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Towards a better understanding of indoor exposure to air pollutants: Window opening occurrence in U.S. residences

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TOWARDS A BETTER UNDERSTANDING OF INDOOR EXPOSURE TO AIR POLLUTANTS: WINDOW OPENING OCCURRENCE IN U.S. RESIDENCES

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ABSTRACT

Opening a window dramatically alters how we are exposed to air pollutants. Online questionnaire surveys were deployed to assess window-opening occurrence of the occupants of US homes. This information will be used to better quantify population exposure to pollutants of indoor and outdoor origin. Frequency distributions of demographics were generated which showed percentages of respondents who participated in the surveys from categories including gender, race, household income and occupancy. In April 2016, 49.3% of the people surveyed opened their windows for at least 1 hour in a day. This increased to 52.5% in September 2016 and reduced considerably to 24.4% in December 2016. “Window hours” defined the behavioral patterns of each respondent with respect to window opening in different rooms of the home and for different time intervals. Respondents opened windows more often in the morning and afternoon. Respondents in the southwestern and northwestern regions of US opened windows more (approximately 74%) than the respondents from other US regions in surveys 1 & 2. For survey 3, northeastern region opened windows least (18.75%) as compared to other regions. These variations in percentage can be associated with the temperature and humidity differences, and the time of the year when the surveys were deployed. Another part of the study focused on field work to estimate the air exchange rate (AER) in a home under windows closed and windows open conditions, using tracer compounds (HFB & OFT). It was observed that, when all the windows were closed, the air exchange rate in the home was approximately 1.97 hr^{-1}. When half a window was opened, the air exchange rate increased to 6.07 hr^{-1}. But when another full window was opened, the AER increased to 1.47 hr^{-1}.

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1. INTRODUCTION

1.1. BACKGROUND

US residents spend over 88% of their time indoors, either in homes, schools or offices. This accounts to spending almost 16 hours indoors out of 24 hours (Klepeis et al., 2001). For this reason, it is important to gauge the air quality indoors. The biggest concern is that people do not tend to open windows or doors often, to remove the excess indoor air pollutants and moisture. Standards for energy efficiency in buildings have resulted in tightly sealed modern homes or other buildings. The US Environmental Protection Agency (USEPA) conducted TEAM (Total Exposure Assessment Methodology) studies in the 1980s and the results indicated that the concentrations of many indoor air pollutants can distinctly exceed the concentrations in outdoor air, resulting in a higher exposure of occupants to them (Wallace, 1991).

Window opening not only helps in the regulation of indoor air temperature but it also dilutes indoor air pollutants, by an increase in air flow and air exchange rate. Factors like temperature, humidity, and indoor air quality greatly influence the overall health, productivity, and comfort of the occupants. There have been a lot of studies relating the effects of ventilation rates, Indoor Air Quality (IAQ), temperature and moisture to the occupant productivity and health in various environments like schools, homes, and offices (Bakó-Biró et al., 2012; Daisey et al., 2003). Bakó-Biró et al. (2012) concluded that low ventilation rates considerably diminish pupils' attention and also affect their cognizance and attention in a negative manner. Daisey et al. (2003) measured pollutants like TVOCs (Total Volatile Organic Compounds), Formaldehyde and CO_2 concentrations in schools. Findings from the study suggested that the CO_2 concentrations exceeded the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) ventilation standard for 1999. Asthma and Sick Building Syndrome (SBS) are the most common health issues related to schools. Some studies also revealed that the symptoms of SBS diminished and productivity increased as the ventilation rate increased in offices and homes, respectively. These studies also supported the fact that ventilation rates maintained above the set standards can influence health, efficiency and comfort level positively (Wargocki et al., 2000; Jones, 1999).

Outdoor air enters a building through mechanical ventilation or natural ventilation in a deliberate way, but it can also enter via cracks or openings via infiltration. This exchange of air directly increases the rate of movement of outdoor pollutants into a building like ozone and dilutes the pollutants which are emitted indoors (e.g. formaldehyde). Numerous studies have shown the relationship between indoor air chemistry and air exchange rate (AER). The concentration of indoor-generated secondary organic aerosols (SOA) increases with an increase in the air exchange rate until it reaches a maximum value and then eventually, decreases. Even though a vast number of modeling studies have pointed out that air exchange rate is an important aspect in deciding the chemical mixture composition, there have not been any indoor studies which have measured and determined all the pollutants in spaces like homes, offices, or schools and also assessed the effects of air mixing and exchange (Sarwar et al., 2007; Carslaw et al., 2012).

1.2. AIMS AND OBJECTIVES

The primary aim of this work was to assess the occurrence of window opening throughout the United States. Factors influencing window-opening behavior have been studied but there is a lack of information concerning the occurrences of window opening across the United States. A secondary aim was to measure how air exchange rates change with window opening in a field home. This will add to the small number of measurements reported in the scientific literature. The following objectives and subtasks were established:

1. Objective 1: Quantify the occurrence of window opening in US residences.
    a. Identify any associations between window-opening occurrence and demographics.
    b. Quantify and compare window-opening occurrence for the 4 major climate quadrants of the US (North-East, North-West, South-East, South-West).
    c. Quantify "window hours" and compare with diurnal patterns of pollutants.
2. Objective 2: Measure the air dilution rate and effective air exchange rate in a residence with windows open and closed.
    a. Measure the concentration of tracer compounds under conditions of open and closed windows in a residence.
    b. Quantify the effective air exchange rate based on tracer concentration measurements.

2. LITERATURE REVIEW

2.1. AIR EXCHANGE RATES AND INDOOR AIR QUALITY

Air exchange rate (AER) is the volumetric flow of air into a room or building divided by the room or building volume. It is an essential attribute for understanding the indoor air quality and also the exposure of occupants to numerous pollutant concentrations. AER is dependent on the following factors in any space which is ventilated (Murray et al., 1995; Iwashita et al., 1997; Wallace et al., 2002; Howard-Reed et al., 2002; Yamamoto et al., 2010):

1. HVAC system,
2. Geographic location,
3. Meteorological conditions like temperature, humidity and wind speed,
4. Occupant behavior like opening/closing of windows or doors, and
5. Building attributes.

The CO_2 level inside a building or a home is a good indicator of the ventilation rate and occupancy. The levels are usually higher in an occupied space when the AER is relatively low. Likewise, the concentrations of any pollutants with indoor sources, such as volatile organic compounds (VOCs), will be elevated due to low AERs. Occupants might open doors or windows while cleaning or sweeping, which might lead to an increase in AER, but the downside is that openings might also increase the rate that outdoor air pollution enters, including ozone or particulate matter. A plethora of techniques are available for the measurement of AER, which can be selected based on the number of samples desired, experimental restrictions, and the steady-state conditions which prevail. Many studies have relied on tracer gas decay techniques, which make use of CO_2, SF_6 or other inert volatile compounds. When these techniques are employed, they consider the building to be a single well-mixed zone, neglecting the flow between rooms (zones), also known as interzonal flow. A single mean AER is typically reported for the sampling period, although some studies report continuous measurements of AER. The AER can vary from room-to-room in a building due to uneven interzonal flows especially when coupled with occupant window-opening behavior (Du et al., 2012).

2.1.1. Sources of Indoor Air Pollution. The sources of indoor air pollution can be categorized into two types: Air pollutants of indoor origin and air pollutants of outdoor origin.

2.1.1.1 Air pollutants of outdoor origin. The quality of the air within a building is influenced by the levels of outdoor pollution. This is because of exchange of air. Therefore, it is easy to assume that almost all the pollutants present outdoors are present indoors and at same levels. But this is not the case. The level of outdoor contaminants found indoors is usually lower that those found outdoors. Many of these pollutants can deposit or react with the building materials thereby lowering air concentrations. The sources of these outdoor pollutants can be factory emissions, vehicular emissions, atmospheric chemistry, combustion, and natural processes like wind-blown dust or even volcanos.

There is a wide range of common outdoor pollutants including: carbon monoxide (CO), oxides of nitrogen (NO_x), oxides of sulfur (SO_x), particulate matter ($PM_{2.5}$ and PM_{10}), ozone (O_3) and lead (Pb). These make up the outdoor sources of air pollution and are detrimental to the health of humans at concentrations higher than the safe limits. Oxides of nitrogen (NOx) and Volatile Organic Compounds (VOCs) react with sunlight and form photochemical smog, which can linger in the atmosphere for extended periods of time. Long-term exposure to such sources of air pollution can cause cancer, heart disease, asthma, and long-term impairment of the respiratory, reproductive, neurological and immune systems.

A consistent correlation has been established between PM levels and death rates in the US. The U.S. Environmental Protection Agency (USEPA) projected that in 2010 there were approximately 160,000 premature deaths in the U.S. due to exposure to $PM_{2.5}$ and approximately 4300 deaths related to ozone exposure. The USEPA also estimated that in 2012 about 74 million people in the U.S. were exposed to levels of $PM_{2.5}$ higher than the limit and that more than 131 million lived in regions which are not in compliance with the maximum allowable ozone levels (USEPA, 2011a, USEPA, 2012b). In the U.S., the ground level $PM_{2.5}$ and ozone concentration are dominated by anthropogenic activities.

2.1.1.2 Air pollutants of indoor origin. Numerous pollutants are present within a house or office or any other enclosed space and have negative effects on humans. Occupants can withstand a few of the airborne pollutants emitted in the indoor environment at low concentrations, while other pollutants are extremely toxic. These pollutants can be classified into the following categories:

1. Volatile and Semi-volatile Organic Compounds (VOCs and SVOCs) emitted from furnishings, chemical products and building materials
2. Soil gas pollutants like Radon
3. Biological agents like Mold
4. Combustion products

Combustion pollutants include carbon monoxide (CO), oxides of nitrogen (NO_x) and oxides of sulfur (SO_x), particulate Matter (PM) and volatile organics. These are emitted from processes like cooking and heating. Environmental tobacco smoke (ETS) is also a pollutant of concern and is a combination of the products released during tobacco smoking. Various VOCs and SVOCs are found in indoor air e.g.: Formaldehyde which "out-gases" from furnishings like particle board, plywood and other household chemical products. Radon is a naturally occurring gas which is found in regions with uranium in the soil. The building is usually at a lower pressure as compared to outside environment. Due to this pressure difference, the building acts like a vacuum and sucks radon inside through cracks and openings. Biological agents include mold, pollen, bacteria, viruses, dust mites, and other allergens which are either produced in the building or enter from outside (i.e. pollutants of outdoor origin).

2.2. VENTILATION AND RESIDENTIAL INFILTRATION

Ventilation refers to two entities; the ventilation rate, which means the amount of outdoor air which flows into the building and the ventilation system, which denotes the means through which air is supplied into the building, for example air conditioning (AC) or through windows. Ventilation brings about a change in indoor exposures but it cannot reduce the emissions occurring indoors. It is helpful in dilution or removal of the pollutants which are generated indoors. The efficacy of ventilation varies for various pollutants. For some, it might be very high and for some it might not be sufficient. It can also bring in pollutants present outdoors into the building. The ventilation needs, based (in part) on the emission rates of indoor-sourced pollutants, can be estimated. Appropriate ventilation can help to keep the pollutants at levels which limited harm to human health (Wargocki, 2013).

Air from outside is continuously mixing with indoor air through small crevices and openings in buildings, as well as through windows, doors and other vents and this phenomenon is called infiltration. This infiltration or exchange of air is led by differences in the pressure due to wind and the difference in temperature between indoors and outdoors (Ilacqua et al., 2015).

2.2.1. Infiltration, Mechanical and Natural Ventilation. Winds, pressure difference and buoyant forces result in the movement of outdoor air into the building through windows, doors and other openings. This phenomenon is called natural ventilation, which depends on factors like occupant behavior, design of the building and climate of the place. When natural ventilation is properly installed and managed, it is more advantageous than mechanical ventilation. The advantages are:

1. Provides a higher ventilation rate in an economic way because of natural forces and big openings.
2. More energy efficient.
3. Gives access to more daylight, if appropriately designed.

Mechanical ventilation is provided by mechanical fans. These fans can be placed directly on walls or in windows, or in air ducts to supply air into or draw air out of a room. It usually depends on the climate of the region. For instance, in hot and humid climates, infiltration is reduced to minimize condensation occurring indoors. In such cases, a positive pressure mechanical ventilation is required. On the contrary, in cold climates, exfiltration is reduced to avoid condensation and therefore, a negative pressure mechanical ventilation should be installed. A balanced mechanical ventilation denotes the system in which all the air supplies and exhausts are tested and maintained to meet design specifications (CDC, 2003; Brager et al., 2011; Atkinson, 2009). Advantages of mechanical ventilation are:

1. Reliable in supplying the designed flow rate. It can be combined with air-conditioning to control indoor temperature and humidity.

2. Mechanical ventilation can be equipped with filtration systems to prevent the harmful particulates, microorganisms, odors, vapors and gases from entering the home or building.

3. Airflow path can be managed in mechanical ventilation.

2.2.2. Standards for Ventilation in U.S. Homes. ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) is a technical body which is responsible for preparing and maintaining ventilation standards for the United States. The ASHRAE 62.2 committee was brought into force in the year 1996 and it develops a residential ventilation standard for buildings which are less than or equal to three stories. This standard is known as "Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings". It is reviewed every 3 years. The two essential requirements of ASHRAE standard 62.2 are (ASHRAE, 2017):

1. Whole house mechanical ventilation in order to maintain acceptable indoor air quality.

2. Local exhaust fans in every kitchen and bathroom for reduction of the level of contaminants and humidity level in these spaces.

The total ventilation rate is determined using a formula that uses the square footage of the building and the potential number of occupants:

$$Q_{Total} = 0.03A_{floor} + 7.5(N_{br} + 1) \quad \text{(Equation 1)}$$

Where; Q_{Total} = Total required ventilation rate, cfm

A_{floor} = Floor area of dwelling unit, ft^2

N_{br} = Number of bedrooms (not less than 1)

It can also be estimated using the following Table 2.1:

Table 2.1. Ventilation air requirements (adapted from https://ashrae.iwrapper.com/ViewOnline/Standard_62.2-2016)

Bedrooms					
Floor area (ft^2)	1	2	3	4	5
<500	30	38	45	53	60
501-1000	45	53	60	68	75
1001-1500	60	68	75	83	90
1501-2000	75	83	90	98	105
2001-2500	90	98	105	113	120
2501-3000	105	113	120	128	135
3001-3500	120	128	135	143	150
3501-4000	135	143	150	158	165
4001-4500	150	158	165	173	180
4501-5000	165	173	180	188	195

The above equation 1 and Table 2.1 assumes two persons in a studio or one-bedroom unit and an extra person for an additional bedroom. For higher occupant densities, the rate will be increased by 7.5 cfm for each additional person. For bathrooms the fan must be capable of delivering a minimum of 50 CFM of exhaust ventilation when installed and for kitchens ventilation it is 100 CFM (ASHRAE, 2017).

2.3. INFLUENCE OF WINDOW OPENING ON AIR EXCHANGE RATES

The effect of window opening on the air exchange rate is essential for exposure modeling. The airflow through a window maybe influenced by a number of variables, according to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Fundamentals handbook (ASHRAE, 1997). Some of these variables are:

1. Location of windows
2. Number of windows
3. Wind speed
4. Width of the opening of the window
5. Temperature (indoor/outdoor)
6. Turbulent eddies near window openings

According to the results of the National Human Activity Pattern Survey (NHAPS), opening windows is a usual everyday activity carried out by the occupants. The NHAPS (1996) was done throughout the year at regular intervals and it was found that, out of the 4723 respondents, 42.5% opened at least 1 window in their home on the day the survey was taken. Out of these 42.5% i.e.: 2006 respondents who opened their windows, 42% opened 1 or 2 windows and about 6% opened more than 10 windows in the home (Tsang and Klepeis, 1996). Wilson et. al. (1996) proposed that the erratic nature of measured air exchange rates was because of the window opening activity by the occupants. Another study carried out by Kvisgaard and Collet (1990) showed that 63% of the average AER in 16 Denmark houses was due to the opening of windows and doors by the occupants (Wilson et al., 1996; Kvisgaard and Collet, 1990).

Window opening does affect ventilation, but it additionally has an impact on the concentration of contaminants in the homes. Due to opening windows, there is an increased flow of outdoor air which may escalate the inflow of outdoor contaminants and decrease the level of indoor contaminant concentrations. Numerous studies have shown the increased correlation of indoor and outdoor contaminant levels during time periods with windows open (Abt et al., 2000; Sarnat et al., 2000; Long et al., 2000). Opening of windows may also affect the dispersal of a pollutant in the home. For instance, an occupant may open a window to remove odors or smoke from a room. This might help to significantly decrease the pollutant level in that particular room, but may not remove it from other parts of the home.

The profound effect of window-opening on AER has been observed in numerous studies (Wallace et al., 2002; Bekö et al., 2010; Mølgaard et al., 2014). Howard-Reed et al. (2002) detected that due to window-opening, there was a definite increase in the air exchange rate from 0.10 to 2.8 hr^{-1} (Howard-Reed et al., 2002). Wallace et al. (2002) concluded that the difference in temperature could not justify the AERs above 0.8 hr^{-1}. It was observed that due to seasonal variations in window-opening (open more than 50% of the time in summer and only 10% in the fall or winter months), there was a significant variation in AER (Wallace et al., 2002). An experiment done in the Los Angeles area gave rise to the opinion that AER increased when the temperature was around 11-24°C but decreased when the temperature went above 24°C. It was concluded that people tend to keep their doors and windows open when the temperatures range from 11-24°C but they tend to keep their homes cooler and tighter when the conditions are hotter or colder (Wilson et al., 1996). In a study in London, 358 measurements of AER were taken in 6 homes by the application of coal-gas decay rate in the year 1943 (Bedford et al., 1943). The main point discussed was the impact of small cracks or other openings on the AER and it was proved that if an ample number of windows are opened, an effective ventilation rate can be achieved. This gave way to homes being tightly sealed, which eventually increased the effect of window-opening on AERs. Studies carried out by Howard-Reed et al. (2002) in two homes in California and Virginia, respectively, confirmed that opening one window increased the AER by a magnitude proportional to the width of the window-opening, amounting in the AERs as high as 1.31 hr^{-1}. Multiple window openings amplified the AERs further, reaching values of 2.8 hr^{-1}. Wallace et al. (2002) quantified AERs in a home in Virginia and found that window-opening had a major effect on AER. Research was performed to observe the effects of having low AERs on the contaminant exposure (Wallace et al., 2002; Offermann et al., 2008; Howard-Reed et al., 2002; Bedford et al., 1943). Bedford et al. observed an AER of about 0.8 hr^{-1} in London, whereas Offermann et al. discovered that approximately 75% new homes in California had AERs less than 0.35 hr^{-1}, without mechanical ventilation. This implied that homes were more tightly sealed and therefore, it was required by the occupants to adjust the building controls in order to control flow rate of fresh air from outdoors. Another study observed that, 50-90% of the homes in California had AERs below 0.35 hr^{-1}, depending on the season (Price and Sherman, 2006). Kvistgaard et al. (1985) estimated AERs and temperature in 16 dwellings in Denmark and found an average AER of 0.68 hr^{-1}. It was proposed that a classification of AERs should be done as follows:

1. Basic air exchange: movement of air from outdoor to indoor or vice versa
2. Air exchange from ventilation system: air flow from ventilation

3. User-influenced air exchange: like window-opening
4. Total air exchange: sum total of all the above

In another paper by Kvistgaard and Collet (1990), they found a huge difference in the total air exchange among the individual houses/dwellings. It was determined that the influence of users on the AER caused the huge differences. Basic AER was comparable in the dwellings (Kvisgaard et al., 1985; Kvisgaard and Collet, 1990).

2.4. OCCUPANT WINDOW OPENING BEHAVIOR

As reviewed in the preceding topics, numerous factors affect AER, either positively or negatively. These are the meteorological conditions, occupancy and the conditions prevailing inside the building. Another important factor to consider is the occupant behavior. Over the years, researchers have tried to understand and demonstrate the effect of occupants' behavior on the AER in a building. Offermann et al. (2008) and Price and Sherman (2006) suggested that a lot of houses in California are under-ventilated in accordance with the local standard recommendations because of small ventilation systems and less use of windows by the occupants. This was more apparent during the winter, suggesting that the occupants used the windows less often in winter. Keiding et al. (2003) conducted a questionnaire survey in Denmark and concluded that approximately 53% people slept with an open window during fall whereas, 25% had a window open at night in winters, resulting in an AER of 0.35 hr^{-1}. One or more windows were opened by 91.5% respondents each day throughout the year to vent out the pollutants. As the lower temperatures are more prevalent at night in winter, there is a definite effect of occupants' behavior on the energy consumption. Iwashita G and Akasaka (1997) conducted a study in Japan, because of which they could estimate the effect of occupant behavior on AER. They not only estimated this effect, but also the link between occupants' behavior and energy consumption by air-conditioning, by using tracer gas measurements and questionnaire surveys. Eventually, they concluded that 87% of the total air exchange occurred due to the occupants' behavior. Bekö et al. (2010) quantified AERs in 500 bedrooms in Denmark. It was found that 57% bedrooms had AERs lower than 0.5 hr^{-1}. In the succeeding year, Bekö et al. (2011) tried to model AERs based on the measurements done in the 500 bedrooms previously. Their best-fit model elucidated 46% of the variance in AERs. The variables used in the model were associated with both building characteristics and occupants' behavior. The other models based on only building characteristics or occupant behavior justified 9% and 30% variance.

As natural ventilation is dependent on the size and type of windows and also where they are located in a building, the window opening and closing behavior is linked to the building characteristics too. The different characteristics may include, the type of home, its orientation and the type of rooms. These features of a home have an influence on the occupant window opening behavior. A study was carried out by the IEA-ECBCS (International Energy Agency- Energy Conservation in Buildings and Community Systems) Annex 8, on the occupant window opening behavior in Belgium, Switzerland, the Netherlands, the United Kingdom and Germany (Dubrul, 1988). The study mainly focused on the determination of the occupants' choice of action for ventilation and the reasons behind those actions. It was showed that the type of homes impacts the length of time the windows were opened and also has an effect on the width of the window-opening. Furthermore, the windows in the living rooms and kitchens were opened for shorter times as compared to bedrooms. According to this study, the main ventilation zones in the homes are bedrooms. This was found consistent with a study done in 24 identical apartments in Germany. Bedrooms were more frequently ventilated by the occupants even in the peak winter season. The orientation of rooms within the homes was also found to be effective. In another study, the type of homes (detached residence) was found to be affecting the opening of windows by occupants in North Carolina between 2001-2003. Discussing the IAE- ECBCS Annex 8 study again, it was observed that when there was sunshine, the south facing living rooms and bedrooms were ventilated more for longer time periods as compared to same rooms facing other directions. It might be noted here that the solar radiation and temperature may also affect occupants' window opening behavior. In this study, it was also shown that the maximum windows were open during morning and early afternoon but the number decreased till evening (around 5 pm). In the Johnson and Long study, the time of the day was influential in the determination of transition probabilities (closed to open or open to closed windows) (Johnson and Long, 2005).

The occupants' window opening behavior is also strongly affected by the occupants' perception of comfort in homes. A lot of factors might influence this perception. Outdoor temperature is one of the most important factors. The temperature ranging from -10° C to +25° C had a linear correlation with the use of windows. Brundett observed that the temperature was the most important variable for the window opening behavior by the occupants (Brundett, 1977). Recently, the results of a study in which a logistic regression model was made based on the long-term monitoring of the environmental variables like temperature and solar radiation, and the occupants' behavior, confirmed that the solar radiation, indoor CO_2 concentration, outdoor and indoor temperature are the most important variables in the determination of the probability of windows opening/closing (Andersen et al., 2011). Erhorn in 1988 correlated the season of the year with window opening behavior and he found that the windows were usually open longest during the summer and shortest during winters. There was no evidence found regarding the effect of solar radiation (Erhorn, 1988). This study was backed by another study done by Herkel et al. (2008), but it was with respect to office buildings (Herkel et al., 2008). The question is whether it is the season itself or the changes in the outdoor conditions that lead to the change in the occupant behavior. The effect of wind speed was also explored in the previous studies and it was learnt that, at high wind speeds, the window opening occurrences decrease. Dubrul found that, indoor temperature is also a key factor in determining the occupants' window opening behavior, and it is strongly related to the perception of comfort by the occupants (Dubrul 1988).

Johnson and Long stated in their field survey that, the income level of the Durham population and the day of week (week day or weekend) were not having an influence on the window opening in residences, significantly (Johnson and Long, 2005). All the studies stated above, found that AERs differ in a significant way from home to home and the window-opening behavior of occupants had a huge impact on the AERs. An important characteristic that has an impact on AER is how often and for how long do the occupants open their windows (Bekö et al., 2010; Bekö et al., 2011; Iwashita and Akasaka, 1997; Keiding, 2003; Fabi et al., 2012).

3. WINDOW OPENING SURVEY

3.1. INTRODUCTION TO WINDOW OPENING SURVEYS AND SPECIFIC OBJECTIVES

As discussed earlier, opening windows and doors influences air exchange in buildings, which in turn influences the concentration of pollutants generated indoors, but also pollutants that enter from outside. Various standards for energy efficiency in buildings have resulted in tightly sealed homes and have depended on occupants to use windows or doors for increasing ventilation (California Energy Commission, 2016).

A telephonic survey involving 1,780 people was done in 1987-88 to gauge the use of natural and mechanical ventilation by the occupants. It was reported that a large number of households only opened windows or doors for ventilation for a few minutes a day, especially in winter (25% never opened windows/doors for ventilation). The conclusion of this survey was that in homes wherein occupants do not tend to open windows or doors a lot, have a higher exposure to indoor air pollutants (Phillips et al., 1990).

In a collaborative report in 2009, it was reported that out of the 1515 new single-family detached homes surveyed using a mail survey, a lot of homeowners never used the windows of their homes for ventilation. 32% did not use their windows in the first 24-hour test day and 15% did not use their windows during the previous week. A concern was raised from this finding; the California residential building code allowance for ventilation through window opening may not be adequate for new homes to get proper ventilation in order to control the levels of indoor contaminants (Offermann, 2009). A pilot study was done in Durham, NC by Johnson and Long in 2005. It was observed during the field surveys that, 19.7% residences had at least one window open during the first visit and 20.2% for the second visit. After doing statistical analysis, it was concluded that the residential openness was affected by the occupancy, season, population and housing density, residence-type, exterior material, number of doors and windows, absence of window and door screens, distance to nearest roadway, presence of a garage with garage door, presence and type of AC unit, operation of AC unit, apparent temperature, wind speed, relative humidity, and cloud cover (Johnson and Long, 2004).

While some regional data has been collected, there have been no nationwide surveys that measure window-opening occurrence. Therefore, it is necessary to deploy surveys for understanding window opening occurrence across the United States. Also valuable are the factors that influence the decisions of the occupants to open or close windows, whether it is the time of the day, meteorological conditions, the location of the home, etc. The data from this kind of survey can be integrated into building characteristics information from existing surveys to help in air chemistry modeling exposure analysis and other residential-specific environmental analysis. The specific objectives are as follows:

a. Identify any associations between window-opening occurrence and demographics.

b. Quantify and compare window-opening occurrence for the 4 major climate quadrants of the US (North-East, North-West, South-East, South-West).

c. Quantify “window hours” and compare with diurnal patterns of pollutants.

3.2. METHODS

The following methods were employed for the analysis of the three surveys:

3.2.1. Survey Development. A web-based survey was developed using Qualtrics (Provo, Utah) software under the guidance of Dr. John Cagle from the University of Maryland. It was developed in January 2016. The online survey encompassed many potential influences on the occurrence of the window opening, including the demographics, region or location, time of day and motivation. The survey comprised 32 questions on:

1. Basic demographic information like gender, race, income range.
2. Information about the household like type of residence, number of occupants, living situation of the occupants and size of residence
3. Number of rooms of each type
4. Window or door-opening occurrences in each room for various time periods of the day
5. Percentage width of open windows
6. Reasons for keeping the windows or doors open/closed
7. Primary source of heating used by occupants

The survey was limited to these points so that the survey was not too long, time-consuming and overwhelming to the respondents. Various types of questions were included in the survey format. The most basic category of questions was the multiple-choice type which included questions like "Please identify your gender". Another category was Input answer type questions, in which a respondent had to type an answer. The third category was multiple-choice response type questions, wherein the respondents could choose more than one option as their answer. The last type was slider type questions which gave the liberty to the respondents to drag a slider across an answer pane and stop at a specific number, for example, "As a percentage, how wide do you typically open a window in each room at this time of the year?". The complete survey is shown in Appendix-A.

3.2.2. Survey Deployment. From the Qualtrics online software, an anonymous link was generated which can be pasted into the interface of Amazon Mechanical Turk (MTurk). Mechanical Turk is an online system which helps to conduct research with an integrated participant compensation scheme, a large pool of workers, data collection and the inbuilt process of worker recruitment (Buhrmester et al., 2011). An account was created on Amazon Mechanical Turk as a requester and a compensation amount is fixed before posting the task (survey in this case), which can be determined based on the length of the survey. The next step was to decide the number of assignments (individuals) per HIT (Human Intelligence Task; each HIT means an entire survey). Once the number of assignments was confirmed, the account is refilled with the compensation plus the MTurk fee. An introduction was written for the workers to read before they decide to take the survey. One of the important pre-requisites was to determine the kind of workers who would be allowed to take the survey. Two main deciding factors were: Living in the US and "Masters" qualification. Masters, in this context, refers to the high performing workers, which have been segregated from the usual workers by MTurk based on their performance over time. They must continue to pass the statistical monitoring done by MTurk to maintain the qualification. Subsequently, the anonymous link generated from Qualtrics software was pasted to the MTurk and a new batch was published and the survey was thus deployed. Surveys were administered during the months of April, September and December 2016.

3.2.3. Data Acquisition and Analysis. Survey data was analyzed using the software IBM SPSS Statistics Version 23 and JMP Pro 12.2.0. Survey analysis was carried out after careful sorting of the data and removing the missing or incomplete data from the whole dataset. Some of the data was also transformed to achieve better statistical significance, without manipulations. Selection of statistical analysis methods was based on 3 aspects:

1. Type of data: Is the data nominal or ordinal or interval/ratio type?
2. Samples: How many samples are we analyzing?
3. Purpose: What is the purpose of the analysis?

A simple flowchart (Figure 3.1) can be used for the step-by-step data analysis:

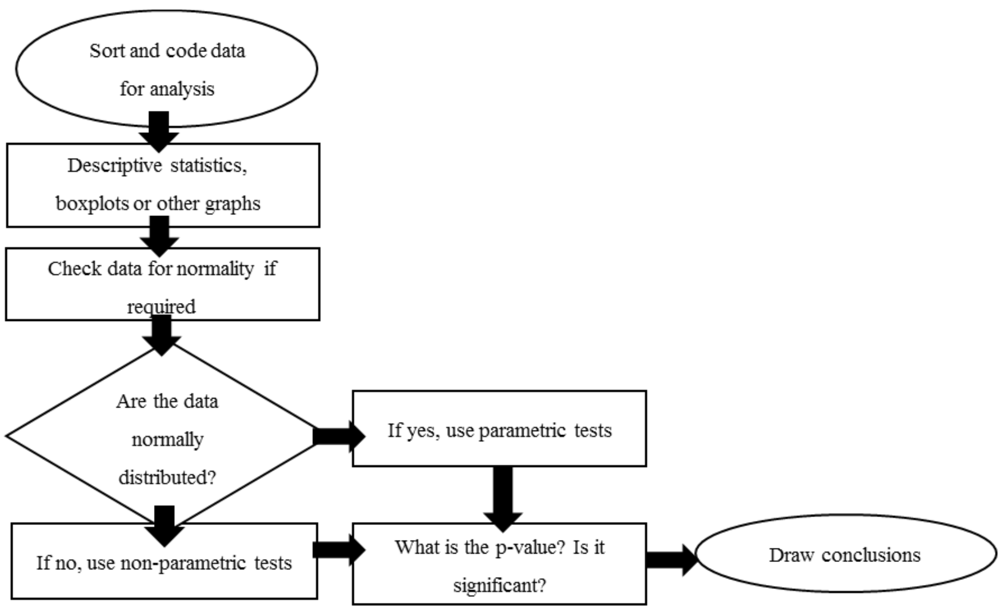


Figure 3.1. Flow-chart for data analysis adapted from “Analysing data using SPSS”

In our case, the data was subjected to analysis techniques which are appropriate for nominal/categorical data, for example, gender. Interval/ratio or ordinal data was not present in our dataset. The purpose of our analysis is to determine the distribution of data over various demographics and also to establish, if any, the relationship or association between different variables. For the analysis of nominal/categorical data from a single sample, the Pearson's chi-square test can be used to determine any possible association between the variables of interest. Descriptive statistics like measures of central tendency or dispersion were not used as they do not produce valid results for nominal data. Frequency distributions of the demographic data were generated. Frequency is the number of responses for each attribute or category of the variable. For determining associations between the variables, Pearson's chi-square test was executed.

3.2.3.1 Window hours. "Window hours" analysis was performed to show the behavioral pattern of all the respondents with respect to window opening occurrences, in various rooms of the home and for different time periods of the day. Window hours were calculated by taking the number of rooms with windows open and multiplying it by the time the windows were open for, in hours. It helps to understand the pattern of window-opening by the respondents throughout the day. This can further assist in relating the window-opening behavior to the diurnal patterns of various outdoor pollutants like ozone, as opening windows might lead to the entry of outdoor pollutants into the homes. In the 3 surveys deployed, the diurnal pattern of ozone concentration was compared with the window-opening occurrences.

3.2.3.2 Visualization/spatial distribution of data. The distribution of data was shown on the map of USA with climate zones (Figures 3.18, 3.19). For this purpose, the median latitude and longitude coordinates were calculated for each survey and subsequently, the data was broken down into 4 quadrants (North-East, North-West, South-East, and South-West). This is helpful in visualizing the trend of survey respondents over the range of the 3 separate surveys.

3.3. RESULTS AND DISCUSSION

After sorting and analyzing data using the above-mentioned software, the following results were obtained. The results are divided into various subtopics based on the levels of analysis. For the first level of analysis, frequency distributions were generated for the dataset which included demographic data. Cross-tabulations were used to determine any associations between data like gender and window-opening occurrences. Window hours were calculated to determine if there was a trend in window-opening occurrence over the day.

3.3.1. Frequency Distributions. Frequency distributions presented in the following pages, show the percentage of respondents for each survey according to various variables used in the surveys. Figure 3.2 shows the gender distribution (males and females). The percentage of males or females does not vary greatly with respect to the time of survey (season). In the first two surveys, the percentage of males (51 and 56%) exceeded that of females (49 and 44%). On the contrary, in the third survey, it was the opposite. Overall, the percentage is close, but not consistently in agreement with the percentage of each gender from the US Census Bureau data 2015 (50.8% females).

Figure 3.3 shows the race distribution (African American, Hispanics, White/Caucasian, Native American, Pacific Islander, Asian and others). The distribution over all three surveys is notably consistent, with the majority of respondents being White/Caucasian (78%). The distribution matches US Census Bureau 2015 data (71.1% Whites).

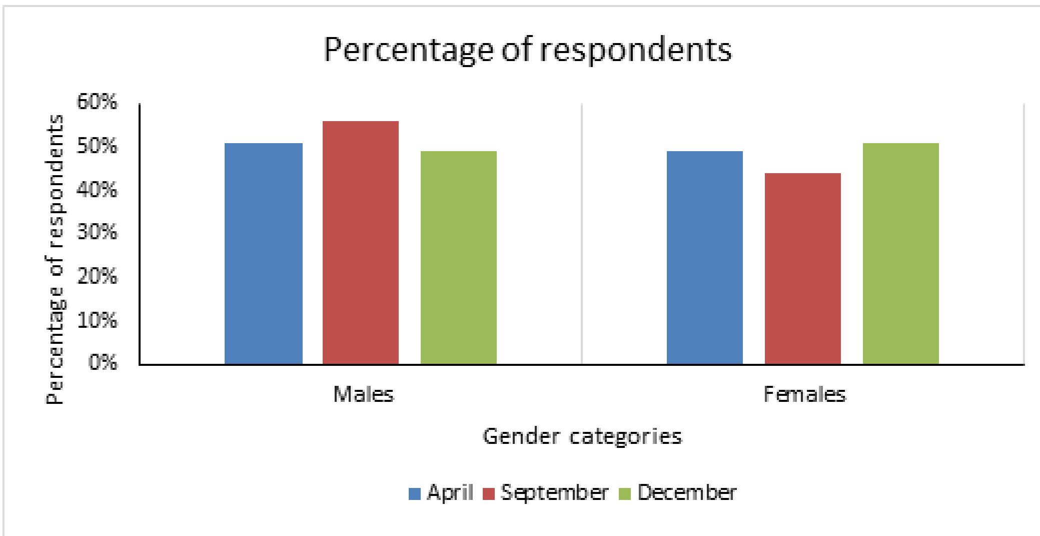


Figure 3.2. Percentage respondents from each gender category

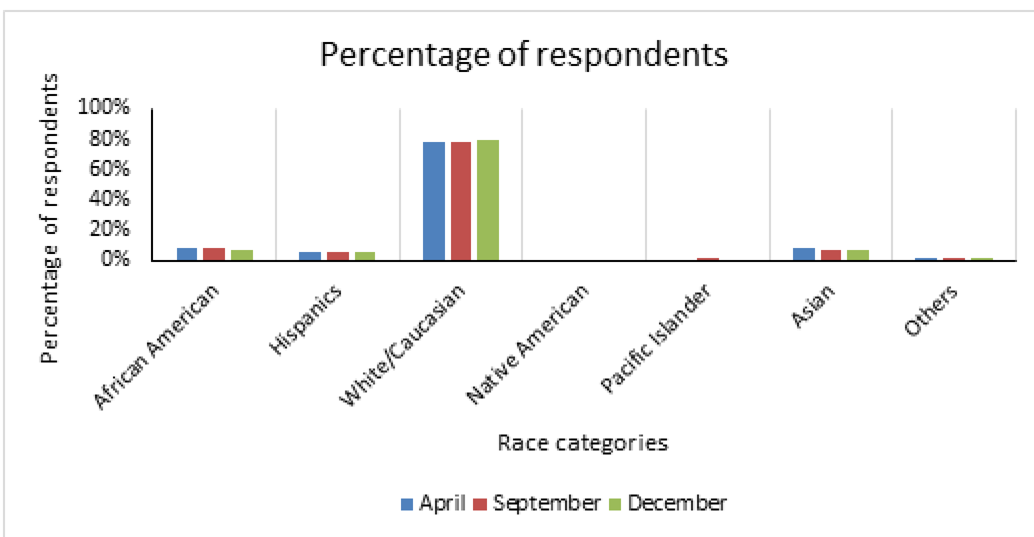


Figure 3.3. Percentage respondents from each race category

As the categories like Asian, Hispanics, Pacific Islanders did not have enough respondents, the categories were combined into "Others" category for performing cross-tabulation. The graphs shown below denote the distribution of respondents according to the household income range and the residence-type. In Figure 3.4, the percentage of respondents is highest for the category "$30,000-$59,999", for all three surveys (39%). The lowest is for the "Greater than or equal to $200,000" category. The median household income in the US, according to the US Census Bureau, is $53,482, which falls in the same category as the highest number of respondents.

Figure 3.5 depicts the distribution of the percentage of respondents according to their residence-type, and the highest percentage is for the respondents who live in detached homes. Respondents living in apartments accounted for approximately 25%. The percentage values across all the 3 surveys remained consistent. This is quite comparable to the US Census Bureau data, which says that people living in detached homes comprise 60.3% of the total population.

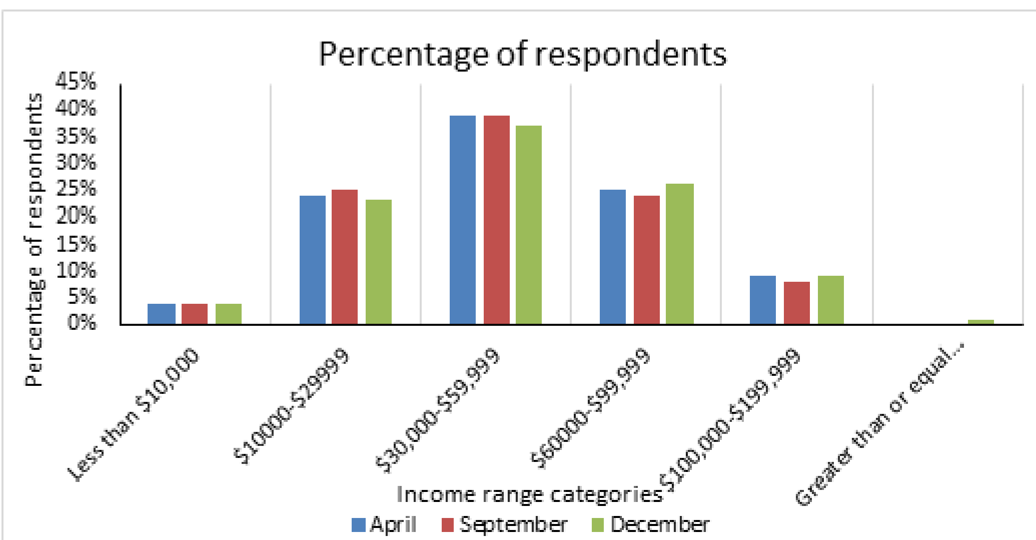


Figure 3.4. Percentage respondents from each income range category

Figure 3.6 shows the distribution of the percentage of respondents who rent or own their homes or live with family or friend. Maximum respondents owned their residences (approximately 50%), respondents who are renters come in a close second with 43%. Data is quite consistent over the period of the three surveys.

Figure 3.7 represents the percentage distribution for occupancy of the respondents taking the survey. The highest percentage of respondents (30%) was obtained for "2 occupants" occupants. The median persons per household according to the US Census Bureau is 2.64, which coincides with the findings of each survey. The median for our data was ~2 occupants per household for the surveys. Figure 3.8 above demonstrates the percentage of respondents for the various categories of "Size of residence". The median area in square feet according to the US Census Bureau is 1,500. From the data analysis of three surveys, the maximum respondents were from the category that coincides with 1,500 square feet, i.e.: 1000-1999 square feet range. The smallest percentage was obtained for the category of 5000 square feet or more.

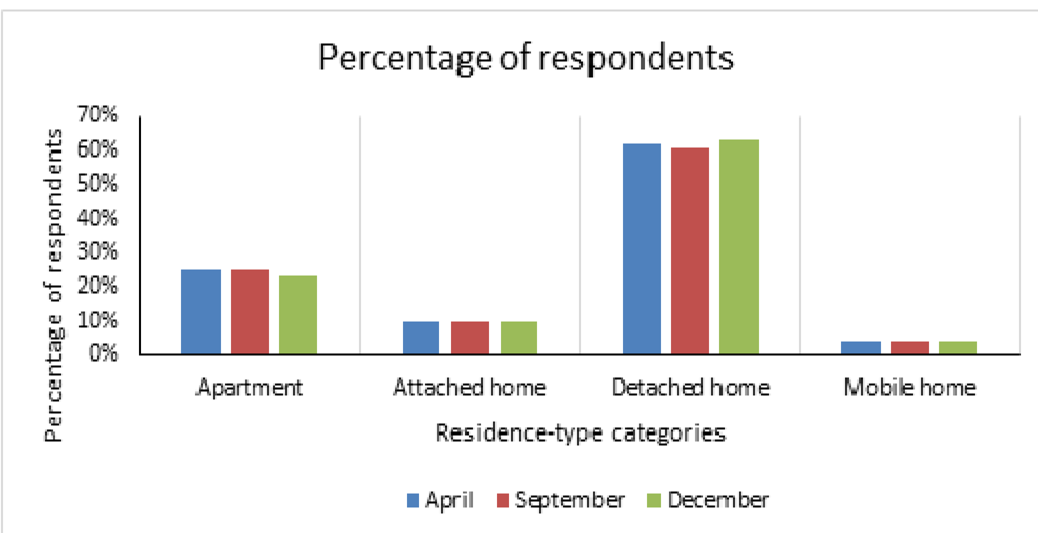


Figure 3.5. Percentage respondents from each residence-type category

The percentage of respondents who opened their windows for survey 1 was 49.3%, for survey 2 was 52.5% and for survey 3 was 24.4%.

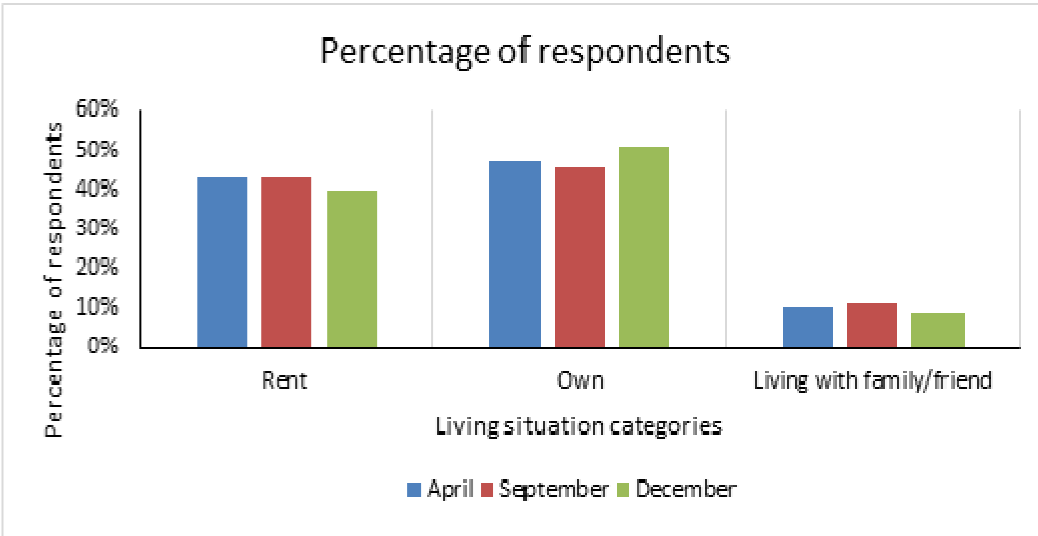


Figure 3.6. Percentage respondents from living situation category

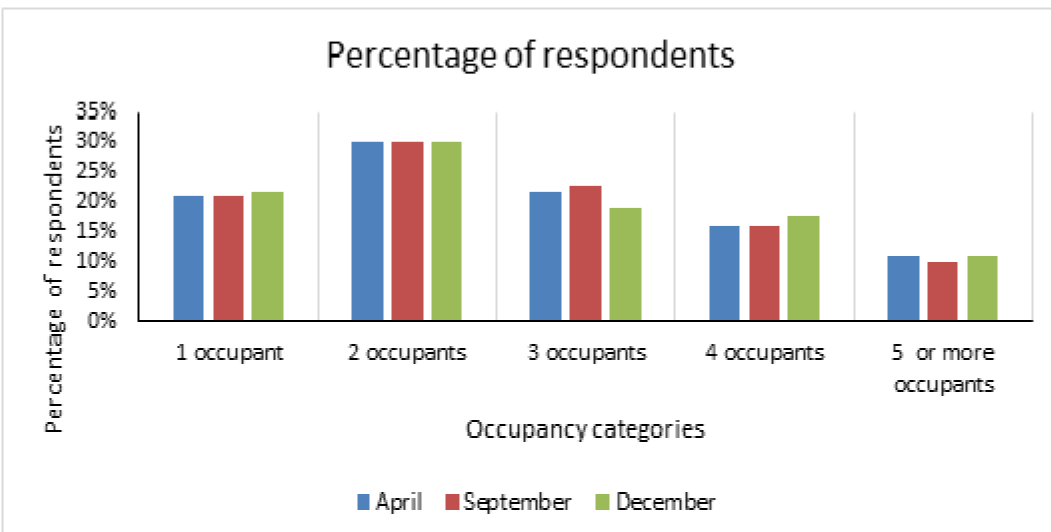


Figure 3.7. Percentage respondents from each occupancy category

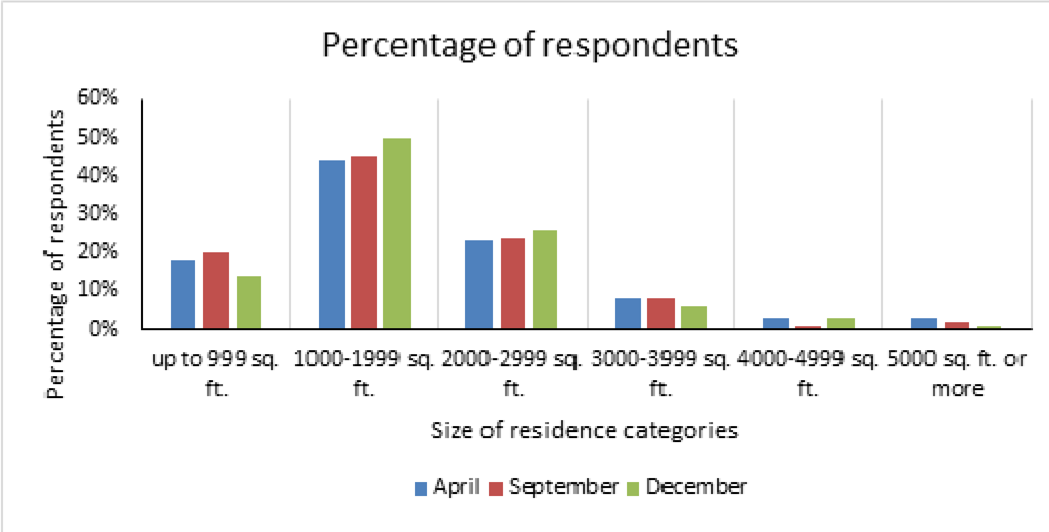


Figure 3.8. Percentage respondents from each residence size category

3.3.2. Cross-tabulations. Cross-tabulations were used to check the associations between the variables with demographic data versus window opening occurrences. Associations were ascertained using Pearson chi-square tests which generated chi-square and p-values ($p \leq 0.05$ was considered significant) for each association (Greasley, 2008). Table 3.1 summarizes the aforesaid values.

Figure 3.9 shows the percentage of respondents who answered “Yes” for the windows open yesterday question according to gender categories. Chi-square statistics depicted that the association between gender and window-opening was not statistically significant for surveys 1 and 3, but was statistically significant for survey 2. It can be inferred that window-opening occurrences were dependent on gender variables in the survey 2. The percentage of females who open windows has significantly decreased from survey 1 to 3, which cannot be said for males. For females, the percentage of yes is 50.2% +/- 6% for survey 1.

Table 3.1. Chi-square and p-values for all associations. Bold indicates p-values ≤ 0.05

Associations (cross-tabulations)	**p-values for each survey**			**Pearson Chi-square values for each survey**		
	Survey 1	**Survey 2**	**Survey 3**	**Survey 1**	**Survey 2**	**Survey 3**
Gender & window opening occurrences	0.72	**0.01**	0.87	0.13	6.41	0.03
Race & window opening occurrences	**0.05**	0.13	**0.025**	5.86	4.08	7.36
Living situation & window opening occurrences	0.13	0.5	0.06	4.13	1.38	5.47
Occupancy & window opening occurrences	**0.02**	0.23	0.5	11.8	5.58	3.35
Income range & window opening occurrences	0.45	0.9	0.2	4.71	1.58	7.32
Residence-type & window opening occurrences	**0.04**	0.27	**0.04**	8.5	3.9	8.35
Size of residence & window opening occurrences	0.81	0.41	0.12	2.25	5.02	8.7

It can be inferred from the Figure 3.10 that the percentage of respondents varies significantly with respect to race. There is an association between the two variables in survey 1 and 3 ($p < 0.05$) but not survey 2 ($p > 0.05$). The percentage of "Yes" by African American respondents and Others has decreased from survey 1 to 3, which is not unusual considering the difference in temperatures in the months of April, September and

December. Some races or cultures prefer to keep their windows open more than other races and therefore, window-opening might have some dependence on the race of a person. For White/Caucasian, the percentage of yes is 48.3 % +/- 5% for survey 1 but for survey 3, it is 21% +/- 4%.

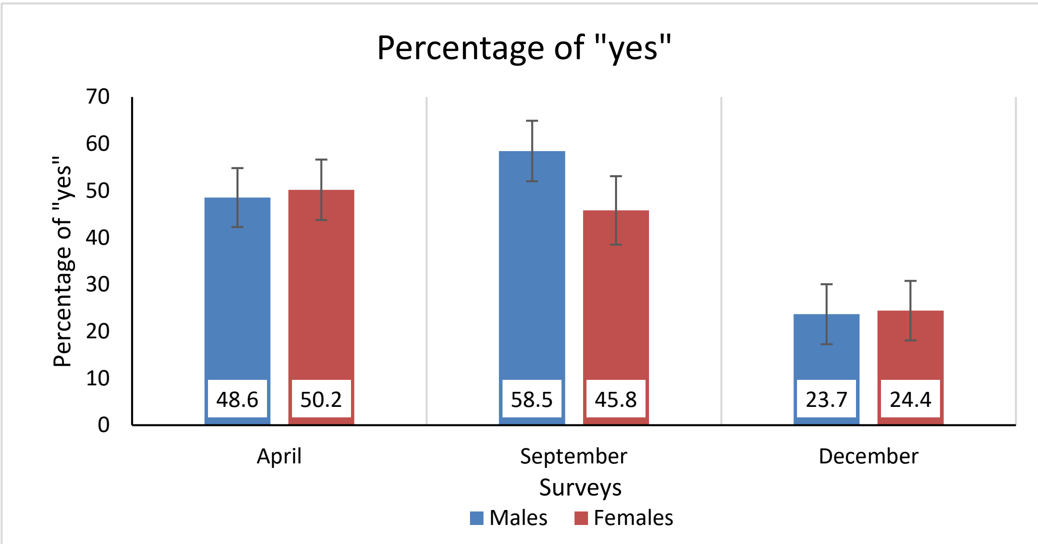


Figure 3.9. Percentage of respondents (gender) who answered “Yes” for windows open yesterday question with 95% CI error bars.

In the following Figure 3.11, the percentage of respondents from various living situations is depicted, who answered “Yes” for windows open yesterday question. From the p-values for all 3 surveys, it can be extrapolated that living situation of an individual does not have any statistical significance when compared to window-opening occurrences. The distribution of the percentage of “Yes” responses for each living situation is consistent over the range of all 3 surveys.

Approximately 55% of the respondents who live as renters opened their windows in the months of April and September but the percentage dropped in December (~29%). In the case of number of occupants (occupancy) versus window-opening occurrences

(Figure 3.12), p-value for survey 1 ($p < 0.05$) shows statistical significance between the two variables but not for survey 2 and 3. The percentage values for 1, 2, 3, and 5 or more occupants remains the same with the maximum in survey 2, but there is a decline in the percentage from survey 1 to 3 for 4 occupants (53.2% to 19%). Percentage of window-opening occurrences by 2 occupants for survey 2 is 57% +/- 8% but for survey 3, it is 28% +/- 8%. In the following Figure 3.13, there is a decreasing trend for all the income range categories for survey 3. In fact, 0% of the respondents from “Greater than or equal to $200,000” category said “Yes” for the window-opening occurrence question. For survey 2, all the percentage values of income ranges are comparable except “Less than or equal to $10,000” category but there is consistency in the percentage of respondents who answered “Yes” for that category for all the three surveys, which might be pointing at lesser dependence of those respondents on air-conditioning system. There is no statistical significance between the two variables of interest in this case ($p > 0.05$).

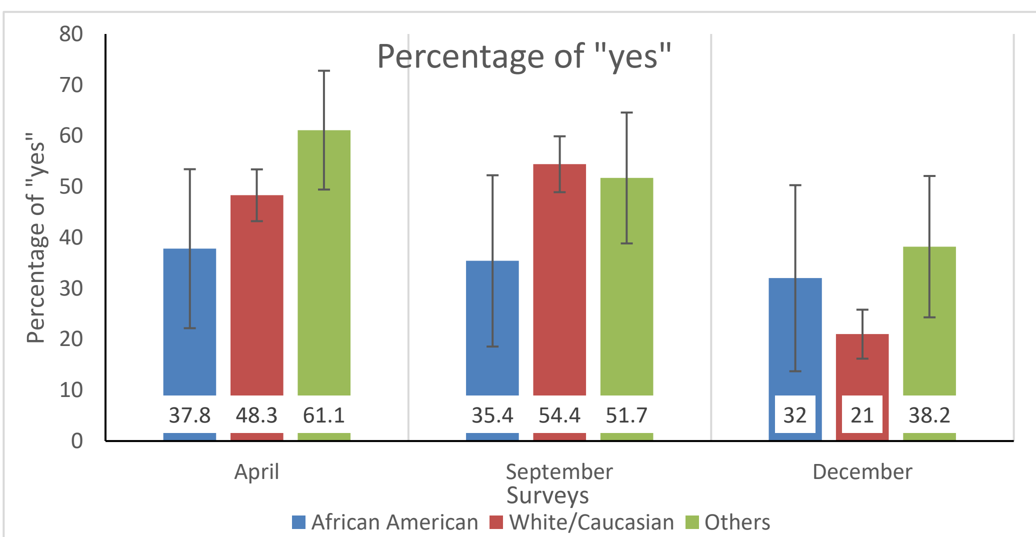


Figure 3.10. Percentage of respondents (race) who answered “Yes” for windows open yesterday question with 95% CI error bars

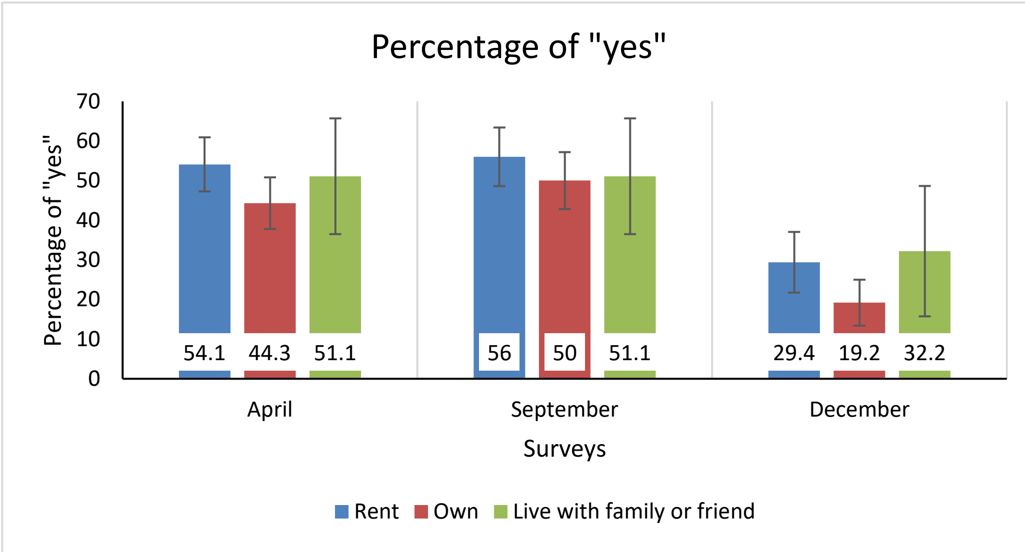


Figure 3.11. Percentage of respondents (living situation) who answered "Yes" for windows open yesterday question with 95% CI error bars

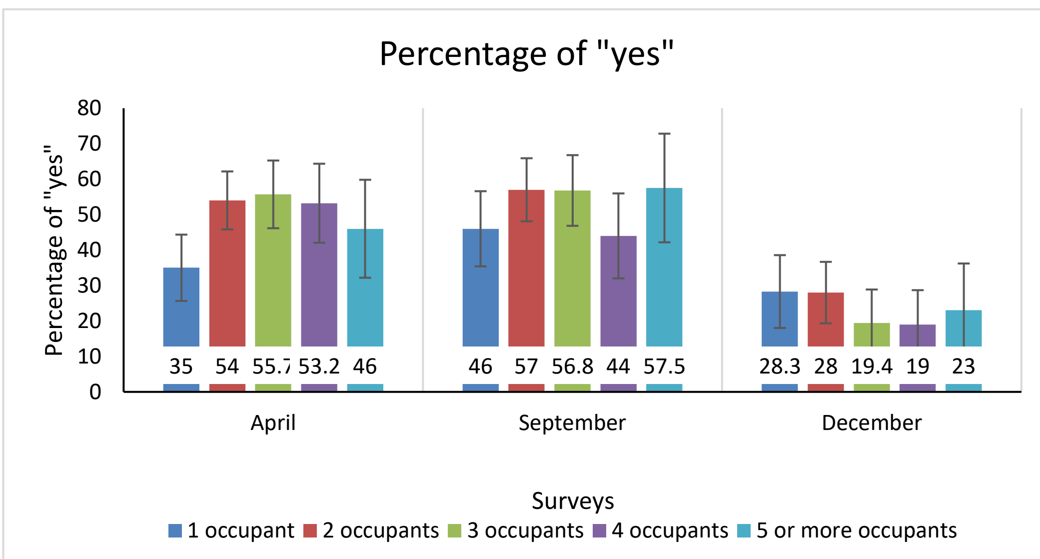


Figure 3.12. Percentage of respondents (occupancy) who answered "Yes" for windows open yesterday question with 95% CI error bars

According to p-values, there is some statistical significance in the variables residence-type and window-opening occurrences ($p < 0.05$). Therefore, it can be understood that there is a greater dependence of window-opening occurrences on residence-type of respondents. From Figure 3.14, the percentage of respondents living in attached or detached homes did not open their windows as much as a percentage of respondents living in apartments or mobile homes for survey 1. Percentages of respondents from apartments and mobile homes, who answered yes, are the same (58%). The percentage of respondents who said "Yes" is the least for mobile homes for survey 3 (7%).

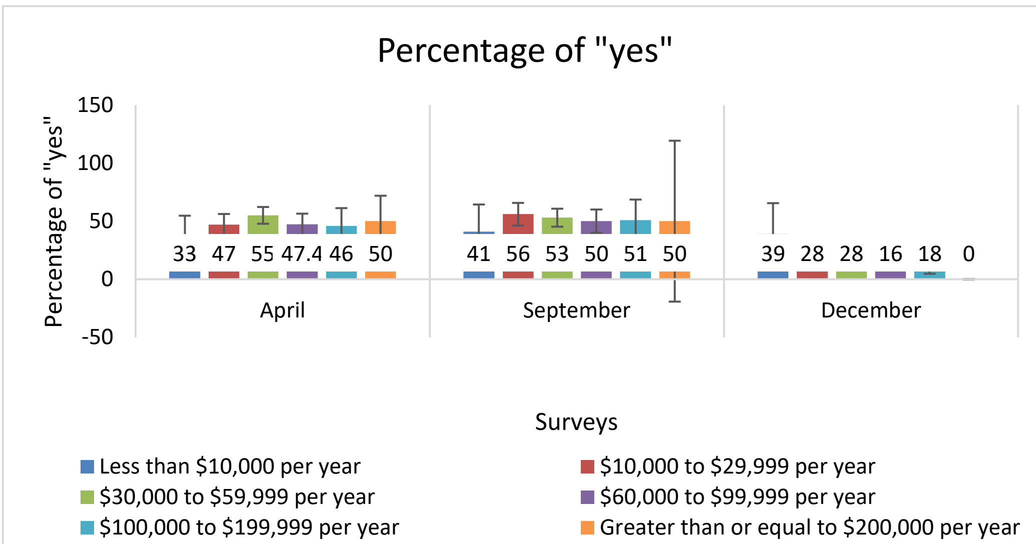


Figure 3.13. Percentage of respondents (income range) who answered "Yes" for windows open yesterday question with 95% CI error bars

Figure 3.15 describes the percentage of respondents for the size of residence categories, who did open windows, for all surveys. The p-values (0.81, 0.41, 0.12) for the surveys show no statistical significance between the two variables (size of residence and window-opening occurrences). The percentages for survey 3 for all the ranges of size (square feet) are consistently less as compared to survey 1 and 2. The least percentage is of the respondents in the range "1000-1999 sq. ft." for survey 3, which represents the median size of residences in the US. The percentage of respondents for the "5000 sq. ft.

or more" who answered "Yes" for windows open yesterday question for survey 2 was highest as compared to other ranges (62.5%).

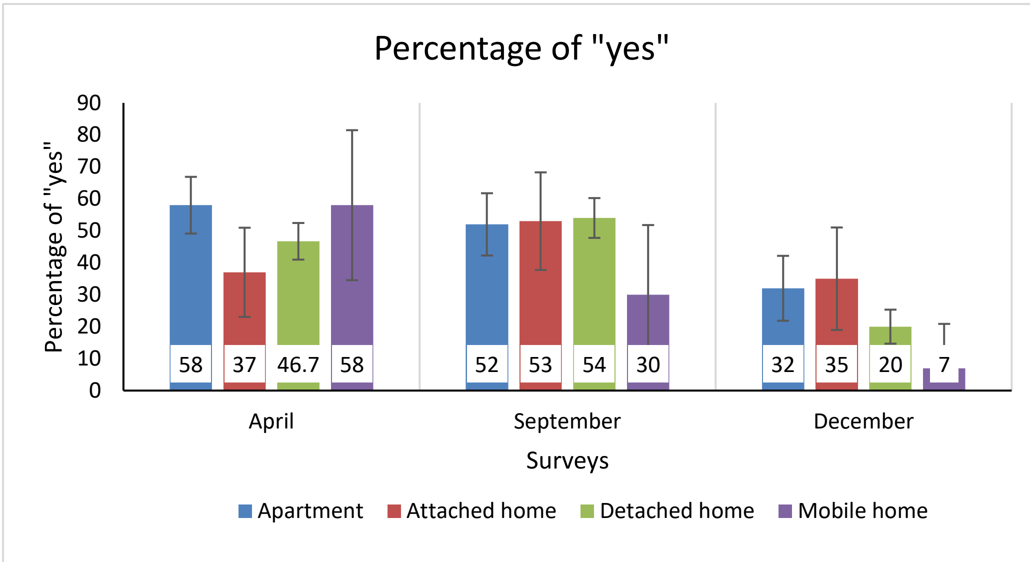


Figure 3.14. Percentage of respondents (residence-type) who answered "Yes" for windows open yesterday question with 95% CI error bars

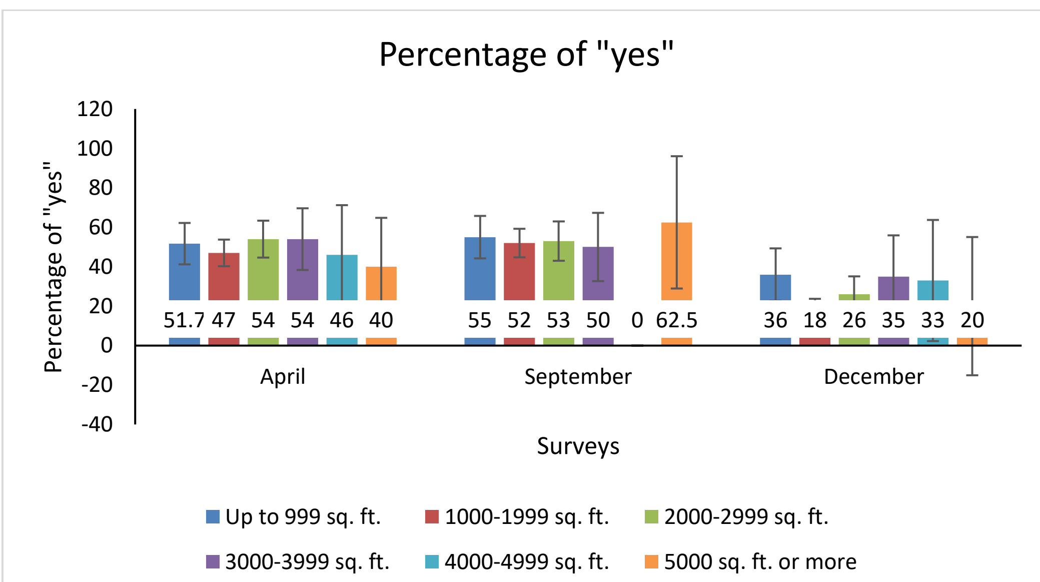


Figure 3.15. Percentage of respondents (size of residence) who answered "Yes" for windows open yesterday question with 95% CI error bars

Overall, it can be said that some factors affect window-opening occurrences more than others. For instance, gender, race, occupancy and residence-type. It can also be inferred that there are some seasonal variations in the window-opening occurrences from April (Spring) to September (Fall) to December (Winter).

3.3.3. Window Hours. "Window hours" can be defined as the behavioral pattern of each respondent with respect to window-opening in different rooms of the building for different time periods of a day. Figure 3.16 depicts the total window hours of all the respondents for the months of April, September, and December. The bars are divided horizontally according to window hours for each room in the homes of the respondents. It is evident from the figure that respondents tended to open windows more during morning or afternoon time periods. This might also be due to the respondents coming back home from work around that time and opening windows for ventilation. Coincidentally, this trend follows a typical diurnal ozone concentration pattern; examples are shown for Riverside, CA in Figure 3.17. It can be observed from the figure that the ozone concentration usually peaks during the afternoon, as compared to other time periods of the day, irrespective of the month (season). It needs to be noted here, that as the windows are opened more during the afternoon, more outdoor ozone can enter the home/building due to air exchange. This ozone when indoors, reacts with surfaces and airborne chemicals to form oxidized organics (e.g. aldehydes, ketones, acids) and SOAs (Secondary Organic Aerosols), which may also be detrimental to the health of the occupants.

3.3.4. Spatial Analysis Using Maps. In the Figures 3.18 and 3.19, the spatial distribution of respondents is represented for surveys 1 & 2 and survey 3, respectively. In Figure 3.18, data from surveys 1 and 2 are combined as the geographic distribution over the whole country was fairly uniform. The division of the respondents was carried out using median latitude and longitude coordinates from the datasets (38°5' N and -100°06' W). The dominating trend in surveys 1 and 2 is that the respondents from North-East and South-East do not tend to open their windows a lot during the months of April and September, which are the Spring and Fall seasons and temperatures were "temperate". Whereas, the respondents from the North-West and South-West tend to open their windows more during the same seasons.

The factors for these differences might be the following:

1. Temperature variations between East and West coasts.
2. The amount of humidity or precipitation on East and West coasts (Higher humidity on the East coast).
3. The difference in climate as shown in Figures 3.18 and 3.19, in the form of zones.

In Figures 3.20 and 3.21, the percentage of respondents is shown in surveys 1, 2 and 3, to get a clearer picture of the geographic trend. It can be seen from the percentages that, in survey 1 and 2, the "% yes" is almost same for North-West and South-West, whereas it is considerably less in South-East. North-West and South-West have similar "% no" also. But the maximum "% no" is from North-East. In survey 3, there is a difference in the % yes for North-East and South-West but "% no" is almost the same for North-East, North-West, and South-East. But the maximum "% no" is from North-East. In survey 3, there is a difference in the % yes for North-East and South-West but "% no" is almost the same for North-East, North-West, and South-East. Survey 3 was deployed around December 25th, when the temperatures around the country were low enough for respondents to keep their windows closed (as seen in Table 3.2).

Figure 3.16. Total window hours for respondents for each time period of the day for survey 1, 2 and 3

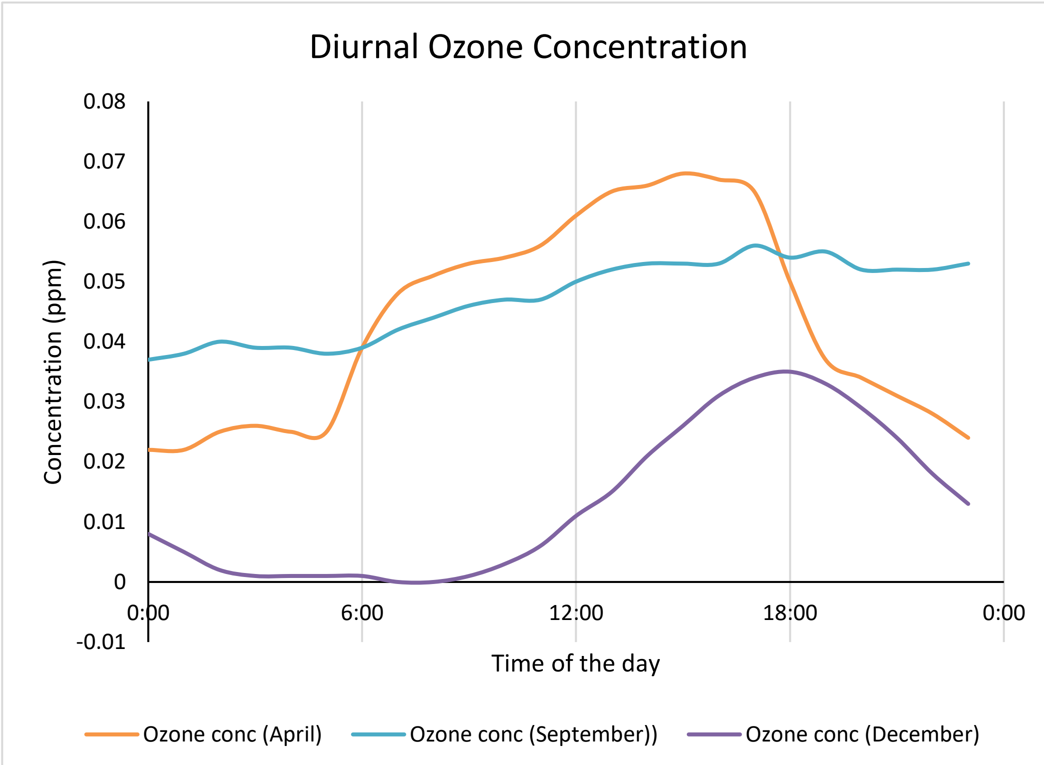


Figure 3.17. Diurnal ozone concentration for a day in the month of April (10th), September (14th) and December (15th) for Riverside, CA. (Raw ozone data source: https://aqsdr1.epa.gov/aqsweb/aqstmp/airdata)

Table 3.2. Average temperatures in the US during the 3 surveys
(Data source: https://www.ncdc.noaa.gov/sotc/national/)

Time of the year	Average temperature
April	53.2 °F or 11.7 °C
September	67.2 °F or 19.5 °C
December	32.9 °F or 0.5 °C

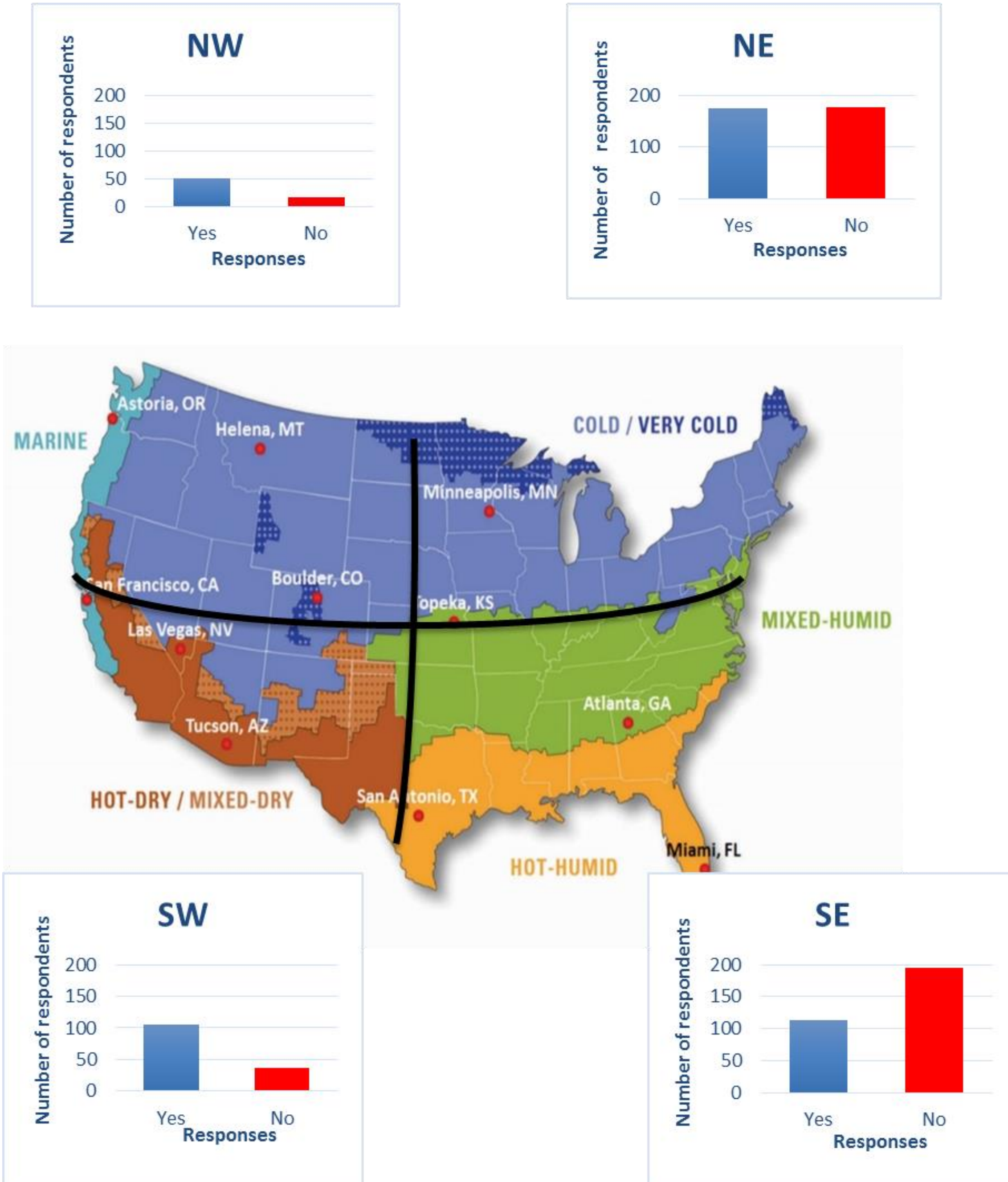


Figure 3.18. Spatial distribution of respondents across the United States for combined surveys 1 & 2. US map image courtesy: U.S. Department of Energy's Guide to Determining Climate Regions by County. (Building America Best Practices Series: High-performance Home Technologies.)

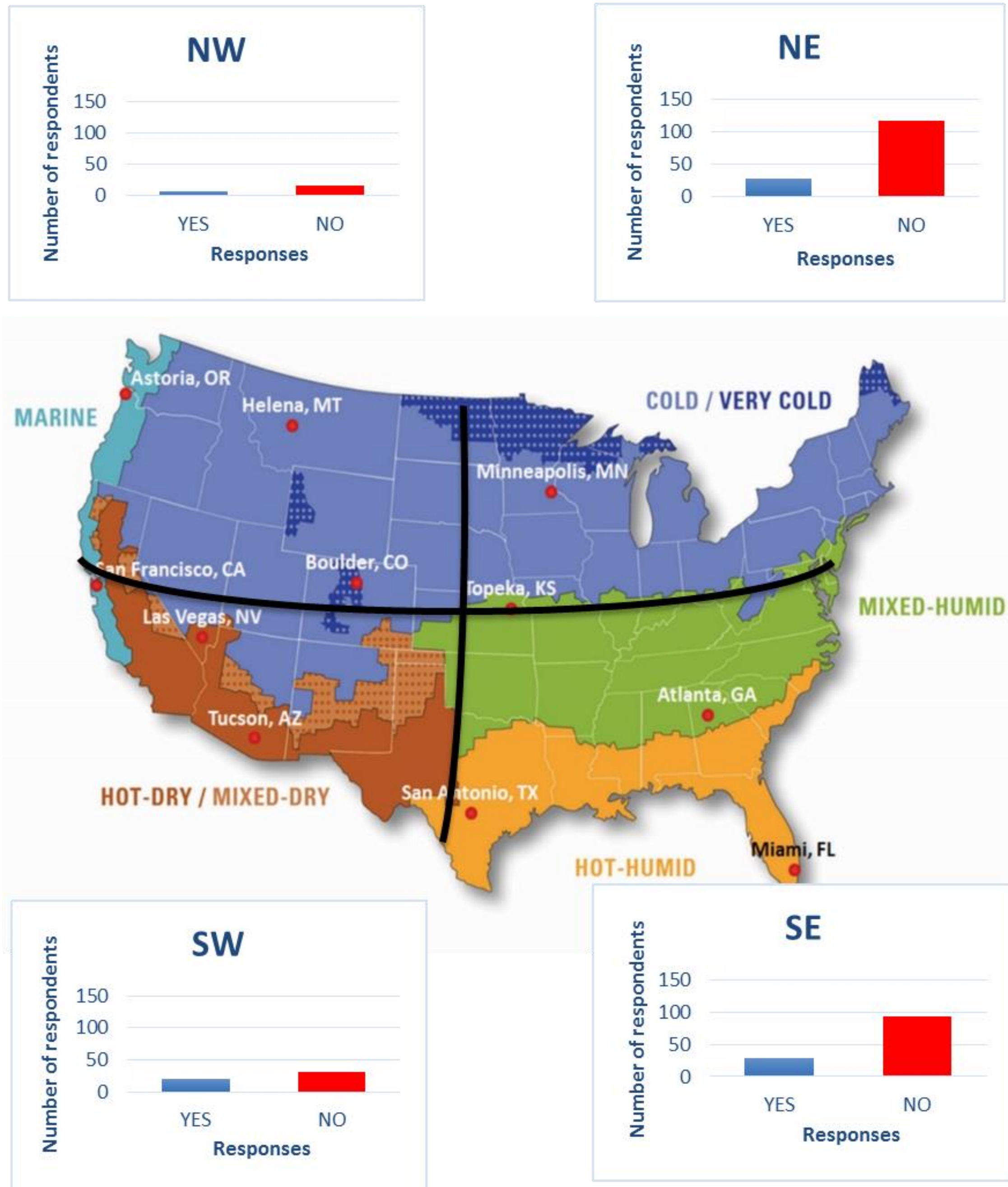


Figure 3.19. Spatial distribution of respondents across the United States for survey 3. US map image courtesy: U.S. Department of Energy's Guide to Determining Climate Regions by County. (Building America Best Practices Series: High-performance Home Technologies.)

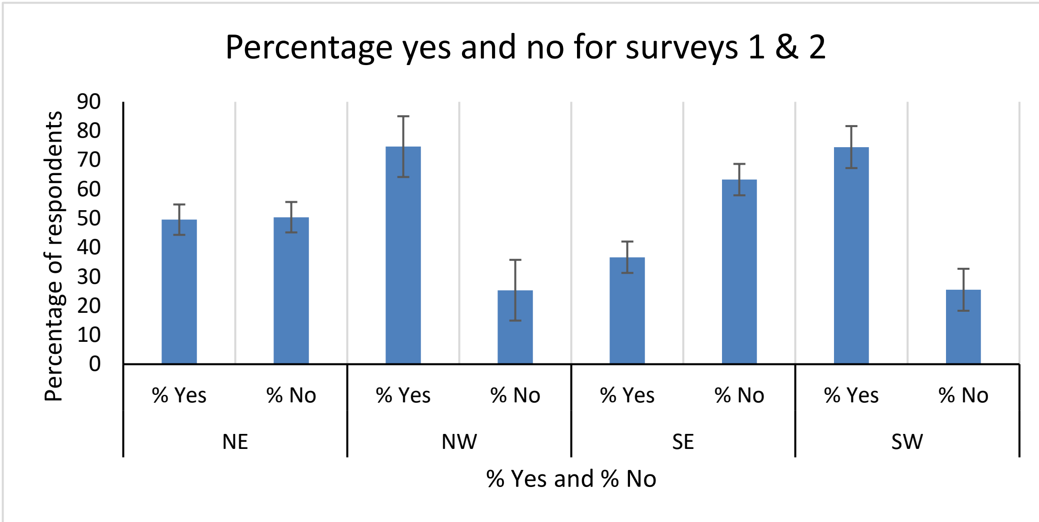


Figure 3.20. Percentage of respondents from each quadrant for survey 1 & 2

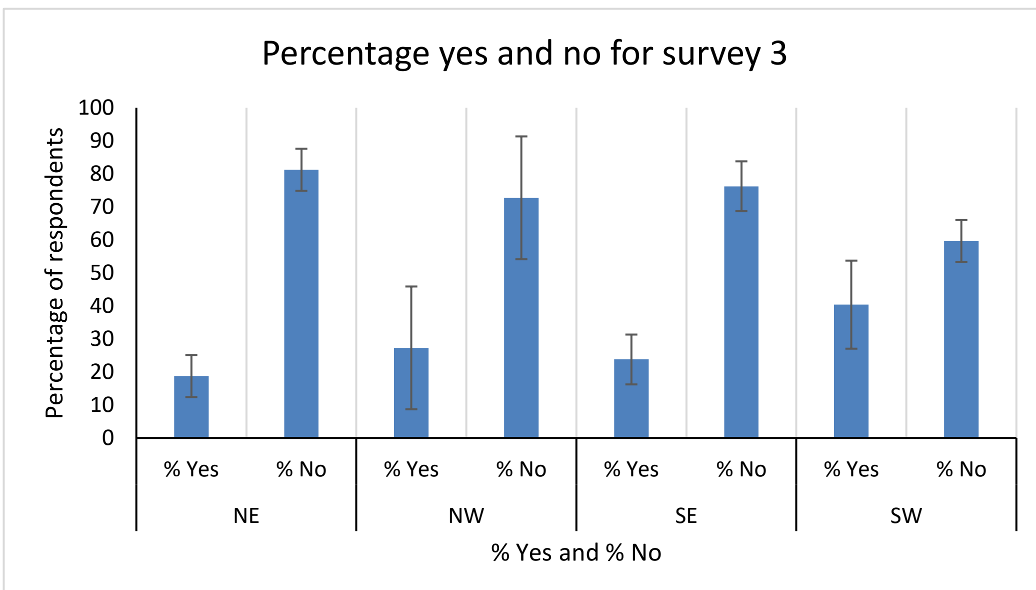


Figure 3.21. Percentage of respondents from each quadrant for survey 3

3.3.5. Major Reasons for Window/Door Opening and Closing. As discussed in the previous sections, several reasons affect the window-opening behavior of occupants'. In the surveys, which were deployed, we found the following to be the main reasons for opening windows and doors, at the time of each survey. It was noticed that the most important reason for which the respondents opened their windows was to bring in fresh air or if it was too stuffy in the homes. Some respondents also included other reasons for opening doors, which were responses like- to enter or leave home, none, waiting for my son, etc. The most important reason for the respondents to keep their windows or doors closed were: too chilly, too warm or for saving energy. Tables 3.3, 3.4, 3.5 and 3.6 demonstrate the reasons and their respective percentages.

Table 3.3. Reasons for opening windows

Reasons for opening windows	Survey 1	Survey 2	Survey 3
Stuffy	27%	27%	23%
Prevent overheating	14%	16%	9%
Air out pollutants such as smoke, odors, etc.	15%	14%	25%
Bring in fresh air	43%	39%	34%
Others	1%	4%	9%

Table 3.4. Reasons for opening doors

Reasons for opening doors	Survey 1	Survey 2	Survey 3
Stuffy	17%	19%	16%
Prevent overheating	9%	8%	4%
Air out pollutants such as smoke, odors, etc.	16%	15%	24%
Bring in fresh air	37%	37%	28%
Others	21%	21%	28%

Table 3.5. Reasons for closing windows

Reasons for closing windows	Survey 1	Survey 2	Survey 3
Too warm	10%	27%	3%
Too chilly	34%	11%	47%
Save energy	12%	12%	24%
Keep out air pollutants, allergens, etc.	13%	13%	4%
Noise	16%	19%	9%
Safety	13%	13%	11%
Others	2%	5%	2%

Table 3.6. Reasons for closing doors

Reasons for closing doors	Survey 1	Survey 2	Survey 3
Too warm	7%	21%	2%
Too chilly	23%	7%	39%
Save energy	12%	12%	21%
Keep out air pollutants, allergens, etc.	9%	11%	6%
Noise	11%	14%	7%
Safety	31%	29%	23%
Others	7%	6%	2%

4. FIELD MEASUREMENTS

4.1. INTRODUCTION TO FIELD MEASUREMENTS AND SPECIFIC OBJECTIVES

For reasons manifold, the air quality in homes has been studied for a long time now. The following aspects are of significance:

1. Americans spend 87% of their time indoors, either in homes, offices, vehicles or bars (Klepeis et al., 2001).

2. Indoor air consists of an array of different components (organic and inorganic), which includes compounds released from daily activities like cooking, cleaning, and smoking. These compounds contribute to indoor air pollution and therefore, the CO_2 concentration by itself cannot be used to gauge indoor air quality (Persily, 1997).

After the energy crisis in the 1970s, there was a perceived need to decrease the overall heat energy consumption. The most effective way to save energy is to prevent heat loss from homes. Thermal insulation helps reduce heat loss but also leads to increased airtightness of homes which can lead to increasing air concentrations of indoor-sourced pollutants. Therefore, there is a need to study or evaluate the indoor air quality. For the assessment of Indoor Air Quality (IAQ), the air exchange rate can be estimated using standard tracer gas measurement. A small quantity of a tracer gas is emitted in a room or a home under observation and its concentration is logged as a function of time. Subsequently, the air exchange rate can be calculated from the emission rates of the tracer gases (Laussmann and Helm, 2011). The specific objectives are as follows:

a. Measure the concentration of tracer compounds, under conditions of open and closed windows in a residence.

b. Quantify the effective air exchange rate based on tracer concentration measurements.

4.2. METHODS

The following methods were employed for field work measurements.

4.2.1. Sampling Site Description. Field measurements were carried out in a single-family detached home located in the City of St. Louis, Missouri. Figure 4.1 shows a map with the location of the home. It is a two-story, three-bedroom home and was unoccupied when the measurements were carried out. Figure 4.2 shows a picture of the experimental home. Figure 4.3 shows a picture of the trailer which housed all the sampling equipment. The first floor consisted of a living room, kitchen, master bedroom, dining room and two bathrooms. The second floor consisted of two bedrooms. The home had a continuously operating recirculation system. The basement was not included in the entire experiment. It was sealed from the rest of the experimental home. The floor plans of the first and second floors of the home are shown in Figures 4.4 and 4.5. The details of the home are described in Table 4.1 below.

Table 4.1. Details of the home

Construction year	1926
Square footage	2645 sq. ft.
Approx. overall volume	509.34 m^3

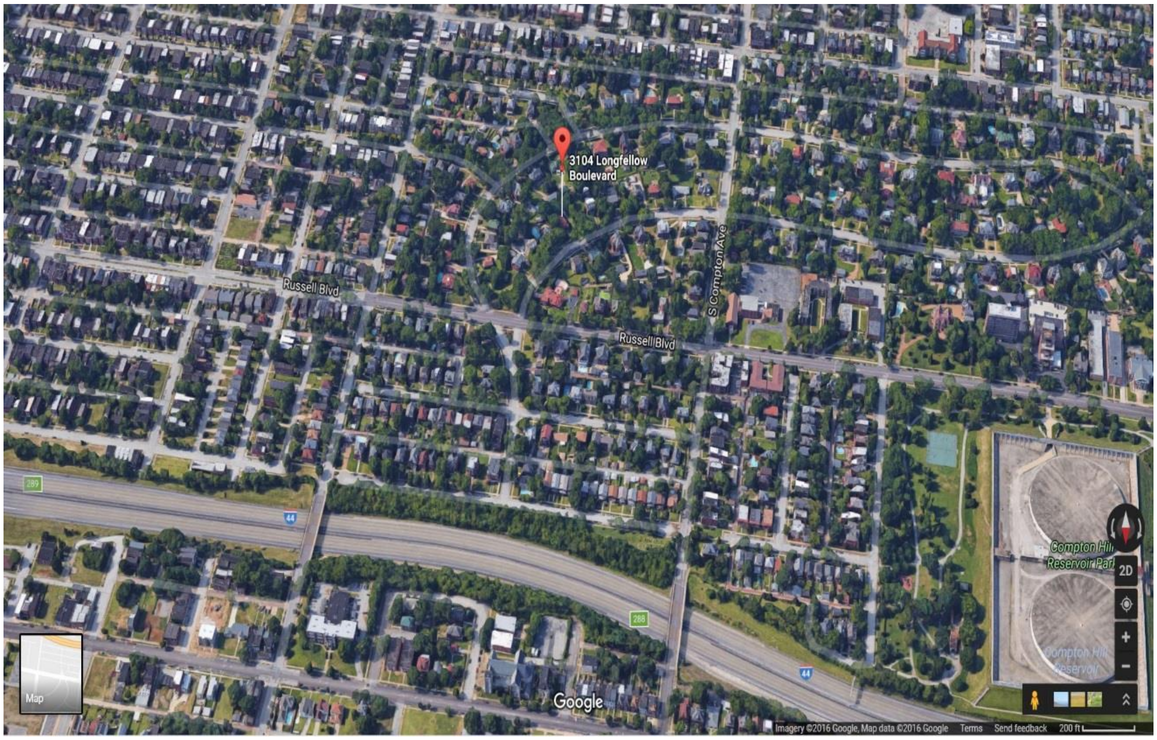


Figure 4.1. Map showing the location of the home

Figure 4.2. Picture of the experimental home taken during sampling period

Figure 4.3. Picture of trailer used to house the sampling equipment

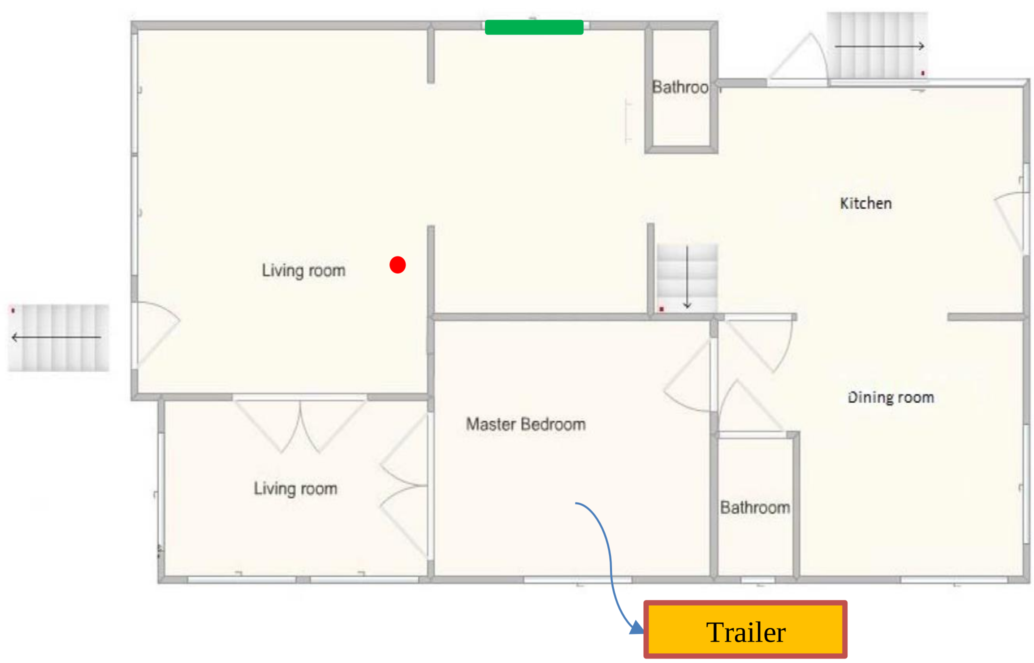


Figure 4.4. First floor of the home (red dot: emitter position, green line: window open, arrow: sampling location)

A diary was maintained during the sampling period and the following parameters were noted for each sample, to check the dependence of air exchange rate:

1. Indoor Temperature
2. Outdoor Temperature
3. Relative Humidity
4. Pressure
5. Conditions: Sunny/cloudy/rainy
6. Time of sample
7. Start and stop flowrate

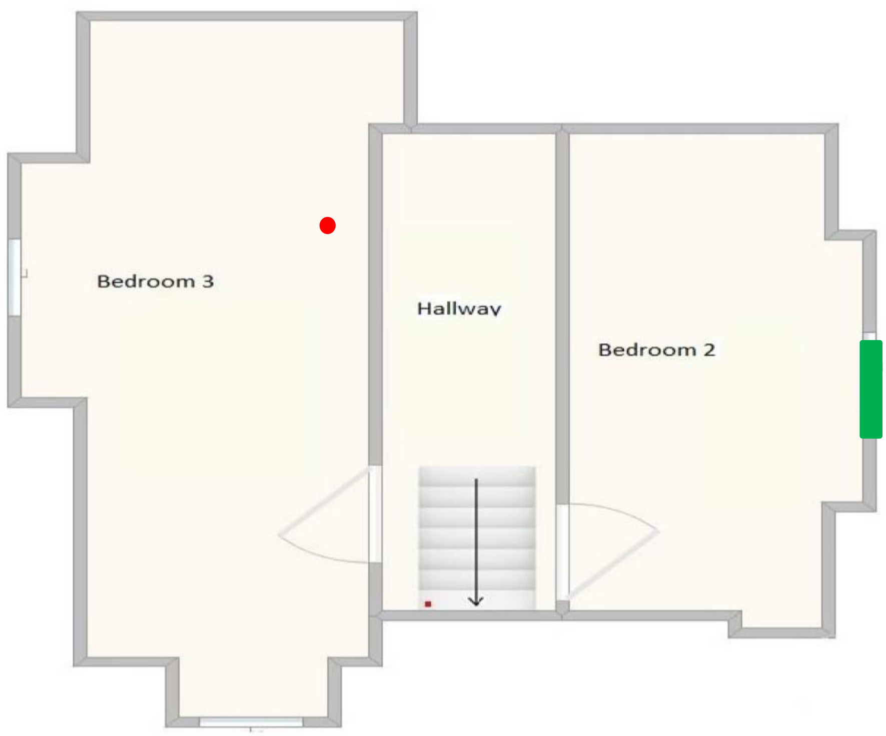


Figure 4.5. Second floor of the home (red dot: emitter position, green line: window open)

4.2.2. Instrumentation and Sampling Protocol. The succeeding topics talk about the specific details about the experimental setup and the related analysis.

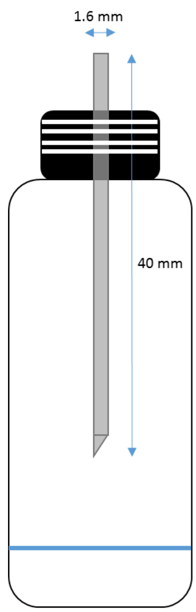
4.2.2.1. Preparation of standards and calibration curve. Calibration was done for the tracer compounds (HFB and OFT) using HPLC grade pure Methanol. A 25 ppm solution HFB in pure methanol was prepared. Similarly, for OFT. A total of 3 different masses were used to establish the calibration curve: 25, 50 and 75 µg. The method was validated for 12 VOCs (including the tracers) with limit of detection (LOD) levels being 0.1– 1µg/m3.

4.2.2.2. Tracer gas emitters and testing for constant emission rates. The tracer compounds or gases should be selected based on a few requirements (Laussmann and Helm, 2011):

1. Safe to use
2. Easy availability
3. Well-recordable for various measurement practices over a range of concentration
4. Environmentally friendly

Perfluorocarbon tracers (PFT) such as Hexafluorobenzene (C_6F_6), Octafluorotoluene (C_7F_8), perchlorodimethylcyclobutane, perfluoromethylcyclobutane, etc. are used as tracer gases in the estimation of air exchange rate with the constant injection method by using passive samplers (Dietz et al., 1982). These compounds are easily adsorbed on activated carbon and Tenax®, which make them useful in conducting field surveys or studies for the determination of indoor air exchange rates. The only disadvantages of these compounds would be that they tend to attach to room surfaces and also, their emission rates may be strongly temperature dependent (Lunden et al., 2012).

Tracer gas emitters were made using 5 mL glass vials with a screw-cap lid and Polytetrafluoroethylene (PTFE) diffusion septa. The tracer compounds used were Hexafluorobenzene (HFB) and Octafluorotoluene (OFT). A needle with a length of 1.2 inches and an outer diameter of 1.6 mm was pierced through the diffusion septum for easy diffusion. These tracer compounds were placed into the different vials using a glass dropper, and the diffusion through the septa and needle was relatively constant. Figure 4.6 shows the specifications of a tracer gas emitter.



Needle specifications:
- Brand: BD PrecisionGlide™ Needle
- Outer Diameter: 16 G or 1.6 mm (approx.)
- Inner Diameter: 1.2 mm (approx.)
- Length: 1.2 inches or 30 mm (approx.)

Vial specifications:
- Volume: 5 mL
- Material: Glass
- Screw-cap lid with 4 PTFE diffusion septa

Figure 4.6. Specifications of a tracer gas emitter

A set of emitters was made and tested for different needle diameters (1.6 mm, 2.0 mm and 2.7 mm). The emission rates for the 1.6 mm needles were constant and therefore, all emitters were fitted with 1.6 mm diameter needles. The next set of emitters was tested for emission rates at different temperatures (25°C and 30°C) for 24 and 48 hours.

Labeling of emitters was done as follows:

Table 4.2. Labelling of tracer emitters

Serial number	Tracer compound	Needle and screw-cap combination	Emitter label
1.	HFB1	A	HFB1A
2.	HFB2	B	HFB2B
3.	HFB1	C	HFB1C
4.	HFB2	D	HFB2D
5.	OFT1	E	OFT1E
6.	OFT2	F	OFT2F
7.	OFT1	G	OFT1G
8.	OFT2	H	OFT2H

The mass of the tracer that was emitted over any given time period was determined by weighing the vial at the beginning and end of the time period (or sampling period). A Denver Instrument Company digital scale, accurate to 1/10,000th of a gram was used to weigh each tracer compound vial. The scale was auto-calibrated prior to each use, and the scale was allowed to zero prior to each weighing. The exact time of the weighing was recorded, so that changes in mass could be combined with the time interval in order to calculate the average mass emission rate in grams per hour.

The mass of tracer emitted into the home was calculated using the following equation 2:

$$Emission\ rate\ (g\ per\ hour) = \frac{(M_{final} - M_{initial})}{t} \qquad \text{(Equation 2)}$$

Where M_{final} = Final mass of emitter (measured in grams)

$M_{initial}$= Initial mass of emitter (measured in grams)

t = Time in hours

4.2.2.3. Sampling procedure. A trailer was used to contain all the sampling equipment and PTFE (Polytetrafluoroethylene) tubing was used for sampling. During sampling, the air-conditioning was kept running in the home, which only used recirculated air. Samples were collected on Tenax® tube (Thermal Desorption tube) for volatile organic compounds (VOCs) and the tracer compounds. A flow rate of 20 cc/min was maintained and each sample was collected for 4 hours using a vacuum pump and flow controllers. For the indoor air samples, PTFE tubing was used, which stretched from inside the house to the trailer containing the sampling equipment. A total of 66 indoor air samples were taken. The samplers consist of a Thermal Desorption Tube made of steel, which has brass end caps (Figure 4.7). A groove is present on the sampling end of the tube. Each tube is packed with Tenax® TA sorbent material which adsorbs the tracer compounds, and the VOCs and SVOCs of interest. Figure 4.9 shows a typical Thermal Desorption Tube. For the determination of AER, emission sources (tracer compound vials) with known emission rates, were deployed in the home along with sampling equipment (Figure 4.8), in order to measure the concentration of the tracer compounds over a period of time. A definite amount of tracer compound was emitted constantly over time.

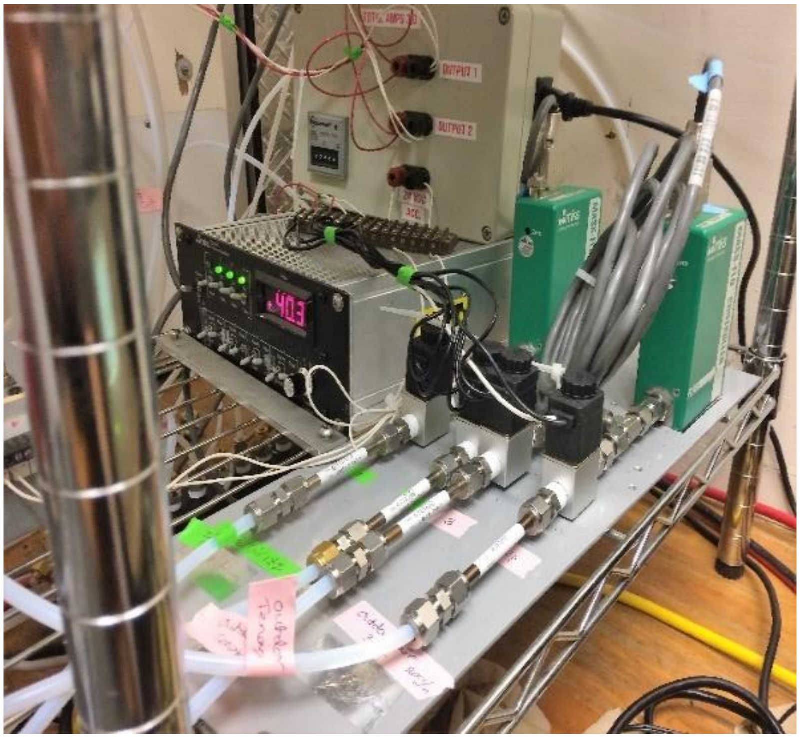


Figure 4.7. Sampling using Tenax® tubes

Figure 4.8. Location of tracer compound vial

Figure 4.9. A typical Thermal Desorption Tube

The concentration of the tracer compound reaches equilibrium after a certain amount of time depending on the volume of the home or building (V), the air exchange rate (λ) and the emission rate (E). Sampling should only be done when the tracers have equilibrated in the space (Laussmann and Helm, 2011; Sherman et al., 2014).

In this particular research, a constant emission rate was not assumed for the two tracers as there was some change seen with respect to temperature. A time-averaged emission rate was determined from the difference in mass over the time of deployment. Tracer emitters were deployed with other sampling equipment in the home and the first set of emitters was kept for 8 days (19^{th}- 27^{th} July 2016) and the next set of emitters was kept for another 8 days (28^{th} July- 4^{th} August 2016). Sampling was started on the 22^{nd} July after setting up all the instruments in a trailer. The building volume was noted for further calculations, in order to achieve an average AER (Dietz et al., 1986). Half a window was opened on the second floor on 29^{th} July at 14:00 pm and another full window was opened on 31^{st} July at 10:10 am.

4.2.2.4. Effective air exchange rate calculation. Assumptions for the model:

1. Steady-state conditions
2. Tracer compound is inert and chemically stable
3. No adsorption processes on walls or other surfaces
4. Completely mixed air
5. The experimental home is considered single-zone

The volumetric flow rate,

$$Q\ (m^3/hr) = E/C; \qquad \text{(Equation 3)}$$

Where; E = Emission Rate of the tracer compound (µg/hr)

C = Concentration of the tracer compound (µg/m^3)

The effective air exchange rate,

$$AER\ (hr^{-1}) = Q/V; \qquad \text{(Equation 4)}$$

Where; Q = Volumetric flow rate (m^3/hr)

V = Volume of the building (m^3)

4.2.2.5. GC-MS analysis. The analysis of the tracer compounds was performed by manual injection, using Thermal Desorption (Unity, Markes International, Ltd., UK) and GC/MS (Agilent 6890, USA). The cold trap (CT) in the TD unit was packed with Carbopack C. The compounds in the sample desorption tubes were desorbed at 300°C and transferred to the CT maintained at 10°C. Subsequently, the compounds in the CT were desorbed at 300°C for 12 min to park the compounds on a HP-5MS UI (0.25 mm ID × 30 m L, 0.25 m film thickness) for subsequent separation. The GC oven was initialized at 38°C for 8 min and ramped to 280°C at a 15°C/min. Helium gas was used for the analysis.

4.3. RESULTS AND DISCUSSION

The following topics elaborate the results obtained from the field work experiments. First, a test was done to understand how the tracer gas emitters work and also to check for reproducible emission rates. This would help to estimate and compare emission rates of field work experiments with those obtained in the lab.

4.3.1. Tracer Gas Emitters and Testing for Constant Emission Rates. Tracer gas emitters were used for the calculation of air exchange rates. For this purpose, a pre-requisite was to achieve reproducibility in the emission rates of these tracers. In Figure 4.10, the loss in masses of four different emitters is shown, two each for HFB and OFT. The experiment was run continuously for 3 days to calculate emission rates for each 24-hour duration. It is evident from the Figure 4.10, that the difference in mass is not significant over the 3 days. The average loss in mass for all the emitters is shown in the following Table 4.3.

In the following Figures 4.11 and 4.12, the variation of emission rates is shown for 25° C and 30° C, of HFB and OFT respectively. The experiment was done by using 6 different emitters for HFB and OFT. The emission rates for the HFB emitters varied from 1533.33 to 2025 µg/hr at 25° C and 1641.67 to 2277.08 µg/hr at 30° C. For OFT emitters, it ranged from 608.33 to 1095.83 µg/hr at 25° C and 709.72 to 1229.67 µg/hr at 30° C. This variation in the emission rates might be because each emitter was made using a different needle and cap combination. The coding of the needle and cap combination was mentioned in the methods section.

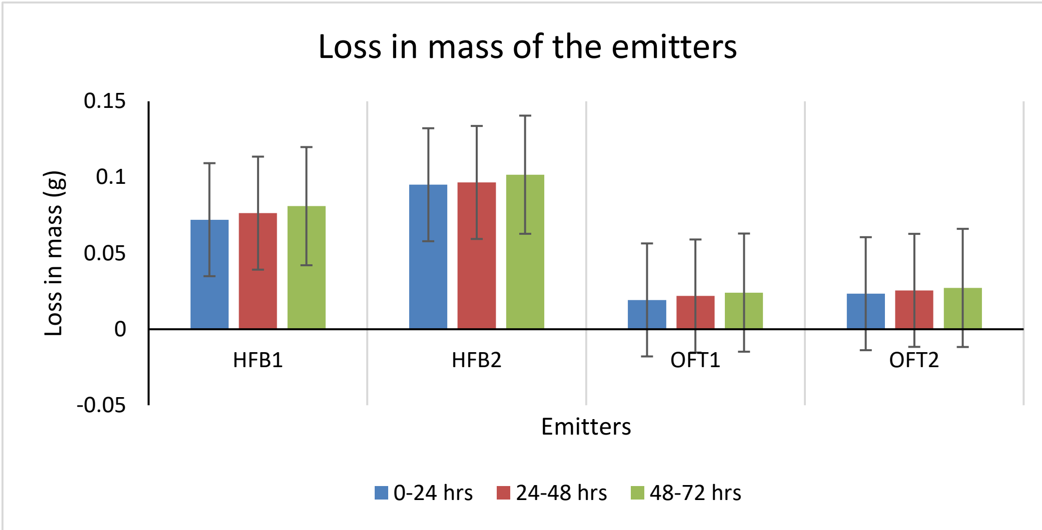


Figure 4.10. Loss in the mass of tracers over 3 days (72 hours) at 25° C. Error bars show standard deviation of ± 0.037

Table 4.3. Average loss in masses of tracer gas emitters

Tracer gas emitter	Average difference in mass (g)
HFB1	0.0765 +/- 0.004
HFB2	0.0978 +/- 0.003
OFT1	0.0217 +/- 0.002
OFT2	0.0254 +/- 0.001

The emission rates obtained were from different emitters and to see the trend of increase in emission rates with respect to temperature, the emission rates obtained at 30° C were divided by emission rates obtained at 25° C and thus, normalized and compared for both the tracer compounds for 25° C and 30° C temperatures. Therefore, the emission rates at 25° C are kept constant at 1. Figure 4.13 shows the normalized emission rates. It can be seen from the figure that, there is a ~9% increase in the emission rates for HFB and ~11% increase in emission rates for OFT, with respect to temperature. It can be concluded that the emission rates of these tracers are temperature-dependent.

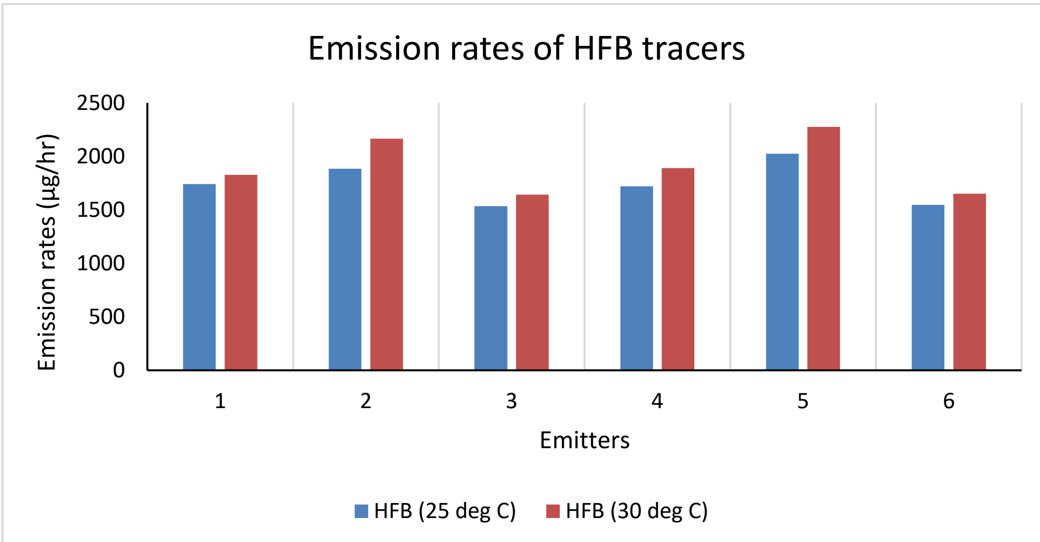


Figure 4.11. Emission rates for 6 HFB emitters for 25° C and 30° C

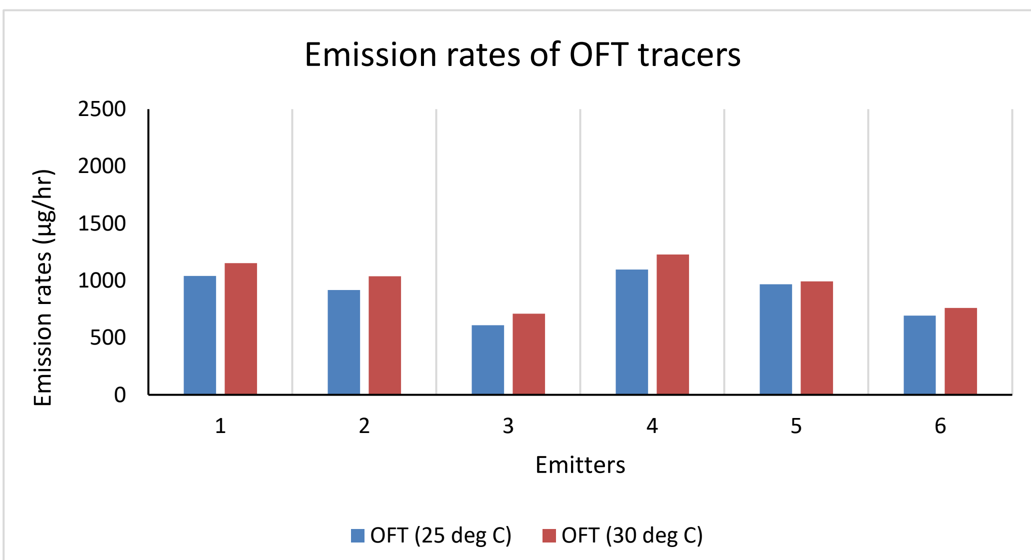


Figure 4.12. Emission rates for 6 OFT emitters for 25° C and 30° C

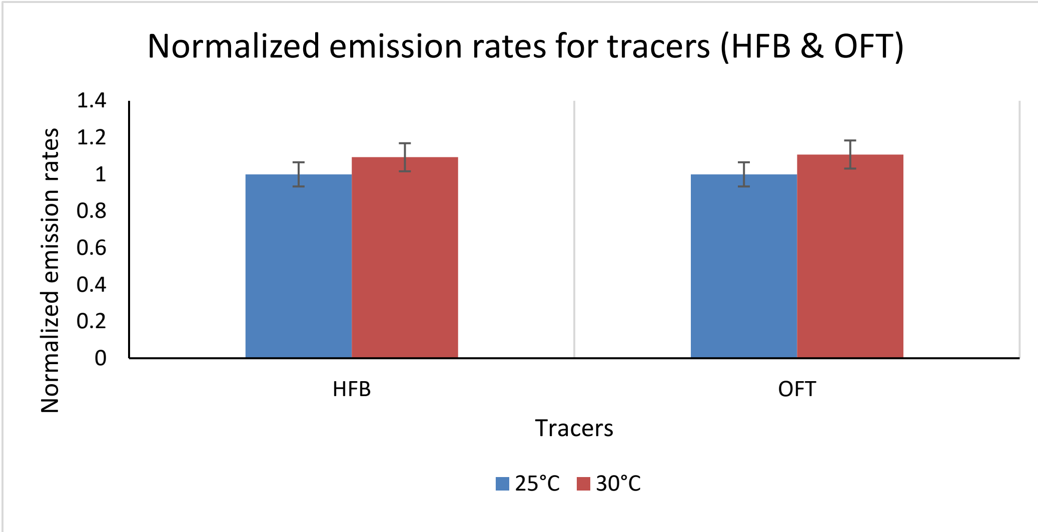


Figure 4.13. Normalized emission rates for tracers for 25° C and 30° C

The emission rates obtained in the field work were, 2652.60 µg/hr for HFB and 1031.25 µg/hr for OFT, for the first set of emitters kept on 19th July 2016. For the second set of emitters which were deployed on the 27th of July 2016, the emission rates obtained were, 1722.40 µg/hr for HFB and 1017.71 µg/hr for OFT. The difference in emission rates can be attributed to the needle-cap combination of the tracer vials.

4.3.2. GC-MS Analysis. The samples were analyzed using TD GC-MS system. The tracer concentration vs. time and the AER vs. time plots are as follows.

4.3.2.1. Tracer concentrations versus time. The concentrations of tracers (HFB and OFT) over the period of the whole experiment is shown in three consecutive stages in Figure 4.14. Impact of window opening at different extents clearly influences the concentration of the tracers from 22nd July to 3rd August 2016. In the first stage, when the windows were closed, the concentration of the tracers ranged from 2.63 to 61.05 µg/m^3 for HFB and 0.28 to 13 µg/m^3 for OFT. For the second stage, when half a window was opened, the concentration range decreased. The concentration range for HFB, for that stage, was found to be 0.08 to 35.05 µg/m^3 and for OFT it was found to be 0.07 to 11.2

μg/m^3. Another full window was opened for the air exchange rate experiment and there was no apparent drop in the concentration of the tracers. The concentration reached an equilibrium after opening the whole window. For HFB, the concentration ranged from 1.6 to 16.3 μg/m^3 and for OFT, it dropped to 0.01 to 6.17 μg/m^3. This is an apparent indication that as the windows are opened, the air exchange rate increases, because of which, there is a drop in the concentration of a lot of chemical species like tracers in the building/home.

4.3.2.2. Air exchange rate versus time. In the case of air exchange rate due to the application of tracers (HFB and OFT) shown in Figure 4.15, there is a reverse trend for the 3 stages. In the first stage, the air exchange rate of the home was found to be low, i.e. of the magnitude of 0.08 to 1.97 hr^{-1} from HFB and 0.15 to 0.6 hr^{-1} from OFT. Opening half a window led to some increase in the AER. For HFB, the increase was up to 6.07 hr^{-1} and for OFT, it was up to 28.5 hr^{-1}. The effect of an increase in AER was not seen efficiently when another full window was opened. This resulted in the AER moving up to 26.83 hr^{-1} for OFT and 1.47 hr^{-1} for HFB. It is evident that when half a window was opened, the effective AER increased with respect to both the tracers, but there was no further substantial increase in the AER after another window was opened. This trend is important to understand that, when occupants use windows as a source of ventilation, the AER increases, depending on the number of windows, wind speed, temperature and other factors. This increase in AER can act as a removal mechanism for indoor pollutants like formaldehyde and an entry mechanism for outdoor pollutants like ozone.

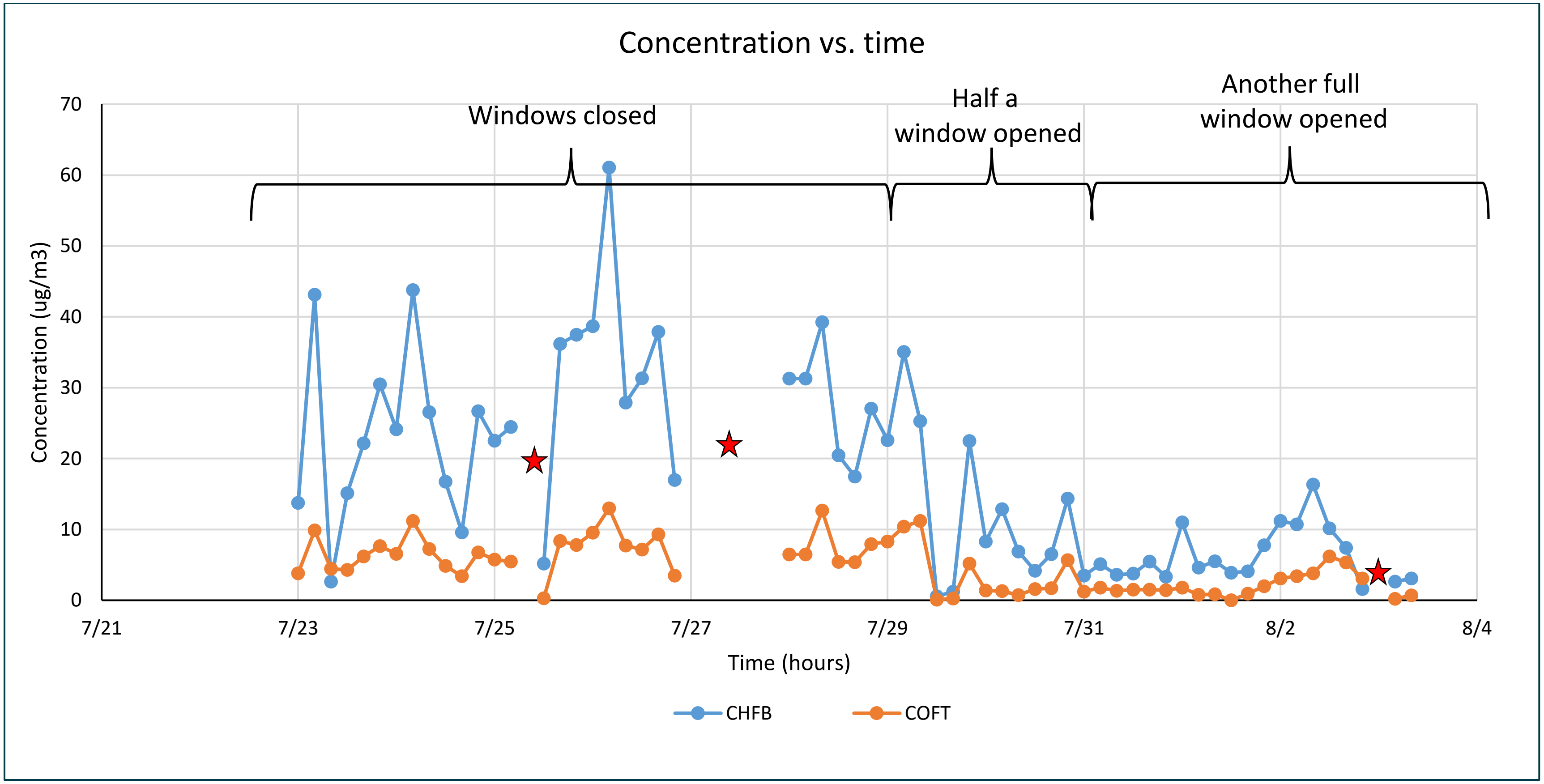


Figure 4.14. 4-hr average concentration determined for both tracers (HFB and OFT) versus time in hours.★ Indicates break in the data due to “bad” data or no sample

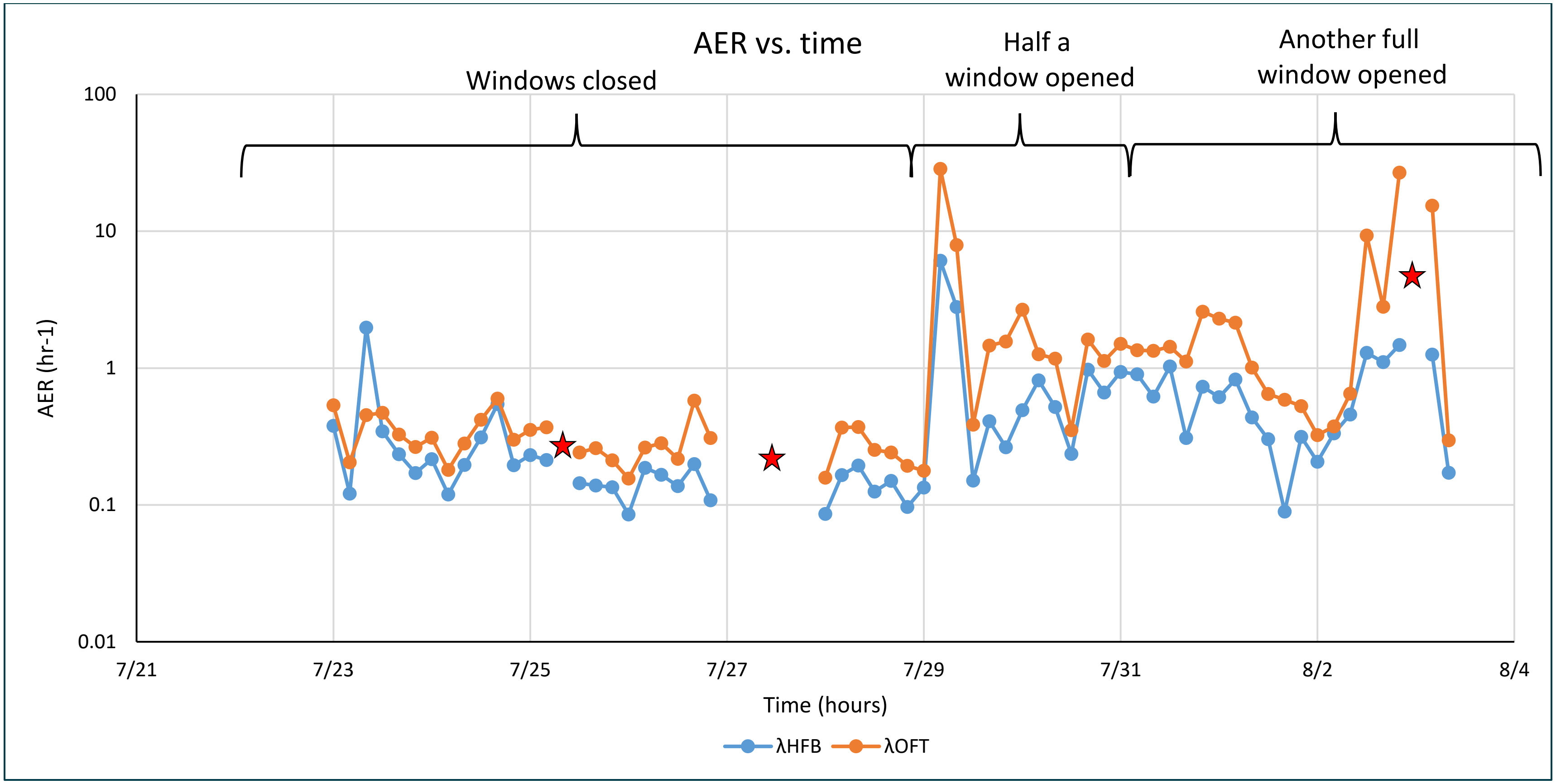


Figure 4.15. 4-hr average AER determined for both tracers (HFB and OFT) versus time in hours. ★ Indicates break in the data due to "bad" data or no sample

4.3.2.3. Air exchange rate for tracers (12-hour average). The below Figure 4.16 represents the 12-hour average AER for the tracer hexafluorobenzene over the whole study period. The trend noted here is like the trend in the previous figure, in which the 4-hour average AER was noted for both the tracers. It can be inferred that the AER due to the use of HFB changes as the windows are opened. When all the windows are closed, the AER remains around 0.35 hr^{-1} with an anomaly of 0.82 hr^{-1}. The lowest AER in that stage was observed to be 0.11 hr^{-1}. In the next stage, there is a definite increase in the AER, as a single half window was opened. Huge increase is seen for a single time period of 3 hr^{-1}. The maximum value obtained in this period is 0.52 hr^{-1} and the lowest is 0.12 hr^{-1}. In the third and the final stage, when another window was opened, the highest AER noted was 1.2 hr^{-1}, which can be attributed to multiple window openings. This drastic increase is significant to prove that window-opening leads to increments in the AER.

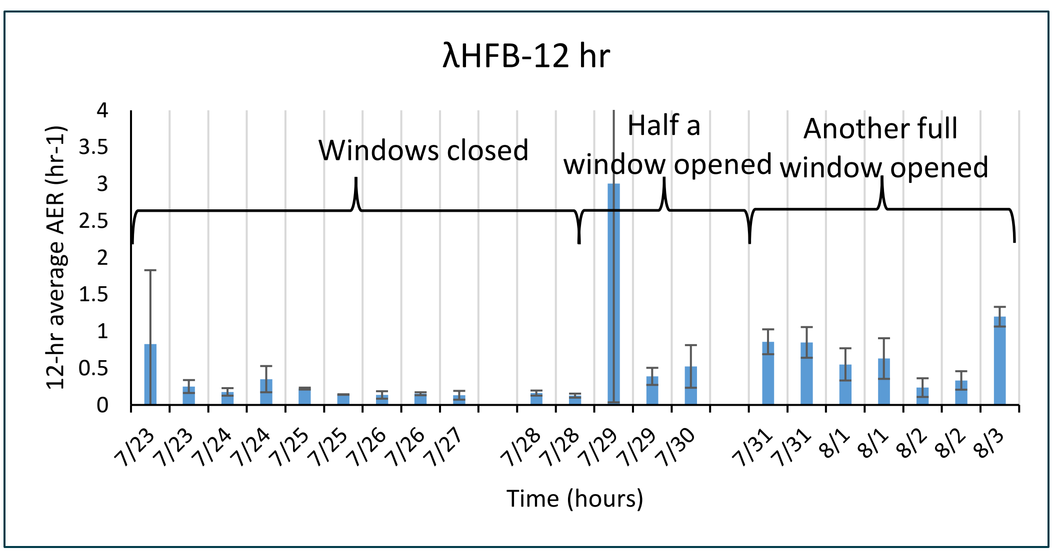


Figure 4.16. AER (12-hr average) for HFB

The same trend is seen in the following Figure 4.17 for the 12-hour average AER from octafluorotoluene. The lowest AER obtained for the first stage is 0.21 hr^{-1}. The second stage shows the leap in the AER to a value of approximately 12.27 hr^{-1}, which can be due to the sudden opening of a window. When the second full window was opened, the AER had increased as compared to the windows closed condition but wasn't as high as when half a window was opened. The highest effective AER achieved was 6.04 hr^{-1}.

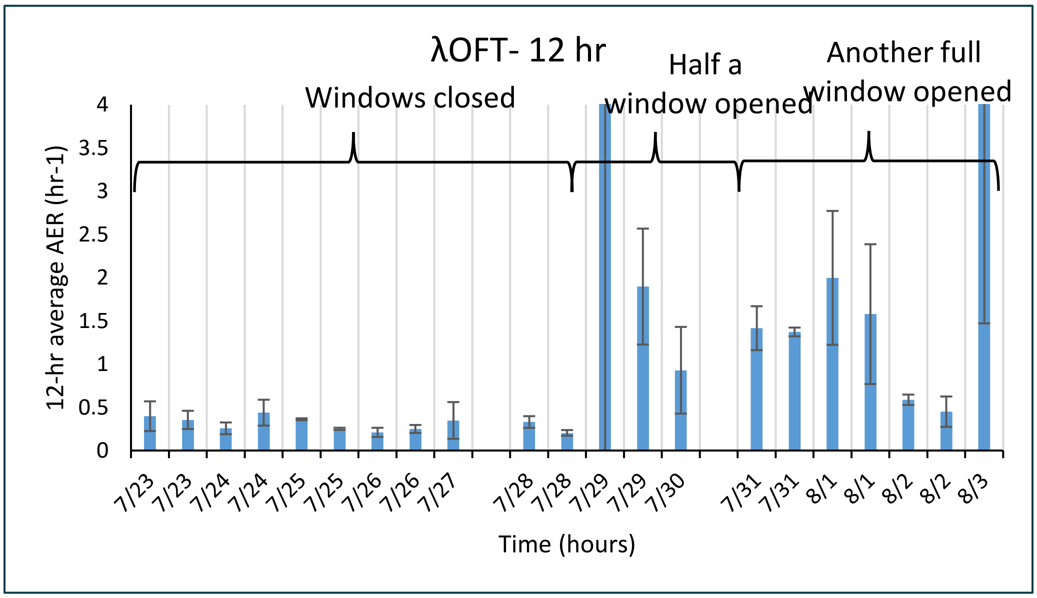


Figure 4.17. AER (12-hr average) for OFT

5. CONCLUSIONS

The first part of the thesis aimed at not only understanding which factors affect window-opening but also to quantify the window-opening occurrence throughout the United States. Studies have been done in the past to understand the factors affecting window-opening behavior by occupants but, very few have been intended at comprehending the occurrences. To understand this, the following objectives and subtasks were fulfilled and it was observed that:

Objective 1: Quantify the occurrence of window opening in US residences.

a. Identify any associations between window-opening occurrence and demographics.

There was a difference in the percentage of respondents who opened their windows during the three surveys. It was found that the percentage for survey 1 was 49.3% and for survey 2 was 52.5% but for survey 3, it was only 24.4%. This means that people tend to open windows more during the spring or fall months rather than winter, which might be due to temperature differences. There isn't a big difference between the window-opening occurrence according to the gender, especially in surveys 1 and 3. But in survey 2, males (58.4%) tended to open more windows as compared to females (45.8%). Similarly, there are some racial or cultural differences in window-opening occurrence. The White/Caucasian respondents opened windows more during first two surveys (48.3% and 54.4%) but their percentage declined in the third survey. The "Others" category respondents opened more windows during surveys 1 and 3 (61.1% and 38.2%, respectively). There wasn't much contrast in the respondents from various living situations but there was some disparity seen in the occupancy patterns. From the residence-type category, there were a lot of discrepancies among all the three surveys and also among the categories of respondents. Income range did not affect window opening significantly, but residence-type did, in which the percentage of respondents living in mobile homes who opened their windows during survey 3 (7%) was least.

b. Quantify and compare window-opening occurrence for the 4 major climate quadrants of the US (North-East, North-West, South-East, South-West).

There were spatial differences seen. Looking at the percentage of respondents who opened their windows in the 4 major climate quadrants, in survey 1 & 2, the value was higher for South-West (74.6%) and North-West (74.4%) regions. Therefore, the West coast tended to open more windows as opposed to the East coast. In the case of survey 3, the highest percentage was obtained for South-West (40.3%), and the least for North-East (18.75%). This variation can be attributed to the differences in temperature and humidity between the quadrants and also the time of the survey.

c. Quantify "window hours" and compare with diurnal patterns of pollutants.

"Window hours" graphs showed that people usually tend to open windows more often during the afternoon as compared to other time periods of the day, which might lead to the entry of outdoor pollutants like ozone.

Objective 2: Measure the air dilution rate and effective air exchange rate in a residence with windows open and closed.

a. Measure the concentration of tracer compounds, under conditions of open and closed windows in a residence.

It was found that, when the windows were closed, the concentration of the tracers reached a high value of 2.68 to 61.05 $\mu g/m^3$ for HFB and 0.28 to 13 $\mu g/m^3$ for

OFT. This might have been due to the air-tightness of the home. In the second stage, when a window was opened half-way, the concentration of the tracers dropped (0.08 to 35.05 μg/m^3 and for OFT it was found to be 0.07 to 11.2 μg/m^3). In the third stage, when another window was opened in addition to the half window, the concentration of tracers did not decrease as expected (For HFB, the concentration it was in the range of 1.6 to 16.3 μg/m^3 and for OFT, it was in the range of 0.01 to 6.17 μg/m^3).

b. Quantify the effective air exchange rate based on tracer concentration measurements.

The air exchange rate of the home was low when the windows were closed, i.e. of the magnitude of 0.08 to 1.97 hr^{-1} from HFB and 0.15 to 0.6 hr^{-1} from OFT. After opening half a window, the AER for OFT was 28.5 hr^{-1} and for HFB, 6.07 hr^{-1}. When another full window was opened, it resulted in the AER of 26.83 hr^{-1} for OFT and 1.47 hr^{-1} for HFB.

This proves that when windows are opened, there is a movement of air between the indoors and outdoors, which leads to increase in AER and ultimately, decreases the concentration of indoor pollutants but might increase the concentration of outdoor pollutants in the homes. Therefore, occupants' window-opening behavior and occurrences are important to maintain a healthy balance between the indoor and outdoor air.

In conclusion of the whole study, the surveys undertaken shall provide valuable information about window opening occurrences, nationwide. In combination, field measurements shall lead to a better understanding of the impact of window opening on indoor chemistry. When combined, the overall window opening behavior will significantly enhance our ability to anticipate the impact of indoor environmental exposures. It will also help to improve future policies regarding exposure to pollutants.

The broader goal of this project is to assess how direct or indirect effects of climate change could change population exposure to air pollution. Hence, the field work experiments and survey results, brought together with existing information on energy, building, construction and climate trends can predict, qualitatively at the very least, future trends in exposure.

6. RECOMMENDATIONS FOR FUTURE WORK

Future work will include deployment of more surveys in other months of the year. This would help to get a more refined picture about the window-opening occurrences over the year for the whole country. Current surveys were only carried out for three seasons. Summer survey data might be useful to expand the understanding of window opening occurrence. Some modifications in the survey pattern can also be done before deployment, to make the survey more respondent-friendly.

As far as the field work is concerned, air exchange rate measurements will be conducted in more homes and in other towns. It would assist in developing a better sense of how AERs vary in association with window opening for different homes and in different weather conditions.

APPENDIX

1. Online survey

In this first section you will be presented with questions about you and your primary residence.

Q1 Please enter your four-digit birth year

Q2 Please identify your gender

- ❍ Male (1)
- ❍ Female (2)

Q3 What is your race?

- ❍ African American (1)
- ❍ Hispanic (2)
- ❍ White/Caucasian (3)
- ❍ Native American (4)
- ❍ Pacific Islander (5)
- ❍ Asian (6)
- ❍ Other (7)

Q4 Please select household income range:

- ❍ Less $10,000 per year (1)
- ❍ $10,000 to $29,999 per year (2)
- ❍ $30,000 to $59,999 per year (3)
- ❍ $60,000 to $99,999 per year (4)
- ❍ $100,000 to $199,999 per year (5)
- ❍ Greater than or equal to $200,000 per year (6)

Q5 Please enter the five-digit Zip code of your primary physical residence (note: not the zip code of a Post Office Box)

Q6 Your primary place of residence is best described as a (an):

- ❍ Apartment (1)
- ❍ Attached home (like a duplex, four-plex or rowhouse) (2)
- ❍ Detached home (a single home not attached to other homes) (3)
- ❍ Mobile home (4)

Q7 How many occupants live in your primary residence (not including pets):

- ❍ 1 (1)
- ❍ 2 (2)
- ❍ 3 (3)
- ❍ 4 (4)
- ❍ 5 or more (5)

Q8 Which best describes your living situation

- ❍ Rent (1)
- ❍ Own (2)
- ❍ Live with family or friend (3)

Q9 Please provide your best estimate of the size of your primary residence. For comparison, a standard US basketball court is 5000 square feet:

- ❍ up to 999 square feet (1)
- ❍ 1000 to 1999 square feet (2)
- ❍ 2000 to 2999 square feet (3)
- ❍ 3000 to 3999 square feet (4)
- ❍ 4000 to 4999 square feet (5)
- ❍ 5000 square feet and more (6)

Q10 How many of the following rooms are in your primary residence? If rooms are combined, choose the primary purpose of the space. For example, if the kitchen and dining room are in the same space but the space is primarily used for dining and not cooking, set the number of kitchens =0 and the number of dining rooms = 1. Each bathroom, regardless of size, should be counted as a "whole" bathroom.

	0 (1)	1 (2)	2 (3)	3 (4)	4 (5)	5 or more (6)
Bedrooms (1)	❍	❍	❍	❍	❍	❍
Bathrooms (2)	❍	❍	❍	❍	❍	❍
Dining rooms (3)	❍	❍	❍	❍	❍	❍
Kitchens (4)	❍	❍	❍	❍	❍	❍
Living rooms/Dens (5)	❍	❍	❍	❍	❍	❍
Offices (6)	❍	❍	❍	❍	❍	❍
Basement or Attic (7)	❍	❍	❍	❍	❍	❍

In the following section you will be asked whether windows were open in your primary residence yesterday. For the purposes of the survey, yesterday starts at 12 am midnight and ends at the following midnight.

Q11 Yesterday, were any windows open in your home at any time?

❍ Yes (1)
❍ No (2)

If No Is Selected, Then Skip to Typically, this time of year, do you ...

Q12 Yesterday, in which of the following rooms did you or someone else open at least one window?

- ❑ Bedrooms (1)
- ❑ Bathrooms (2)
- ❑ Dining rooms (3)
- ❑ Kitchens (4)
- ❑ Living rooms or dens (5)
- ❑ Offices (6)
- ❑ Basement or Attic (7)

Display This Question:

If Yesterday, did you open any of the windows in any of these rooms (if available)?

Bedrooms Is Selected

Q13 During these time periods yesterday, how long were windows open in a bedroom?

	none (1)	Up to 1 hour	1 to 2 hours	2 to 4 hours	4 to 6 hours
Overnight	❍	❍	❍	❍	❍
Morning	❍	❍	❍	❍	❍
Afternoon	❍	❍	❍	❍	❍
Evening	❍	❍	❍	❍	❍

Display This Question:

If Yesterday, did you open any of the windows in any of these rooms (if available)?

Bathrooms Is Selected

Q14 During these time periods yesterday, how long were windows open in a bathroom?

	none (1)	Up to 1 hour	1 to 2 hours	2 to 4 hours	4 to 6 hours
Overnight	❍	❍	❍	❍	❍
Morning	❍	❍	❍	❍	❍
Afternoon	❍	❍	❍	❍	❍
Evening	❍	❍	❍	❍	❍

Display This Question:

If Yesterday, did you open any of the windows in any of these rooms (if available)? Dining rooms Is Selected

Q15 During these time periods yesterday, how long were windows open in a dining room?

	none (1)	Up to 1 hour	1 to 2 hours	2 to 4 hours	4 to 6 hours
Overnight	❍	❍	❍	❍	❍
Morning	❍	❍	❍	❍	❍
Afternoon	❍	❍	❍	❍	❍
Evening	❍	❍	❍	❍	❍

Display This Question:

If Yesterday, did you open any of the windows in any of these rooms (if available)?

Kitchens Is Selected

Q16 During these time periods yesterday, how long were windows open in a kitchen?

	none (1)	Up to 1 hour	1 to 2 hours	2 to 4 hours	4 to 6 hours
Overnight	❍	❍	❍	❍	❍
Morning	❍	❍	❍	❍	❍
Afternoon	❍	❍	❍	❍	❍
Evening	❍	❍	❍	❍	❍

Display This Question:

If Yesterday, did you open any of the windows in any of these rooms (if available)?

Living rooms or dens Is Selected

Q17 During these time periods yesterday, how long were windows open in a living room or den?

	none (1)	Up to 1 hour	1 to 2 hours	2 to 4 hours	4 to 6 hours
Overnight	❍	❍	❍	❍	❍
Morning	❍	❍	❍	❍	❍
Afternoon	❍	❍	❍	❍	❍
Evening	❍	❍	❍	❍	❍

Display This Question: If Yesterday, did you open any of the windows in any of these rooms (if available)? Offices Is Selected

Q18 During these time periods yesterday, how long were windows open in an office?

	none (1)	Up to 1 hour	1 to 2 hours	2 to 4 hours	4 to 6 hours
Overnight	❍	❍	❍	❍	❍
Morning	❍	❍	❍	❍	❍
Afternoon	❍	❍	❍	❍	❍
Evening	❍	❍	❍	❍	❍

Display This Question: If Yesterday, did you or anyone else open any of the windows in any of these rooms (if available)? Basement or Attic Is Selected

Q19 During these time periods yesterday, how long were windows open in the basement or attic?

	none (1)	Up to 1 hour	1 to 2 hours	2 to 4 hours	4 to 6 hours
Overnight	❍	❍	❍	❍	❍
Morning	❍	❍	❍	❍	❍
Afternoon	❍	❍	❍	❍	❍
Evening	❍	❍	❍	❍	❍

In the following questions, you will be asked about window opening that occurs this time of year. This time of year means within a month of today.

Q20 Typically, this time of year, do you open one or more windows at any time during the day?

- ❍ Yes (1)
- ❍ No (2)

If No Is Selected, Then Skip to When you keep windows closed, why? Ch...

Display This Question: If Typically, this time of year, do you open one or more windows at any time during the day? Yes Is Selected

Q21 During this time of year, check time periods when you usually have at least one window open somewhere in the home (not including a garage)?

	none (1)	Up to 1 hour	1 to 2 hours	2 to 4 hours	4 to 6 hours
Overnight	❍	❍	❍	❍	❍
Morning	❍	❍	❍	❍	❍
Afternoon	❍	❍	❍	❍	❍
Evening	❍	❍	❍	❍	❍

Q22 As a percentage, how wide do you typically open a window in each room at this time of year? (I do not open windows=0%, a quarter open = 25%, half-open = 50%, 3/4 open = 75%, fully open = 100%) (Slider-type question)

Bedroom (1)
Bathroom (2)
Dining room (3)
Kitchen (4)
Living room or den (5)
Office (6)
Basement or Attic (7)

Q23 How many windows are open in your house right now?

- ❍ 0 (1)
- ❍ 1 (2)
- ❍ 2 (3)
- ❍ 3 (4)
- ❍ 4 (5)
- ❍ 5 or more (6)

Q24 For which of the following reasons do you keep windows open this time of year, why? Check all that apply, but please only check major reasons

- ❑ Stuffy (1)
- ❑ Prevent overheating (2)
- ❑ Air out pollutants such as smoke, odors (3)
- ❑ Bring in fresh air (4)
- ❑ Other (5) ____________________

Q25 For which of the following reasons do you keep windows closed this time of year, why? Check all that apply, but please only check major reasons

- ❑ Too warm (1)
- ❑ Too chilly (2)
- ❑ Save energy (3)
- ❑ Keep air pollution/allergens/dust out (4)
- ❑ Noise (5)
- ❑ Safety (6)
- ❑ Other (7) ____________________

In the following questions, you will be asked about exterior door opening in your primary residence.

Q26 During these time periods yesterday, how long were one or more exterior doors open?

	none (1)	Up to 1 hour	1 to 2 hours	2 to 4 hours	4 to 6 hours
Overnight	❍	❍	❍	❍	❍
Morning	❍	❍	❍	❍	❍
Afternoon	❍	❍	❍	❍	❍
Evening	❍	❍	❍	❍	❍

Q27 During these time periods this time of year, how long are one or more exterior doors open?

	none (1)	Up to 1 hour	1 to 2 hours	2 to 4 hours	4 to 6 hours
Overnight	❍	❍	❍	❍	❍
Morning	❍	❍	❍	❍	❍
Afternoon	❍	❍	❍	❍	❍
Evening	❍	❍	❍	❍	❍

Q28 How many exterior doors are open in your house right now?

- ❍ 0 (1)
- ❍ 1 (2)
- ❍ 2 (3)
- ❍ 3 (4)
- ❍ 4 (5)
- ❍ 5 or more (6)

Q29 For which of the following reasons do you keep one or more exterior doors open this time of year, why? Check all that apply, but please only check major reasons

- ❑ Stuffy (1)
- ❑ Prevent overheating (2)
- ❑ Air out pollutants such as smoke, odors (3)
- ❑ Bring in fresh air (4)
- ❑ Other (5) ____________________

Q30 For which of the following reasons do you keep an exterior door closed this time of year, why? Check all that apply, but please only check major reasons

- ❑ Too warm (1)
- ❑ Too chilly (2)
- ❑ Save energy (3)
- ❑ Keep air pollution/allergens/dust out (4)
- ❑ Noise (5)
- ❑ Safety (6)
- ❑ Other (7) ____________________

Q31 Please select all that apply to your primary residence.

- ❑ Central air conditioning and heating (1)
- ❑ Split air conditioning system (2)
- ❑ Window-unit air conditioner(s) (3)
- ❑ Use of portable heaters (4)
- ❑ One or more fireplaces (5)
- ❑ Heat recovery ventilation (HRV) or energy recover ventilation (ERV) (6)
- ❑ Wood burning stove (7)

Q32 What is your primary energy source for heating?

- ❍ Electricity (1)
- ❍ Natural gas (2)
- ❍ Propane (3)
- ❍ Fuel oil (4)
- ❍ Wood or fuel pellets (5)
- ❍ Other (6)

Thank you for your responses.

1. Field work sampling information

Sample no.	Date	Start	Stop	CHFB	COFT	QHFB	QOFT	λHFB	λOFT
55	7/22/2016	22:00	2:00	13.76	3.79	192.78	272.12	0.38	0.53
57	7/23/2016	2:00	6:00	43.11	9.88	61.53	104.36	0.12	0.20
63		6:00	10:00	2.64	4.47	1006.24	230.92	1.98	0.45
59		10:00	14:00	15.12	4.30	175.47	239.72	0.34	0.47
67		14:00	18:00	22.15	6.18	119.78	166.84	0.24	0.33
65		18:00	22:00	30.47	7.64	87.05	135.01	0.17	0.27
61		22:00	2:00	24.13	6.53	109.94	157.85	0.22	0.31
62	7/24/2016	2:00	6:00	43.79	11.22	60.57	91.92	0.12	0.18
70		6:00	10:00	26.54	7.22	99.93	142.81	0.20	0.28
89		10:00	14:00	16.75	4.84	158.36	213.24	0.31	0.42
73		14:00	18:00	9.56	3.39	277.32	303.98	0.54	0.60
75		18:00	22:00	26.68	6.76	99.41	152.61	0.20	0.30
77		22:00	2:00	22.51	5.72	117.82	180.19	0.23	0.35
79	7/25/2016	2:00	6:00	24.44	5.47	108.52	188.46	0.21	0.37
81		6:00	10:00	0.00	0.02	0.00	43722.00	0.00	85.84
83		10:00	14:00	5.16	0.28	513.87	3625.97	1.01	7.12
90		14:00	18:00	36.17	8.37	73.33	123.28	0.14	0.24
85		18:00	22:00	37.48	7.79	70.78	132.46	0.14	0.26
87		22:00	2:00	38.68	9.56	68.57	107.92	0.13	0.21
91	7/26/2016	2:00	6:00	61.06	12.98	43.44	79.44	0.09	0.16
93		6:00	10:00	27.88	7.72	95.14	133.62	0.19	0.26
96		10:00	14:00	31.33	7.17	84.66	143.92	0.17	0.28
99		14:00	18:00	0.00	0.00	0.00	0.00	0.00	0.00
101		18:00	22:00	37.86	9.31	70.06	110.82	0.14	0.22
111	7/27/2016	22:00	2:00	16.98	3.46	101.44	294.21	0.20	0.58
112	7/28/2016	2:00	6:00	31.27	6.48	55.08	156.95	0.11	0.31
103		6:00	10:00	39.26	12.64	43.87	80.51	0.09	0.16
106		10:00	14:00	20.45	5.43	84.24	187.50	0.17	0.37
109		14:00	18:00	17.45	5.40	98.71	188.57	0.19	0.37
107		18:00	22:00	27.05	7.93	63.68	128.32	0.13	0.25

Sample no.	Date	Start	Stop	C_{HFB}	C_{OFT}	QHFB	QOFT	λHFB	λOFT
128		22:00	2:00	22.60	8.29	76.21	122.79	0.15	0.24
137	7/29/2016	2:00	6:00	35.06	10.37	49.13	98.14	0.10	0.19
135		6:00	10:00	25.28	11.22	68.14	90.73	0.13	0.18
129		10:00	14:00	0.56	0.07	3094.28	14520.33	6.08	28.51
120		14:00	18:00	1.21	0.25	1419.33	4033.65	2.79	7.92
123		18:00	22:00	22.49	5.18	76.59	196.62	0.15	0.39
122		22:00	2:00	8.28	1.37	208.10	743.48	0.41	1.46
132	7/30/2016	2:00	6:00	12.84	1.28	134.11	795.36	0.26	1.56
124		6:00	10:00	6.87	0.75	250.69	1359.19	0.49	2.67
125		10:00	14:00	4.15	1.58	414.90	643.40	0.81	1.26
127		14:00	18:00	6.52	1.71	264.34	596.20	0.52	1.17
126		18:00	22:00	14.37	5.67	119.88	179.36	0.24	0.35
146		22:00	2:00	3.48	1.24	495.62	823.33	0.97	1.62
140	7/31/2016	2:00	6:00	5.09	1.77	338.20	575.51	0.66	1.13
148		6:00	10:00	3.61	1.33	476.81	763.75	0.94	1.50
142		10:00	14:00	3.75	1.48	459.88	688.12	0.90	1.35
149		14:00	18:00	5.46	1.50	315.29	680.06	0.62	1.34
143		18:00	22:00	3.30	1.40	522.16	727.97	1.03	1.43
141		22:00	2:00	10.98	1.79	156.82	569.09	0.31	1.12
168	8/1/2016	2:00	6:00	4.62	0.78	372.49	1312.37	0.73	2.58
156		6:00	10:00	5.52	0.87	312.28	1169.72	0.61	2.30
159		10:00	14:00	3.87	0.01	445.10	87546.55	0.87	171.88
163		14:00	18:00	4.10	0.93	420.28	1094.80	0.83	2.15
158		18:00	22:00	7.77	1.99	221.62	512.50	0.44	1.01
155		22:00	2:00	11.21	3.08	153.68	330.04	0.30	0.65
160	8/2/2016	2:00	6:00	37.82	3.41	45.54	298.22	0.09	0.59
169		6:00	10:00	10.73	3.79	160.52	268.72	0.32	0.53
171		10:00	14:00	16.34	6.18	105.43	164.75	0.21	0.32
173		14:00	18:00	10.15	5.33	169.71	191.03	0.33	0.38
180		18:00	22:00	7.39	3.07	233.19	331.19	0.46	0.65
181		22:00	2:00	1.60	0.00	1078.16	0.00	2.12	0.00

Sample no.	Date	Start	Stop	C_{HFB}	C_{OFT}	QHFB	QOFT	λHFB	λOFT
188	8/3/2016	2:00	6:00	2.62	0.22	658.19	4727.67	1.29	9.28
175		6:00	10:00	3.06	0.71	562.10	1431.73	1.10	2.81
177		10:00	14:00	2.29	0.07	752.09	13668.94	1.48	26.84
179		14:00	18:00	4.24	0.92	405.98	1101.32	0.80	2.16
184		18:00	22:00	2.70	0.13	638.73	7824.04	1.25	15.36
186		22:00	2:00	19.71	6.73	87.37	151.19	0.17	0.30

2. Weather station information

Date and time	λHFB	λOFT	Outdoor temperature (avg.) (°C)	Wind speed (mph)	Indoor temperature (avg.) (°C)
7/22/2016 22:00-2:00	0.38	0.53	25.79	0	24.86
7/23/2016 2:00-6:00	0.12	0.20	24.28	0	25.00
7/23/2016 6:00-10:00	1.98	0.45	25.99	0.44	25.00
7/23/2016 10:00-14:00	0.34	0.47	32.72	0.84	25.00
7/23/2016 14:00-18:00	0.24	0.33	33.78	0.96	25.00
7/23/2016 18:00-22:00	0.17	0.27	31.26	0.08	25.00
7/23/2016 22:00-2:00	0.22	0.31	28.59	0	25.00
7/24/2016 2:00-6:00	0.12	0.18	26.68	0	25.00
7/24/2016 6:00-10:00	0.20	0.28	27.58	0.4	25.00
7/24/2016 10:00-14:00	0.31	0.42	34.14	1	25.00
7/24/2016 14:00-18:00	0.54	0.60	35.06	1	25.00
7/24/2016 18:00-22:00	0.20	0.30	31.98	0.6	25.00
7/24/2016 22:00-2:00	0.23	0.35	28.83	0.88	25.00
7/25/2016 2:00-6:00	0.21	0.37	22.74	0.96	25.00
7/25/2016 14:00-18:00	0.14	0.24	23.35	0.04	25.00
7/25/2016 18:00-22:00	0.14	0.26	25.81	0.4	25.00
7/25/2016 22:00-2:00	0.13	0.21	29.03	0.72	25.00
7/26/2016 2:00-6:00	0.09	0.16	28.17	1.08	25.00
7/26/2016 6:00-10:00	0.19	0.26	26.88	0.16	25.00
7/26/2016 10:00-14:00	0.17	0.28	25.73	0.04	25.00
7/26/2016 18:00-22:00	0.14	0.22	25.72	0.24	25.00
7/27/2016 22:00-2:00	0.20	0.58	30.00	0.68	25.00

Date and time	λHFB	λOFT	Outdoor temperature (avg.) (°C)	Wind speed (mph)	Indoor temperature (avg.) (°C)
7/28/2016 2:00-6:00	0.11	0.31	30.01	0.64	25.00
7/28/2016 6:00-10:00	0.09	0.16	27.37	0.36	25.00
7/28/2016 10:00-14:00	0.17	0.37	25.44	0	25.00
7/28/2016 14:00-18:00	0.19	0.37	24.36	0	25.00
7/28/2016 18:00-22:00	0.13	0.25	24.78	0.04	25.00
7/28/2016 22:00-2:00	0.15	0.24	29.14	0.92	25.00
7/29/2016 2:00-6:00	0.10	0.19	30.57	0.56	25.07
7/29/2016 6:00-10:00	0.13	0.18	28.13	0.12	25.00
7/29/2016 14:00-18:00	2.79	7.92	26.58	0.04	25.00
7/29/2016 18:00-22:00	0.15	0.39	24.02	0	25.00
7/29/2016 22:00-2:00	0.41	1.46	25.69	0.24	25.00
7/30/20162:00-6:00	0.26	1.56	30.64	1.12	25.00
7/30/2016 6:00-10:00	0.49	2.67	31.14	1.36	25.00
7/30/2016 10:00-14:00	0.81	1.26	29.31	0.64	25.00
7/30/2016 14:00-18:00	0.52	1.17	26.89	0.36	25.00
7/30/2016 18:00-22:00	0.24	0.35	24.51	0.48	25.00
7/30/2016 22:00-2:00	0.97	1.62	24.71	0.32	25.00
7/31/2016 2:00-6:00	0.66	1.13	28.34	1	25.00
7/31/2016 6:00-10:00	0.94	1.50	29.13	0.8	25.53
7/31/2016 10:00-14:00	0.90	1.35	26.72	0.8	25.60
7/31/2016 14:00-18:00	0.62	1.34	24.73	0	25.60
7/31/2016 18:00-22:00	1.03	1.43	22.81	0	25.62
7/31/2016 22:00-2:00	0.31	1.12	23.79	0.28	25.62
8/1/2016 2:00-6:00	0.73	2.58	28.52	1.12	25.60
8/1/2016 6:00-10:00	0.61	2.30	27.50	0.47	25.09
8/1/2016 14:00-18:00	0.83	2.15	27.13	0.4	25.60
8/1/2016 18:00-22:00	0.44	1.01	24.80	0	25.60
8/1/2016 22:00-2:00	0.30	0.65	23.58	0	25.60
8/2/2016 2:00-6:00	0.09	0.59	24.34	0.12	25.60
8/2/2016 6:00-10:00	0.32	0.53	30.07	0.92	25.60
8/2/2016 10:00-14:00	0.21	0.32	30.03	0.28	25.60
8/2/2016 14:00-18:00	0.33	0.38	28.68	0.04	25.60
8/2/2016 18:00-22:00	0.46	0.65	25.51	0.08	25.60
8/2/2016 22:00-2:00	2.12	0.00	22.45	0.12	25.60
8/3/2016 2:00-6:00	1.29	9.28	21.91	0	25.88
8/3/2016 6:00-10:00	1.10	2.81	24.92	0.08	25.96
8/3/2016 14:00-18:00	0.80	2.16	28.19	0.64	25.60
8/3/2016 18:00-22:00	1.25	15.36	27.22	0.08	25.10
8/3/2016 22:00-2:00	0.17	0.30	24.95	0	23.79

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