ventilation control systems must provide sufficient outside air flow to remove non-occupant generated pollutants such as radon gas. Radon control can take the form of a minimum air exchange rate, a air purge before scheduled occupancy or source control procedures such as foundation gas barriers, sealing and sub-slab de-pressurization.

Radon gas may pass through building foundations in areas where soil gas radon concentrations are high. Increasing the ventilation rate from 0.07 to 0.80 ACH in a low infiltration research house in Maryland, USA is found to reduce basement radiation levels from 30 pCi/L to 1 pCi/L [19] or 1100 Bq/m^3 to 37 Bq/m^3. The concentration of radon gas in basements is highly dependant on the local geology, imported fill and choice of building materials so providing higher ventilation rates or radon control procedures makes sense only when unacceptable levels of radioactivity are measured after construction. The first Canadian residential radon limit was set at 800 Bq/m^3 in 1988, and this was subsequently reduced to 200 Bq/m^3 in 2007 [20]. Remedial action is required if the annual average radon concentration exceeds 200 Bq/m^3.

Decorative granite counter tops are also a source of radon, although the contribution to total radon is less than 1% [21] under normal conditions. The average granite slab is found to release 42 ± 6 Bq/m^2 per day which is insignificant unless there is no ventilation via windows or mechanical means. The possibility of radon infiltration is one of the reasons for the specification of a minimum air exchange rate based on floor area.

1.4.5 Infiltration Measurement Techniques

When the natural infiltration rate of a ventilation zone is known, the future CO_2 concentration of the unoccupied ventilation zone can be determined. If CO_2 reaches a steady state during occupancy and the natural and effective mechanical infiltration rates are known, the CO_2 generation rate can also be determined. The natural ventilation rate is a useful input to an intelligent control system, but one which is generally not known.

Perfluorocarbon tracer gasses can be used to measure the ventilation rate of buildings by emitting the tracer gas at a constant rate and measuring the resulting time averaged concentration [22]. It is also shown that the adsorbent used to capture the tracer gas can also be used to collect VOC for simultaneous analysis via gas chromatography.

410 new (built in 1984) energy efficient single family homes in the United States Pacific Northwest, built to follow the guidelines of the model conservation standard developed by the Northwest Power Planning Council in 1983 were compared with a different control group of 410 new homes, also built in 1984, constructed using conventional techniques. The homes were tested using fan pressurization and perfluorocarbon tracer gasses [23] which found the control group averaged 0.4 ACH while those built to the model code averaged 0.25 ACH. Heat recovery ventilation (HRV) units were used to increase the flow rates in the model homes to 0.35 ACH. The study found that homes tended to use the HRV continuously or not at all, averaging 9 hours per day. Tracer gas testing on 120 units of the control group indicated an infiltration rate of 0.31 ACH while blower door testing indicated 0.55 ACH.

A subsequent study [24] researched the effectiveness of estimating ventilation rates with tracer gasses as presented by Parker [23] and found the variability in estimated ACH was heavily influenced by air mixing, temperature differences and wind conditions. Only in a single zone with completely mixed air would it represent the actual infiltration rate, and only for the prevailing atmospheric conditions. The author also notes that the tracer gas tests always represent the dissipation rate of pollutants in the zone being measured.

Air change effectiveness (ACE) is the average age of air in a well mixed building divided by the age of air in the breathing zone. When all air throughout the building is perfectly mixed, ACE is equal to 1 while displacement ventilation using perforated floors can approach 1.9 [25]. Recirculation aids mixing and increases ACE. Ceiling supply and return vents supplying heated air allow heated air to travel along the ceiling thus short circuiting air exchange, thus reducing ACE. Systems with the fan set at low, or variable air volume systems set at minimum also reduce mixing and therefore the ACE. Offermann [26] uses SF_6 tracer gas to determine the ventilation effectiveness of diffuser configurations in an office building. Ceiling and return mounted diffusers are found to have an effectiveness of 0.73 while high wall supply and return ducts that face each other have an effectiveness of 0.57.

Heated air flow, using the minimum flow rate of a variable air volume (VAV) system and no recirculation were found to have an ACE between 0.69 and 0.89 [27]. Cooling the supply to ceiling mounted supply and exhaust vents results in an ACE of 0.99 to 1.15.

In cool climates where outside ventilation is provided via outside air through ceiling vents, or where forced air heating systems have floor mounted supplies, reduced ACE is not an issue. None of this would be an issue for a control system that can calculate the infiltration rate directly, but does become a design issue the design ventilation rate does not achieve its goals due to reduced ACE.

Shaw [28] finds the pressure differentials across walls in two schools built in 1968 and 1972 to be proportional to the square of the wind velocity and dependant on wind direction. Air leakage is found to be a function of the mean pressure difference across walls. Li [29] derives analytical solutions for natural ventilation as a function of thermal buoyancy, heat loss through the building envelope and wind force. The envelope heat loss component is found to be a significant driving factor of natural ventilation, and thermal buoyancy can assist or retard the wind force component.

A ventilation control system can calculate the instantaneous infiltration rate using CO_2 as the tracer gas and potentially correlate them with wind speed and temperature for increased accuracy. Typically, the CO_2 sensors used in DCV systems are compared to current concentration to pre-set thresholds and do not analyse sensor data to determine infiltration rates.

1.4.6 Proxies for pollutants

Many pollutants do not have inexpensive sensors available as no sensor exists that can categorize odours as objectionable as a human nose would. Some dwelling pollutants, such as CO_2 are produced solely by its occupants and therefore make useful proxies for other pollutants that are generated by humans or their activities.

Atmospheric carbon dioxide concentrations measured at Mauna Lao Observatory between 1958 and 1979 are found to vary annually by 5.5 ppm, with the peak increasing linearly from 329 ppm in 1974 to 337 ppm in 1981 [30]. This linear trend may not continue since historical analysis of CO_2 concentrations by chemical analysis over the 180 year period from 1810 to 1960 indicate variations from a low of 310 ppm to peaks above 410 ppm [31]. This indicates that the annual average is not a fixed reference that can be used for calculating the indoor-outdoor concentration differential.

The CO_2 concentration in a suburb of Phoenix is measured continuously during the year 2000 [32]. The daily minimum CO_2 concentration is found to be a constant 390 ppm and generally occurs during the afternoon when thermal induced air currents induce mixing. Daily maximums are found to have a mean peak of 490 ppm in December and 423 ppm in July and occur just before sunrise. The traffic peak induced differential between week day and weekend is 36 ppm in winter and 22 ppm in summer. The differential between winter peak and daily lows is 100 ppm, and this must be accounted for by any control system that responds to CO_2 levels since it would otherwise increase the ventilation rate during winter nights which is also the period of greatest heating demand.

Yawning is a component of empathy in some species, and not caused by elevated carbon dioxide concentrations as commonly believed [33]. Yawning is not found to be affected by CO_2 concentrations between 3% and 5% nor inhibited by breathing pure oxygen [34].

Carbon dioxide is produced in proportion to the metabolic rate and weight of human occupants and has been found to be a useful proxy for both pollutants of human origin and workplace generated pollutants. Carbon dioxide does not directly irritate mucous membranes, skin or lungs but is produced in proportion to activity. Home activities such as cooking and cleaning lead to increased concentrations of volatile organic compounds, while in an office environment, particulate and gaseous pollutants could originate from printers, photocopiers, writing instruments, coffee machines and kitchens.

An analysis of one hundred office buildings from the US EPA *1994-1998 Building Assessment Survey and Evaluation Data Set* [35] found a correlation between Sick Building Syndrome (SBS) and indoor CO_2 concentration. The eight hour time weighted average difference between indoor and outdoor CO_2 concentrations is found to have a statistically significant correlation with sore throats, mucous membrane and lower respiratory symptoms and reducing indoor CO_2 levels to outdoor levels would be expected to reduce SBS symptoms by 85%.

1.5 Sensor Technologies

Won and Yang [1] review sensor technologies suitable for ventilation control and compare the specifications needed for DVC control with the characteristics of available sensor technologies.

Pollutant	IAQ Range	Typical Range	Resolution
CO_2	800-3500 ppm	350-2000 ppm	$\leq$ 50 ppm
Water	30-80% RH	10-80% RH	$\leq$ 5%
TVOC	0.8-2.5 ppm	.02-1 ppm	$\leq$ 3 ppb
PM_{10}	20-180 $\mu g/m^3$	10-100 $\mu g/m^3$	$\leq$ .05 $\mu g/m^3$
Rn	2.7-5.4 pCi/L	1.3 pCi/L	0.7 pCi/L

Table 1.4: DVC Sensor Requirements adapted from [1]

Non dispersive infrared (NDIR) sensors are reported having ranges of zero to 5000 ppm with a resolution of 1 ppm with no calibration required. Thin film capacitive sensors for relative humidity are reported to have a range of 0-90% with a resolution of 0.1% and no calibration required. TVOC photo ionization sensors are reported to have a range of 0.02-20 ppm but are expensive, costing CAD$2000 or more. Formaldehyde electrochemical sensors have a range of 0.2 to 10 ppm and resolution of 0.1 ppm. Light scattering particle counters for PM_{1_0} are available but expensive, costing CAD$3000 or more and require zeroing with a filter as well as flow rate calibration. The prices and capabilities of these sensors at the time of the comprehensive review (2005) have changed very little in the subsequent 9 years with the exception of capacitive and NDIR sensors which are now mass produced for automotive applications.

Fisk et al [36] analyse CO_2 sensors in commercial buildings and find building managers do not recalibrate sensors and that accuracy is often insufficient to meet the California title 24 standard of 75 ppm. Wall mounted sensors are found to give more variable results than air return mounted sensors since occupants breathing near wall sensors can drastically raise the local CO_2 concentration. Single wavelength sensors are found to be more accurate than dual wavelength designs and automatic background calibration can be problematic if the lowest recently encountered concentration is not equal to 400 ppm, the assumed default outdoor concentration.

Inexpensive and accurate sensors for temperature, relative humidity and CO_2 are readily available and can be incorporated into a DCV controller. PM_{10} and TVOC are currently too expensive for general purpose control systems.

1.6 Control Strategies

The simplest indoor air pollution mechanical control strategy is to provide fans and ductwork with sufficient fresh air flow capacity that regulatory limits for pollutants are not exceeded during peak occupancy or peak pollution emission. This can be enhanced by careful attention to air diffuser design and placement to ensure the fresh air is well mixed resulting in an ACE of one. In some applications such as computer rooms and laboratories, displacement ventilation can be implemented via injection of fresh air through perforated floors to further increase the ACE. If pollutant emissions are not uniform throughout the building, such as a closed master bedroom or auditorium with higher emissions than surrounding rooms, then these areas can be zoned independently. Assuming that the outdoor air is always acceptable and that the pollutant sources are well understood, the only disadvantage is the energy wasted in heating or cooling the incoming fresh air.

To save the energy costs of ventilating unoccupied rooms as if they were at full capacity, demand controlled ventilation (DCV) can be used to reduce the flow rate as occupancy drops. The simplest such strategy is a calendar based schedule to switch the outdoor ventilation rate between a high flow rate for maximum occupancy and a low rate based on floor surface area or known non-human generated pollution sources. This works well in program driven buildings such as a school with fixed classroom hours, fixed activities such as art, science lab, general classrooms and a constant room population. In this strategy, time of day is a proxy for demand. If the schedule is unpredictable or the activities in the rooms are unknown, then this type of schedule driven DCV becomes dysfunctional. Alternately, passive infrared sensors could be used as motion detectors to avoid having to program the schedule.

If a building is constantly occupied and the infiltration rate is known, CO_2 concentration will achieve a steady state value, which in turn can be used to calculate CO_2 generation rate. This in turn can be used to adjust the additional flow required to dilute human-generated pollutants. However, most buildings are occupied intermittently and have variations during events such as meal times such that steady state plateaus are rare.

CO_2 sensors are commonly used as a switch to increase ventilation when levels exceed a fixed threshold of approximately 1000 ppm. There is a delay between the commencement of increased occupancy and reaching the threshold and triggering full speed ventilation, nor does it allow proportional control which would have allowed variable frequency drives (VFD) to slowly, and unobtrusively adjust the ventilation and prevent overshooting the threshold.

Fisk [37] reviews sensor based demand controlled ventilation strategies from 31 papers published between 1979 and 1989 and a DCV review by the International Energy Agency. The authors find that sensor based demand controlled ventilation (SBDCV) is cost effective when controlling the dominant pollutant is sufficient to control all other pollutants present, occupancy levels are unpredictable and space heating and cooling is expensive. The authors also note that humidity is not well correlated with residential pollutants, TVOC sensors are useful for triggering extra ventilation during extreme events such as fresh paint, that CO_2 sensors are the basis for most sensor based DVC systems.

Chao and Hu [38] choose CO_2 as a proxy for human generated pollutants and radon gas as the dominant non-human pollutant in a lecture hall. Radon is purged periodically such that a one hour purge before classes begin is sufficient to reduce the concentration of all non-human generated pollutants to acceptable levels before occupants arrive. A set point of 50 ppm above outdoor levels is used to activate a PID controller with a set point of 1000 ppm. The radon input also feeds a PID controller and the greater flow rate required by either the CO_2 sensor or radon sensor is used to control the flow rate when the building is occupied.

Mui and Chan [39] calibrate a building by determining the flow rate required to dilute expected, non-occupant generated pollutants. The authors record occupant satisfaction data, T, RH and the concentrations of HCO, CO, CO_2 and Rn for a year to determine the emission rates and specific building issues. They calibrated the fresh air damper by injecting SF_6 tracer gas to determine the effective air exchange rate. The ACH values are to determine the fresh air damper position required to keep known non-occupant generated pollutants such as radon or HCO below the statutory limits.

Sun et al [40] implement a DCV strategy in a multi zoned 98 story building in Hong Kong and find that the number of occupants calculated from the CO_2 concentration of a floor highly correlate with the occupant count as

determined from monitoring security cameras. The authors use incoming an outgoing flow rates and CO_2 concentrations to validate mass balance as a method to check for sensor accuracy. The CO_2 setpoint is determined by the occupant count however if the CO_2 concentration does not respond, the setpoint is changed to that of the building management control system.The authors find significant energy savings in the hot summer months but find enthalpy control to be superior at saving energy costs in the winter months.
Nielsen and Drivsholm [41] present a two speed DCV system fitted to a residential dwelling in Sweden, occupied by two adults and two children, with ventilation flow rates of 216 m^3/hr and 80 m^3/hr. When the difference between indoor and outdoor CO_2 concentrations exceed 150 ppm, the larger flow rate is selected. To keep the relative humidity in the heating season below 50%, when the differential between indoor and outdoor absolute humidity exceeded 2 g/kg, high speed was selected. The humidity threshold was based on a typical outdoor weather of 5 °C and 100% relative humidity (5.4 g/kg) and an indoor set point of 20 °C 50% relative humidity (7.3 g/kg). If the indoor RH exceeds 50%, then the absolute humidity differential will exceed 2 g/kg, triggering increased ventilation which would reduce indoor RH. This strategy results in the low fan speed being selected 37% of the time.

Sachs et al [42] evaluates field programmable thermostats to determine if easy to use thermostats are more likely to be used by occupants than the hard to program variety. Thermostats were installed in 77 low income apartments where occupants were financially responsible for their power bills. They find that thermostat usability had no influence on occupant behaviour and that only 3% of occupants used the nocturnal setback. When devices were re-programmed by occupants, they were not used to lower temperatures to save money. The mean temperature day and night setback temperature was 71 °F and the authors conclude that thermal comfort overrides any desire to save utility costs.

1.6.1 Air Distribution Strategies

Most residential buildings that were constructed before 1970 have sufficient natural air leakage that no additional mechanical ventilation is needed. As the trend towards tighter building envelopes progressed, mechanical ventilation became common although natural ventilation was still permitted provided window openings were sized adequately.

Houses with forced air heating and cooling are very well mixed which prevents pockets of poor air quality but homes heated with electric baseboard or hydronic systems lack a large circulation fan and can have local areas of poor air quality. Often, the only mechanical fans are the local bathroom and kitchen exhaust fans required by building code, where the make up air is supplied by uncontrolled infiltration. Reardon [43] evaluated five different ventilation arrangements in a two story research house owned by the Research Council of Canada using gas diffusion testing and found that only ducted, balanced systems provided the air flow rates required for each room type.

Although the bathroom and kitchen fans were capable of providing sufficient air flow for the whole home, when the bathroom fans were engaged, air was pulled in from the lower story and basement over ventilating those floors while under ventilating the upstairs master bedroom. Adding passive inlets to provide fresh air to the bedrooms helped, but only a ducted system provided the designed air flows per room.

There is little benefit in adding demand controlled ventilation systems to buildings that are leaky enough to not require ventilation, nor is it practical to control the ventilation in structures that lack fresh air ducting to each zone or room since the design goals of acceptable IAQ cannot be met. Homes built after the year 2000 generally do have HRV units and balanced inlet and exhaust ducting and are candidates for control systems.

Persily et al. [44] compare several DVC ventilation strategies on an office, conference room, lecture hall, classroom, portable classroom and a restaurant.

Classroom example using a proportional algorithm giving minimum fresh air flow rate when the zone CO_2 is ambient plus 50 ppm and the maximum fresh air flow rate when the zone is at or above its design steady state concentration with the exception of the last case where the upper limit for the linear control region was set to 800 ppm.

Method	Ventilation Rate	Min airflow	Max airflow	CO^2 steady state ppm (limit)
ref	7.1 L/s per person * design capacity			1106
1	7.1 L/s per person	zero	7.1 L/s * current occupancy	1106 (1106)
2	7.1 L/s per person	zero	7.1 L/s * design capacity	1106 (1106)
3	7.1 L/s per person	25% of max	7.1 L/s * design capacity	1106 (1106)
4	4.7 L/s per person + floor area * 0.6 L/s*m2	floor area * 0.6 L/s*m2	4.7 L/s * design capacity	1174 (1174)
5	7.1 L/s per person	greater or floor area * 0.76 L/s*m2 or 7.1 L/s per person	7.1 L/s * design capacity	1106 (800)

Method	avg CO_2	max CO_2	avg VOC	max VOC	MJ/m2
ref	866	1060	.06	.06	446
1	1015	1090	.22	1.04	202
2	938	1199	.24	1.01	228
3	920	1100	.17	.64	264
4	978	1180	.15	.52	230
5	874	1080	.12	.41	303

1.7 Ventilation energy losses

One of the design goals of any DVC control system after satisfying acceptable IAQ is to minimize operational costs. The operation of energy recovery ventilators (ERV) is found to reduce annual heating requirements by 40% [45]

Lawrence and Brown [46] model modular school buildings in Oakland California using software modelling and finds that DVC using a fixed CO_2 set point reduces the annual energy required by the cooling compressor and fans by 4.3%. The heating demands are too low to overcome the statistical noise and thus not evaluated. Similar tests on McDonald's children's play areas predicted an 8.7% annual decrease in compressor and fan energy and an increase of 0.3% in a similar restaurant. DVC is found to increase the mean CO_2 concentration in the McDonald's play areas between 7% and 15%.

Lawrence and Brown [46] find modular classrooms using a fixed ventilation scheme satisfying ASHRAE 62-1999 exceeds 1200 ppm CO_2 60% of the hours, whereas the DVC strategy exceed 1000 ppm 11% of the time and never exceeded 1200 ppm.

Pavlovas [47] implements a proportional control algorithm for ventilation control in single bedroom apartments in a three story apartment building in Sweden. CO_2 and relative humidity are used individually to vary the kitchen and bathroom exhaust fans from 10 l/s to 30 l/s. CO_2 setpoints of 800 ppm, 1000 ppm and 1200 ppm were evaluated along with two separate proportional gains.The heat lost due to excessive ventilation can be reduced by 50% using relative humidity or CO_2 based DVC control and 20% using occupancy sensors.

Wang and Xu [48] implement PID control of heating and cooling coils as well as the fresh air damper. When the heating coil is active, fresh air is modulated to maintain a fixed CO_2 setpoint while the heating coil is modulated to maintain a temperature setpoint. Once the heating coil demand drops to zero, fresh air is controlled via PID control to maintain the temperature set point to provide free cooling. As cooling loads increase, fresh air cooling is reduced and mechanical cooling increased until the system is completely mechanically cooled, using PID control and a temperature setpoint with the fresh air damper PID control maintain a fixed CO_2 setpoint. The challenges with the multi phased approach relate to stability and damper oscillation s during the transition between modes. The authors minimize this by adjusting the integral terms of the newly active PID control equal to the previously active PID control and adjusting the gain terms incrementally. The authors report winter energy savings of 28%, summer savings of 4% and significant CO_2 reduction of 400 ppm in the winter season.

Fisk and Sullivan [49] evaluate optical people counters as a method to determine the required ventilation rate in a building. The evaluated systems are accurate to approximately 10% but can also be inaccurate by 100% or more with challenging situations such as two people entering a doorway together with winter clothing that masks their thermal signature.

1.8 Objectives of this Thesis

An intelligent ventilation control system requires a knowledge of the natural infiltration rate so that future CO_2 concentrations can be predicted. Patterns of occupancy are normally pre-programmed into HVAC controllers as a recurring weekly schedule. An intelligent ventilation control system would ideally be able to learn occupancy patterns and the probability of an arbitrary future vacancy by data analysis. Learning avoids the need for manually programming that may become obsolete.

The use of carbon dioxide thresholds by DCV systems to trigger increased ventilation over and above the regulatory minimum air flow rates in commercial buildings represents a missed opportunity to extract additional information contained in the sensor data stream.

This objective of this thesis is to prove that the natural infiltration rate of a ventilation zone and its occupancy patterns can be derived from the continuous data stream from a commercially available NDIR CO_2 sensor in near real-time and used for DVC control strategies.

1.9 Organization of this Thesis

Chapter one is a comprehensive literature review of current control methodologies and relevant IAQ issues and discussion of the arbitrary legal regulatory framework that may prohibit certain DVC techniques. The components of IAQ are discussed, including particulate matter, volatile organic compounds, radon and sensor technologies.

Chapter two is a description of the designed apparatus for this research. It describes the test home, modifications to the mechanical ventilation system, layout of supply and return ducts and the design of the central air sampler. The data acquisition system is discussed as well as the occupancy patterns of the test house.

Chapter three presents the general characteristics of the test building, the effect of wind speed on the natural infiltration rate and issues with the coupling of intake and exhaust streams. The identification of vacancy periods and infiltration rates are discussed using the collected data is discussed.

Chapter 4 is the conclusion and suggestions for further research which include using vacancy maps for heating control, alternate sensors for better characterization of IAQ.

Chapter 2

Designed Air Handling and Air Sampling Apparatus for this Research

This thesis required methods to control the incoming fresh air flow rate, re-circulate air within the dwelling and to monitor the concentration of CO_2 in both the incoming fresh air and dwelling exhaust air streams. Additionally, the controls had to be under computer control with data logged continuously for analysis.

2.1 HRV Modification

Most new Canadian residential dwellings are equipped with a heat recovery ventilator (HRV) because it inexpensively satisfies the exhaust airflow and pressure balancing requirements mandated by the NBC. Additionally, HRV units are ducted to provide fresh air to bedrooms and living spaces and usually receive stale air from multiple locations which are combined in a common return duct. The HRV return duct provides a useful location for the centralized control and monitoring of IAQ.

Figure 2.1 shows a typical ducting arrangement where fresh air, shown as blue lines, passes through the heat recovery core and is warmed or cooled by the outgoing exhaust, shown as red lines. The fresh air ductwork branches out and feeds multiple living spaces such as bedrooms and living rooms. Usually there are equal quantities of intake and exhaust ducts to simplify balancing. The exhaust ducts are placed to receive air from zones with elevated levels of humidity and odour such as bathrooms and cooking areas. During commissioning of the HRV, a manually adjustable damper is positioned to achieve a balance between incoming and outgoing air flow rates. This ensures that the home air pressure is equal to the outdoor pressure thus preventing back drafts from chimneys or forced exfiltration through the building envelope. Air flows within the home from rooms with fresh air ducts and towards rooms with exhaust vents. Typically the exhaust ductwork combines and is reduced to a single duct a few meters before it returns to the HRV. Therefore, the pollutant concentration in the exhaust input of the HRV is representative of the whole house average.

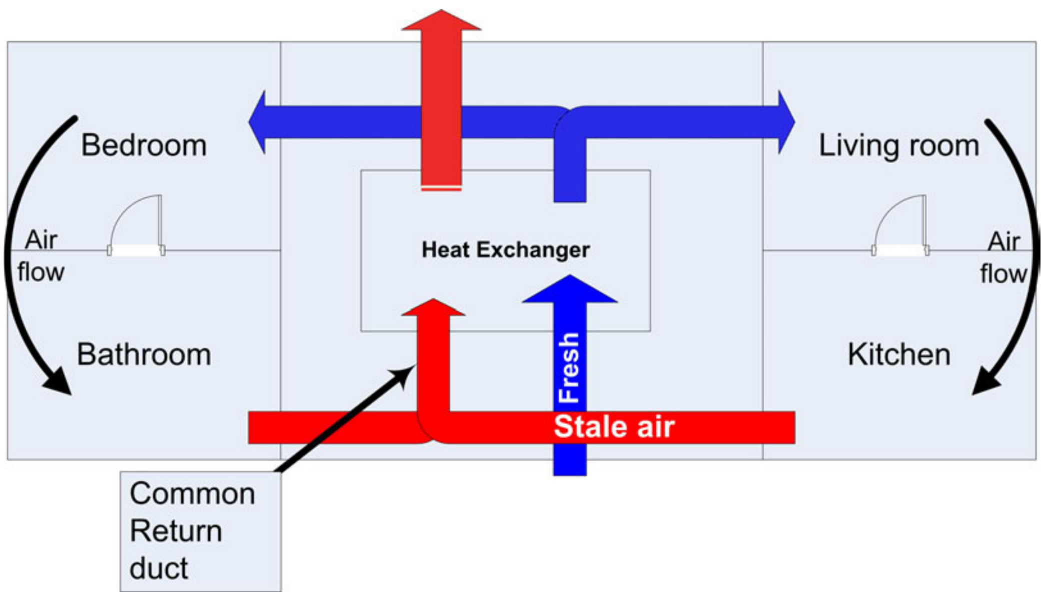

Figure 2.1: Typical HRV ducting concept

The HRV in the test home is the Constructo model manufactured by Venmar. The unmodified HRV has a two speed induction motor and uses timed periodic recirculation to defrost the heat exchanger core when the outside air temperature is below 0 °C. The unmodified HRV has no mechanism to intentionally place the unit in continuous recirculation.

Figure 2.2 shows the HRV unit, located in the basement of the dwelling and suspended from the ceiling by chains with the top hinged front cover

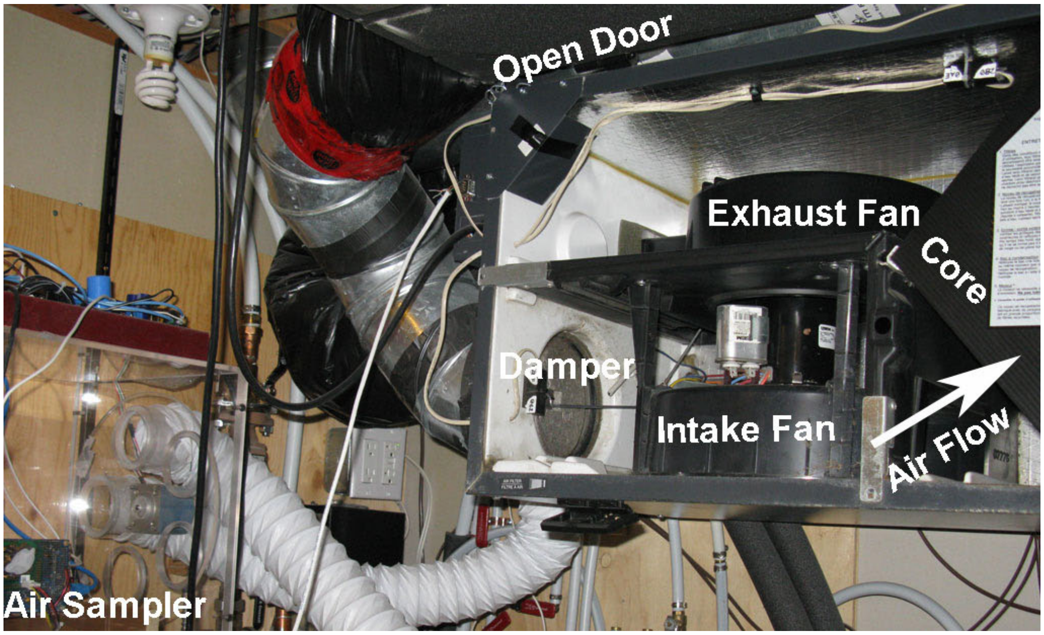

Figure 2.2: modified HRV and central air sampler

open and lifted upwards. Dual centrifugal fans are driven by a double shaft, vertically mounted induction motor. An electric actuator closes the intake damper via a connecting rod while simultaneously opens a door between the upper and lower chambers of the HRV to force recirculation for defrosting the heat exchanger core.

To allow direct computer control of the HRV, the original control board supplied by Venmar was replaced with a new circuit board designed for this thesis work.

Two PIC microcontrollers and a communications interface were added which

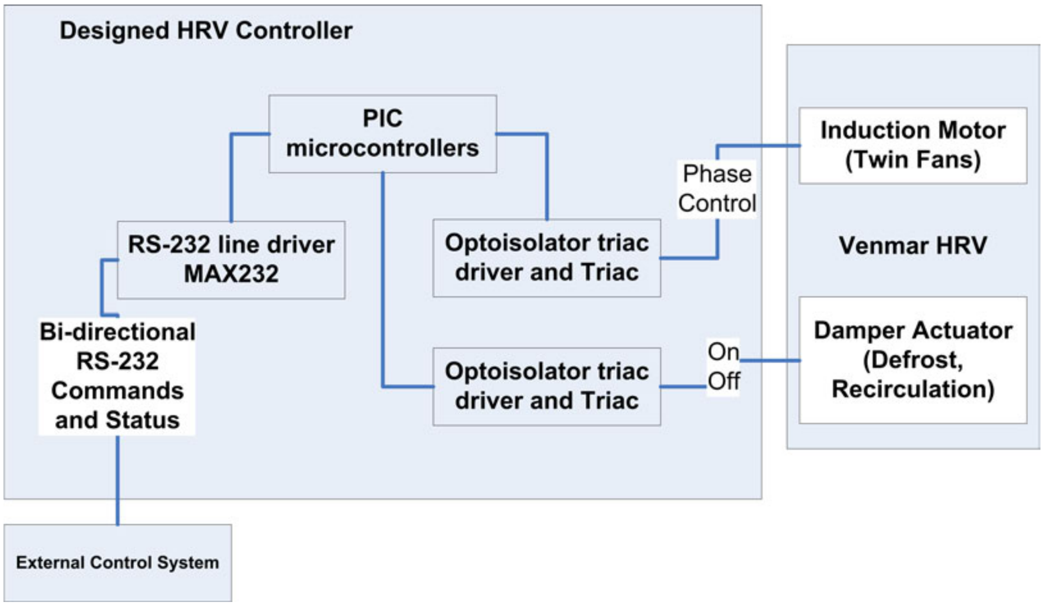

Figure 2.3: Designed Venmar controller block diagram

respond to commands for recirculation and airflow rates. Figure 2.3 shows the conceptual design and figure 2.4 shows the detailed schematic diagram. Figure 2.5 shows the completed board.

The fan motor speed is varied by adjusting the triac triggering delay after zero crossing while the actuator motor is switched on and off by an optically isolated triac. The controller is commanded by simple ASCII commands sent via the RS-232 interface from the main system controller, a Parallax Propeller^{TM}.

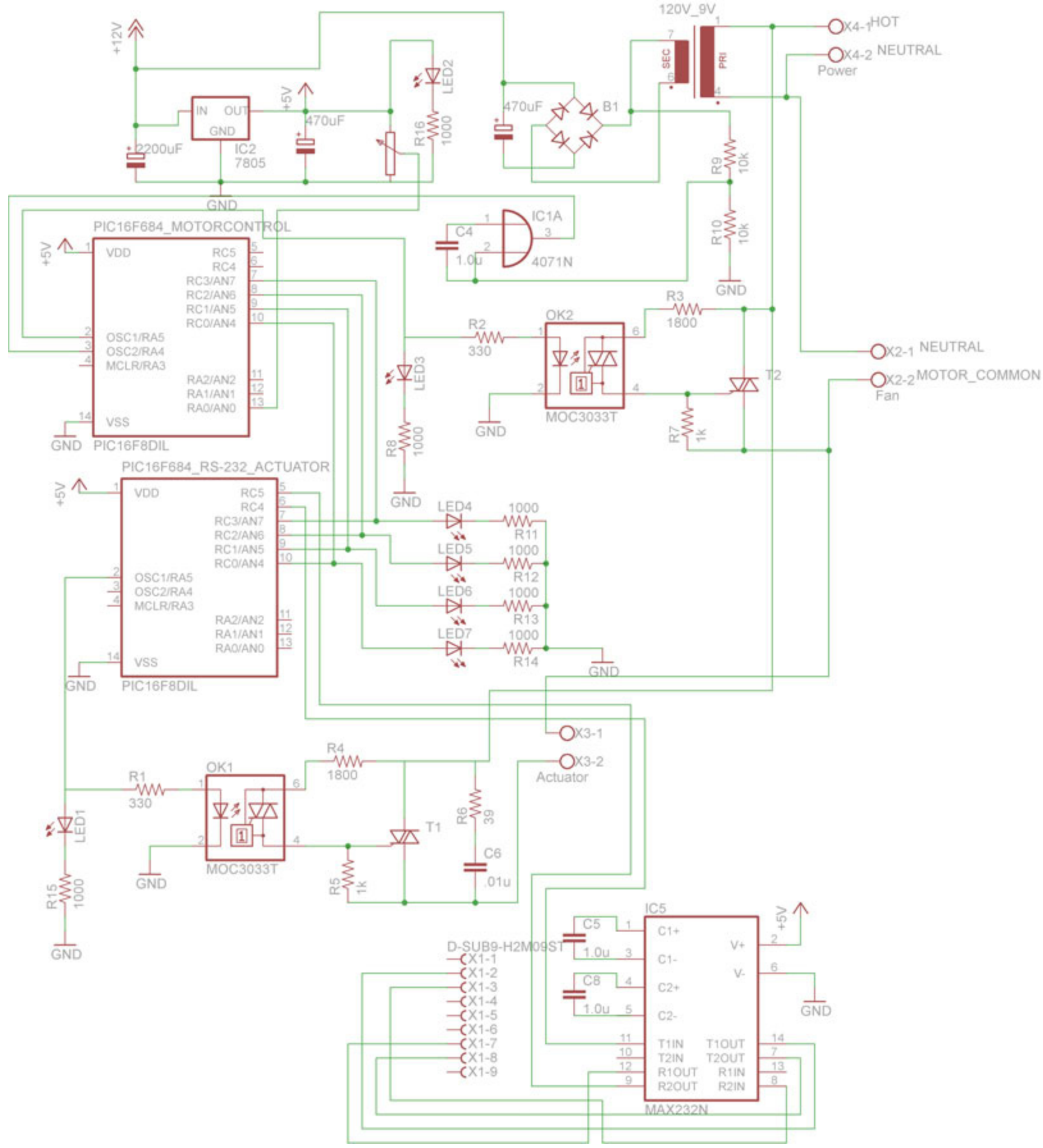

Figure 2.4: Designed Venmar controller schematic

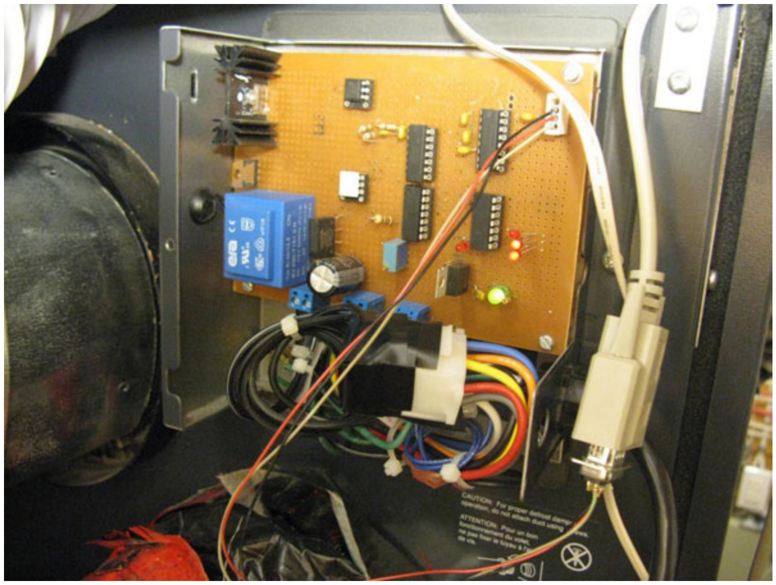

Figure 2.5: Designed motor and damper controller

2.2 Air Sampling System

A Figaro K30 NDIR sensor was chosen for the CO_2 sensor. To avoid potential problems with sensor drift and to allow relative measurements, a single sensor was used for both incoming and outgoing air streams. This was accomplished by housing the instrumentation in a sampling box and using a stepper motor to select the air stream via a rotating disk. Figure 2.6 shows the conceptual design where by one of several air streams is allowed to enter an airtight box containing a gas sensor. Figure 2.7 shows the CAD design and dimensions in SolidWorks.

Figure 2.8 shows the sampler as constructed from transparent polycarbonate.

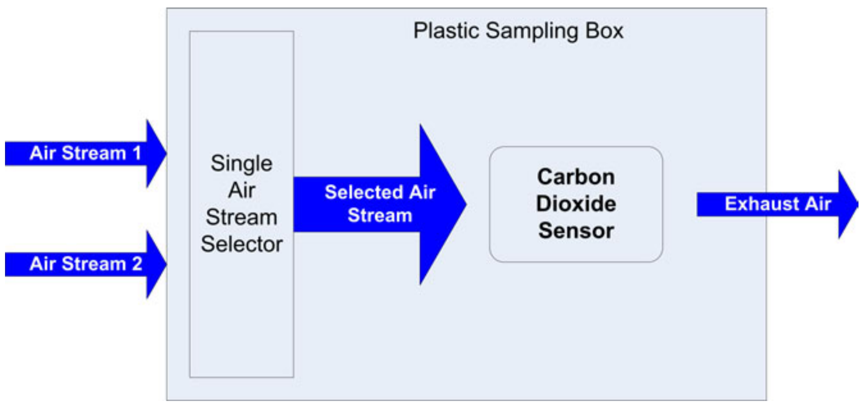

Figure 2.6: Central sampling box concept diagram

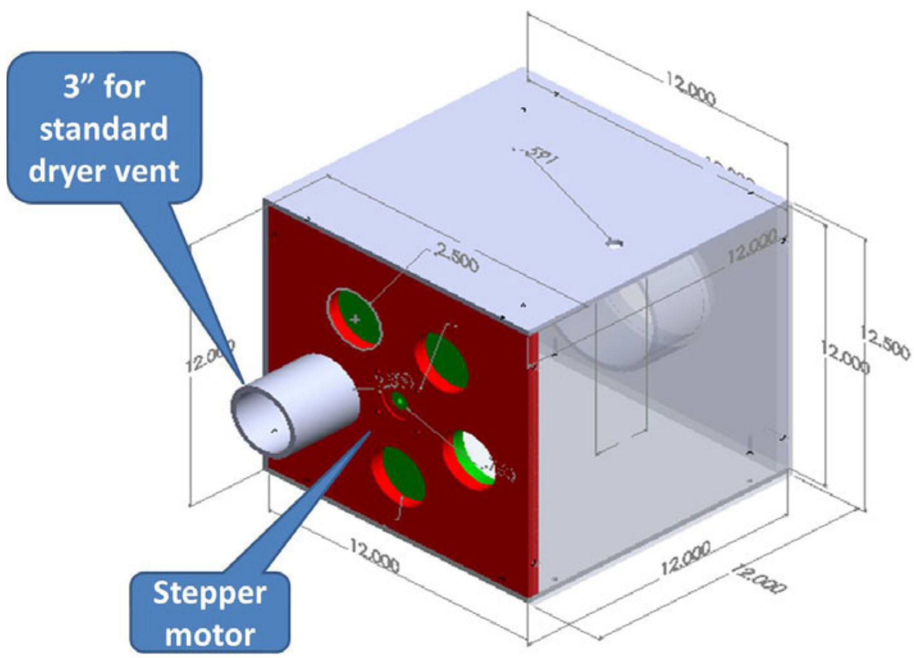

Figure 2.7: CAD drawing of sampler box

Two flexible ducts are connected so that intake and exhaust streams can be sampled at arbitrary intervals while the remaining three ports were not used.

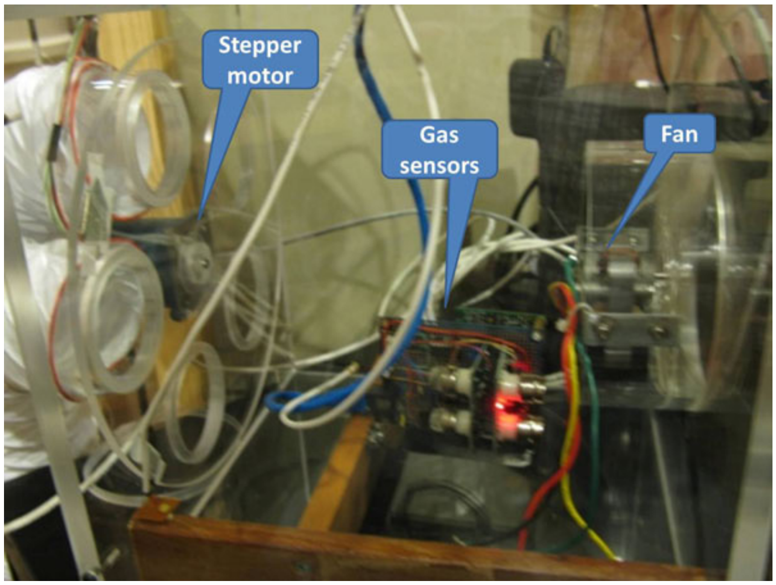

Figure 2.8: Central sampling box

The sampler controller is the master controller of the system. The system block diagram, figure 2.9 shows connections to three independent sub systems: a data acquisition computer, the venmar controller board and a touch panel user interface. It also interacts with the sensors using the MODBUS protocol.

The sampler controller, the middle circuit board in the photo, figure 2.10, implements a stepper motor controller for the air stream selector and on/off control for the sampler exhaust fan. The board on the far right is a Parallax Propeller™board which implements the control algorithms and exports data

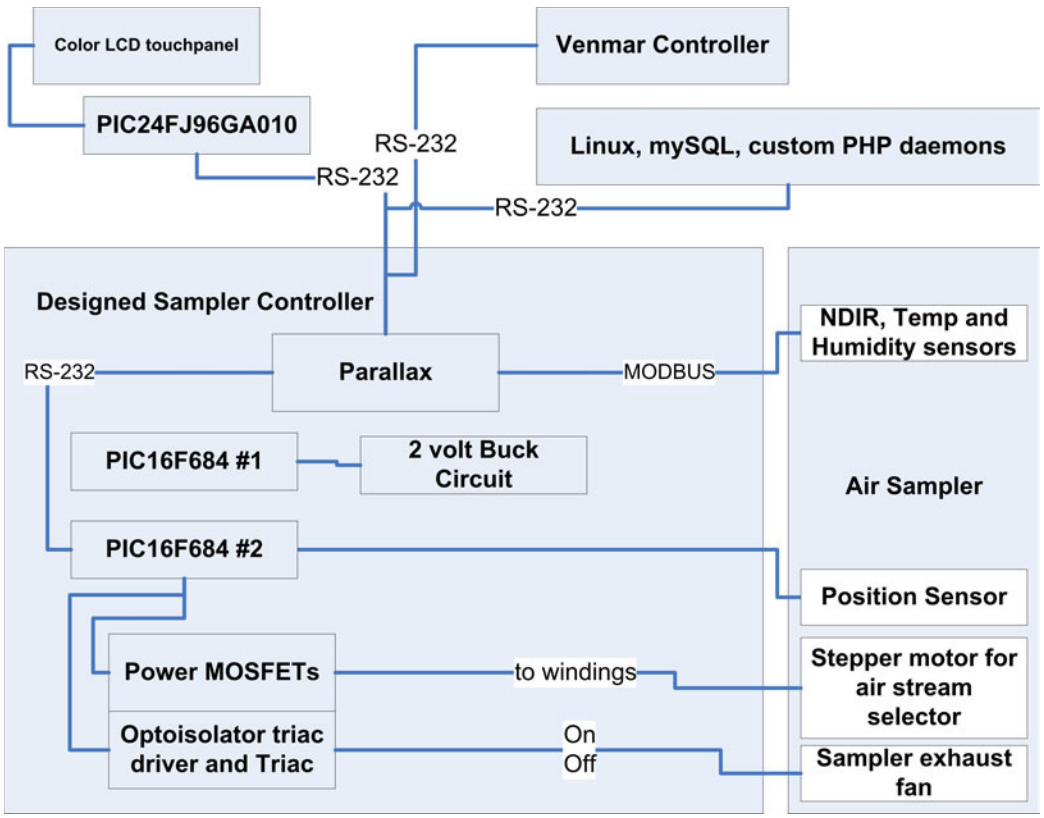

Figure 2.9: System block diagram

via a communications port to a data logger.

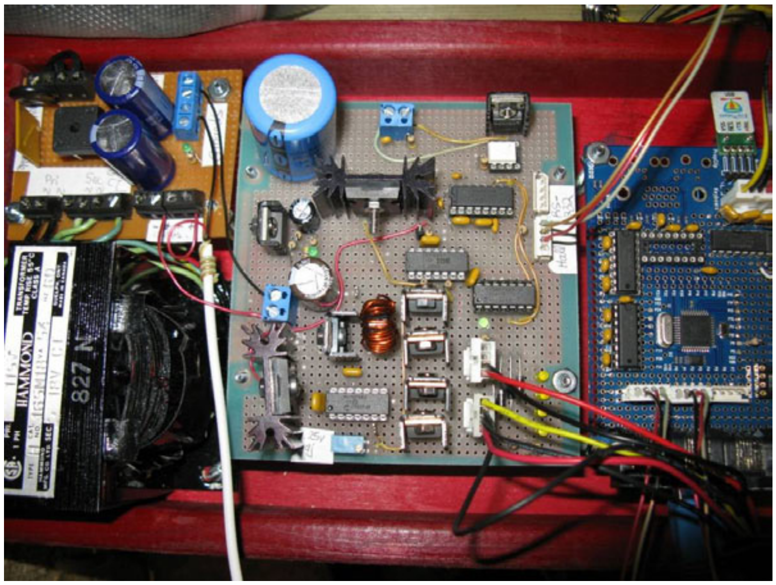

Figure 2.10: Control electronics

Figure 2.11 is the electronic component schematic of the air sampler.

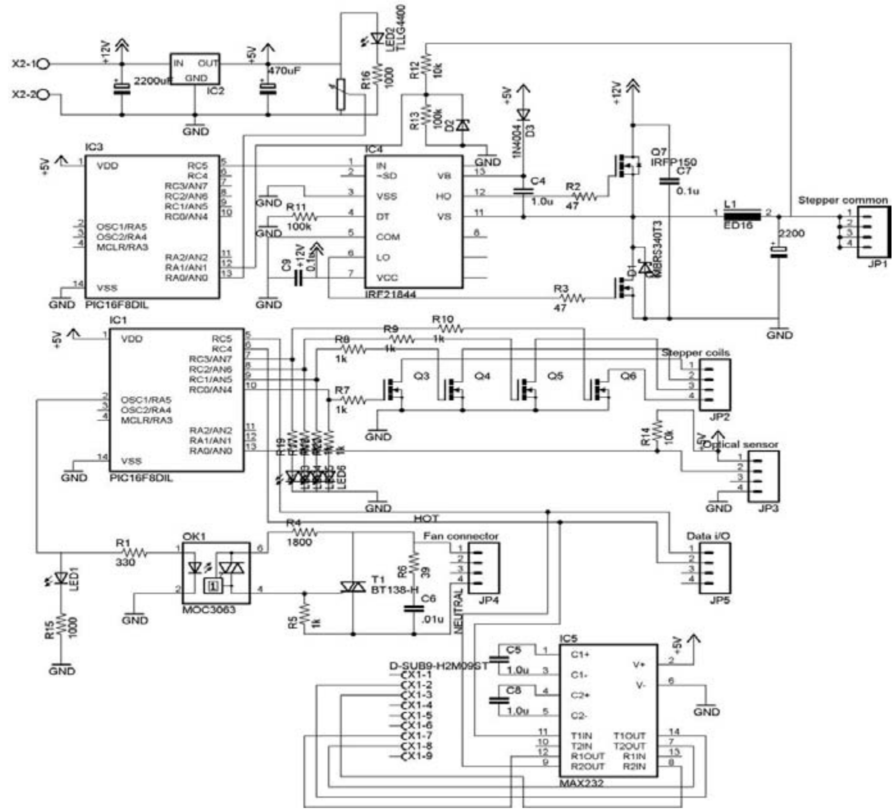

Figure 2.11: PCB Schematic of modified HRV and air sampler

2.3 Details of the Test House

The data collected for this thesis was obtained from an occupied two story, 650 m^3, wood framed home, shown in figure 2.12 and built to Canadian residential standards in 2003. It is located in Atlantic Canada and subject to a windy, maritime climate with cool summers and mild winters. Statistics Canada climate normals [50] for the period 1981 to 2000 indicate a daily average of -4.9°C in February to a daily average high of 16°C in August. The annual average wind speed is 21.9 km/h.

The 50 Pa infiltration rate, η_{50}, was measured at 2.55 air changes per hour (ACH) using a Minneapolis Blower Door ^{TM}. The maximum flow rate of the Venmar Constructo HRV was 385 m^3/hr while low speed was 90 m^3/hr.

Figures 2.13, 2.14 and 2.15 use red circles marked “in”, to represent ceiling mounted HRV intake grills (removing stale air) while blue circles, marked “out”, represent ceiling mounted HRV fresh air grills. Air flows from tbe blue circles to the red circles, but since the incoming air in this climate reaches a daily average maximum of 16°C in August, it is generally cooler than room temperature. Since the HRV fresh air grills are ceiling mounted, the cooler fresh air falls, avoiding short circuiting the breathing zone by travelling along the ceiling, and leads to a ventilation efficiency approaching one.

Figure 2.12: Canadian home built in 2003

The first floor, figure 2.13, is unoccupied and forms a single space without doors and therefore behaves as a single ventilation zone. A normally closed doorway separates the basement from the first floor.

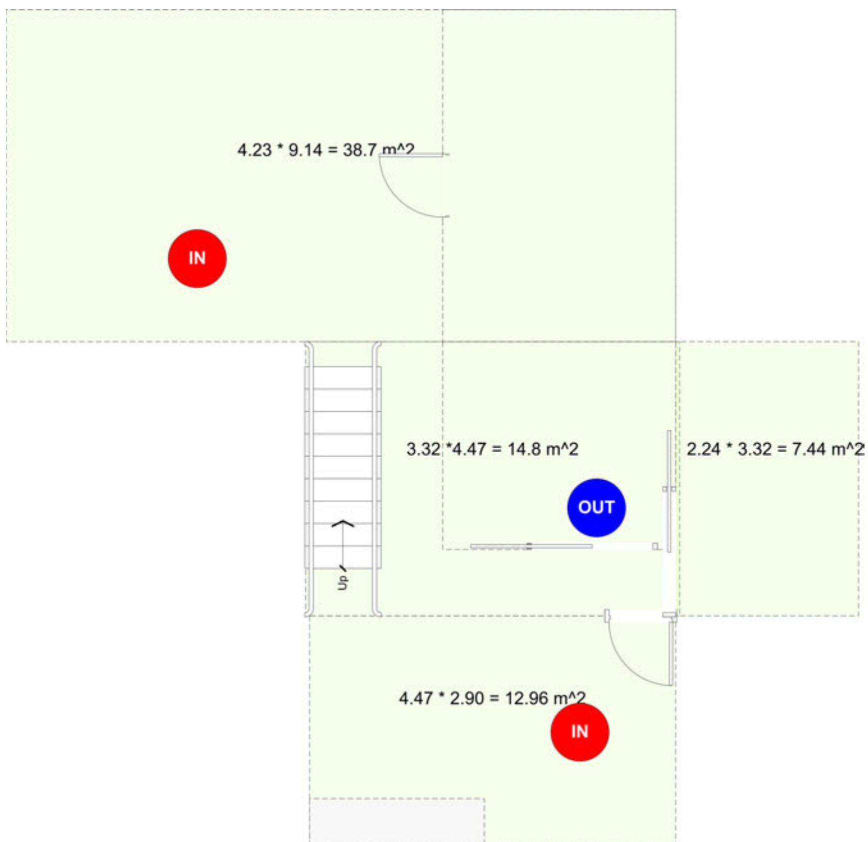

Figure 2.13: 1st level floor plan, HRV air intake and exhaust locations

The second floor, figure 2.14 has an open floor plan such that the kitchen, dining room and living area and staircase to the third floor is a single ventilation zone without doorways or restrictions. Only a small bathroom, porch and office have doors. Ceiling mounted intake and exhaust are marked as coloured circles. Fresh air is generally cooler than room temperature in the Canadian Maratimes so there is minimal short circuiting of the ventilation flow since the fresh air settles towards the floor rather than travelling along the ceiling directly towards the ceiling exhaust vent.

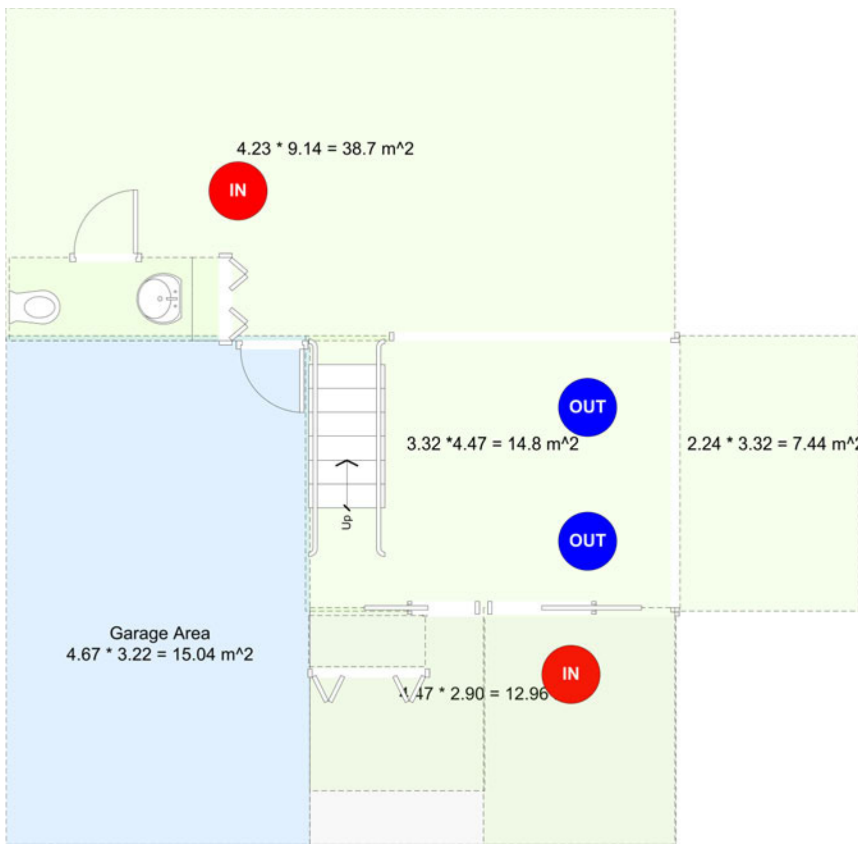

Figure 2.14: 2nd level floor plan, HVAC air intake and exhaust locations

The third floor, figure 2.15, is open to the second floor. The three bedrooms have individual doors that are normally closed but contain a large gap under each door. The master bedroom is normally occupied at night and open to the en suite bathroom. The master bedroom suite contains both an intake and exhaust grill.

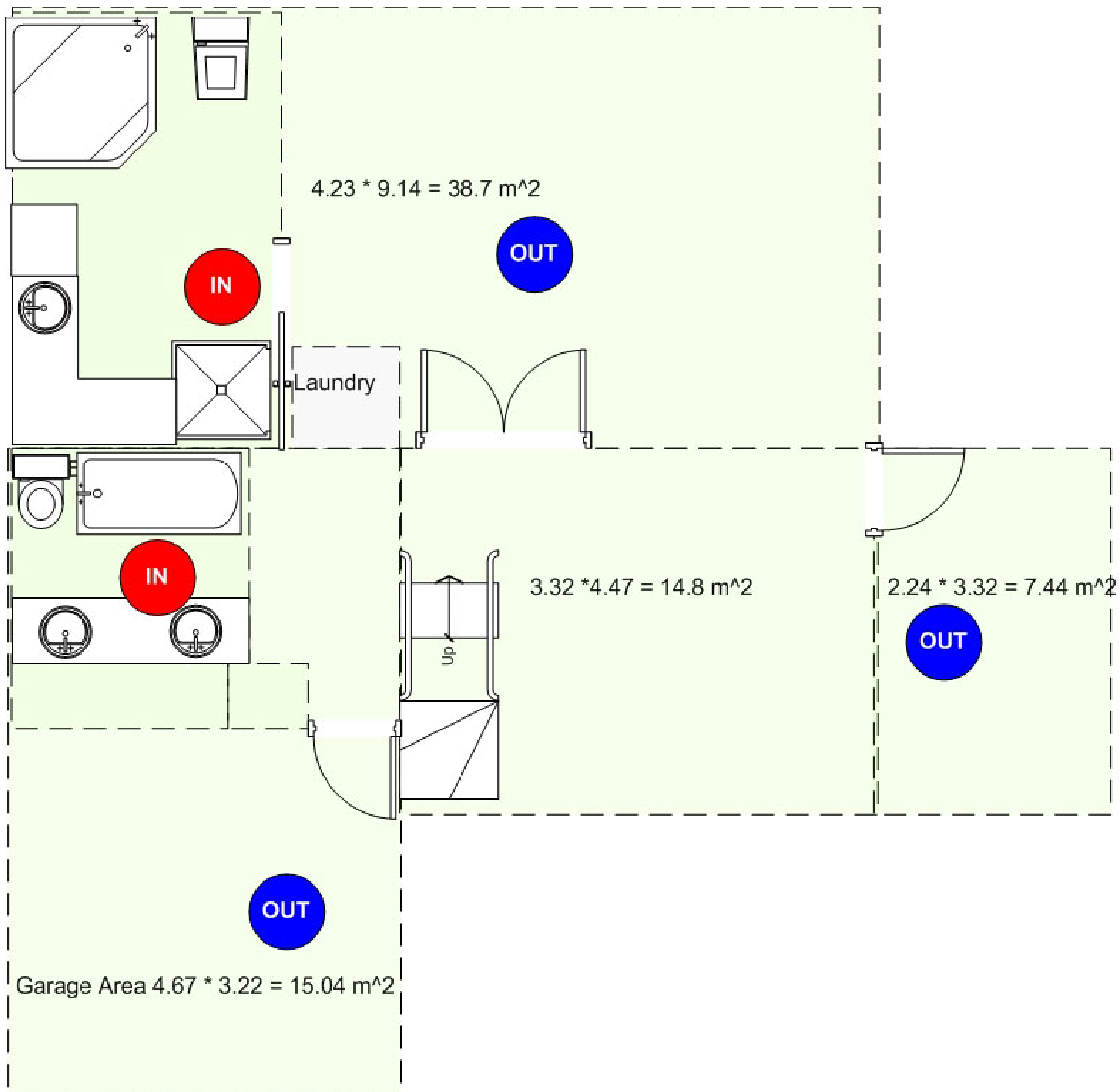

Figure 2.15: 3rd level floor plan, HVAC air intake and exhaust locations

2.4 TFT Touch Screen Interface

A color TFT with touch screen was designed for communication with the system module. A PIC24F series processor was used to implement the TFT controller and touch screen signal processing as well as process bi-directional RS-232 communications.

Figure 2.16 shows the first level menu while 2.17 shows a status display. Schematic, figure 2.18 shows the PIC signal connections to the TFT module.

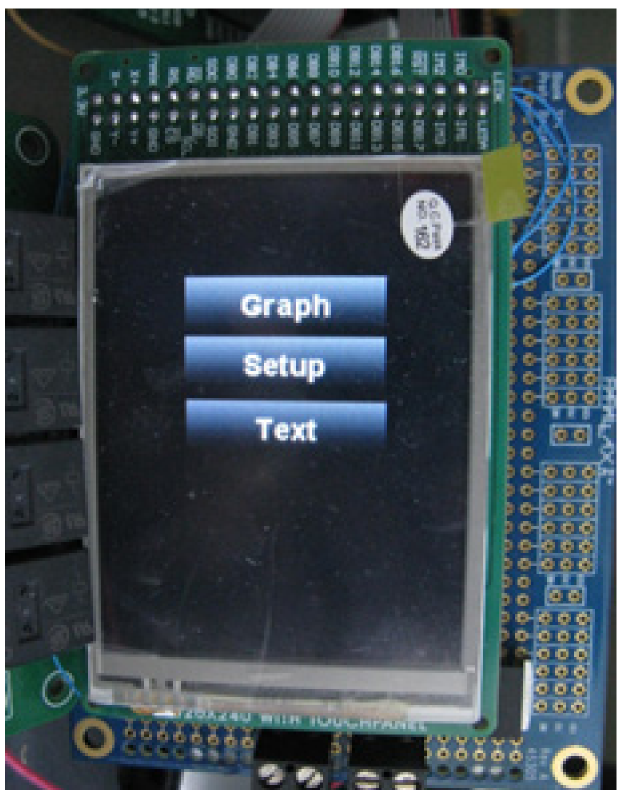

Figure 2.16: TFT Touch Screen main menu

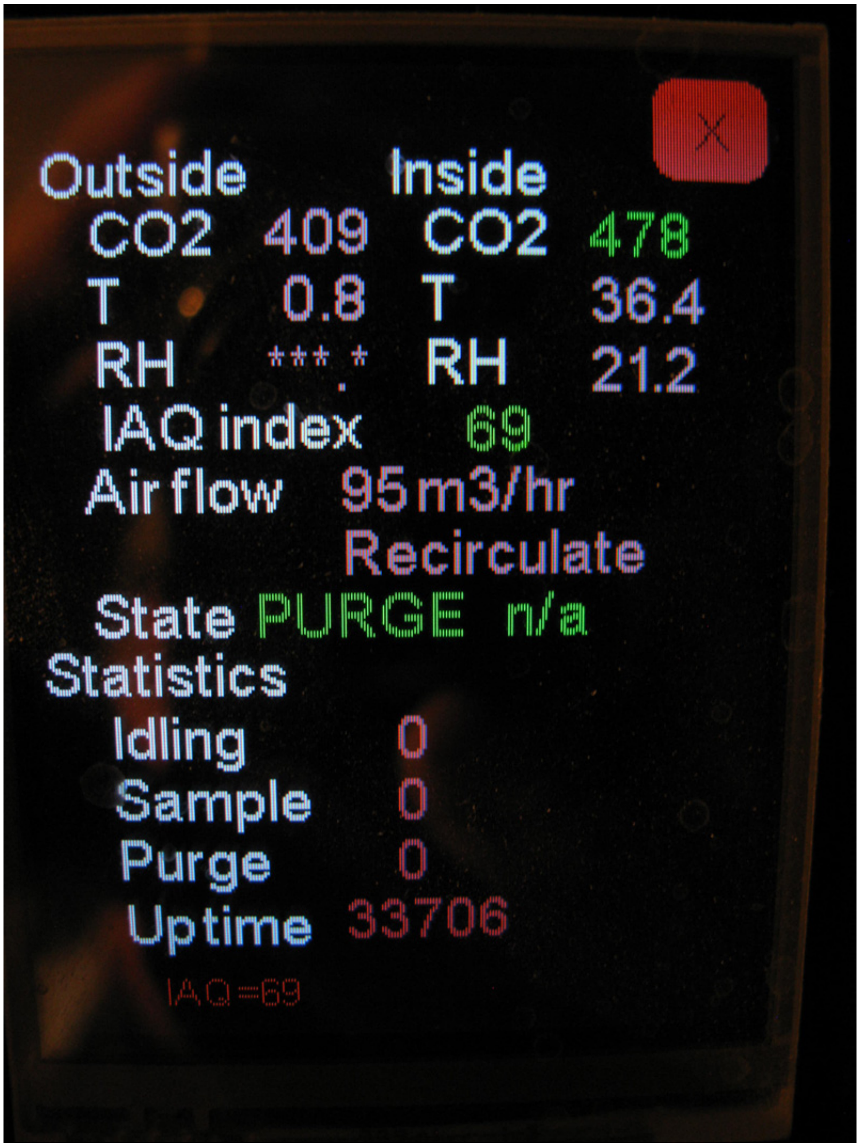

Figure 2.17: TFT Touch Screen status screen

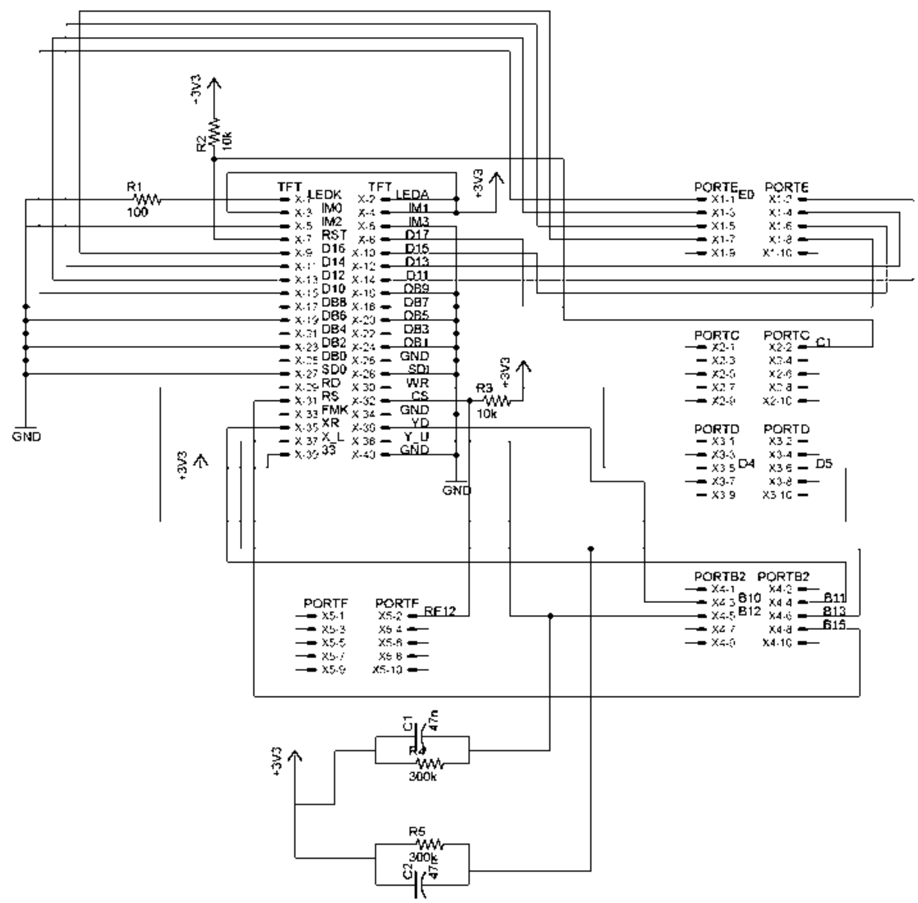

Figure 2.18: TFT Touch Screen Signal Connections

2.5 Data Acquisition System

The sampling system was designed to run continuously, so a data acquisition system was designed for long term monitoring. A computer running Debian Linux was configured with mySQL^{TM}as the relational database and a PHP interpreter to run a data acquisition program custom designed for the system. The air sampling system controller, the Parallax Propeller^{TM}, sends out a continuous stream of status messages that are parsed into records and inserted into the appropriate database tables.

The SQL database was configured to allow remote connections.This allowed a workstation running Microsoft Excel to connect over the local area network to extract data from arbitrary date ranges. The data was then processed using Visual Basic for Applications (VBA).

Figure 2.19 shows the spreadsheet program with the IP address of the SQL server in cell J1. Cells D1 and D2 allow the date range to be set. The button near cell L1 then runs VBA code to retrieve the dataset from the SQL server.

Figure 2.20 shows the graph that is generated by the Excel formulas immediately after importing the data from mySQL^{TM}. The command buttom at cell position AC6 labeled "seek right" implements a moving window and identifies periods of exponential decay with high correlation coefficients and

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Period of Analysis		From	20131201					Server	192.168.2.18		Retrieve	
2		584	To	20131210									
3		1709	RowCount	-1									
4													
5	Offset	406	ppm										
6	Lower bound	3665	row	Dec-08 05:48								Fit Calculations	
7	Upper bound	3865	row	Dec-08 15:36								n	201
8	TimeDif	9.8	hours									sum x	1496
9	Min and Max CO2	465.0	520.0	ppm		Calculations for curve fitting by least squares							
10	Date/Time	[CO2]	Time Offset	[CO2] reduced by offset		ln(y)	xy	x2	(y-meany)^2	(y-intercept-slope*x)^2	Calc from formula	sum y	893
11	Dec-01 00:01:58	516.0	0:00:00	110.0		4.70048	0	0	0.066293	135.043417	12253618	sum xy	6642
12	Dec-01 00:04:23	517.0	0:02:25	111.0		4.70953	0.01	2.8E-06	0.071036	134.770971	12220842	sum x2	11137
13	Dec-01 00:06:48	513.0	0:04:50	107.0		4.672829	0.02	1.1E-05	0.052819	135.562079	12188155	mean x	7.4427
14	Dec-01 00:09:18	515.0	0:07:20	109.0		4.691348	0.02	2.6E-05	0.061674	135.066773	12154432	mean y	4.4430
15	Dec-01 00:11:43	516.0	0:09:45	110.0		4.70048	0.03	4.6E-05	0.066293	134.792384	12121922	**slope**	-1.5960
16	Dec-01 00:14:08	516.0	0:12:10	110.0		4.70048	0.04	7.1E-05	0.066293	134.730198	12089498	**intercept**	16.3213
17	Dec-01 00:16:38	516.0	0:14:40	110.0		4.70048	0.05	0.0001	0.066293	134.665882	12056048	ssy	7.3680
18	Dec-01 00:19:03	517.0	0:17:05	111.0		4.70953	0.06	0.00014	0.071036	134.393817	12023802	ssr	0.5778
19	Dec-01 00:21:38	517.0	0:19:40	111.0		4.70953	0.06	0.00019	0.071036	134.327442	11989426	**R2**	0.921576
20	Dec-01 00:24:03	516.0	0:22:05	110.0		4.70048	0.07	0.00024	0.066293	134.475171	11957357	12253211.67	
21	Dec-01 00:26:33	513.0	0:24:35	107.0		4.672829	0.08	0.00029	0.052819	135.052841	11924273	-1.5960	
22	Dec-01 00:28:58	517.0	0:27:00	111.0		4.70953	0.09	0.00035	0.071036	134.139109	11892379	**15.0**	hours

Figure 2.19: Excel with VBA for selection analysis period

enters them in the region near AC10. The button labelled “Adjust Times” optionally adjusts the start time of the fixed window period to maximize the correlation coefficient to more accurately catch the beginning of the occupancy period. Once the vacancy periods are identified, the button ”Fit Segments” generates data that fits the calculated decays and overlays these on the graph in red. The only purpose is for easy visual identification.

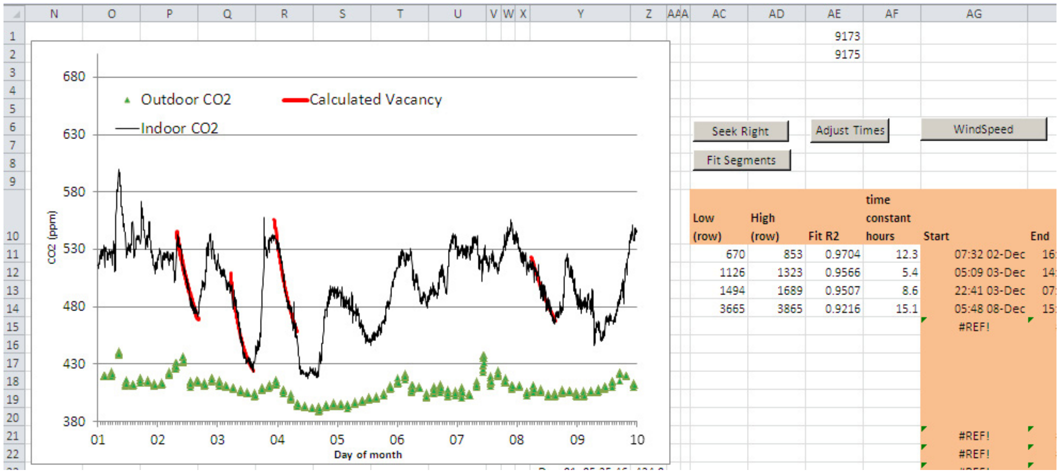

Figure 2.20: Excel with VBA for selection analysis period

2.6 Carbon Dioxide Sensor Specifications

The specifications in table 2.1 are from the documentation provided by the NDIR CO_2 sensor manufacturer Figaro. These specifications are typical for CO_2 sensors intended for ventilation control systems.

Parameter	Manufacturer's specification
Storage Temperature Range	-30 to +70 °C
Sensor Life Expectancy	$\geq$ 15 years
Maintenance Interval	no maintenance required
Self-Diagnostics	complete function check of the sensor module
Warm-up Time	1 min
Operating Humidity Range	0 to 95% RH (non-condensing)
Operating Environment	Residential, commercial, industrial spaces and Potentially dusty air ducts used in HVAC (Heating Ventilation and Air-Conditioning) systems
Sensing Method	non-dispersive infrared (NDIR) waveguide technology with ABC automatic background calibration algorithm
Sampling Method	diffusion
Response Time ($T_{1/e}$)	20 sec diffusion time
Measurement Range	0 - 5,000 ppmvol
Sensitivity	$\pm$ 20 ppm $\pm$ 1% of measured value
Accuracy	$\pm$ 30 ppm $\pm$ 5 % of measured value
Pressure Dependence	+ 1.6% reading per kPa deviation from normal pressure, 100 kPa

Table 2.1: DVC Sensor Specifications from Manufacturer

2.7 Occupancy Patterns

During the data collection period, the house was occupied by a single adult. The house was generally vacant from 8:30 AM to 5:00 PM, Monday to Friday. The lowest level of the home was seldom occupied and the top floor containing the bedrooms was only occupied after 10 PM. Exterior doors and windows were closed during all testing periods.

Data was collected for several months under these conditions and saved in the SQL database for analysis, which is covered extensively in the next chapter.

Chapter 3

Experimental Data

3.1 General Characteristics of Dwelling, Wind Speed Effects and Coupling of Intake and Return Air

A preliminary analysis of the characteristics of the test home was carried out by recording the relative humidity and CO_2 concentration in the HRV return air duct over a period of several days. The home had a single occupant and system was set up as shown schematically in figure 3.1. The HRV was operated using the low fan speed and set to 100% recirculation. This turned the home into a single well mixed ventilation zone. The HRV recirculation was disabled, i.e. set to 100% fresh air and the fan switched to full speed any time the CO_2 in the exhaust stream exceeded 750 ppm. The relative humidity and CO_2 concentration in the return air duct of the HRV, immediately before it returned to the HRV, was recorded every 120 seconds. Meteorological data was recorded every 10 minutes by a Davis Vantage Pro2 weather station, shown in figure 3.2, was mounted such that the elevation was approximately at the mid point of the top story of the house and 10 meters from the dwelling. This preliminary analysis was intended to clarify the following:

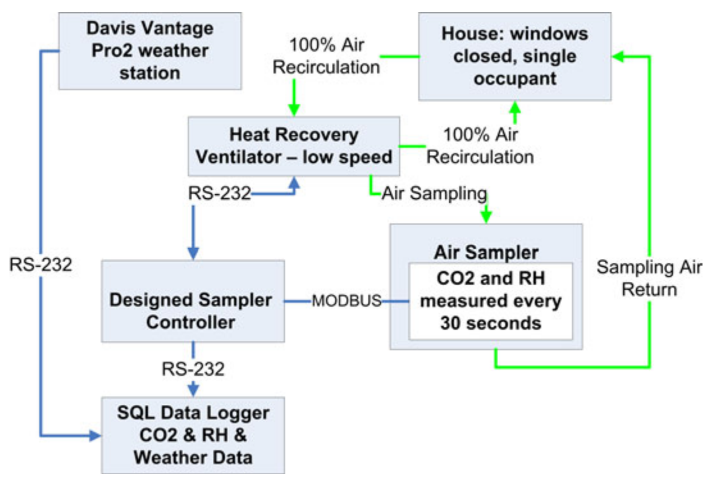

Figure 3.1: Experimental Setup for Initial Evaluation

- To determine the impact of dwelling occupancy on humidity and CO_2 concentration and whether these physical parameters are suitable as proxies for human generated pollutants. The literature suggests that RH would not be suitable despite the common usage of humidistats on HRV units but that CO_2 would be suitable. The relationship between

Figure 3.2: Test house to left, Davis Vantage Pro2 circled

relative humidity and occupants was worth investigating since it if was a viable alternative to sensing CO_2 in a residential setting, it would have significantly reduced the cost of the sensor system. Humidistats are a standard control system option for residential HRV units.

- To determine the peak CO_2 concentration likely to be achieved in the absence of mechanical ventilation. The literature suggests that most houses have significant natural air leakage and that the steady state value of CO_2 will be well below the threshold limit value and vary with wind speed. If the values are equal to or below the typical 1000 ppm threshold then health concerns from human generated pollutants are minimal and the control algorithms would be better focused on energy savings or adjusting humidity levels to minimize microbial growth .

- To verify the ability of the residential sized HRV unit, when set to maximum fan speed, to prevent a further CO_2 concentration increase. If the maximum air flow rate is inadequate to do this then no control mechanism can prevent the occasional overshoot of a typical CO_2 set point.

- To determine the suitability of the household environment for sensing with an NDIR sensor. The assumption is that the particle content of household air is well within the limits of the chosen Figaro K30 NDIR sensor and will not lead to premature failure of the device.

- To determine if intake and exhaust air stream mixing affects the accuracy of outdoor CO_2 concentration measurements. The minimum allowable spacing between intake and exhaust vents is determined by building code. If this physical separation leads to significant mixing, it would make differential measurements using the incoming fresh air stream complicated.

All data was stored in a SQL database and then imported into Microsoft Excel for analysis. This initial testing was followed with several months of continuous monitoring. The following sections discuss the results of the preliminary analysis.

3.2 Wind Speed Effects

CO_2 concentrations and relative humidity were recorded between February 10 and February 13 as shown in figure 3.3. The CO_2 concentration threshold required to trigger full speed ventilation was set at 750 ppm. Air was circulated continuously at low speed through the heat recovery ventilator so that the central CO_2 sensor would measure an average CO_2 concentration in the house. The first notable event in figure 3.3 is the two day period where no additional mechanical ventilation was required because the 750 ppm threshold was not exceeded. This is expected to be quite common in most residential settings on windy days because most homes have significant air leakage under high wind conditions. 750 ppm is a low threshold for demand controlled ventilation, and using a more common limit of 1000 ppm in a home with low occupancy would lead to the HRV never needing to introduce fresh air.

The second notable event in figure 3.3 is that during periods of high human activity and low wind, shown within the second set of red brackets, the high fan speed setting of the residential heat recovery ventilator was insufficient to terminate the rise in the concentration of CO_2. Therefore, the CO_2 set point will be exceeded regularly unless the occupants manually open windows to increase air-exchange. Residential HRV units are sized to fit within the range of flow rates required by building code, and opposed to sizing to mitigate peak loads such as a large family gathering.

Illustration 3.4 compares a windy day with a calm day for the period February 11 through February 15. During the day with low wind speeds, the HRV unit ran continuously whereas during a 30 hour windy period, the HRV was not required for introducing fresh air at all. In this climate, there are approximately 50 days a year [50] with hourly wind speeds greater than 56 km/h and wind gusts exceeding 100 km/h are not unusual.

Illustration 3.5 plots wind gusts and average wind speed along with the indoor CO_2 concentration. The red bracketed region had wind gusts between 30 km/h and 50 km/h and the threshold of 750 ppm used in this test was never reached. The graph lines are not smooth due to random wind fluctuations which in turn introduce random changes to the natural infiltration rate. The direction of wind gusts also affects the natural infiltration rate due to asymmetrical window placement so wind speed alone isn't perfectly correlated with changes in CO_2 concentration. Of particular significance is that during periods of high wind, which can span multiple days, no additional mechanical ventilation is required. Given the low CO_2 set point of 750 ppm, it is likely that both human and non-human derived pollutants are adequately mitigated and that mechanical ventilation could be eliminated during windy conditions, when permitted by building code.

Illustration 3.6 shows the CO_2 levels rapidly rising once the wind died down.

Illustration 3.7 shows the CO_2 concentration rapidly declining once the high speed fan setting on the HRV was activated and the wind speed picked up.

These general observations are as follows: the natural infiltration rate and wind speed are correlated; mechanical ventilation is not required in homes with low occupancy during windy days but is required on calm days when the windows are closed and the occupants are performing physical activities. The high speed fan setting on residential sized HRV units is inadequate to prevent a rise in CO_2 concentration and therefore no control system operating a typical residential sized HRV unit is capable of preventing the CO_2 set point from being occasionally exceeded. In this test, CO_2 remained below the common 1000 ppm IAQ threshold because one of two recurring events intervened; vacancy or high wind speeds.

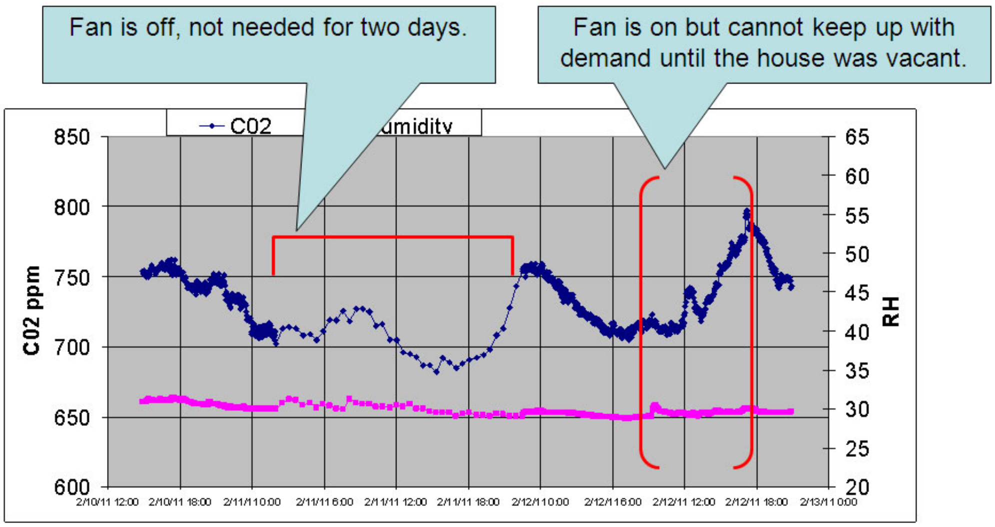

Figure 3.3: Ambient CO_2 concentrations Feb 10 to Feb 13

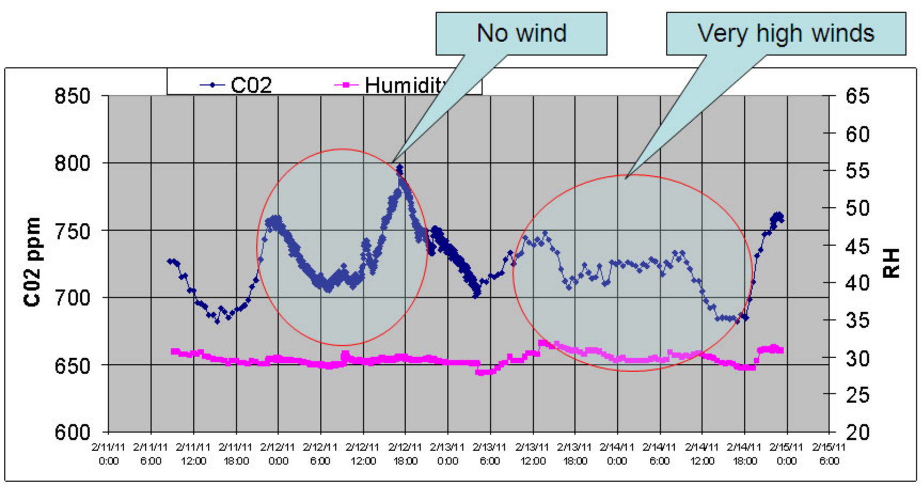

Figure 3.4: [CO_2] vs wind conditions Feb 11 to Feb 15

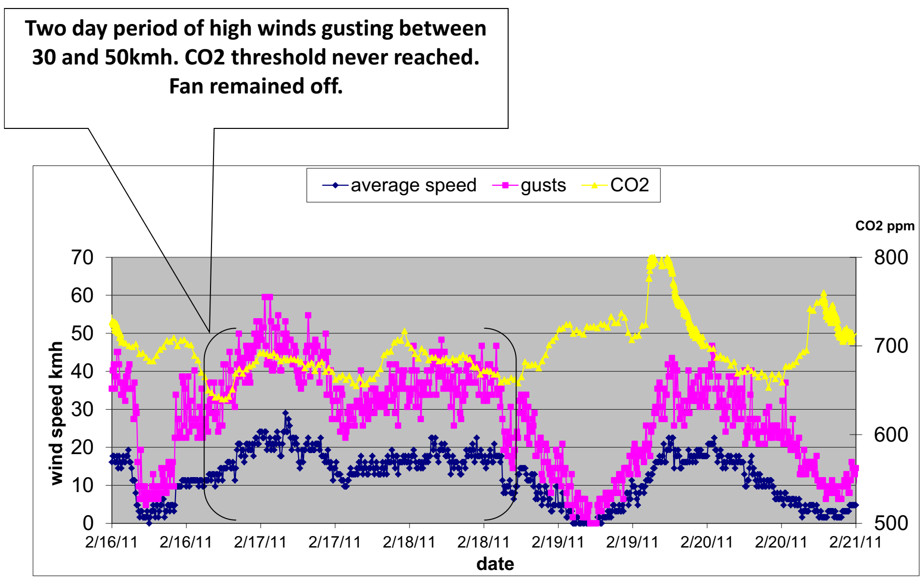

Figure 3.5: [CO_2] under high winds Feb 16 to Feb 21

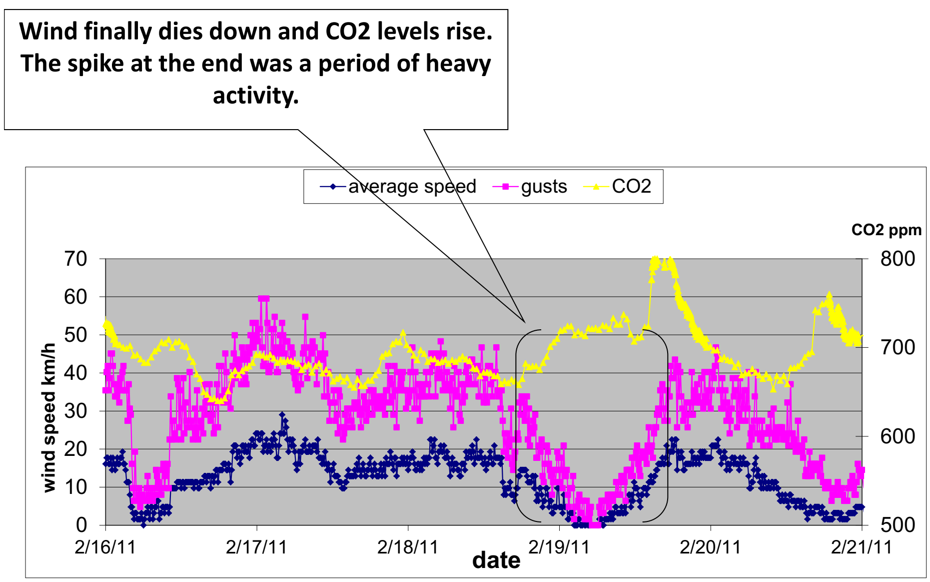

Figure 3.6: Winds calm, $[CO_2]$ rises

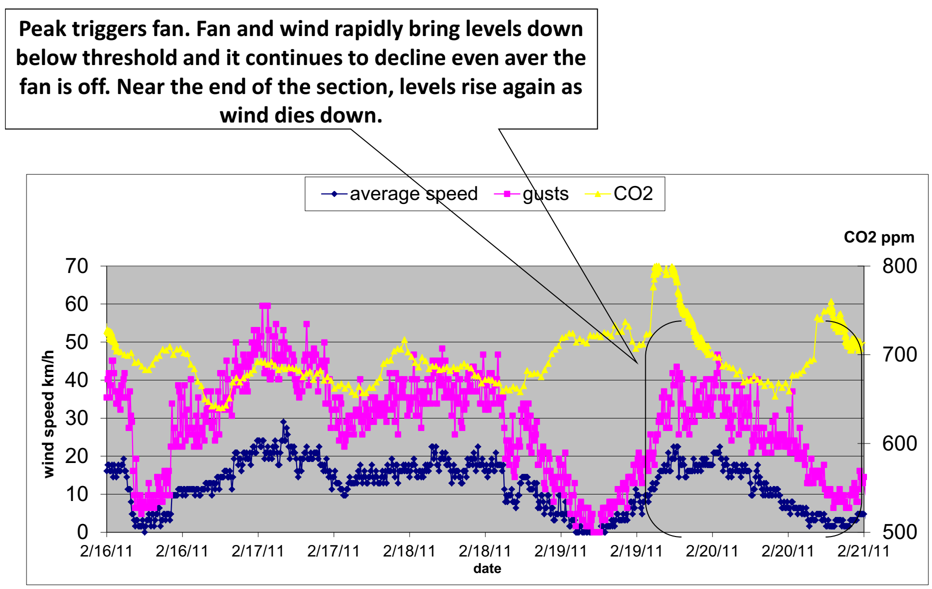

Figure 3.7: [CO_2] Feb 16 to Feb 21

3.3 Relative Humidity

Humidity was found to be a poor indicator of indoor air quality. Illustration 3.8 shows three spikes in humidity that correspond to morning shower activity. These are short lived and have no correlation with indoor CO_2 concentrations. Most residential HRV units are equipped with a humidistat that turns the HRV on or off based on a humidity threshold. Humidity control would have resulted in running the HRV continuously, not at all or for 10 minutes per day during shower activity depending on the chosen threshold.

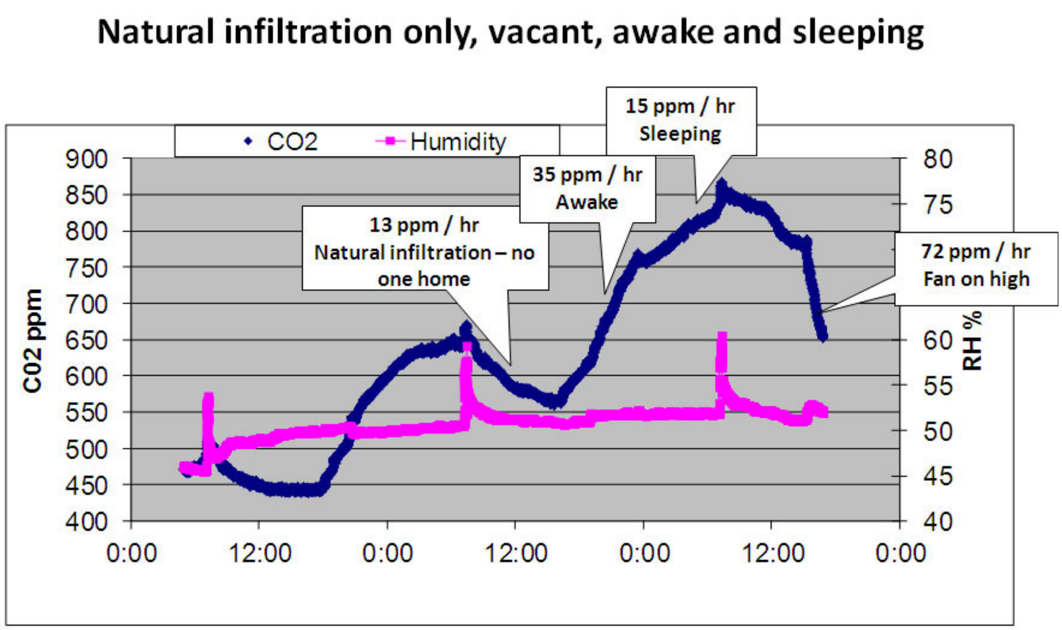

Figure 3.8: Natural Ventilation vacant, awake and sleeping

3.4 Diurnal variations in CO_2 generation rate

Illustration 3.8 also shows the CO_2 generation rate for a single adult is reduced by approximately one half during sleep. This indicates that any calculation of sedentary adult equivalents used to comply with building codes that specify air exchange per person would have to make assumptions as to the sleep schedule of residential occupants. The period of vacancy shown indicates an approximately exponential decay.

3.5 Particulate Matter

To further characterize the environmental conditions a PM_{10} aerosol monitor (TSI model AM510) was equipped with a 10 mm Nylon Dorr-Oliver Cyclone. The results in figure 3.9 show very low particulate levels that are well below national guidelines for respirable dust and had no obvious correlation to occupancy in the manner CO_2 concentrations would. This indicates that respirable dust is unlikely to impact the optical path of the NDIR gas sensor used for CO_2 concentration measurements and that PM_{10} would be a poor proxy for of human generated pollutants in households where there are no significant particle sources such as cigarette smokers. The chosen NDIR sensor specifically states in its specification, table 2.1, that it is suitable for "potentially dusty air ducts used in HVAC".

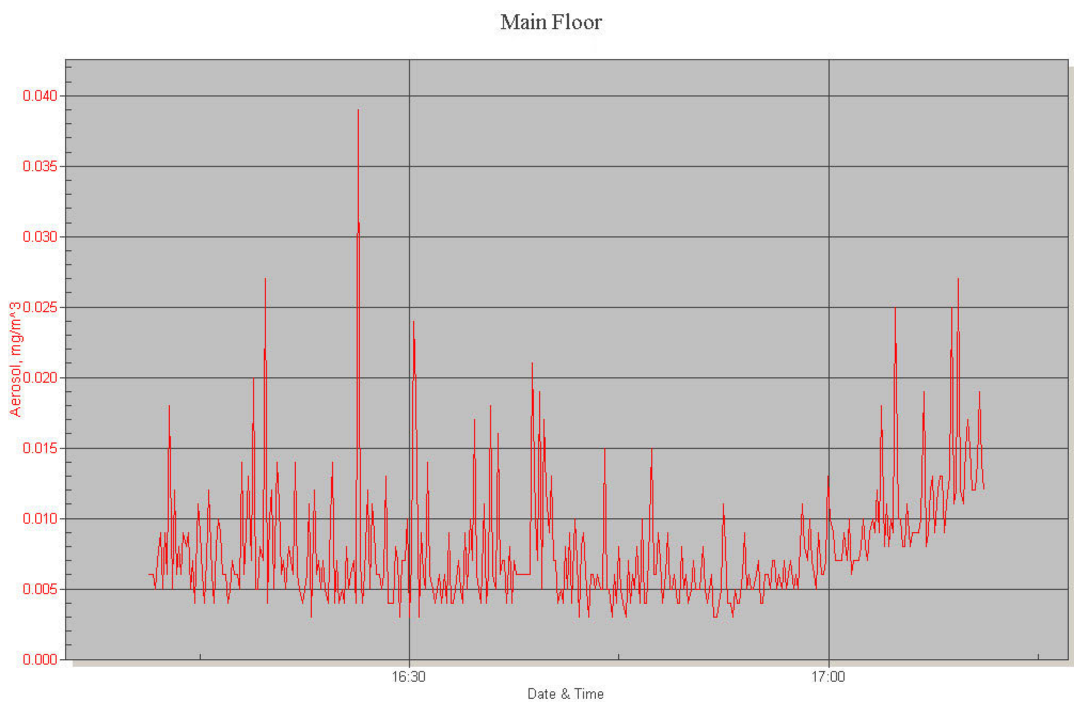

Figure 3.9: Respirable dust, 1st floor of house

3.6 Coupling of HRV Intake and Exhaust

The typical spacing between intake and exhaust vents of residential HRV units is insufficient to prevent mixing of the air streams. This is evident in figure 3.10, where the outdoor CO_2 concentration plotted in green correlates visually with the exhaust air stream plotted in blue. The HRV unit was switched from recirculation into regular operation so that the incoming fresh air could be sampled in order to get the outdoor CO_2 concentration. In an attempt to smooth out random fluctuations, ten samples were made. When the inside concentration of CO_2 was near the outside concentration, the outside samples were very close together in value. When the inside CO_2 concentration was 600 ppm, the outside readings shown in green are scattered due to random wind turbulence that constantly changed the extent of mixing. In later experiments this was minimized by extending the exhaust with a length of flexible duct as shown in figure 3.11. This unintentional mixing reduces the rate of pollutant removal, impacts the ability to make consistent differential gas measurements and reduces the accuracy of outdoor measurements. Practical solutions include installing the exhaust and intake ports on different edges of a house, designing a much larger physical separation appropriate for the geometry of the home and location of exterior decks or feeding the ventilation exhaust into the intake of a heat pump for heat recovery and rapid dispersion. In the data analysis that follows, a fixed CO_2 outdoor value was found to work much better than calculating the differential directly due to this air stream mixing issue.

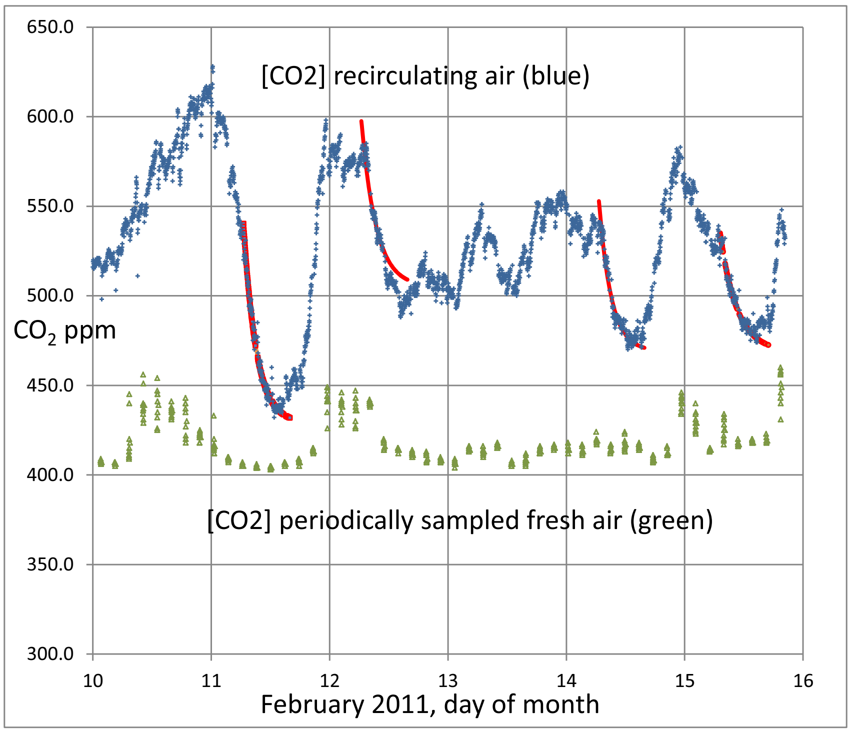

Figure 3.10: Mixing of exhaust and intake air streams

Figure 3.11: HRV fresh air intake extension

3.7 Long Term Analysis of CO_2 Concentrations in the House

Since CO_2 is non-reactive in the indoor environment and the dwelling volume is a constant, the total mass of CO_2 and therefore its concentration, can change only if more is added by human activity or if it is diluted via air exchange from outside. The portion of CO_2 concentration change over time within the dwelling due to human activity is the CO_2 generation rate divided by the total volume of the ventilated area. Assuming that the indoor air is well mixed and therefore the concentration throughout the building is a constant at any instant, the rate of concentration change due to outgoing exhaust air is the mechanical ventilation rate multiplied by the indoor concentration divided by the room volume. Similarly since the outdoor concentration is approximately a constant, the change due to incoming fresh air is the mechanical ventilation rate times the outdoor CO_2 concentration divided by the room volume. This is expressed as a differential equation 3.1.

$$\frac{dC(t)}{dt} = \frac{R}{V}(C_o - C(t)) + \frac{G(t)}{V} \tag{3.1}$$

where:

C(t) = concentration of CO_2 at time t,

R = mechanical ventilation rate,

V = dwelling volume,

C_o = atmospheric CO_2 concentration,

G(t) = CO_2 generation rate by occupants

Separating the variables and integrating dt from zero to t and dC(t) from C(0) to C(t) we obtain equation (3.2):

$$C(t) = C_o + \frac{G}{R} + \left(C(0) - C_o - \frac{G}{R} \right) e^{-(R/V)t} \tag{3.2}$$

where

C(t): indoor concentration of CO_2 at time t (mass/volume)

C(0): initial indoor CO_2 concentration (mass/volume)

When all occupants vacate a dwelling, the remaining CO_2 can be used as a tracer gas to measure natural infiltration. When the house is vacant, G(t) is zero and the CO_2 concentration is a decaying exponential asymptotic to C_o. The beginning of the exponential decay marks the onset of vacancy and the natural infiltration rate of the dwelling is its volume divided by the time constant of the decaying exponential.

The CO_2 concentration was measured at the return duct every 180 seconds while the HRV recirculated air at 153 m^3/hr. Every 2.5 hours recirculation was disabled and fresh air was pumped into the building at 385 m^3/hr. Once the fresh air readings stabilized the CO_2 concentration was recorded and the system reverted to recirculation at 153 m^3/hr. All measurements were logged into a database.

A moving window of 200 CO_2 concentration values, corresponding to 8.3 hours was curve fit to a theoretical decay by subtracting the background CO_2 concentration from each datum and then taking its natural logarithm. The linearised data were then fit to a straight line using the least squares method. The window was advanced one data point at a time until the correlation coefficient R^2, calculated as per equations (3.3) (3.4) (3.5), peaked at a value ≥ 0.90 marking the beginning of a vacancy period. The window was further advanced sequentially until R^2 dropped below 0.50, marking the end of the vacancy period. Each exponential decay meeting the criteria $R^2 > 0.90$ was then mapped into one hour time slots to produce an occupancy map. The map was then compared with personal notes from the occupants for verification.

$$slope(s) = \frac{\sum xy - \sum x \sum y}{\sum x^2 - \sum x \sum x} \tag{3.3}$$

$$intercept(i) = \frac{\sum y}{n} - s\frac{\sum x}{n} \tag{3.4}$$

$$correlation(R^2) = 1 - \frac{\sum(y - i - xs)^2}{\sum(y - \frac{\sum y}{n})^2} \tag{3.5}$$

where

x: seconds elapsed from start of window

y: natural log of CO_2 concentration

n: number of measurements in window period

A Davis Vantage Pro2 weather station, positioned as shown in figure 3.2 with the test home in the left of the photo, was used to record local meteorological data.

Sequences of exponential CO_2 decline were identified and the curves they were fit to, shown as red segments in figure 3.12 through figure 3.16, were superimposed on a graph of actual indoor and outdoor CO_2 concentrations. These red overlays were generated using the equation calculated when the correlation coefficient was maximal and used to visually verify the fit. The date range is January 20 through March 14.

Table 3.1 lists the start and end of potential vacancy periods, correlation with a pure exponential decay, decay time constant, lowest CO_2 and whether the identification of vacancy was correct.

The vacancy map in table 3.2 shows a weekly calendar with 24 hourly time slots. Each period shows the CO_2 concentration at the end of the period. Cells with multiple values represent multiple vacancies during the same time slot, over the five week observation period.

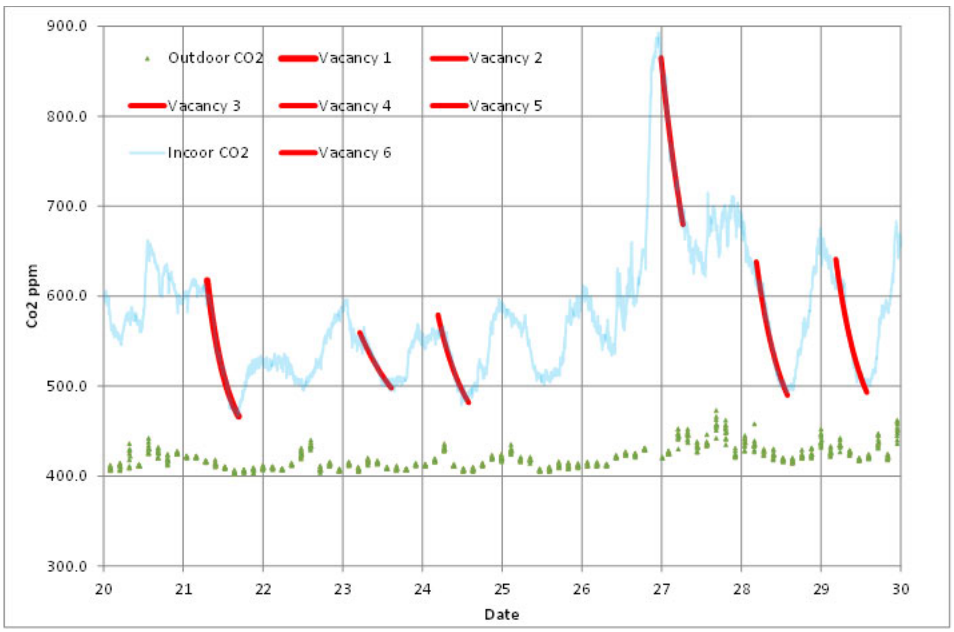

Figure 3.12: Calculated Vacancies - Set 1

Setting the threshold for correlation to $R^2 \geq 0.90$ identified all true vacancies and included three false positives.

Using decays where $R^2 \geq 0.95$, the 95% confidence interval for the mean of the decay constant during vacancies is (8.5, 11.5) hours with a standard deviation of 2.3 and mean of 10 hours. Low wind speeds of 4 km/h yielded

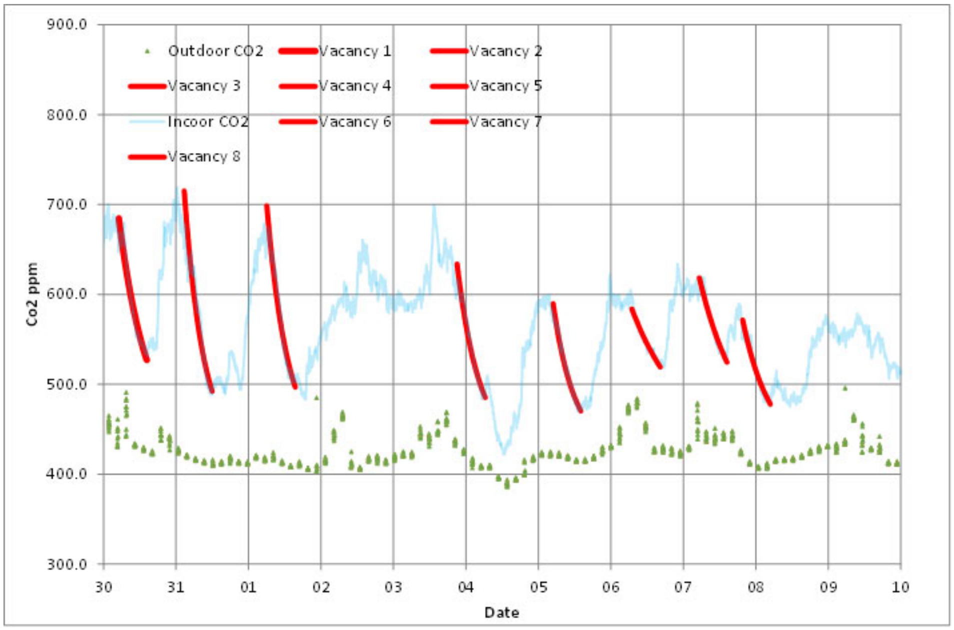

Figure 3.13: Calculated Vacancies - Set 2

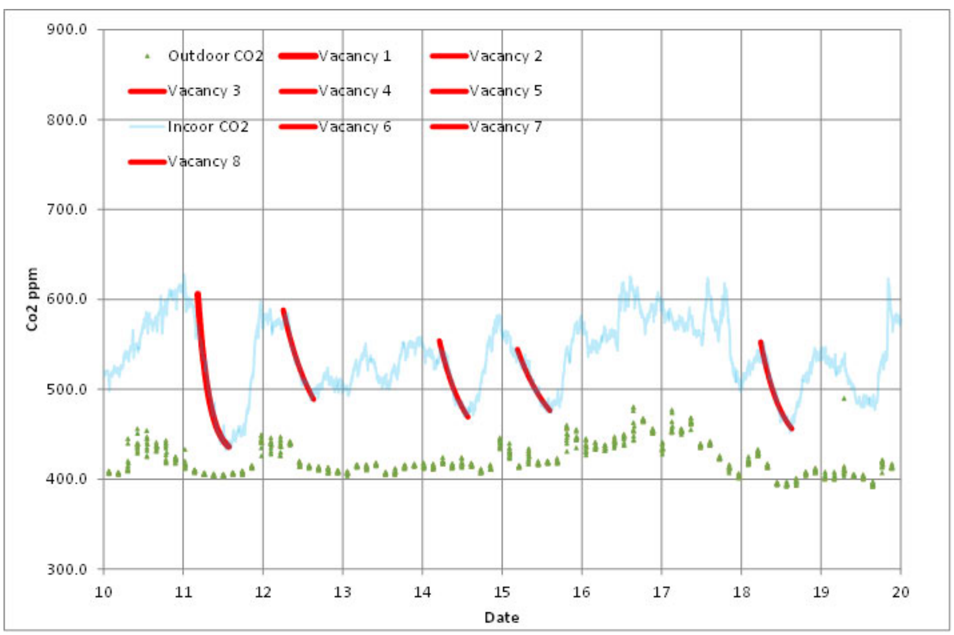

Figure 3.14: Calculated Vacancies - Set 3

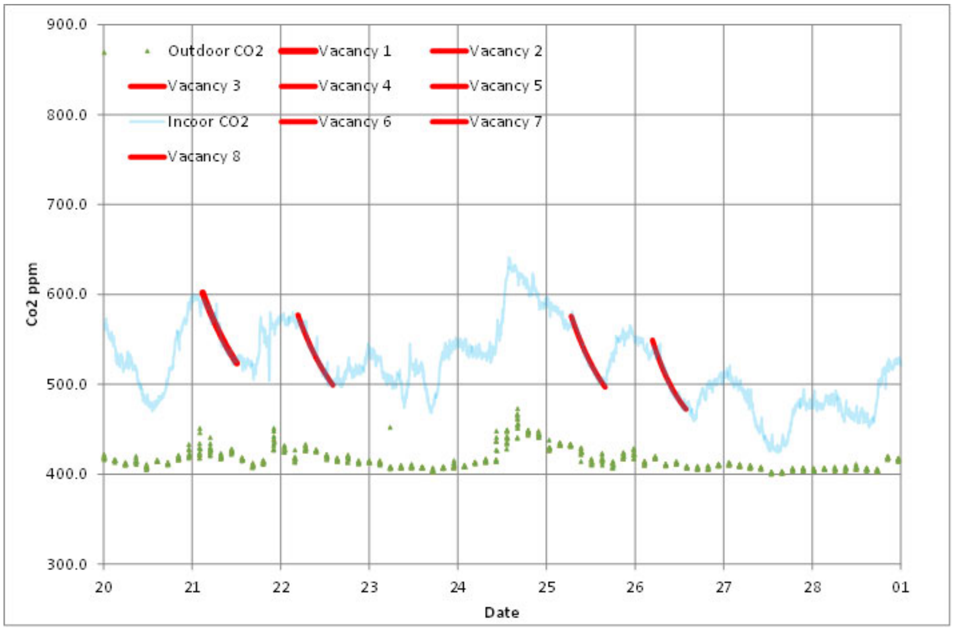

Figure 3.15: Calculated Vacancies - Set 4

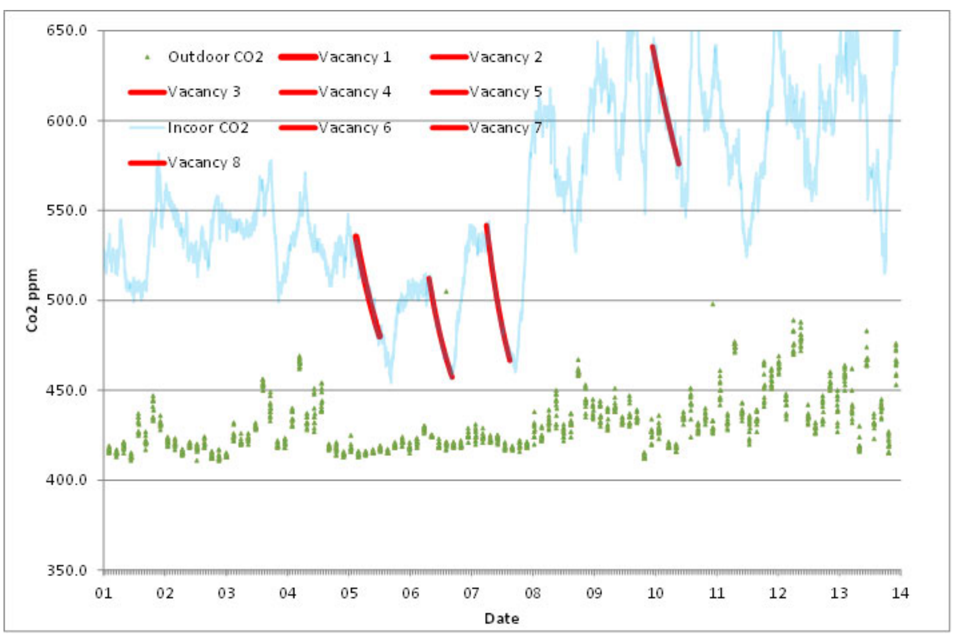

Figure 3.16: Calculated Vacancies - Set 5

Fit R^2	TC (h)	Start (m-d hh:mm)	End (m-d hh:mm)	Low CO_2 (ppm)	Wind (kmh)
0.9811	6.0	Jan-21 07:24	Jan-21 16:43	466	15.2
0.9178	15.3	Jan-23 05:10	Jan-23 14:41	495	9.7
0.9460	7.6	Jan-24 05:46	Jan-24 13:16	479	9.0
0.9817	12.2	Jan-26 22:55	Jan-27 06:33	676	4.1
0.9614	7.8	Jan-28 04:34	Jan-28 13:52	493	9.7
0.9330	7.9	Jan-29 04:27	Jan-29 13:40	497	8.7
0.9593	9.9	Jan-30 05:00	Jan-30 14:23	531	3.0
0.9291	6.3	Jan-31 02:40	Jan-31 12:26	489	18.7
0.9586	7.0	Feb-01 06:04	Feb-01 15:29	502	15.6
0.9800	7.4	Feb-03 21:13	Feb-04 06:26	483	16.1
0.9804	7.1	Feb-05 04:58	Feb-05 13:59	470	15.9
0.9560	17.9	Feb-06 06:47	Feb-06 16:25	517	4.7
0.9473	13.6	Feb-07 05:23	Feb-07 14:27	527	3.1
0.9451	9.0	Feb-07 19:38	Feb-08 04:48	475	19.1
0.9617	3.4	Feb-11 04:21	Feb-11 13:54	432	8.5
0.9625	9.8	Feb-12 06:06	Feb-12 15:14	488	5.7
0.9341	8.6	Feb-14 05:06	Feb-14 13:43	470	12.4
0.9373	11.6	Feb-15 04:34	Feb-15 14:44	474	9.2
0.9460	06.7	Feb-18 05:48	Feb-18 15:10	452	11.6
0.9482	15.8	Feb-21 02:50	Feb-21 12:15	522	10.4
0.9631	13.2	Feb-22 04:39	Feb-22 14:29	498	4.5
0.9714	12.5	Feb-25 06:42	Feb-25 15:53	498	3.5
0.9532	09.6	Feb-26 04:42	Feb-26 13:49	471	5.5
0.9486	16.6	Mar-05 02:46	Mar-05 12:35	475	18.6
0.9795	12.7	Mar-06 07:21	Mar-06 16:24	456	5.9
0.9791	11.4	Mar-07 05:51	Mar-07 15:02	468	4.0
0.9336	31.5	Mar-09 22:52	Mar-10 09:25	568	10.1

Table 3.1: Vacancy Periods identified via CO_2 analysis

an infiltration rate of 650 m^3/12.2 = 53 m^3/hr. The mean time constant of 10 hours represents a infiltration rate of 650 m^3/10 = 65 m^3/hr.

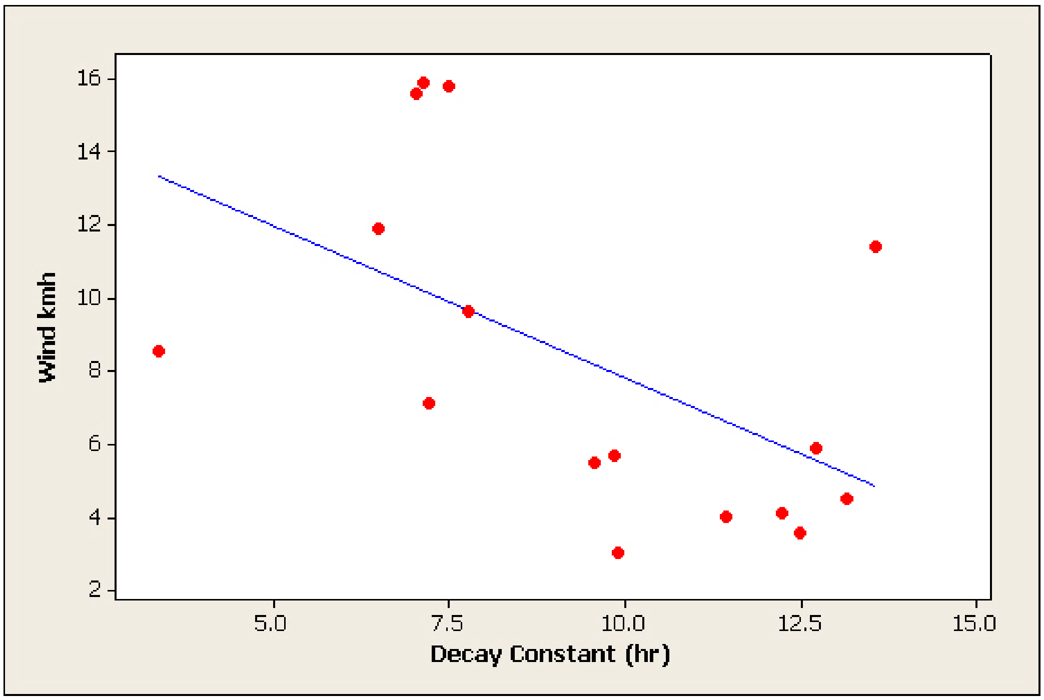

Figure 3.17: Correlation between wind speed and natural infiltration rate

The infiltration rate was too low to return the indoor CO_2 concentration to background levels for short vacancy periods so some vacancies would have been missed had the identification been based on absolute levels.

Table 3.3 shows a variation in infiltration rate with wind speed. The correlation between decay constants and average wind speed during the measurement period was significant with a Pearson correlation coefficient of -0.833

and a p-value of 0.001. Figure 3.17 shows a negative correlation between the time constants and average wind speed which is expected. Wind direction is also a factor in asymmetrical houses as is turbulence [51] [52] [53]. The low end of the infiltration rate range can be used to conservatively predict CO_2 and the end of a vacancy period although if a wind sensor was installed the infiltration rate could be adjusted dynamically for improved predictions.

The maximum mechanical ventilation rate of the HRV was 384 m^3/hr therefore natural infiltration was approximately 17% of what the HRV was capable of providing. This natural leakage rate prevented interior CO_2 levels from exceeding 710 ppm during the observation period with one exception during a gathering of many people where it reached 880 ppm. Three adults engaged in light activity would have been expected to ultimately produce CO_2 concentrations levels of approximately 650 ppm.

Periodic variation in outside CO_2 concentrations, figure 3.10 lower green line, were correlated with changes in indoor concentrations. The intake and exhaust vents from the HRV were installed as per building code but this resulted in mixing of the air streams that varied with atmospheric conditions. To improve the accuracy of outdoor readings, an extension duct was added to the exhaust vent which greatly reduced mixing. Random mixing made differential measurements inaccurate and resulted in missing most vacancy periods because of lower R^2 values. Since the NDIR sensor drift was negligible, the analysis was based solely on absolute indoor concentrations.

During the observation period, CO_2 concentrations never exceeded 710 ppm with three occupants indicating that the greatest saving from DCV would come from disabling fresh air intake most of the time.

A control system which has learned the occupancy map and average infiltration rate over a period of a few weeks could be implemented as follows:
If the CO_2 rises above a threshold then look ahead to the next hourly time slot. If the probability of vacancy exceeds 50%, calculate the CO_2 concentration at the end of the projected vacancy using the average infiltration rate. If this is less than the threshold, then do not introduce fresh air.

Example 1:
The CO_2 concentration is 800 ppm above outdoor levels at 7:30 AM Monday morning, and the threshold for ventilation is 600 ppm above background levels. Should mechanical ventilation be used to bring this down by 200 ppm?
The Monday 8 AM to 1 PM time slot was vacant the last five weeks without exception, the probability of vacancy is estimated at 100%. Anticipating 5 hours of vacancy and time constant of 2.6 hours, CO_2 should decayed to 800*e^{-}(5/2.6) = 117 ppm above outdoor levels. This is negligible and well below the 600 ppm threshold. Therefore, fresh air ventilation at 7:30 is not

necessary and will not be required until some time after 1 pm.

Example 2:

As above, but assume occupancy is 75% likely and 1 hour in duration.

Since there is a greater than 50% chance of upcoming vacancy the system expects CO_2 should decay to $800{*}e^{-}(1/2.6) = 544$ ppm above outdoor levels. This is just below the threshold, so ventilation can be deferred.

Had this been a newer home with a tighter building envelop and a time constant of 12 hours, the system would expect CO_2 to decay to $800{*}e^{-}(1/12) =$ 736 ppm above outdoor levels. In this case, fresh air would be provided until CO_2 levels returned to a concentration that could be reduced to 600 ppm by natural infiltration during the remainder of the vacancy period. Alternatively, the fan could be run at a lower speed sufficient to augment natural infiltration such that 600 ppm was reached just as occupants were expected to return.

A HRV could be controlled as show in block diagram 3.18. The CO_2 concentration would be continuously logged for a period of one week in recirculation mode with fresh air being introduced only when the inside CO_2 concentration exceeded 1000 ppm. The analysis does not need to be performed in real time. During this start up period, vacancies would be mapped and used to calculate the average natural infiltration rate. The learning period would be interrupted occasionally as the 1000 ppm threshold triggered full speed ventilation. It would be operating as a standard DCV system using a fixed set point.

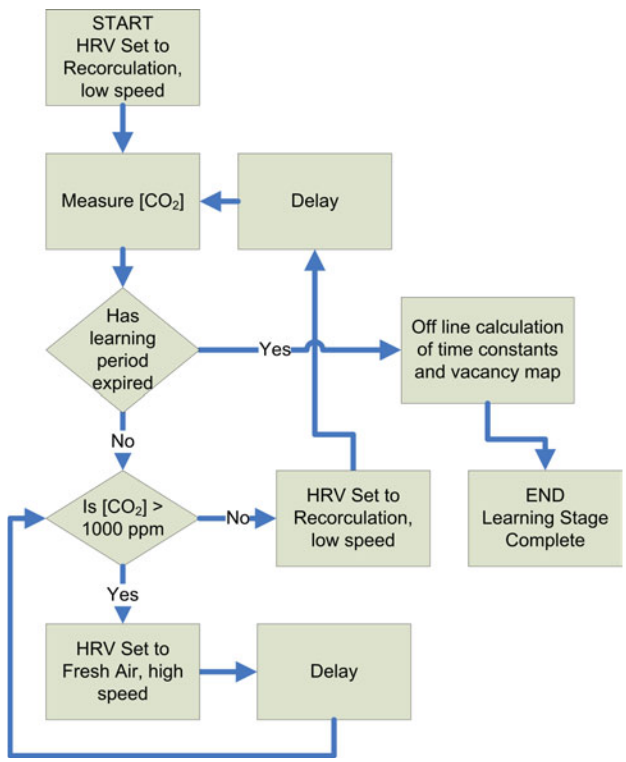

Figure 3.18: HRV Control: Learning Phase

Once the learning period had elapsed, the system could be controlled as shown in block diagram 3.19. When the CO_2 concentration exceeds the threshold, a determination is made as to how soon the home is expected to be vacant, and if the natural infiltration rate will clear the room before the expected end of the vacancy. If vacancy is imminent or expected to be lengthy, the introduction of additional fresh air can be deferred. The calculated vacancy map can also be sent to the heating control system for supplementary set back periods based on vacancy.

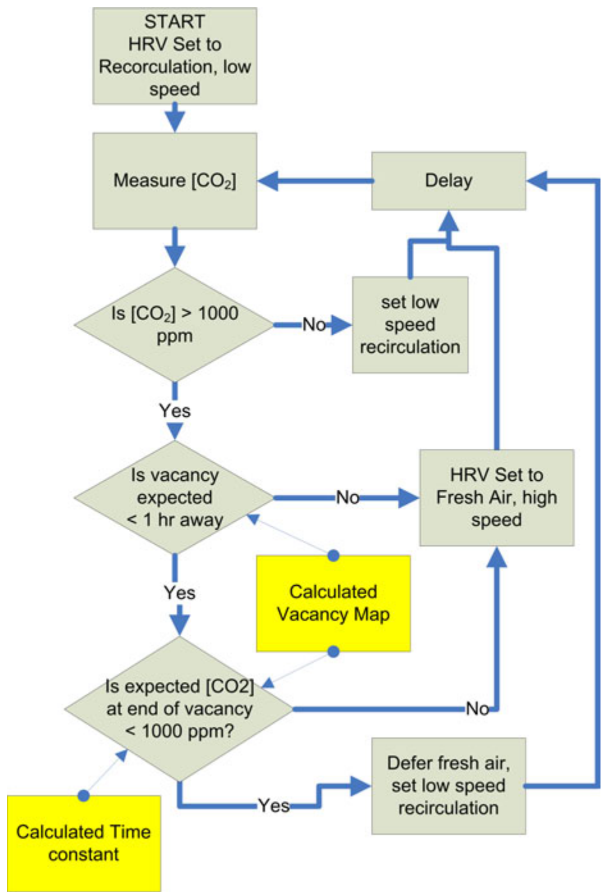

Figure 3.19: HRV Control: Normal Operation Phase

The major energy savings for such a control strategy would come from the following:

1) Automatically setting occupied and unoccupied temperatures based on the vacancy probability map.
2) Disabling fresh air ventilation when not needed, which in this case for a threshold of 1000 ppm, would have been all the time.
3) Disabling fresh air ventilation before vacancy periods which for a 9 am to 5 pm work schedule might eliminate an hour of fresh air each work day depending on the initial concentrations.

This analysis was performed off line and some of the control methods proposed do not require real time analysis. Data could be processed daily or weekly by the data acquisition computer as a periodic task and used to update the occupancy map. The calculated natural infiltration of the ventilation zone should not change unless the building envelope is modified so this parameter only needs to be calculated as part of system commissioning. While the natural infiltration rate and occupancy map could be entered by the user during commissioning, calculating them periodically and automatically would offer better accuracy and require no future human intervention. For control of heating and cooling, the occupancy map would be used to switch between the "at home" and "away" temperatures and overlaid with an optional time based night-time temperature setback.

The real time identification of vacancy periods requires additional analysis. It is straight forward to identify vacancy after the fact, but early identification of a vacancy in progress is prone to error since there are fewer data points to fit to a decay curve and the decline might be simply random or the result of opening a door or window. If the off-line technique was used in real time, the vacancy would be identified approximately a half hour after it began. Once the vacancy is identified, the fresh air intake could be reduced to either a minimum value sufficient for non-human generated pollutants or set to zero.

Further analysis could reduce the moving window width and correlate it with the accuracy of vacancy identification. The additional value of potential energy savings by identifying a vacancy several minutes earlier and this reducing the fresh air intake rate a few minutes earlier may not be worth the cost in terms of reduced accuracy of the vacancy map. Further analysis could also determine the best way to accurately and quickly identify the return of occupants. It could be as simple as an upward trend in concentration that exceeds 50 ppm over 10 minutes.

Indoor air quality is a very complex area that is generally at odds with the energy management since supplying large quantities of fresh air is generally the best possible strategy for IAQ and the worst possible strategy for energy conservation in a cold climate. The fundamental issue with the proposed algorithms and well as commonly used DCV algorithms such as the fixed set point based on occupancy is that they are limited in their ability to understand the true health needs of the occupants. The minimum ventilation rate for example could be too low due perhaps to radon or respirable dust, or wastefully high. Technology exists to inexpensively measure many more components of IAQ allowing the identification and elimination of numerous hazards and conversely, reducing ventilation when no hazard exists. The following chapter outlines several such areas for further research.

Hour	Sun	Mon	Tue	Wed	Thu	Fri	Sat
1	13	0	0	0	14	0	29
2	13	0	0	0	14	0	29
3	13	0	13	0	29	0	29
4	13	0	13	0	29	0	29
5	13	25	50	0	29	29	29
6	13	38	50	13	71	29	29
7	13	50	63	25	71	43	29
8	0	63	63	38	71	43	14
9	0	63	63	38	71	43	14
10	0	63	63	38	71	43	14
11	0	63	63	38	71	43	0
12	0	63	63	38	71	43	0
13	0	63	63	38	71	43	0
14	0	63	50	38	57	43	0
15	0	38	13	38	29	43	0
16	0	38	13	25	14	14	0
17	0	13	0	25	0	0	0
18	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0
20	0	0	0	0	14	0	0
21	0	0	0	0	14	0	0
22	13	0	0	0	14	0	0
23	13	0	0	0	14	0	29
24	13	0	0	0	14	0	29

Table 3.2: Vacancy Map for $R^2 \geq 0.93$

Wind (kmh)	TC (h)	R^2	Infiltration (m^3/h)
4.1	12.2	.982	53
9.7	7.8	.961	84
3.0	9.9	.959	66
15.6	7.0	.957	92
15.8	7.5	.979	87
15.9	7.1	.979	91
5.7	9.8	.963	66
4.5	13.2	.963	49
3.5	12.5	.971	52
5.3	9.6	.953	68
5.9	12.7	.979	51
4.0	11.4	.979	57

Table 3.3: Wind speed vs Time Constant

Chapter 4

Conclusions and scope for future work

This thesis provided data acquisition and off-line data analysis of a house. The objective was to calculate the natural infiltration rate and identify periods of occupancy that could be used for scheduling future HVAC operations while implementing a basic DCV setpoint based control system. Based on the analysis of this data, a self learning antonymous ventilation zone controller for residential and commercial buildings could be developed using the methods outlined in this thesis. The natural infiltration rate of a zone and patterns of occupancy can be learned by observation of a continuous data stream. These parameters allow the prediction of future occupancy and indoor air quality which in turn can be used to implement expert systems. The processing power required is minimal and the system can be implemented on an inexpensive micro controller. While using such a system to maintain acceptable IAQ by controlling ventilation flow rates and fresh air percentage is worthwhile from a health perspective, using it to control heating and cooling is likely the most profitable application. Unlike programmable thermostats which are seldom programmed and used effectively to conserve energy, self learning systems would achieve their savings automatically. A thermostat with embedded NDIR CO_2 sensor would require some additional refinements to the control logic since sampling the outside air stream for differential measurements would be impractical and it would need to filter out CO_2 spikes encountered when occupants breathed near them. Neither of these problems are difficult to solve.

There are no impediments for using a self learning system for heating and cooling control, however for ventilation, there are issues with current building codes and ventilation standards. Control systems for residential buildings have the freedom to balance IAQ with energy costs and are free to use any method including setting the recirculation to 100% during periods of vacancy or shutting down ventilation entirely when not needed during periods of low occupancy and high winds.

Commercial buildings ventilation control systems are more restricted because building code mandates minimum flow rates based on occupancy and floor area. These minimum flow rates were mandated because the commercially available demand controlled ventilation technology that existed at the time the codes were developed could not accurately quantify indoor air quality. Instead, flow rates that would maintain the concentration of CO_2 below 1000 ppm were codified into law assuming that such flow rates would be adequate to ensure public safety. It is reasonable to expect that as DCV control systems and their sensors evolve into expert systems with the ability to detect all major indoor pollutants of concern, that the minimum flow rates specified in code will become optional provided that an engineering analysis has been performed which indicates that the control system will maintain IAQ at acceptable levels.

In summary, periods of vacancy a residential homes were successfully mapped using occupant generated CO_2 as a tracer gas and following the decay in concentration. An accurate occupancy map was generated, indicating the probability and duration of future vacancies. The upper and lower limits of natural infiltration were determined from the time constant of the decay and statistically correlated with wind speed as expected.

Substantial energy savings are possible by using the system simply to automatically and dynamically program heating and cooling system set points thus eliminating the need and desire of occupants to understand the thermostat and successfully program it as well as updating the programming when occupancy patterns change.

4.1 Ideas for Additional Work

4.1.1 Real Time Analysis

The identification of vacancy periods and calculation of infiltration rates was performed off-line. Inexpensive open source miniature embedded Linux platforms are now available for approximately US$50 and typically include a 400MHz CPU, 8GB of flash memory, 512M of SDRAM, a USB controller, RS-232 and microSD interfaces and 10/100 Ethernet. The BeagleBoard is an example of this trend, measuring 3.4 by 2.1 inches and small enough to embed inside a typical wall mounted HVAC control unit. The trend towards smaller, cheaper and faster integrated computer system hardware coupled with open source software is likely to continue, driven by the huge market for sophisticated and intelligent consumer devices such as wireless internet routers than can be managed from the built in web server. These Linux systems can run a compiled C language program to perform the calculations used for this thesis in real-time and store important data in non-volatile memory making them immune to power failures. The Linux based data acquisition used for this thesis work had similar specifications, although its AMD E-350 processor operated at 800 MHz, the typical CPU loading was only 1%.

4.1.2 Alternate Sensors

CO_2 was used as a proxy for the human generated component of IAQ. Additional sensors could be added to the sensor array to detect additional chemicals that need to be controlled, both from a health and safety perspective. An IAQ index could be developed that assigned a weighted average based on multiple measured pollutants to produce a feedback signal instead of relying solely on the CO_2 concentration value.

4.1.3 Radiation Sensors

Radon decay should be detectable in the air stream using commercially available PIN diode array based detectors. These should be much cheaper than geiger tubes. Ideally, radon is inexpensively mitigated with sub-fundation depressurization and radon resistant building techniques such as polyethylene barriers, however once a structure has been built, these techniques are prohibitively expensive leaving mitigation via HVAC control as the only option. Measuring radioactivity in the return air could be used to set the minimum ventilation rate to comply with current health standards or using the vacancy map presented in these thesis, be used to trigger a pre-occupancy radon purge.

4.1.4 Tin Oxide Sensor Arrays

Tin oxide sensors are not specific for any particular VOC, but can be optimized for detection of a specific chemical, such as alcohol or formaldehyde. If several tin oxide sensors with different characteristics are used, the set of sensor output voltages can be used to identify complex odours. Arrays of tin oxide sensors (either different sensor models, or the same model operating at different temperatures via changes to the sensor heater voltage) could be used to characterize undesirable odours. It should be possible to characterize acceptable odours such as perfumes and odours from cooking so that only odours such as floor cleaning chemicals, fresh paint and cigarette smoking triggered an air purge. An objectionable odour button could be added to the control unit to be pressed by the occupants on demand. The system would then catalogue these sensor patterns and used them to increase ventilation. The opposite approach might also work – purge when VOC levels are high, but prompt the user with a message asking if the odour is acceptable. This could be used to catalogue the signatures of commonly cooked meals, baked bread, air fresheners, etc. Using this strategy, all elevated levels of VOC would be deemed hazardous unless they matched the signature of known good odours.

4.1.5 Humidity Control

The control of humidity by injecting steam into the fresh air stream or operating refrigeration equipment to condense excess moisture is energy intensive. The relative humidity data of the incoming and outgoing air streams could be analysed in real time to determine periods when fresh air could be used to beneficially adjust indoor humidity levels. A one year historical analysis could be performed to exclude periods where fresh air was required to reduce CO_2 levels thus identifying periods where additional fresh air could improve indoor RH and calculate the potential annual energy savings.

4.1.6 Particulate Matter

Airborne particle counts can be estimated using inexpensive smoke detector modules. Sampling the exhaust or recirculating air streams using both ionization and optical smoke detector modules and comparing the data with a multichannel particle counter such as TSI AeroTrak 9306 would verify the reliability of this approach. If tobacco smoke can be positively identified, it could be used to trigger increased ventilation. It might also be used along with the signature from a tin oxide sensor array to improve the detection accuracy of tobacco. It might be possible to identify back draft conditions from wood burning appliances and trigger a warning. Back drafts and inadvertent introduction of soil gasses are a symptom of unbalanced HVAC systems which could be better solved using inexpensive pressure sensors. If these sensors were added to the control system, they could be used to independently modulate the intake and exhaust fans to maintain the pressure balance and to detect clogged HVAC filters.

4.1.7 Vacancy Maps for Heating Control

The real time determination of vacancy could be used to set thermostats to a lower temperature automatically. This is a standard feature of some residential bugler alarm systems which use alarm activation as a control signal to thermostats that respond by choosing the "away temperature" and restore the "at home temperature" once the alarm is disarmed. The major disadvantage of waiting until the alarm system is disabled is that it could take an hour to reheat the home.

The real time mapping of vacancies onto a calendar could be used to control the automatic restoration of temperatures so that the set point would be reached just as occupants were expected to arrive. Data could be analysed for the fastest and most reliable way to detect the return of occupants since occupancy will have common exceptions to historical patterns.

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Glossary

Volatile Organic Compound (VOC) - Any organic chemical with a low vapour pressure, which allows substantial evaporation at room temperature. Alcohol and vinegar are common examples.

Sensor Based Demand Controlled Ventilation (SBDCV)- Any ventilation control system that uses sensing, feedback and control to adjust the quantity of fresh air as occupancy changes, as opposed to a system that is based on a fixed schedules.

Indoor Air Quality (IAQ) - a loosely defined concept with no generally agreed upon method to quantify it. Most occupants consider indoor air with a CO_2 concentration below 1000 ppm to be acceptable i.e. acceptable IAQ, however the many other contaminants could be present, resulting in it being harmful to health - e.g. poor IAQ.

Chapter 5

Publications and Presentations Developed From This Research

Parsons, Peter. "Determining Infiltration Rates and Predicting Building Occupancy Using CO_2 Concentration Curves." Journal of Energy 2014 (2014)

Parsons, Peter. "Predicting Building Occupancy using CO_2 Concentration Curves" IEEE Newfoundland Electrical and Computer Engineering Conference (2013)