Modeling Contaminant Exposure in a Single-Family House

by

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Abstract

New, stricter building codes for energy conservation mandates tighter building construction, which directly reduces the amount of available fresh air from infiltration. This decrease in fresh air is a subject of intensive study as health becomes a progressively sensitive issue. Mechanical ventilation is a system increasingly implemented to respond to and aid these burgeoning trends to reduce the risk of overexposure to indoor pollutants.

In this study, occupational exposure to household contaminants in a single-family house with several ventilation, heating, and climactic conditions was simulated using CFD. Typical household exposure to CO_2, CO, HCHO (formaldehyde), NO_2, and water vapor is evaluated over the day for a generic occupational schedule of four family members, consisting of a mother, father, son, and daughter. The ventilation types included a bimodal, relative humidity controlled, and balanced system, coupled with either room convectors, or a combination of a heated floor and room convectors. Both the winter and summer conditions were considered to the drastic difference in outdoor conditions, as well to isolate the effects of the heating system.

Characteristically, high degrees of thermal and contaminant stratification were found during the winter months, where low infiltration rates mimic displacement ventilation. This leads to lower contaminant exposure due to a lower concentration reservoir of air below the breathing zone. Entrainment of this air to the breathing region results in lower exposure. Also, it is found that the stratification effect is more efficient at curbing exposure than increasing the global ventilation rate for the cases evaluated.

Door positions play a key role in the mitigation of contaminant migration throughout the house. In addition, the centralized location of the exhaust devices draws contaminated air from the periphery of the house inward to the core, where the occupants are less likely to be during the day. The period of sleeping greatly dictates the overall exposure to bioeffluents, as this is the activity in which the family partakes for the greatest percentage of time they are at home.

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Jeffrey M. Huang
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1 Introduction

Since residential housing traditionally has relied on infiltration to provide adequate ventilation [1, 2], newer and stricter building codes for energy conservation suggests tighter building construction (ASHRAE Standard 119, National Building Code of Canada 1995), which directly reduces the amount of available fresh air. This decrease in fresh air is a subject of intensive study as health becomes a progressively sensitive issue. Mechanical ventilation is a system increasingly implemented to respond to and aid these burgeoning trends to reduce the risk of overexposure to indoor pollutants, while allowing more occupant control over the method and timing of ventilation needs.

In order to understand the impact of pollutants on human health, it is necessary to assess the actual exposure to these household contaminants. As personal exposure monitors are cumbersome and do not provide predictive data for unbuilt domains, alternative methods are quite necessary when determining certain precautionary liabilities. A variety of experimental and computational tools are available to the designer for analyzing complex floorplans and scenarios, accounting for common household contaminants to more accurately assess the indoor air quality (IAQ).

Since the indoor flows are quite complex and the transport of contaminants is highly dependent on these room airflows, often a perfect mixing model is used to determine an average room contaminant concentration level. The clear advantage of such a model is its simplicity, which is calculable by hand. The heavy tradeoff stems from the fact that it assumes instantaneous and complete mixing of the volume in which the contaminant source is located, in effect averaging a value throughout the whole room. It is understandable from both numerical and experimental results that there are definitive stratifications or non-uniformities (when the airflow rate is low, as in the case of infiltration) in the distribution of pollutants [3], and this phenomenon may be significant when comparing occupational exposure with this simplified method [4].

Through better approximations of the equations that govern fluid flow, computational fluid dynamics (CFD) provides better insight into the actual distribution of contaminants, while providing a degree of foresight into predicting the flows in unbuilt spaces. Though expensive with regard to the effort spent, this method provides a clearer understanding of pollutant transport and personal exposure.

This thesis evaluates the performance of two heating systems and three ventilation systems in summer and winter to help curb the accumulation of contaminants within a single-family house. To be evaluated is the concentration and occupational exposure level to CO_2, CO, NO_2, HCHO and water vapor, all considered to be common household contaminants emitted as byproducts of human metabolism, gas cooking, and smoking.

The household conditioning system consists of two major parts: the ventilation and heating system. Both systems are placed independently in the house. That is, the mutual impacts of the two systems on household contaminant levels are not considered. This study then correlates the systems, which in some cases enhances each constituent's ability to reduce exposure.

This thesis first covers the scientific literature of what has already been done for the case of household exposure to contaminants, and the methods currently used to evaluate the systems, including

- Air distribution methods
- Comparisons with and without mechanical ventilation
- Kitchen range hood exhaust
- Multizone airflows

The research approach undertaken provides much of the primary boundary conditions and other information that will be used to conduct the research. Validation of the CFD code them provides both the confidence and the experience necessary to utilze the tool for the specific cases. Then, a battery of cases are simulated and evaluated as to their effectiveness to curtail indoor pollutants. The cumulative exposures are then compared to current international ventilation and exposure standards to determine whether or not the systems are necessary.

1.1 Methods of Air Distribution for Maximal Contaminant Removal

Air distribution methods are integral to the health and comfort of an occupant, as it provides the streams of fresh air, which can be conditioned through heating or cooling. Different methods invariably induce different sensations and effects on the air quality of the interior space, and there is still much debate as to which is the most effective implementation. To be sure, there are application specific advantages to each method of air distribution, but it is necessary that a universal model be used for the residential case to garner wide support for a variety of applications. Certainly the domestic scenario should be very important in the determination of legislative contingencies, as the conditions seem to be the easiest to manipulate, due to the lack of laws mandating ventilation requirements of standards. However, it is in this realm that the standards are as yet undefined since litigious repercussions are spread too wide for calculable fault to bear.

The two main classifications of air distribution methods are controlled through momentum (jets) or buoyancy [5]. Major methods of momentum induced ventilation include: unidirectional ventilation, mixing or convective ventilation, and displacement ventilation. All these methods are produced with the aid of mechanical systems.

Acting externally on these distribution methods is an uncontrollable introduction of outside air due to temperature or pressure differences between the inside and outside of the building caused by fluctuations in the local weather, known as infiltration. The main

differences between the mechanical ventilation systems and infiltration is that the former is controlled, where the flow rates and locations of the ventilation are designed within the system, and the latter is uncontrolled and induced by the local weather conditions. Whether or not matters of a measure of in-built uncontrolled infiltration suffices to provide enough ventilation to provide a comfortable environment is debatable and remains to be proven.
To understand the effects of the various types of ventilation, ventilation effectiveness is usually used as an index to determine the relative effectiveness of each ventilation type based on either an air change time, τ_r, or an air change efficiency, ε_a.

1.1.1 Ventilation effectiveness

The concept of ventilation effectiveness or efficiency expresses the ability of a system to remove indoor contaminants, and is closely related to the air freshness in the enclosure being ventilated [6]. It cannot be determined by one index alone since the dispersal of pollutants from a source is often spread in a different way as the supply air, in the case of mechanical ventilation [7]. Ventilation effectiveness ranges from the ventilation efficiency at each point of a room to expressing the ventilation characteristics of an entire room [8].

The mainstay in attempting to determine a standard for ventilation is the air change rate. It is archaic in a sense, since it is the least accurate in assessing the goings on in the space. Though it is not a measure of efficiency, a plethora of international standards to provide proper minimum ventilation for acceptable indoor air quality are based solely on this index, which assumes perfect mixing.

Differing air distribution methods provide varying degrees of ventilation efficiency. Perfect mixing provides 50% air change efficiency, while unidirectional or piston flow gives the upper limit of 100% [5], where air change efficiency is defined as

$$\varepsilon_a = \frac{\tau_n}{2\langle\bar{\tau}\rangle} \times 100 = \frac{\tau_n}{\tau_t} \times 100$$

where the nominal time constant is defined as

$$\tau_n = \frac{V}{q_v}$$

where V is the volume of space ventilated, and q_v is the ventilation flow rate.

Table 1.1.1.1 Mixing Types

Airflow types	Air change efficiency, ε_a
Piston/unidirectional flow	$\varepsilon_a = 100\%$
Displacement flow	$50 < \varepsilon_a < 100\%$
Complete mixing	$\varepsilon_a = 50\%$
Poor mixing (short circuit)	$\varepsilon_a < 50\%$

According to Sandberg [7], complete mixing is a condition where the concentration outside the source region is uniform and equal to the concentration in the extract duct. So there is a degree of recirculated contaminants that is not present in displacement or piston flow, making forced air convection not the optimally efficient technique. He shows that there is a clear relationship between the air exchange efficiency and the exposure to contaminants in the case of forced air. When the air exchange efficiency is greater than 50% the average exposure becomes less than the concentration in the exhaust, and vice versa. However, a major problem involving the prediction of ventilation efficiency is the notion of a short circuit, whereby air entering a space through an inlet may directly flow to the outlet, bypassing a large portion of the space volume. A situation with short circuiting of air will falsely predict good ventilation efficiency.

A battery of indices may be consulted as a clearer picture is approached including the air exchange efficiency, average ventilation effectiveness, and local ventilation index, among others. However, a singular indicator that attempts to predict efficiency may, however be used to evaluate generalized trends in cases that the assumed effectiveness diverges from that which is measured.

Even with an assumption of complete mixing, it can be shown that 37% of the air is not exchanged when the air change rate is resumed to be one [9]. In this regard, a development in an alternative evaluation method is formed around the notion of the age of air (Figure 1.1.1.1). The mean age of air, $\langle \bar{\tau} \rangle$, is equal to the nominal time constant, which is the space volume divided by the ventilation flow rate [7]. With this number as a standard, the evaluation of ventilation effectiveness results from a comparison of the age of a contaminant compared with the mean age of air. If it is found that the local age of air is greater than that of the mean age, poor circulation is assumed to be present.

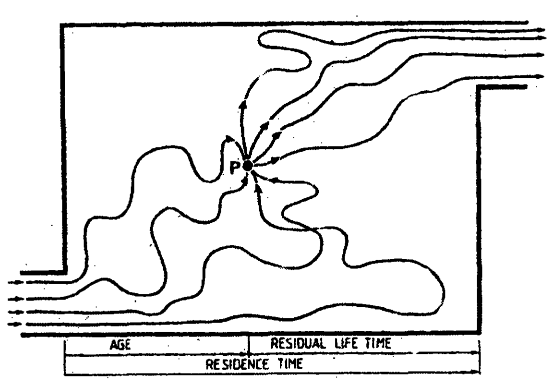


Figure 1.1.1.1 Different contaminant age characteristics [7]

There is a relationship between the mean age of internal air $\langle \tau \rangle$, and the mean residence time of the air $\langle \tau_r \rangle$ entering the room:

$$\langle \tau \rangle = \frac{\langle \tau_r \rangle}{2}$$

It is erroneously thought that these two values are the same. The mean age of air depends on the degree of internal mixing, whilst the mean residence (the nominal time constant) time does not. As piston flow is attained the mean residence time of air is the same as the nominal time constants τ_n.

It should be reiterated that none of these methods should be taken as an absolute measure of the ventilation efficiency, since there are factors that govern each method that may be bypassed, such as sort circuiting, thus giving a false impression of the effectiveness. As a precaution, two or several indices should be evaluated simultaneously; if these criteria are well met, then ventilation effectiveness is likely to be good. From the air change efficiency alone, it is clear that piston or displacement flow is most favorable to remove contaminants from a space.

Within the context of ventilation effectiveness, a variety of ventilation conditions are introduced in the next section, and categorized based on their performance to reduce indoor contaminants and thus reduce occupational exposure.

1.1.2 Ventilation Types

The main ventilation types and the surrounding background research are presented here. The groundwork for the presentation of the following material draws from the fact that there are widely differing methods for space air distribution. Integral within air distribution is conditioning, where the air is brought to a certain temperature to provide thermal comfort to the occupant.

The most effective type of ventilation to remove contaminants is known as piston flow. This idealized method allows the supplied air to move uniformly and unidirectionally across an entire cross-section of a space, shown in the figure below. Piston flow, while being the best form of ventilation, is very difficult to achieve, and is therefore primarily used in such environments as clean rooms where cross-contamination must be avoided. Otherwise, piston flow is not practical for everyday ventilation.

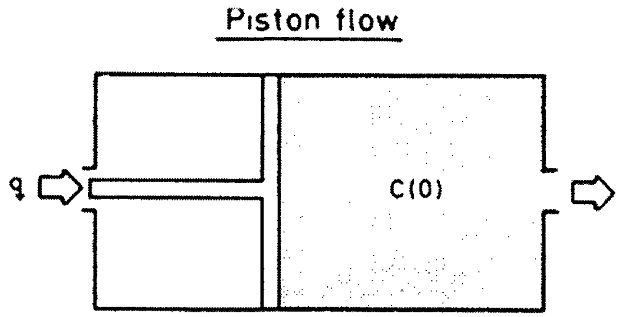


Figure 1.1.2.1 Schematic showing the method of piston flow [5]

Mixing type ventilation, or what ASHRAE calls entrainment flow, utilizes strong jets of air to internally stir relatively stagnant room air as seen in Figure 1.1.2.2. In doing so, pollutants are more evenly distributed, and high localized concentrations of contaminants are dispersed throughout the room. Consequently, areas of low contaminant concentration become worse in terms of indoor air quality. It then depends on where a person stands to determine whether or not mixing ventilation is effective in keeping room concentrations of pollutants to an acceptable level. Room concentration levels for perfect or complete mixing follow the following partial differential equation

$$q(C_s - C_e) = V\frac{dC_e}{dt} \qquad [5]$$

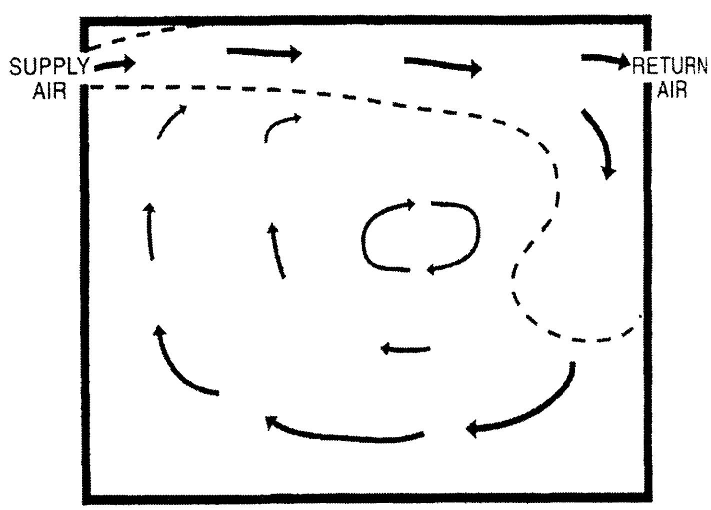


Figure 1.1.2.2 Schematic showing the method of mixing or convective flow [2]

Mixing ventilation has its drawbacks in the form of imperfect mixing, where regions of stagnation allows a buildup of contaminants, leaving pockets of poor air quality. For very large rooms, the distribution systems must supply the space using high velocity jets to ensure good mixing to the far reaches of the room as well as to counteract the effect of momentum-damping entrainment; this often leads to thermal comfort problems related to draftiness.

Displacement ventilation cooling uses low velocity diffusers located near the ground to distribute air. This fresh slow moving air stays close to the ground and when encountering a heat source such as a person or appliance, it rises due to thermal buoyancy. Contaminants are then swept away in this upward plume towards the exhaust, typically located near the ceiling, shown in Figure 1.1.2.3. In cooling, the system has been used for its ability to remove localized contaminants near the occupants quite effectively [10]. When heating is necessary, the displacement diffusers are usually used in a similar manner for normal mixing if district heating is not available.

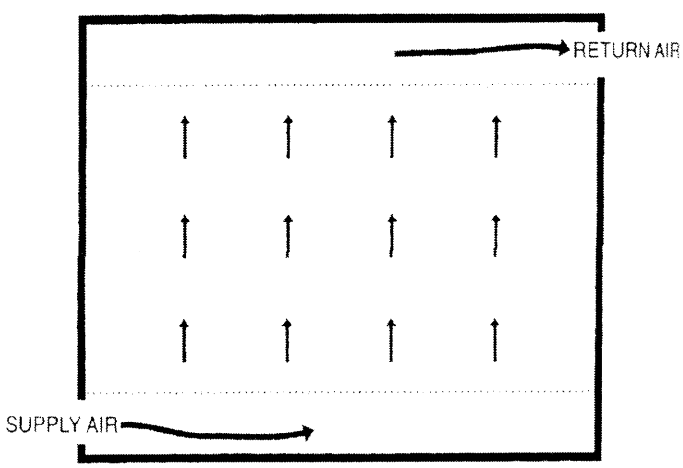


Figure 1.1.2.3 Schematic showing the method of displacement flow [2]

Displacement ventilation is the closest conventional ventilation technique to piston flow. Normally its air change efficiency is within the rage of 50%-100%, whereas the commonly used mixing ventilation can only achieve a maximum of 50%.

The cases at hand involve the introduction of outdoor air at low flowrates (and therefore velocities), which likely mimic the phenomenon generated by displacement ventilation. This is especially the case in the winter, when the outdoor air is introduced at a lower temperature than the room air. Once meeting heat sources such as the human body, the cold air heats up, and rises upward due to buoyancy.

Effects of displacement ventilation include thermal stratification and contaminant stratification, both of which are highly correlated and thus key issues in the IAQ context. Holmberg [11] has conducted numerical studies with displacement ventilation and pollutant sources. The results show characteristic similarity with that measured by Stymne [12] of contaminant stratification, but with a contaminant source close to the floor, it is difficult to avoid entrainment of these particles into the breathing zone. Thus it is imminently important to take the correct reading point for exposure, as well as to ensure that pollution sources are not located too much below the breathing zone that thermal body entrainment is not effective in bringing clean air to the occupant's breathing zone.

Stymne [12] has shown the correlation of temperature and concentration gradients with respect to the dispersal of contaminants under displacement ventilation. Experiments show that person simulators at the same level do not affect each other very much. Levels of cleaner air are located near the breathing zone, however, the body thermal boundary layer locally changes the position of the clean air interface to benefit the occupants. Pollutants located close to the body of the simulators are transported upwards due to buoyancy.

Though concentration stratifications may occur with displacement systems, the low velocity of air distribution becomes a great asset to the occupants if their breathing zone is within this region of high concentration. In a very similar manner to the theory of thermally induced buoyancy in displacement flow, occupants can generate their own "boundary layer" close to the body, entraining up cleaner air from lower levels according to experiments by Bjorn and Brohus [13, 14] and CFD simulations by Murakami [14]. Measurements indicate that the measured concentration at the orifice of the mannequin is lower than that of the general breathing zone, bolstering the notion that cleaner air is entrained from below.

However, there are disadvantages to the effects of the thermal boundary layer if the source of pollution is located in the lower occupied zone. According to Bjorn [13] the contaminants will then tend to be entrained into the breathing zone, increasing exposure. This phenomenon is shown numerically by Holmerg [11]. However, in most cases, residential contaminant sources (exhaled bio-effluents, side stream cigarette smoke, combustion products from cooking, etc.) are located high enough so that this phenomenon does not occur. Only if the supplied air is itself contaminated should there be a risk of such situations.

In a relatively quiescent case (0.03-0.08 air changes per hour or ACH), the presence of a moderately strong internal heat source (500W) will induce moderate thermal stratification according to Baughman [16]. Traditional displacement ventilation systems definitively show contaminant gradients, with lower concentrations near the floor as shown by Chen [10]. A vertical displacement ventilation system experiment by Olesen [17] reveals contaminant stratification while still allowing for high contaminant removal effectiveness, up to 200% in some locations. The lower portion of the room clearly exhibits a reduced contaminant concentration compared to higher zones. Lu [18] also shows that heat sources cause convection and "greatly influences the airflow pattern, temperature distribution and pollutant particle movement." Lu also maintains that smaller pollution particles will become entrained in the upward rising plume and become suspended in the warmer upper regions of the room.

Mixing ventilation is one of the most common methods of indoor air distribution. It counts on the dilution effect, where enough lower concentration air is mixed with higher concentration air to effectively reduce and create a more uniform distribution of contaminants in a volume. However, instead of displacing the contaminated air, the pollutants remain in the general vicinity, but at a lower concentration. A major concern in the implementation of mixing ventilation is the assurance that the combination of room air velocity is not too high (1.5-2 m/s) and temperature is not too low to cause occupant discomfort due to draft. The highest theoretical value of air change effectiveness under perfect mixing conditions is 50%.

Mixing ventilation is not the most effective method for contaminant removal, and it still poses some problems in that designed systems sometimes do not perform adequately to provide good mixing within the room [19]. Depending on the throw length of the jets that cause mixing air, the diffuser may not be able to effectively mix the room air evenly or thoroughly. In addition, the relatively high velocities involved with mixing ventilation does not allow for good thermal comfort due to draftiness.

Even at very low air flow velocities, contaminant distributions are dominated by convective over diffusive forces, where the characteristic mixing times may differ greatly according to Baughman [16]. The stronger the heat source, the greater the internal mixing will be due to natural convection.

For the cases evaluated in this thesis, the connection between displacement ventilation systems and ventilation from natural infiltration is the common theme of low velocity for the introduction of fresh air. Since mechanical extraction for infiltration cases usually consist of a range hood exhaust fan or a bathroom extract fan or a combination of the two, the locations are usually on the ceiling or high on the wall, well mimicking traditional displacement systems. What to expect in terms of performance from a displacement or low velocity ventilation situation is an ability to avert high exposure due to contaminants through both stratification and the human thermal boundary layer.

Though it is certainly difficult to assess which ventilation system is most effective at contaminant dispersal or removal, attempts have been made to characterize each of the defining physical attributes of the airflows induced by the various methods. Indeed it is the case that the study of indoor air distribution will carry on for a long time, as tools and techniques become refined over the years.

1.2 Comparison of houses with and without mechanical ventilation

In determining whether or not residential mechanical ventilation is actually effective in reducing indoor contaminant concentrations, it must be taken into consideration what levels of contaminants are likely to build up within a particular space. Parent [20] conducted a survey study of pollutant exposure in Canadian houses with differing occupancy, source strengths, air change rate, etc. The average natural infiltration rate was 0.22 air changes per hour, which is considered to be a low to medium rate. With the room occupied and the door closed, CO_2 levels in the bedroom increased steadily during the night until morning, when the door was opened, to levels greater than 3500ppm with one person occupying the room, and greater than 4500ppm with two people. Quiet replacement fans noticeably improved indoor air quality when these were operated over 50%-100% of the time.

Stratification of pollutant levels can be detected in spaces without an air distribution system. Readings show that there is a zone of higher concentration of CO_2 (200ppm) near the ceiling when people are present in the room. In addition, a difference of 300-400ppm may be measured between occupied and unoccupied rooms during sleeping hours even with the doors open. With doors closed, the CO_2 concentration in a bedroom may rise to 4000ppm until the door is opened in the morning, at which time it takes approximately 30 minutes for the concentration of the bedroom and the living room to equalize.

Studies by Fehlmann [21] show that there is little correlation between occupant's ventilation habits and the tightness of the building; it is therefore convincing that passive techniques for ventilation would be a solution to the problem. In houses without mechanical ventilation and with closed doors and windows, the air quality in bedrooms is sufficiently poor within short periods during the night; in some cases the median room concentration of CO_2 with two occupants is found in a range between 999-2973ppm (with air change rate$<0.1h^{-1}$).

With an air change rate of $0.3\ h^{-1}$ supplied by mechanical ventilation, the median concentration of CO_2 rises to 1131ppm and the CO_2 levels after 10 hours never significantly exceeded 1500ppm. Though it was not clear whether or not the windows and doors were closed, it is still significant in the fact that there is a dramatic reduction in the concentration of CO_2 in the bedrooms, where the most stagnation occurs for the longest period of time.

As seen in Figure 1.2.1, the CO_2 concentration of a room without mechanical ventilation rises almost exponentially throughout the night until morning when the door is finally opened. If the door is left open, the adjacent living room acts as a contaminant sink, tempering the accumulation of CO_2 within the room, and almost evenly dispersing between the two rooms.

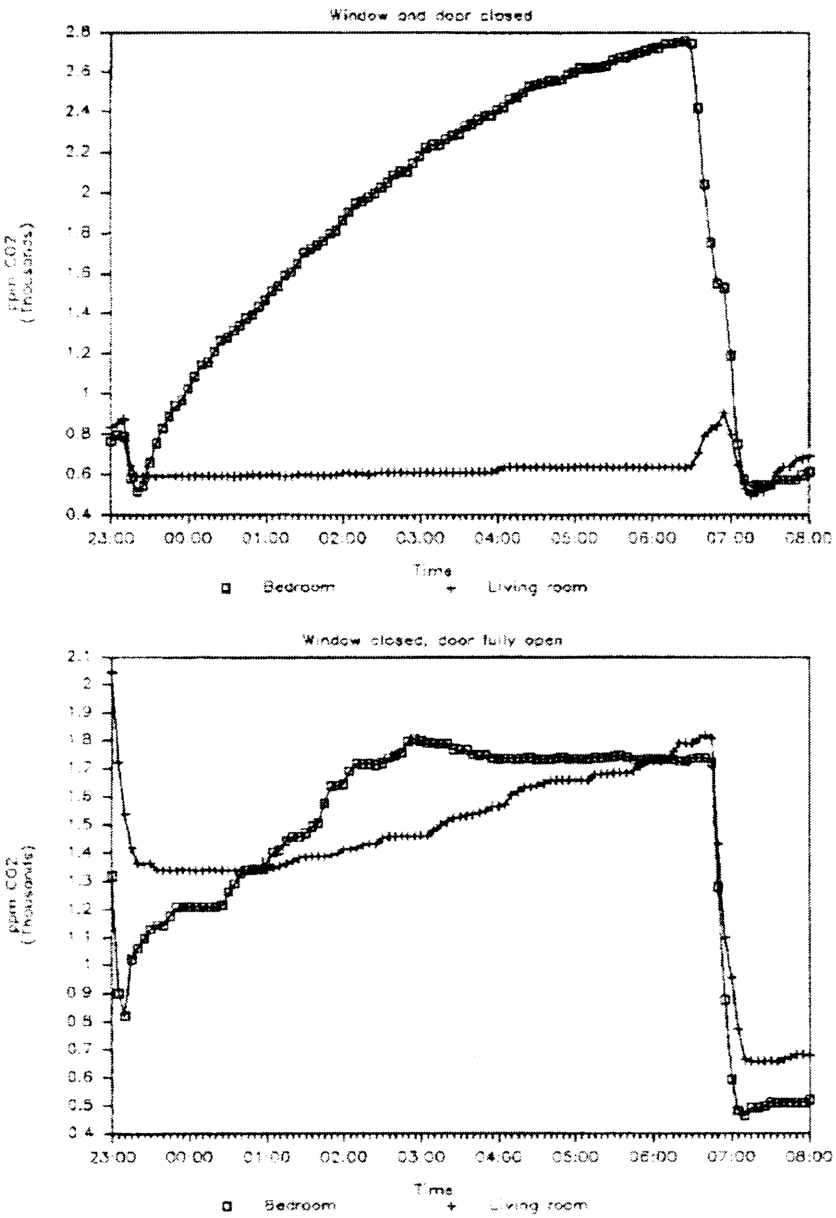


Figure 1.2.1 The measured concentration of CO_2 in a bedroom with varying ventilation conditions [21]

A study of low-infiltration housing in Rochester, NY was performed by Offermann [22] in which the indoor air quality was compared with and without mechanical ventilation for airtight houses. With an increase in the average air change rate by 80% by mechanical ventilation, the radon concentration decreased 50%, HCHO concentration decreased 21% and the average relative humidity decreased from 39% to 35%. For NO_2, the concentrations increased the average indoor concentrations slightly since the outdoor concentrations were generally higher than indoors.

When comparing a house modeled with ventilation by infiltration and active whole house ventilation, a tripling of the air change rate in the latter method decreases the CO peak emanating from a gas-fired range by 20% [23]. The whole house ventilation attempts to distribute the pollutants evenly throughout the house, making use of the fact that each of the other rooms can be considered to be a low concentration sink. This is a similar notion to leaving doors open during prolonged periods of occupation (e.g. sleeping), although it would not be quite as effective as active ventilation (with the doors open).

Tichenor's [24] data suggests that different ventilation and extraction techniques have different effects on the reduction of aerosol pollutants as well as the total personal long-term exposure. In all cases, dilution reduces the concentration and thus exposure to pollutants. The data shows that an increase in the ventilation rate by 10 times from 0.2ach may lead to a 99% reduction in exposure time to certain aerosols. Spot ventilation in the bathroom may totally eliminate the escape of an aerosol product (used in the bathroom) to the rest of the house when other distribution systems are shut off.

Much of the literature suggests that mechanical ventilation, though not often able to eliminate pollutants, can certainly help reduce the accumulated concentrations or affect migration. Specifically, the combination of supply and localized extraction can work in tandem to provide an adequate IAQ.

1.3 Kitchen Range Hood Exhaust

In addition to the ventilation inflow, extraction devices are part of the system that plays a significant role in curbing indoor contaminant buildup as well as room to room migration. Many houses, nationally and internationally use kitchen range hoods to ventilate the kitchen to reduce the amount of contaminants generated from cooking. Two common methods for cooking include the use of either an electric or gas range. While both exhibit similar performance, the gas range generally produces a greater amount of airborne contaminants due to combustion by-products or incomplete combustion. These pollutants can cause a range of influence on the occupants from mild irritation to death. Curbing the amount of contaminants is therefore a serious issue.

It may be more beneficial to the overall quality of the indoor environment if spot ventilation removed much of the contaminant at the source. This is the case for the kitchen range hood, where heat induced buoyancy and large quantities of combustion products are locally introduced and mixed. Whereas a distributed ventilation system passively waits until the pollutants migrate throughout a series of spaces and to extract them, a source ventilator can reduce the migration of much of the contaminants and eject them from the space.

Li [25] found that there are two range hood parameters of most importance: the exhaust flow rate and the horizontal dimensions of the hood. Numerical simulations show that if the hood covers the thermal plumes generated, then a 100% capture efficiency requires that the exhaust flow rate must be greater than the total plume flow rate. If, however, the exhaust flow rate is smaller than the total plume flow rate, the difference will escape into the room. If the heat source is concentrated in a much smaller area, the capture efficiency will increase; however if the size of heat source is larger, the capture efficiency will decrease. If the hood does not cover the thermal plumes, some of the cooking-polluted air can still escape even if the exhaust flow rate equals the total plume flow rate. The extra air needed for air mass conservation in the hood must be provided by room air entrainment. To have a 100% capture efficiency, the exhaust flow rate must be sufficiently high to introduce high velocity in the opening area to "suck" the escaping air into the hood. Thus the velocity-capture principle works together with the buoyancy-capture principle in this situation. It is found that buoyancy-capture is the dominant mechanism in kitchen rage hoods.

Two types of tests were done by Gotoh [26] to evaluate the boundary condition effects on the range hood capture; one type was with the door opposite the gas range open, and the other with the door closed. From the experimentation, the collection efficiency is best when the door is left open, and the air supply inlet is the furthest away from the range with a value range of about 90% when the flow rate ratio range is between 0 to 50%. A reason that there may be discrepancy between the two case types is that some of the contaminants migrate out of the testing chamber through the open door. The nominal time constant for inlet C (see Figure 1.3.1) fell just below unity, suggesting that there was not complete mixing at high inlet flowrates. It can be concluded that the open door allowed some effective dilution of the contaminants. It can be generally seen that efficiencies are highest when the inlet flow rate is about half that of the extract. But 100% capture efficiency is never attained, and is highly dependent on the flow rate and its source location.

Where Li [25] notes that buoyancy-capture methods are dominant in kitchen range hoods, Gotoh [26] says that the effectiveness of buoyancy-capture is dependent on the air inlet location. Citing a numerically derived tracer gas analysis, an air inlet located above the range hood interferes with buoyancy-driven flows (Figure 1.3.1).

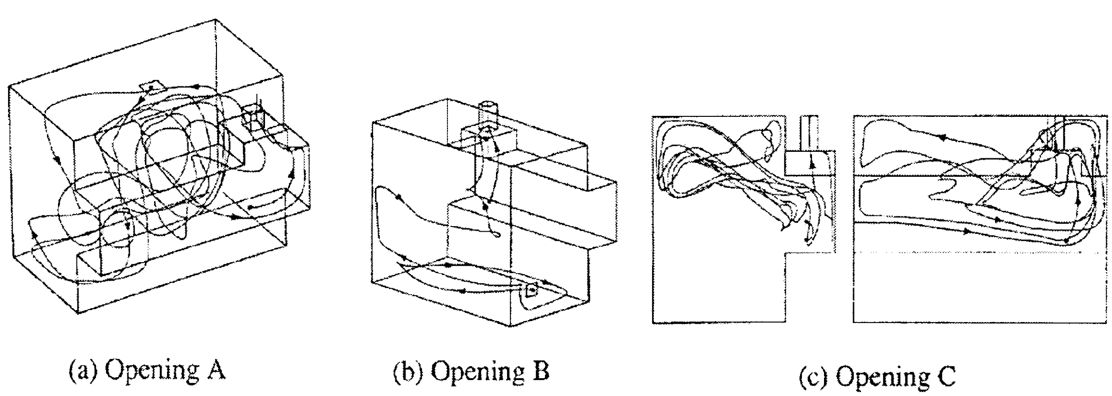


Figure 1.3.1 The influence of inlet location on contaminant removal through range hood [26]

The effectiveness of the device is dependent on when it is used. Nagda [27] has performed experiments on an unoccupied test house, and has found that a range hood fan can reduce the interior peak concentration from combustion products by 50% if the fan is turned on at the beginning of the cooking period. However, these fans were only present in about 50% of those surveyed, and were used frequently by less than half of those. The study concluded that only 12% benefited from the fans when all the factors were included.

In order to characterize the exhaust efficiency of a device, Geerinckx [28] suggests that efficiency should be directly related to the air flow rate. A proposed pollution index is defined as the relative concentration in the occupied zone for a certain extraction flow rate compared to a reference extraction at $100m^3/h$, and, according to Geerinckx, gives more information about the room pollutant levels. The pollution index has a greater bearing on the pollution concentrations in the room, and is therefore an index of "quality performance."

Though in theory, 100% capture efficiency may be achieved, it must be realized that these are for the most ideal conditions. Lateral airflows or obstructions (such as a person standing) near the exhaust have a great potential to alter flow patterns, reducing actual capture efficiency. Geerinckx's results show that an interference device (simulated by a mannequin) greatly decreases the ability of pollutant extraction.

Traynor [23] tracked emissions in a residence with a gas-fired range, to which indoor air quality was compared without ventilation (infiltration only), whole residence ventilation, and spot ventilation (range hood). The experimental data shows that the spot ventilation increased the overall air change rate by two, while the concentration of NO_x was reduced to one sixth that achieved by whole-house ventilation (Figure 1.3.2). Whereas the whole building ventilation scheme will help the transport of the pollutants to reduce the overall concentrations, localized ventilation above the source will immediately remove contaminants without their dispersion throughout the house. The range hood reduction of the average source strengths of CO, CO_2 and NO_x by 60-87% is clearly seen to be of great help to the supply of indoor air.

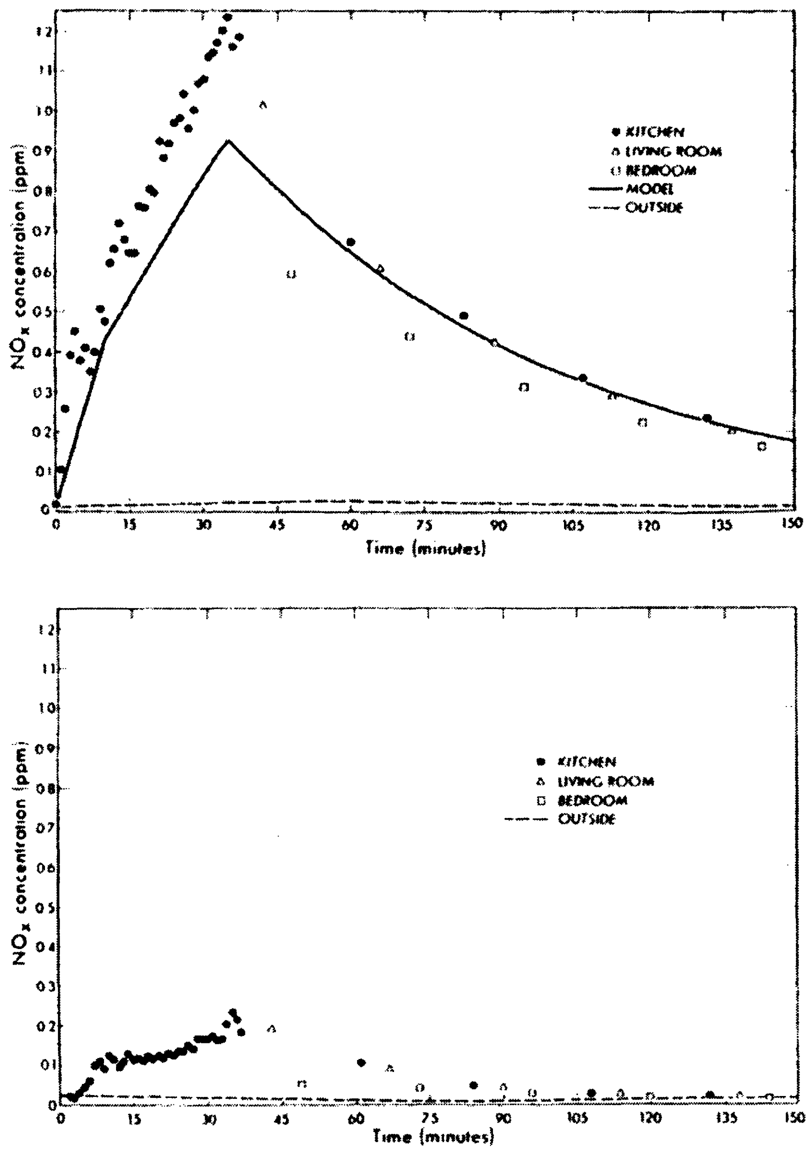


Figure 1.3.2 NO_X concentrations due to cooking throughout a house with whole building ventilation and local range hood ventilation [23]

Since whole house ventilation plays a much greater role after the range burn cycle in the reduction of contaminants, a scheme in which only the range hood is activated during the burn cycle, with whole house ventilation following the cooking time, may be employed. It would allow optimal front-end reduction through a local extract, while dispersing the remaining contaminants throughout the house effectively through dilution.

The efficacy of singular constituents of a system relies heavily upon the conditions surrounding their use. In a sterile experimental environment that is highly controlled, efficiency may be inflated over actual in-situ conditions. There is great difficulty then, in determining how each component affects the larger system. Thus it is often necessary to model situations at large, taking into considerations all the elements and their respective interactions on each other. This is most commonly known as multizone modeling.

1.4 Multizone Airflows

A more holistic view of building ventilation effectiveness integrates the effectiveness from each of the constituent spaces, thereby uniting the interactions exhibited through every room [29]. A major factor that the multi-room approach incorporates is the inclusion of fresh air moving between rooms, which may be an important event as differing rooms attain different ventilation rates and occupational habits. As is often the case, room ventilation rates are set at a constant, while the necessary fresh air requirements change as people enter or leave the room.

The overall ventilation rate fulfillment can be used to measure the effectiveness of ventilation under varying conditions. It is based on the concept of an effective fresh air supply in each room, part of which may come from interactions with other rooms. Therein lies a generalization about the evaluation in the performance of building ventilation, in which personal exposure is directly dictated by occupation and space usage.

From a microscopic scale of a single room to a macroscopic scale of a group of rooms, multizone airflows provide designers with serious challenges in terms of pollutant transport and IAQ. Room partitions and doors affect airflow and pollutant transport in different ways [4], and since exposure to contaminants is ultimately affected by occupation, different positions of these space demarcations are quite important. The issue is so important and complex that the International Energy Agency (IEA) has commissioned a branch devoted solely to the study of multizone airflow modeling within Annex 23.

In the case for residences, ventilation and extraction devices are such that inlet sources are located remotely, while the exhausts are placed centrally (as in the cases for the kitchen range hood exhaust and bathroom extraction usually located in the core of a house). This has an effect of drawing large concentrations of contaminants to specific local rooms of the house, be it the kitchen or the bathroom. If the occupants are in this immediate vicinity, the exposure to these contaminants would be proportionally increased in other ways that it normally might not. Typically when locating a source in a part of a house, the more remote a room is, the greater the effects of migrating contaminants lag their emittance. The effects of this can be either advantageous or not.

In addition to be much more spatially complex, multizone systems also have uneven air distribution due to different room sizes and varying degrees of airflow resistance between rooms. Interroom airflow is uncontrolled, in that there is not a specific system that is in place to regulate the exchange of air between zones. Since more flow will occur through rooms with the least amount of flow resistance, to specify this value beforehand for numerical simulation is a difficult task. In-situ measurements of building systems presents its own set of difficulties, mainly stemming from uncontrolled infiltration of outside air though the inevitable cracks in the walls.

Experimental methods to track multizone flow are somewhat more straightforward that that derived from CFD calculations, as they are based on the performance of a physical space. Data collected from Traynor [23, 30] show that pollution sources in one room of a single-family house can have a significant effect on the room concentrations in another corner of the house. The interroom transport may be a strong enough mechanism to reduce the concentration of migrated contaminants due to dilution. Depending on the distance between the measurement point and the source location, the concentration of the room exhibits varying degrees of concentration increase, although the decay after the peak concentration falls at a somewhat constant rate. This seems to show that there is a degree of mixing to an extent that there is even dilution of contaminants throughout the house after a certain amount of time, and that the ventilation system then removes these pollutants at an even rate.

It was observed that small increases in ventilation rates resulting from the opening of the doors 2.5cm did not reduce short-term peak pollutant concentration in the bedroom only because the shutdown point for the heaters (temperature increase of 8°C) took longer to achieve. Although the peak pollutant concentrations may not be reduced, the effect of inter-room transport is high enough to invoke pollution dilution for a single room. The study also shows that even with doors closed, there is a small exchange rate between rooms, thus allowing for pollutant migration, even after the heaters are shut off. With the bedroom door wide open, just as in Fehlmann's case [21], the bedroom CO_2 concentration was almost identical to the living room and kitchen values.

Rudd [31] tracked an injected amount of SF_6 though the supply air ducts of a single-family house without the operation of the central distribution fan. Non-uniform distribution of the tracer gas throughout the various rooms of the house was most likely due to the various distances between the location of the tracer gas injection and the detection sensor, although each of the six zones measured showed a growth and decay of SF_6. Time lag due to system complexity is exhibited quite clearly here.

In a study performed by Kolokotroni [32], vapor and SF_6 were tracked through a house with humidity controlled ventilation systems consisting of a range hood extract and a bathroom extract. Correlations between the migration of vapor and the tracer gas were liked to an index called the transfer index (TI). The linkages between the rooms are based on how close the rooms are to each other. With higher proximity to the extract outlet, fans situated closer to the source of effluents increase the removal efficiency. The study also shows that moisture deposition composes a large portion of the transfer, so that it should not be considered negligible, in this case. The intermittency of the humidity-controlled system increases the effect of extraction over the uniform increase of ventilation rates, as well as reducing energy usage.

Door positions not only reduce the volume of airfow in and out of a zone, it also reduces the total available volume of air for which a contaminant is present for dilution. Leslie's [33] measurements of a single-family house indicated that the isolation of rooms via doors provide an effective deterrent for pollution flow, as well as increasing the concentrations in the room that the source was located due to a reduced potential volume. Again, weak coupling of pollutant transport between zones occurs due to unintended cracks around the doorways.

Boassaer [34] measured the concentration of CO_2 injected into a bedroom with the door open and closed and found that with the door closed, there may be more than four times the peak concentration of CO_2 in the room. When comparing the experimental data with that obtained through a numerical simulation, fractional factorial analysis shows that other influences other than the rate of contaminant injection may greatly influence the outcome of the results. This shows that the use of a simulation method is a delicate process, and if not performed correctly, may not prove to be a robust enough tool for analysis.

In addition to the fact of the existence of a door in a partition, the position of the door with respect to the walls is an important consideration that must be taken into account according to Haghighat [35]. For a forced air system in a two partitioned room, the average age of air in the room containing the supply air decreases as the door opening is moved from one side of the room to the other, while in the exhaust room, the age of air is greatest when the door is in the middle of the partition. Also show is the relative unimportance on exhaust position in the x-direction, while the position of the supply location (y-direction) and the door position (y-direction) affects the contaminant concentration in the supply room only; the exhaust room is relatively unaffected by these changing positions.

Like doorways, obstructions have serious effects on indoor airflow distribution. Chung [36] evaluated a semi-partitioned room to find that there is a buildup of low ventilation efficiency downstream of the partition with respect to the inlet location. This has serious implications for people that are occupied in this location, in that they may be subject to air quality that may be detrimental to their health, or at least make them uncomfortable.

For a multi-story apartment building, Herrlin [37] has examined, using a proprietary nodal multi-zone modeling tool, two ventilation conditions of supply with and exhaust system (ES), and an exhaust system with passive makeup air inlets (E). His studies show that a mechanical extract exhaust system is generally a good method to prevent the spread of contaminants from one apartment to another. Overall, the ES system decreased the concentrations of contaminants in the lower level apartments better than the exhaust only system, but has shown that there is a higher rate of attenuation of the pollutants in the upper apartments due to buoyancy induced cross contamination (through a stairwell between the lower and upper floors) that was more dominant in the ES case. Though the results are based on apartment units that are closed off from one another, leakages between the apartments allowed also an interchange of contaminants. Time lags for the migration of pollutants between apartments are show for both transient and steady-state cases, and show that the behavior on a large-scale system is similarly exhibited on a smaller, apartment-level scale.

The modeling of multizone systems is a difficult matter, since room interactions play a significant role in determining the general airflow throughout the building. Usually, two zone systems are modeled. Lu [38] concludes that particle movement between zones is highly dependent on the airflow pattern. Main discrepancies between the numerical model and the experimental data occur due to a divergence of curves due to increased uncertainty of both systems. As well, the study indicated that the geometry of the interzonal opening plays a role in the ability for migration, where larger openings help to distribute the particles more quickly.

In another experiment performed by Chung [39], correlations between experiments and CFD for a three room multizonal model, velocities have a reasonably small difference on average (9%), but may be as large as 32% in specific locations. Contaminant particle paths are dependent on the region of the room in which they originate due to localized flow effects (recirculation zones, etc.) and are highly dependent on a correct velocity field, as Lu states.

Multizone systems force a great deal of difficulty on numerical modeling as there are a greater number of uncertainties that present itself with a more complex system. To say that CFD or other such techniques can predictively model airflow patterns and contaminant distributions would be somewhat of a stretch. The technique should be seen as one that might provide one solution, or part of a solution to the multizone problem. Experimental measurements provide another such technique to come up with a solution. Both methods present idealized situations of actual occurrences in nature, and because of uncertainty, both solution methods are inherently misleading.

The coupling or at least validation of a computer model to the data derived from experimental measurements is tricky. Although simplifications may be enforced with the modeling (such as the assumption of perfect mixing), the specifics may not be fully captured by these methods. To be sure, even with some of the data provided by experimentation, a limited view of the airflow interactions between the rooms is not detailed. The large system precludes even simplification of testing methods to such a degree that implementation of any evaluation tool may be fundamentally feasible, but specifically flawed.

1.5 Conclusion

Separately, constituent aspects of room ventilation and conditioning play an important role in the method of occupational exposure. Many techniques may be utilized to reduce contaminant concentrations while providing the necessary indoor comfort. As noted in the section about multizone modeling, geometries and situations are very complex, and are often in flux so that temporal and spatial concerns must be incorporated to derive a more correct modeling procedure. This study intends not only to find correlations between the individual components to study the combination as a system, but how location and time affects exposure. This system approach is quite important, since constituent interactions often are not predictable without modeling or testing them together. It is in this context that the thesis should be evaluated.

2 Research Approach

To model the contaminant exposure that the occupants face, it is necessary that an accurate modeling technique be employed. Since the indoor flows are quite complex and the transport of contaminants is highly dependent on these room airflows, often a perfect mixing model is used to determine an average room contaminant concentration level. The clear advantage of such a model is its simplicity, which is calculable by hand. The heavy tradeoff stems quite clearly from the fact that it assumes instantaneous and complete mixing of the volume in which the contaminant source is located, in effect averaging a value throughout the whole room. Experimentation is another method to assess pollutant migration, but the test facilities are very costly and the data collection time consuming. It is therefore determined that CFD provides the most accurate results in a minimum amount of time and without expensive experimental infrastructure. Most CFD simulations can be performed on a personal computer with commercial software. The CFD model solves the conservation equation of mass, momentum, energy, and species concentrations.

2.1 House Plan

This study used a house plan transcribed directly from the Mozart House from "Catalogue de Logements-Types [40]," shown in Figure 2.1.1. The Mozart House has a floor area of 99.6 m^2 and is considered to be a typical French dwelling, to which the greatest universality may be applied. The single-family house shown below in Figure 2.1.2 is the CFD model adaptation without the garage, and consists of a dining/living room (36.5m^2), a kitchen (9.5 m^2), two childrens' bedrooms (10.9m^2 and 11.1m^2), a bathroom with a shower (3.2m^2), a WC (1.7 m^2), and a master bedroom (10.1m^2), each containing a variety of everyday furniture. Furniture is included as it normally affects the airflow throughout the house [5] as well as changes the location of the person relative to the room (e.g. sleeping on a bed elevates the body). These factors have been included for a closer approximation to reality.

4.2 - Maison Mozart

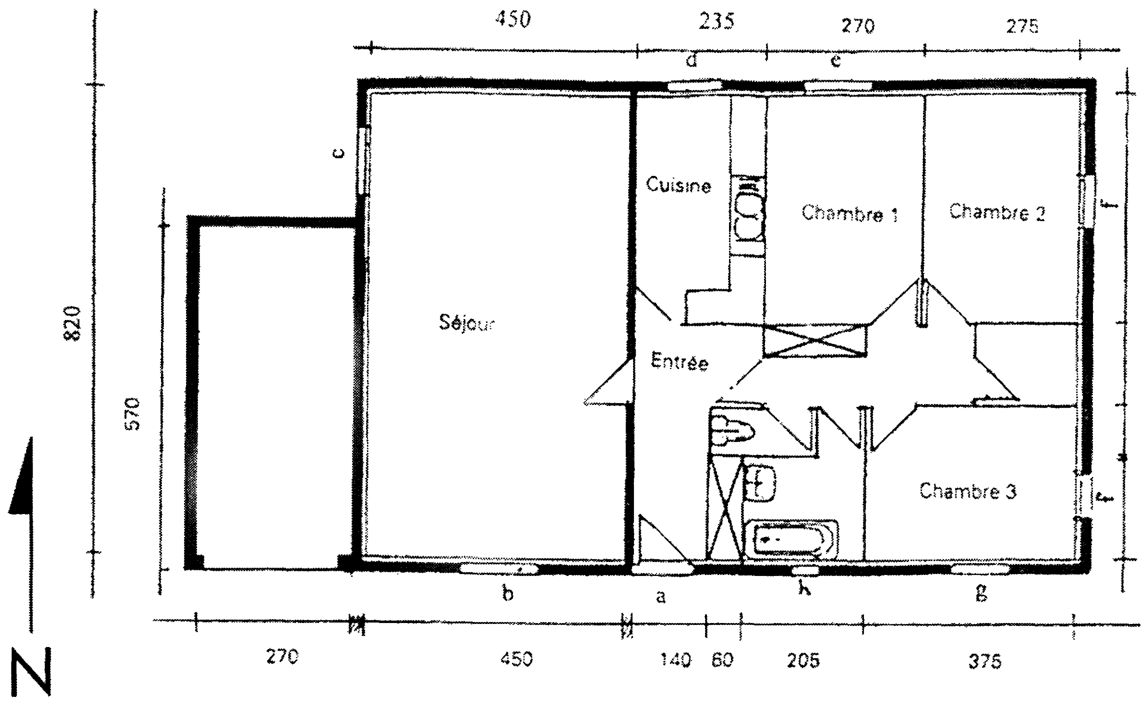


Figure 2.1.1 Mozart House floor plan from "Catalogue de Logements-Types" used in the research [40]

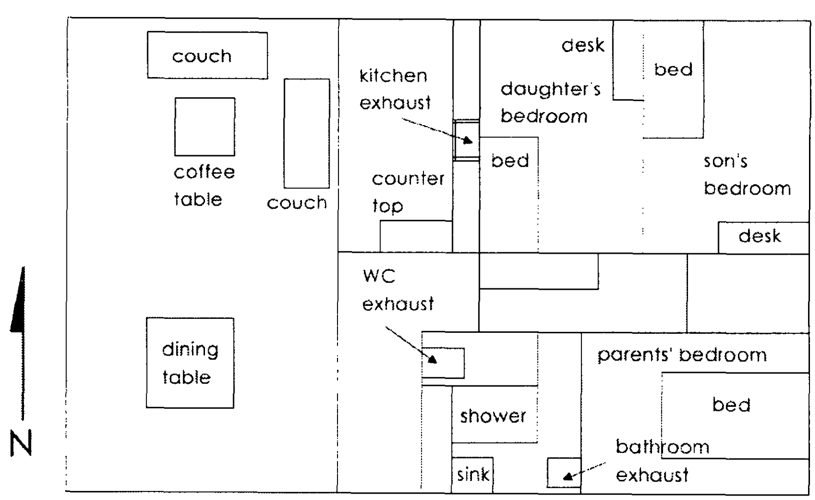


Figure 2.1.2 CFD model adaptation of the Mozart House including furniture types

2.2 Occupancy Scenario

A typical family of four, including two parents, a son, and a daughter occupies the house for about fifteen hours of the day. The location of each person in the house throughout the day is shown in Table 2.2.1. Between 09.00-18.00h, the parents work and the children attend school, so nobody is at home. Each person's activity throughout the day is shown in Table 2.2.1.

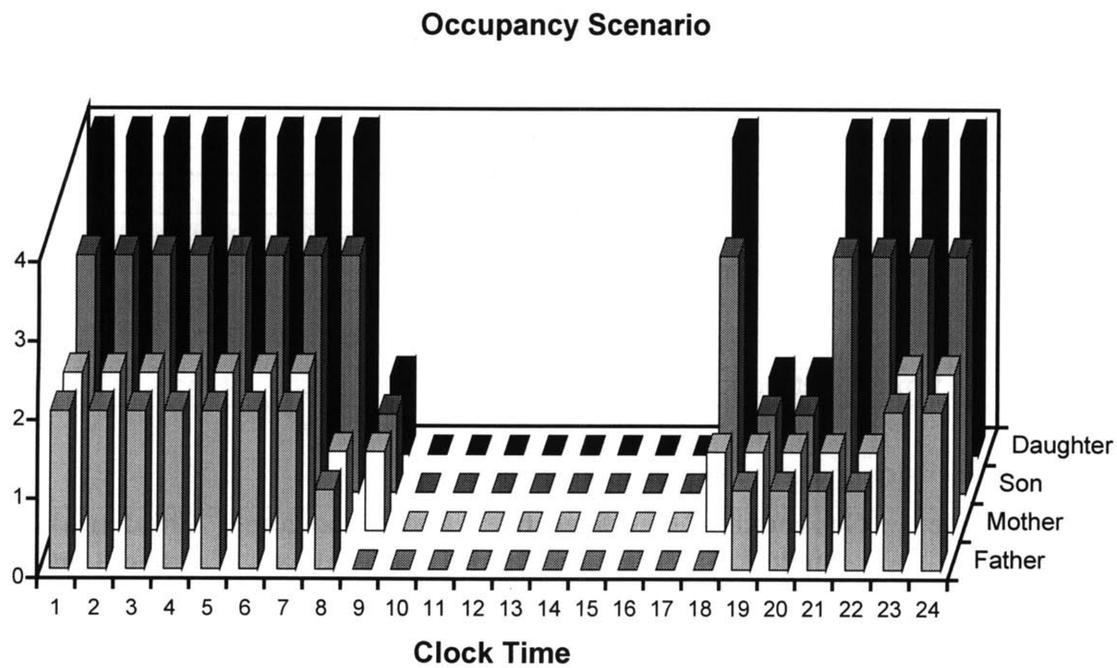


Figure 2.2.1 Occupancy scenario for each person spent at home: (0) not at home (1) dining/living room (2) parents' bedroom (3) son's bedroom (4) daughter's bedroom

Table 2.2.1 Person's activity throughout the day

<table>
<tr><th>Hour</th><th>Mother</th><th>Father</th><th>Son</th><th>Daughter</th></tr>
<tr><td>18.00-19.00</td><td>Cooking</td><td>Not home</td><td>Studying</td><td>Studying</td></tr>
<tr><td>19.00-21.00</td><td>Eating Dinner</td><td>Eating Dinner</td><td>Eating Dinner</td><td>Eating Dinner</td></tr>
<tr><td>21.00-22.00</td><td rowspan="2">Reading</td><td rowspan="2">Reading (Smoking)</td><td>Studying</td><td>Studying</td></tr>
<tr><td>22.00-23.00</td><td rowspan="6">Sleeping</td><td rowspan="6">Sleeping</td></tr>
<tr><td>23.00-07.00</td><td>Sleeping</td><td>Sleeping</td></tr>
<tr><td>07.00-07.15</td><td>Cooking</td><td>Showering</td></tr>
<tr><td>07.15-07.30</td><td>Showering</td><td rowspan="2">Eating Breakfast</td></tr>
<tr><td>07.30-07.45</td><td rowspan="2">Eating Breakfast</td></tr>
<tr><td>07.45-08.00</td><td rowspan="4">Not home</td></tr>
<tr><td>08.00-08.15</td><td rowspan="2">Cooking</td><td>Sleeping</td><td>Showering</td></tr>
<tr><td>08.15-08.30</td><td>Showering</td><td rowspan="2">Eating Breakfast</td></tr>
<tr><td>08.30-09.00</td><td>Reading</td><td>Eating Breakfast</td></tr>
</table>

2.3 Pollution Sources and Boundary Conditions

Characteristic of residential indoor environments, a variety of pollutant sources are placed within the house based on the type and level of activity. These include CO_2, CO, HCHO (formaldehyde), NO_2, and water vapor (H_2O). The characteristics of the pollutants are shown in Table 2.3.1, and the pollutant source strengths used in the simulations are shown in Table 2.3.2 and Table 2.3.3. It should be noted that the ambient condition for water vapor is taken to be zero. This is due to the fact that in the summertime, when the humidity is high, the background concentration for water vapor would be too high for any appreciable increase due to metabolic activities to be relevantly detected in the analysis.

Table 2.3.1 Pollutant description of typical indoor contaminants used

Pollutant	Description
CO_2	Typical metabolic bioeffluent that changes based on type of activity
CO	Typical cooking pollutant
NO_2	Typical cooking pollutant
HCHO	Tracer for contaminants associated with smoking
Vapor (H_2O)	Typical metabolic bioeffluent and tracks the influence of the shower

Table 2.3.2 Pollution source strengths used in the simulations

	Outside [ppm]	Gas cooking [g/kJ]	Cigarette Smoking [g/s]	Adult awake (asleep) [g/s]	Child awake (asleep) [g/s]
CO_2	307.4	0.045	0.00065	0.0099 (0.0066)	0.0066 (0.0022)
CO	0.116	0.00005	0.00011	0	0
NO_2	0.064	0.000011	0.0000018	0	0
HCHO	0.00896	0	0.0000037	0	0

Table 2.3.3 Vapor source strengths used in the simulations

	Adult awake (asleep) [g/h]	Child awake (asleep) [g/h]	Breakfast [g/person]	Dinner [g/person]	Shower [g/person]
Vapor	55 (30)	45 (15)	50	300	300

There are three factors to consider with respect to air conditioning when simulating the indoor environment. These factors include:

1. Ventilation System
2. Heating System
3. Climactic Conditions

2.3.1 Ventilation System

Three ventilation systems are evaluated in this study are:

1. Bimodal exhaust: varies between the base rate and the increased rate only when cooking
2. Relative humidity controlled exhaust (RHC): varies between a minimum and maximum exhaust value based on the relative humidity at the exhaust
3. Balanced ventilation: directly introduces (forced) conditioned air into the rooms, with the bimodal exhaust system in place

The bimodal ventilation system has constant exhaust at the bathroom and WC locations, with a kitchen range hood exhaust fan that increases its flow rate only when cooking. All other times, it exhausts at the base rate. Table 2.3.1.1 outlines the exhaust rates used for the bimodal ventilation system.

Table 2.3.1.1 Exhaust flow rates for bimodal ventilation

	Kitchen	Bathroom	WC
Normal flow rate [m^3/h]	45	30	15
Cooking flow rate [m^3/h]	120		

In addition to a bimodal ventilation system, a relative humidity controlled (RHC) system will be simulated to see the differences in performance on personal exposure. Table 2.3.1.2 and Table 2.3.1.3 describe the variation of the ventilation rate at the exhausts based on the relative humidity recorded at the exhaust.

Table 2.3.1.2 Minimum and maximum flow rates of the humidity controlled ventilation system

	Kitchen	Bathroom	WC
Minimum flow rate [m^3/h]	45	30	15
Maximum flow rate [m^3/h]	120	65	30

Table 2.3.1.3 Humidity controlled ventilation rate changes

	RH < 30%	30% < RH < 70%	70% < RH
Exhaust ventilation rate	Minimum value	Linear variation between min and max	Maximum value

The balanced ventilation system is the most complex of the three systems. Each of the three bedrooms and the living room are supplied with conditioned air from diffusers at a constant rate of 22.5m^3/h. Due to the limitations of the bimodal exhaust, there is a mass flow imbalance during cooking when the exhaust rates increase. Therefore, all makeup air is taken up through inlets (simulated as the window area) to draw in outdoor air. These principles are outlined in the following section about the infiltration setup.

2.3.2 Heating System

Two types of heating are evaluated:

1. Radiant panels in the living room, convectors in all other rooms (convector case)
2. Heated floor in the living room, convectors in all other rooms (heated floor case)

For space heating, room convectors condition the interior with a heat of 750W. They are generally situated underneath a window to counteract cold air infiltration and negative buoyancy. In the living room, there are two radiation panels located underneath the windows. The simulated occupied zone had a temperature between approximately 17.5-21°C in the winter cases. For the summer cases, no heating or cooling is used.

This CFD model does not include a radiation model. The impact of radiation is taken into consideration when setting the wall temperatures and other heat fluxes. The wall temperatures were set using data provided by a Clim2000 simulation [41], which provides the exterior wall, ceiling, and floor temperatures for the convector cases as shown in Table 2.3.2.1. Table 2.3.2.2 shows the data associated with the heated floor case. The heated living room floor is assumed to have a uniform temperature along the entire area of the floor. The interior walls are adiabatic and do not affect pollutant concentrations due to absorption. The day zone includes the living room, kitchen, and hallway, while the night zone encompasses the three bedrooms and the bathroom. Table 2.3.2.3 shows the data for the summer case, while Table 2.3.2.4 shows the results of the convector case with balanced ventilation.

Table 2.3.2.1 Clim2000 data including exterior wall, floor and ceiling temperatures at hourly intervals throughout a typical winter day for the convector case with bimodal or RHC ventilation

	Day Zone Temperature [°C]			Night Zone Temperature [°C]		
Hour	Walls	Floor	Ceiling	Walls	Floor	Ceiling
0	18.0	18.0	18.5	18.0	17.9	18.5
1	18.2	18.0	18.7	18.02	18.0	18.7
2	18.2	18.0	18.7	18.2	18.0	18.7
3	18.2	18.0	18.7	18.2	18.0	18.7
4	18.2	18.0	18.7	18.2	18.0	18.7
5	18.2	18.0	18.7	18.2	18.0	18.7
6	18.2	18.0	18.7	18.2	18.0	18.7
7	18.2	18.0	18.7	18.2	18.0	18.7
8	18.2	18.0	18.7	18.2	18.0	18.7
9	18.2	18.0	18.7	18.2	18.0	18.7
10	18.2	18.1	18.7	18.2	18.0	18.7
11	18.2	18.1	18.7	18.2	18.0	18.7
12	18.2	18.1	18.7	18.2	18.1	18.7
13	18.2	18.1	18.7	18.2	18.1	18.7
14	18.2	18.1	18.7	18.2	18.1	18.7
15	18.2	18.1	18.7	18.2	18.1	18.7
16	18.2	18.1	18.7	18.2	18.1	18.7
17	18.2	18.1	18.7	18.2	18.1	18.7
18	18.2	18.1	18.7	18.2	18.1	18.7
19	18.2	18.1	18.7	18.2	18.1	18.7
20	18.2	18.1	18.7	18.2	18.1	18.7
21	18.2	18.1	18.7	18.2	18.1	18.7
22	18.2	18.1	18.7	18.2	18.1	18.7
23	18.2	18.1	18.7	18.2	18.1	18.7

Table 2.3.2.2 Clim2000 data including exterior wall, floor and ceiling temperatures at hourly intervals throughout a typical winter day for the heated floor case with bimodal or RHC ventilation

	Day Zone Temperature [°C]			Night Zone Temperature [°C]		
Hour	Walls	Floor	Ceiling	Walls	Floor	Ceiling
0	18.2	23.5	18.7	18.0	17.9	18.5
1	18.2	23.6	18.7	18.2	18.0	18.7
2	18.2	23.6	18.7	18.2	18.0	18.7
3	18.2	23.5	18.7	18.2	18.0	18.7
4	18.2	23.5	18.7	18.2	18.0	18.7
5	18.2	23.5	18.7	18.2	18.0	18.7
6	18.2	23.5	18.7	18.2	18.0	18.7
7	18.2	23.5	18.7	18.2	18.0	18.7
8	18.2	23.5	18.7	18.2	18.0	18.7
9	18.2	23.5	18.7	18.2	18.0	18.7
10	18.2	23.5	18.7	18.2	18.0	18.7
11	18.2	23.5	18.7	18.2	18.1	18.7
12	18.2	23.5	18.7	18.2	18.1	18.7
13	18.2	23.5	18.7	18.2	18.1	18.7
14	18.2	23.5	18.7	18.2	18.1	18.7
15	18.2	23.5	18.7	18.2	18.1	18.7
16	18.2	23.5	18.7	18.2	18.1	18.7
17	18.2	23.5	18.7	18.2	18.1	18.7
18	18.2	23.5	18.7	18.2	18.1	18.7
19	18.2	23.5	18.7	18.2	18.1	18.7
20	18.2	23.5	18.7	18.2	18.1	18.7
21	18.2	23.5	18.7	18.2	18.1	18.7
22	18.2	23.5	18.7	18.2	18.1	18.7
23	18.2	23.5	18.7	18.2	18.1	18.7

Table 2.3.2.3 Clim2000 data including exterior wall, floor and ceiling temperatures at hourly intervals throughout a typical summer day

	Day Zone Temperature [°C]			Night Zone Temperature [°C]		
Hour	Walls	Floor	Ceiling	Walls	Floor	Ceiling
0	25.0	25.0	25.0	25.0	25.0	25.0
1	25.0	25.0	25.0	25.0	25.0	25.0
2	25.0	25.0	25.0	25.0	25.0	25.0
3	25.0	25.0	25.0	25.0	25.0	25.0
4	25.0	25.0	25.0	25.0	25.0	25.0
5	25.0	25.0	25.0	25.0	25.0	25.0
6	25.0	25.1	25.0	25.0	25.2	25.0
7	25.1	25.2	25.0	25.1	25.3	25.1
8	25.1	25.3	25.1	25.2	25.8	25.3
9	25.2	25.5	25.2	25.4	25.9	25.4
10	25.3	25.7	25.3	25.6	26.2	25.6
11	25.5	25.9	25.4	25.8	26.4	25.8
12	25.6	26.0	25.5	26.0	26.4	25.9
13	25.7	26.1	25.6	26.2	26.6	26.0
14	25.8	26.3	25.8	26.3	26.7	26.2
15	25.9	26.3	25.8	26.4	26.7	26.3
16	26.0	26.5	25.9	26.5	26.8	26.4
17	26.1	26.6	26.0	26.6	26.8	26.4
18	26.2	26.7	26.1	26.6	26.7	26.4
19	26.3	26.6	26.2	26.6	26.7	26.4
20	26.3	26.4	26.2	26.5	26.6	26.4
21	26.2	26.3	26.1	26.5	26.5	26.4
22	26.2	26.3	26.1	26.4	26.5	26.3
23	26.1	26.3	26.1	26.3	26.5	26.3

Table 2.3.2.4Clim2000 data including exterior wall, floor and ceiling temperatures at hourly intervals throughout a typical winter day for the convector case with balanced ventilation

	Day Zone Temperature [°C]				Night Zone Temperature [°C]			
Hour	Walls	Floor	Ceiling	Inlet	Walls	Floor	Ceiling	Inlet
0	18.1	18.6	18.2	13.2	18.0	18.5	18.0	13.2
1	18.2	18.7	18.2	13.3	18.2	18.7	18.0	13.3
2	18.2	18.7	18.2	13.3	18.2	18.7	18.0	13.3
3	18.2	18.7	18.2	13.3	18.2	18.7	18.0	13.3
4	18.2	18.7	18.2	13.3	18.2	18.7	18.0	13.3
5	18.2	18.7	18.2	13.3	18.2	18.7	18.0	13.3
6	18.2	18.7	18.2	13.3	18.2	18.7	18.1	13.3
7	18.2	18.7	18.2	13.3	18.2	18.7	18.1	13.3
8	18.2	18.7	18.2	13.3	18.2	18.7	18.1	13.3
9	18.2	18.7	18.2	13.3	18.2	18.7	18.1	13.3
10	18.2	18.7	18.2	13.3	18.2	18.7	18.1	13.3
11	18.2	18.7	18.2	13.3	18.2	18.7	18.1	13.3
12	18.2	18.7	18.2	13.3	18.2	18.7	18.1	13.3
13	18.2	18.7	18.2	13.3	18.2	18.7	18.1	13.3
14	18.2	18.7	18.3	13.3	18.2	18.7	18.1	13.3
15	18.2	18.7	18.3	13.3	18.2	18.7	18.1	13.3
16	18.2	18.7	18.3	13.3	18.2	18.7	18.1	13.3
17	18.2	18.7	18.3	13.3	18.2	18.7	18.1	13.3
18	18.2	18.7	18.3	13.3	18.2	18.7	18.1	13.3
19	18.2	18.7	18.3	13.3	18.2	18.7	18.1	13.3
20	18.2	18.7	18.3	13.3	18.2	18.7	18.1	13.3
21	18.2	18.7	18.3	13.3	18.2	18.7	18.1	13.3
22	18.2	18.7	18.3	13.3	18.2	18.7	18.1	13.3
23	18.2	18.7	18.3	13.3	18.2	18.7	18.1	13.3

2.3.3 Climactic Conditions

Winter and summer are the two seasonal conditions that are also considered. Winter outdoor conditions are at 0°C and 50% relative humidity, corresponding to a humidity ratio of $2\frac{g_{water}}{kg_{dry-air}}$. The infiltration air during the summer is at 25°C with a humidity ratio of $15.5\frac{g_{water}}{kg_{dry-air}}$, corresponding to a relative humidity of 78%.

The combination of cases evaluated is shown in Table 2.3.3.1.

Table 2.3.3.1 The cases to be evaluated from a combination of the three parameters

Season	Ventilation System	Heating System
Winter	Bimodal	Convectors
Winter	Bimodal	Heated Floor
Winter	RHC	Convectors
Winter	RHC	Heated Floor
Winter	Balanced	Convectors
Summer	Bimodal	N/A
Summer	RHC	N/A

2.4 Infiltration Setup

When the windows are closed and there are active extract devices, the only way to conserve mass is through infiltration. Extraction of indoor air through the exhausts creates a low pressure, or a vacuum inside the house. In an attempt to equalize the amount of air within the house, air is either drawn in or pushed out through the exterior, usually through cracks in the walls. Typically, the area around the windows has large cracks due to improper sealing of the window casing. It is around the windows that infiltration is thus modeled in CFD. This section describes the method of infiltration modeling within the CFD simulations.

2.4.1 Bimodal and RHC ventilation

Since it is considered to be the season that would contribute to the worst indoor air quality, the winter season is simulated. As the windows are shut for the entire day, fresh air is induced only through infiltration. The bedroom and bathroom doors are open, unless the room is occupied; all other doors are left open. The closed doors have a 0.1m gap between the bottom of the door and the floor, which weakly couples the rooms to the hallway. For the summer case, the windows are still modeled shut to make independent the effects of mechanically induced infiltration and that created through wind driven pressure. Since only mechanical extract devices are used in the bimodal and RHC systems, only infiltration occurs.

As the floor plan is complicated, infiltration for each room is based upon the varying pressure drops that occur through the rooms with the exhaust fans. Since doorways constitute a greater resistance to airflows, a separate simulation must be performed beforehand to determine the amount of mass flow through each of the windows. Every time that there are different boundary conditions (e.g. closed doors or different kitchen exhaust rate), a new preliminary simulation must be performed to ascertain the correct mass flow rate of the infiltrating air.

Table 2.4.1.1 shows an example of the changing infiltration rates due to various differences in the boundary conditions for the bimodal system. From 18.00-19.00h, the kitchen exhaust fan is at the high setting, and the childrens' bedroom doors are closed. From 19.00-21.00h, the kitchen exhaust fan is at the low setting, and the childrens' bedrooms doors are open. There is a decrease in the infiltration for each room due to the decrease of the kitchen exhaust rate. These values are subsequently set as the boundary condition for the real simulation.

Table 2.4.1.1 An example of differing infiltration due to changing boundary conditions for the bimodal system that shows a decrease in room infiltration when the exhaust rate decreases

	Infiltration mass flow rate per window area [$m^3/h/m^2$]	
	18.00-19.00h	19.00-21.00h
Living Room	21.48	11.39
Kitchen	11.84	5.89
Daughter's Bedroom	6.86	5.79
Son's Bedroom	10.73	5.78
Parent's Bedroom	21.50	11.52
Bathroom	11.46	5.96

Figure 2.4.1.1 shows examples of possible infiltration pathways. Path A from the living room has a relatively easy and direct trajectory to the kitchen exhaust, whereas Path B from the son's bedroom is relatively complicated. The air must pass through more flow restrictions that decrease the effect of infiltration.

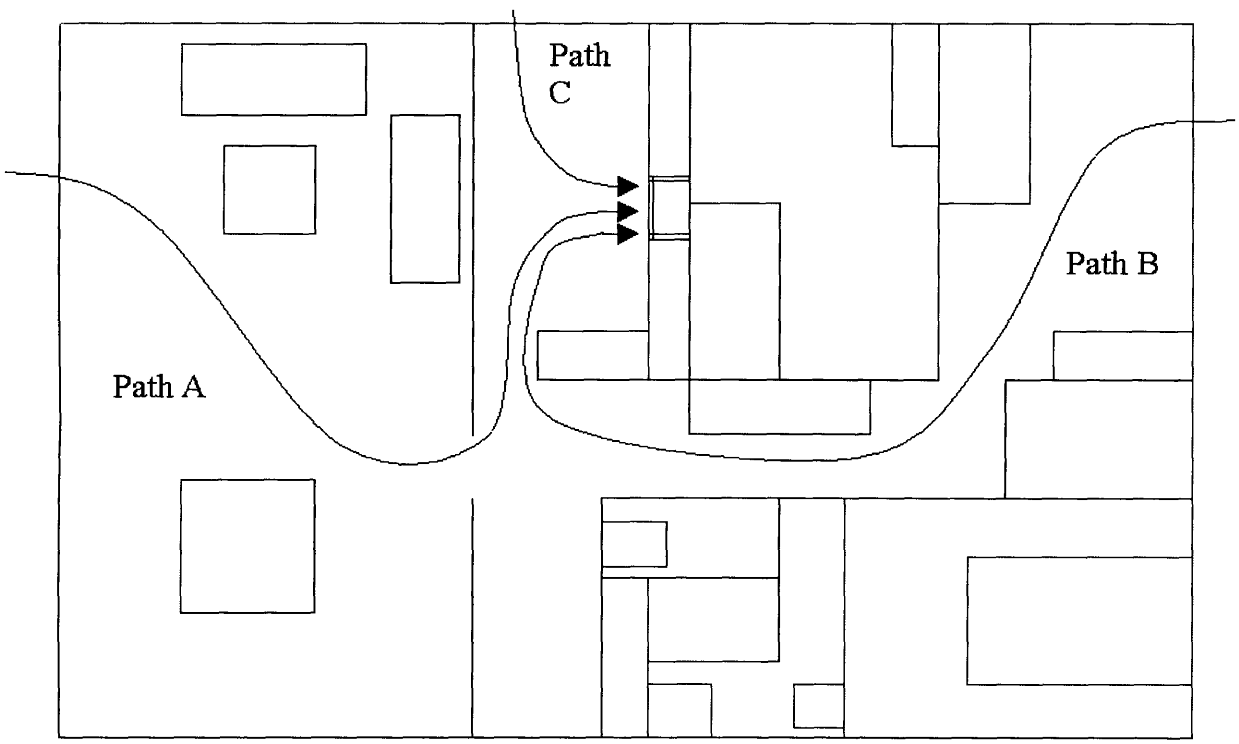


Figure 2.4.1.1 Schematic of infiltration pathways with different flow restrictions

A room with a closed door is less influential with regard to infiltration, since the small opening under the door inhibits free flow of the interior air out into the hallway. Thus windows in rooms that contain exhaust fans should induce the most infiltration per window area, as shown in Table 2.4.1.1. For instance, the kitchen window experiences the most infiltration as it has the most direct pathway to the kitchen exhaust (Path C of Figure 2.4.1.1). When the bathroom door is closed when the family showers in the morning, the bathroom window infiltrates the most outside air, since it the most direct route to the exhaust fan.

The following table shows an example of how the operation of the fan and the door positions affect room airflows for the bimodal system. Decreasing the kitchen exhaust rate by 62.5% (from 120m^3/h to 45m^3/h) incurs a decrease of the whole house ACH due to infiltration by 46.3%, and decreases the kitchen ACH by 50.0%. Although the global ACH always remains at the two values of 0.67 and 0.36 respectively for times of cooking and non-cooking (since the exhaust fan rates dictate whole house ACH), individual room ACH differ based upon whether or not the doors are closed. The values of the room ACH are presented in Table 2.4.1.3.

Table 2.4.1.2 An example of ACH comparison showing the disproportionate decrease of the air change rate for each room when the exhaust rate decreases for the bimodal system in winter

	Individual Room ACH		
	18.00-19.00h	19.00-21.00h	% Decrease of room ACH
Living Room	0.69	0.37	46.4
Kitchen	0.54	0.27	50.0
Daughter's Bedroom	0.33	0.28	15.2
Son's Bedroom	0.75	0.41	45.3
Parents' Bedroom	1.24	0.66	46.8
Bathroom	0.61	0.32	47.5
Whole House	0.67	0.36	46.3

Table 2.4.1.3 Varying room ACH throughout the day for the bimodal system

	18.00-19.00h	19.00-21.00h	21.00-23.00h	23.00-07.00h	07.00-07.15h	07.15-07.30h	07.30-08.00h	08.00-08.30h	08.30-09.00h
Living Room	0.69	0.37	0.40	0.45	0.69	0.71	0.40	0.64	0.37
Kitchen	0.54	0.27	0.30	0.33	0.54	0.55	0.30	0.50	0.27
Daughter's Bedroom	0.33	0.28	0.22	0.25	0.33	0.34	0.22	0.49	0.28
Son's Bedroom	0.75	0.41	0.26	0.28	0.75	0.39	0.26	0.70	0.41
Parents' Bedroom	1.24	0.66	0.71	0.36	1.24	1.27	0.71	1.15	0.66
Bathroom	0.61	0.32	0.34	0.38	0.61	1.47	0.34	1.45	0.32

Similar effects of varying room ventilation rates are seen when using the RHC system, caused by the fluctuating relative humidity of the air passing through the exhausts, as well as the opening and closing of room doors throughout the day.

2.4.2 Balanced Ventilation

The balanced ventilation calls for diffuser inflow of 22.5m^3/h for each of the three bedrooms and the living room, while maintaining bimodal extraction. Since the total rate of extraction only varies between 165m^3/h and 90m^3/h, a volume flow imbalance occurs. This discrepancy is thus made up through infiltration when the extraction rate is higher than the inlet rate. Thus at a constant input rate of 90m^3/h, air infiltrates at a rate of 75m^3/h when cooking. All other times, there is mathematical a balance between the input and extraction rates however, due to the complexities of the houseplan coupled with open and closed doorways, there is no preclusion of infiltration or exfiltration during these periods.

Table 2.4.2.1 Balanced ventilation input and extraction rates

	18.00-19.00h	19.00-21.00h	21.00-23.00h	23.00-07.00h	07.00-07.15h	07.15-08.00h	08.00-08.30h	08.30-09.00h
Bimodal extraction [m^3/h]	165	90	90	90	165	90	165	90
Balanced ventilation input [m^3/h]	90	90	90	90	90	90	90	90
Difference [m^3/h]	75	0	0	0	75	0	75	0

For example, when the childrens' bedroom doors are closed between 21.00-23.00h, though there should be a global mass balance, locally there is exfiltration through the windows of these two bedrooms. Since the extracts are located outside the room with only a small opening at the bottom of the door, the balanced ventilation system inlets pump in more air than can escape under the doorway. To equalize the high pressure buildup in these rooms, air leaks out through cracks at the windows. Table 2.4.2.2 below describes the mass flow rates through each of the window infiltration/exfiltration locations throughout the day (not including the balanced ventilation inlets through the diffusers). Note that only when the extract devices are on the low setting and the room doors are fully open (19.00-21.00h, 08.30-09.00h) does the least amount of infiltration/exfiltration occur due to the relatively free movement of the air from the diffuser to the exhaust locations.

Table 2.4.2.2 Volume flow rates [m³/h] of infiltration (positive) or exfiltration (negative) at each of the infiltration locations

	18.00-19.00h	19.00-21.00h	21.00-23.00h	23.00-07.00h	07.00-07.15h	07.15-07.30h	07.30-08.00h	08.00-08.30h	08.30-09.00h
Living Room	41.7	-0.3	9.0	16.9	38.5	5.5	9.1	12.7	-0.3
Kitchen	9.2	0.2	1.9	3.4	8.5	1.3	1.9	18.4	0.2
Daughter's Bedroom	-6.8	-0.2	-9.4	-8.7	-7.1	-9.8	-9.4	5.3	-0.2
Son's Bedroom	-7.7	-0.3	-10.7	-9.8	-7.9	-11.1	-10.7	7.7	-0.3
Parents' Bedroom	19.5	-0.3	4.2	-10.2	18.2	2.1	4.0	11.6	-0.3
Bathroom	3.4	0.2	0.8	1.4	10.4	9.2	1.0	9.8	0.2

The diffuser is simulated as a 15cm X 15cm square, the locations of which are shown in Figure 2.4.2.1.

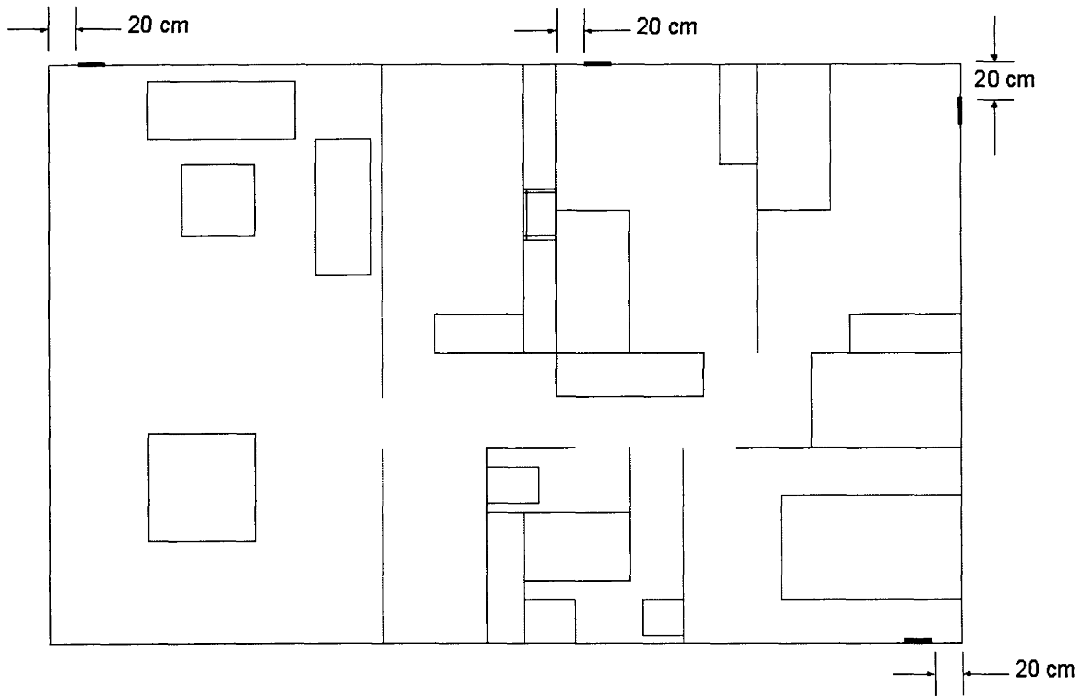


Figure 2.4.2.1 Balanced ventilation inlet locations (all diffusers are located 2m from the floor)

There are differences in the modes of ventilation as seen in Table 2.4.2.3. There is always a base ventilation in each of the bedrooms, upon which is superimposed either infiltration or exfiltration, depending on the pressure buildup due to door positions. The childrens' bedrooms experience the greatest change in ventilation due to the fact that with the balanced ventilation inlet in place and their rooms being occupied the most. The constant inlet rates of 22.5m^3/h induce exfiltration through the windows, but the majority exits underneath the doorway. This ventilation is thus much larger than the ventilation rate due to infiltration induced by the remotely located exhausts alone.

Table 2.4.2.3 Percent differences between the volume flow rate supplied to each room through balanced ventilation (including infiltration/exfiltration) compared to the bimodal system

	18.00-19.00h	19.00-21.00h	21.00-23.00h	23.00-07.00h	07.00-07.15h	07.15-07.30h	07.30-08.00h	08.00-08.30h	08.30-09.00h
Living Room	2.9	-32.8	-12.0	-2.3	-4.7	-14.1	-11.9	-17.4	-32.8
Kitchen	-27.6	-96.2	-72.4	-56.9	-35.1	-79.7	-72.5	56.7	-96.2
Daughter's Bedroom	72.8	190.8	121.6	105.8	67.0	131.8	121.3	108.4	190.8
Son's Bedroom	-28.6	98.4	66.1	63.7	37.1	71.4	65.8	55.2	98.4
Parents' Bedroom	35.2	33.0	49.5	37.2	27.5	51.3	48.5	17.6	33.0
Bathroom	-30.2	-93.1	-69.3	-54.3	-9.6	-10.8	-63.5	-14.3	-93.1

Again, extra simulations must be performed to determine the exact rate of infiltration/exfiltration through each of the inlet locations (at the windows) based upon indoor occupancy. The values for infiltration/exfiltration are set as the new boundary conditions for the real simulations. Thus at each hour, door positions and exhaust rates affect each of these conditions.

2.5 CFD Model

A view of the grid density is found in Figure 2.5.1. A nearly uniform grid scheme is adopted due to the complexity of the house layout in order to capture as much relevant information as possible. The x-direction is divided into 95 grids, 63 in the y-direction, and 24 in the z-direction to make a total of 143,640 grid locations.

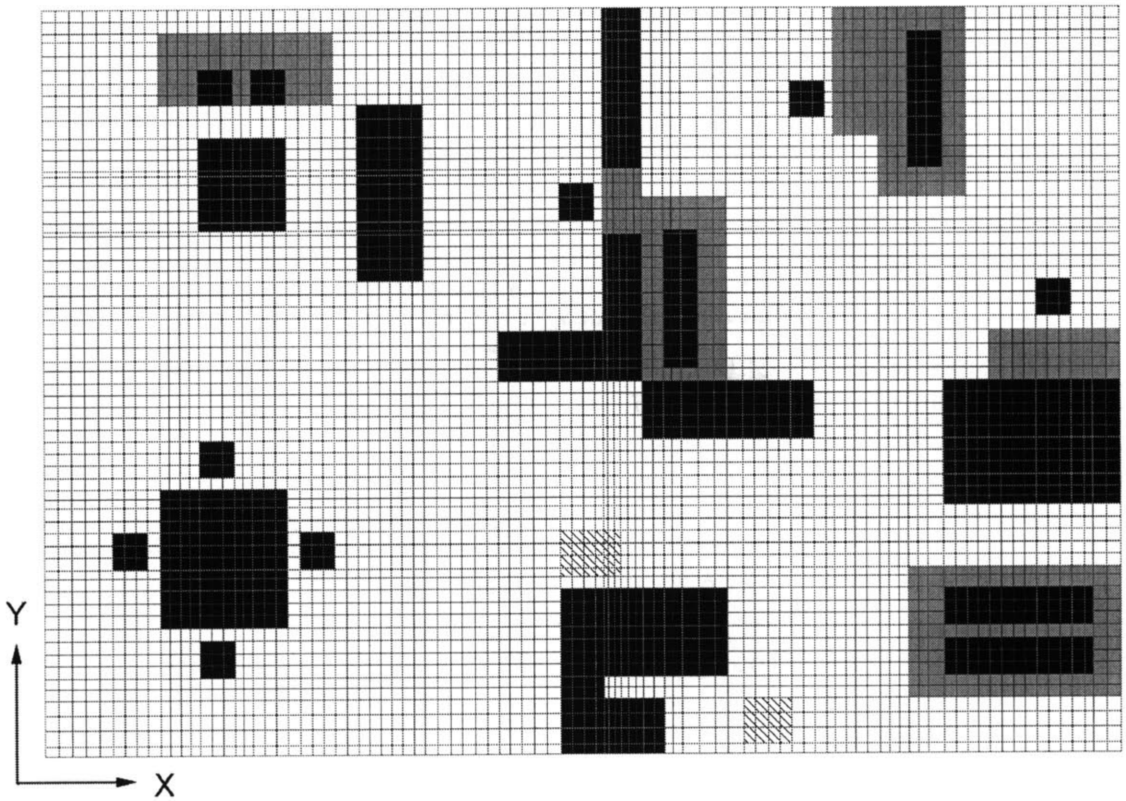


Figure 2.5.1 Grid location with respect to the objects and occupants used in the CFD simulations

Due to the complexity of the model and the changing occupancy conditions, the day is broken up into a number of periods according to the hour, as described in Table 2.2.1. Within each of these time periods, there is another step of discretization that breaks the period into a number of time-steps as shown in Table 2.5.1. This technique is called quasi-steady discretization, since there is a time dependency, though within each time-step, the flows are treated as being in steady-state.

Table 2.5.1 Quasi-steady discretization for the time periods and time-steps throughout the day

	18.00-19.00h	19.00-21.00h	21.00-23.00h	23.00-07.00h	07.00-07.15h	07.15-07.30h	07.30-08.00h	08.00-08.30h	08.30-09.00h
Number of time-steps	4	6	8	8	1	1	2	2	2
Clock time for each time-step	15 min	20 min	15 min	1 hour	15 min	15 min	15 min	15 min	15 min

This scheme is chosen to provide the most detailed information about the most important times of the day (mainly during cooking and smoking), whilst preventing undue computing time. The period of sleeping clearly has the coarsest discretization, since during this time, everything is assumed to be steady, and the occupant location and activity does not change throughout the period.

2.6 CFD Measurement Location

It is important to select the correct location for data extraction for the numerical simulation. Due to thermal buoyancy from metabolic heat generated by the occupants, there is a boundary layer of fresher air that clings to the body as it travels upward to the breathing zone; as such, the inhaled air is different from the ambient air at the same height [42]. Since low infiltration generally produces low airflow velocities, and natural convection is dominant, exposure is influenced by entrainment in the human boundary layer [43]. It is therefore more accurate to obtain the pollutant data below the facial region, as cleaner air tends to be transported upwards to the breathing orifices. For upright occupants (e.g. sitting or standing), the point used to determine pollutant concentration was 0.2m below the top of the head.

3 Experimental Validation of CFD

In order to assure that the CFD tool is correctly utilized, experimental validation of the CFD tool is necessary. Experiments were performed in the MIT Test Facility, which consists of two adjacent rooms that comprise the test chamber and the climate chamber, shown schematically in Figure 3.1. Since each chamber has its own air conditioning capability with the capacity to control the air temperature and flow rate, the climate chamber was set up to simulate the outdoor environment while the test chamber simulates the indoor environment. The ceiling, floor, and outer walls are heavily insulated with a thermal resistance of 5.3 Km^2/W. The window between the two chambers is a double glazed unit spanning the entire width of the rooms with a thermal resistance of 0.27 Km^2/W.

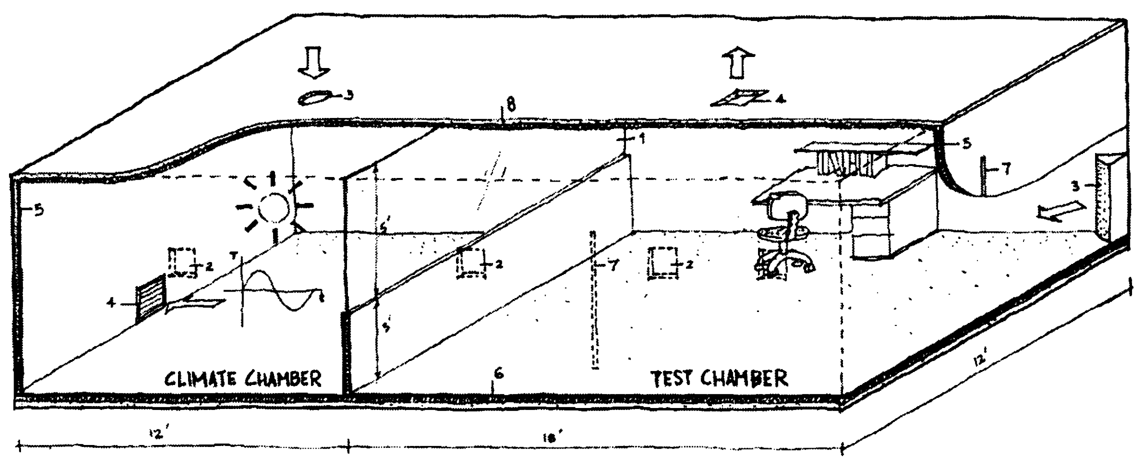


Figure 3.1 Schematic of climate (left) and test (right) chambers

Two sets of experimental data are compared here

1. Low infiltration with convector and partitioned room
2. Displacement ventilation

The purpose for the experiments is to validate the use of CFD for a case of low infiltration, displacement ventilation, high degrees of thermal stratification, as well as multizonal flow.

3.1 Low Infiltration Case

A schematic for the experimental setup for in the test chamber in the first case is shown in Figure 3.1.1. Included is a large displacement diffuser, used to simulate the low ventilation rates associated with infiltration. A wall with an open doorway is located in the middle of the chamber to divide it in two. Some simple furniture is located in the room, as well as two person simulators. A baseboard convector is located on the opposite wall as the diffuser, and under a double glazed window that is adjacent to the climate chamber. Zone A is considered the room that contains the diffuser, while Zone B contains the convector.

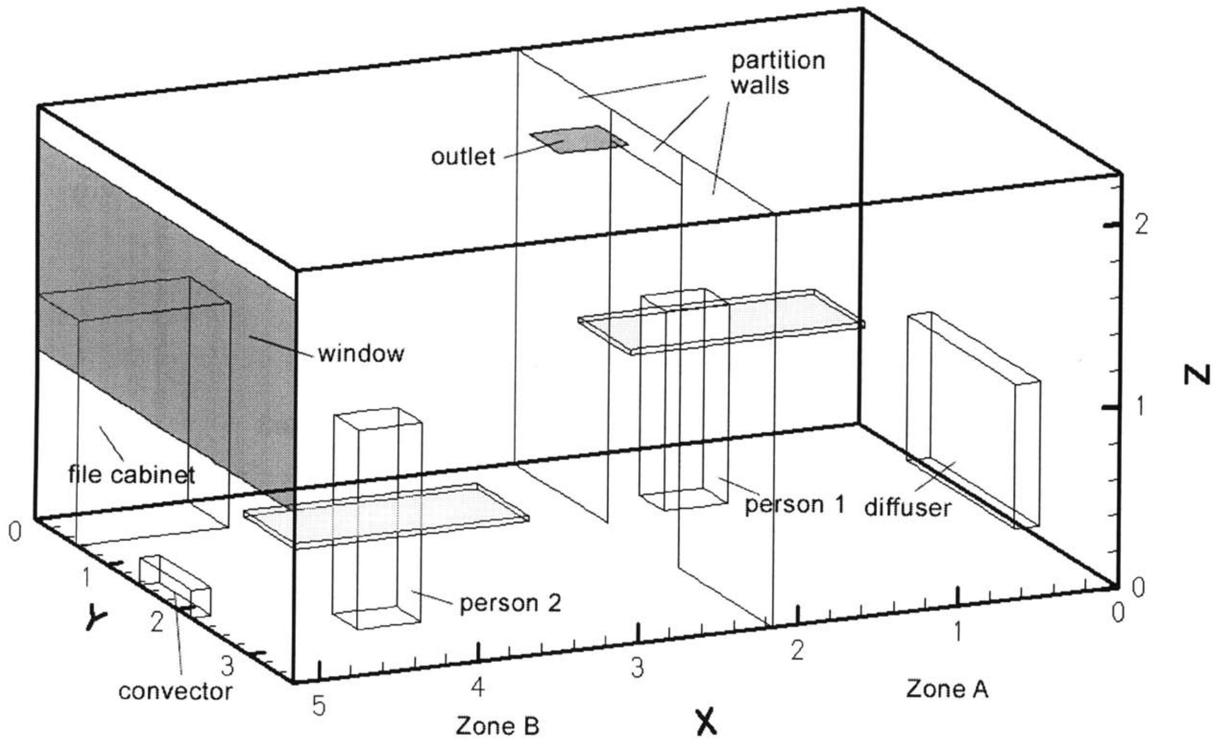


Figure 3.1.1 Schematic of the low infiltration case setup in the test chamber including the diffuser, outlet, heat sources, partition walls, people and furniture

The large displacement diffuser introduces air at 18°C, to maintain an air change rate of 1.63 for the entire test chamber, which corresponds to an average diffuser face velocity of 0.023 m/s. Partition walls partially block off two sections of the room, and simulate an open doorway for large opening flow. The outlet is located in the partitioned space opposite the diffuser. The climate chamber maintains a constant temperature of 9.5°C, keeping the window temperature between 30-35°C, depending on the location. It is so warm due to a 1500W baseboard convector located just beneath the window to counteract the sheeting effect produced by the negative buoyancy. It also provides strong room-wide circulation, and a high heat source to ensure thermal stratification. Two occupants at 75W each are located on each side of the partition, and four overhead lamps are in place, but are turned off.

Due to the low ventilation rate of the test chamber, the HVAC controller lacks the accuracy necessary to maintain the flow rate at a constant level. The introduction of the high convective heat source attempts to stabilize the fluctuations due to the unsteady ventilation by providing a strong buoyant convection to help make the room airflow independent of the ventilation fluctuations, although it does not help to the extent of inducing a steady flow throughout the chamber, as presented in the next section.

Air and wall surface temperatures and tracer gas (SF_6) concentrations are all collected. Five movable poles are used to measure temperature, velocity, and tracer gas concentration in ten locations. Location 1 consists of the locations off the centerline of the chamber, while location 2 contains the centerline values; the location schematic is shown in the figures below. Temperature and velocities are measured with hot sphere anemometers and wall surface temperatures are obtained with thermocouples. Since the air change rate of the chamber is so small, and the accuracy of the anemometers is 0.1 m/s, velocity was measured but is not reported here. A gas multiplexer and gas analyzer measures tracer concentration. SF_6 is used since background concentrations are generally quite low, and it is considered to be neutrally buoyant.

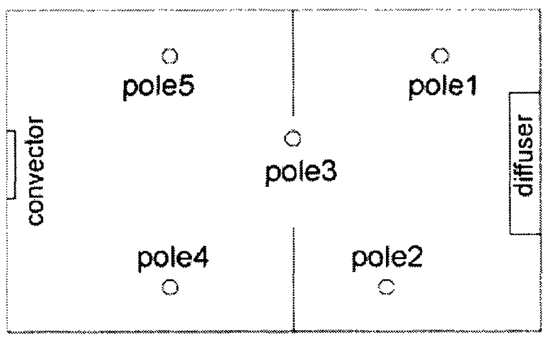


Figure 3.1.2 Location 1 pole positions

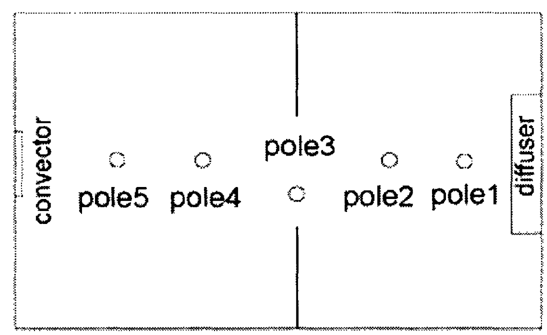


Figure 3.1.3 Location 2 pole positions

The data for velocity and temperature were taken when steady-state flow in the chamber is achieved over an eight-hour period.

The error of measuring the temperature is ±0.3°C, which accounts for both the measurement error and that superimposed by the data acquisition system.

PHOENICS [44], a commercial software, was the CFD model used to solve the conservation equation of mass, momentum, energy, and species concentrations with a renormalized (RNG) k-ε turbulence model [45], which is generally considered to perform well for buoyancy induced turbulent flows [46], as well as indoor flows [47]. The advantage of using CFD for the assessment of exposure lies in its ability to clearly model and approximate real situations. However, the fine resolution leads to increased expenditure of resources, thus taking a long time to complete the evaluation.

3.1.1 Results and comparison

From the computed flow pattern, we can see that the diffuser introduces cold air, which sinks towards the floor due to negative buoyancy and a very low velocity as shown in Figure 3.1.1.1. As the air travels along the floor from Zone A to Zone B, it gets heated once it reaches the convector on the opposite side. Due to the high heat output of the convector, a large upward current is produced near the window, despite the cold temperatures of the adjacent climate chamber. The buoyant flow impinges on the ceiling, and continues to travel back towards Zone A. Some of the air is removed through the exhaust before reaching the partition. For the rest of the air, the header of the doorway (at the partition) hinders the flow slightly, but due to the large temperature difference generated by the convector and the subsequent momentum of the air, the air simply flows around it to reenter Zone A. The air then reaches the wall opposite the window, and turns downward toward the diffuser, thus creating a large circuit of bi-zonal circulation. This general flow pattern was observed in the test chamber through smoke visualization.

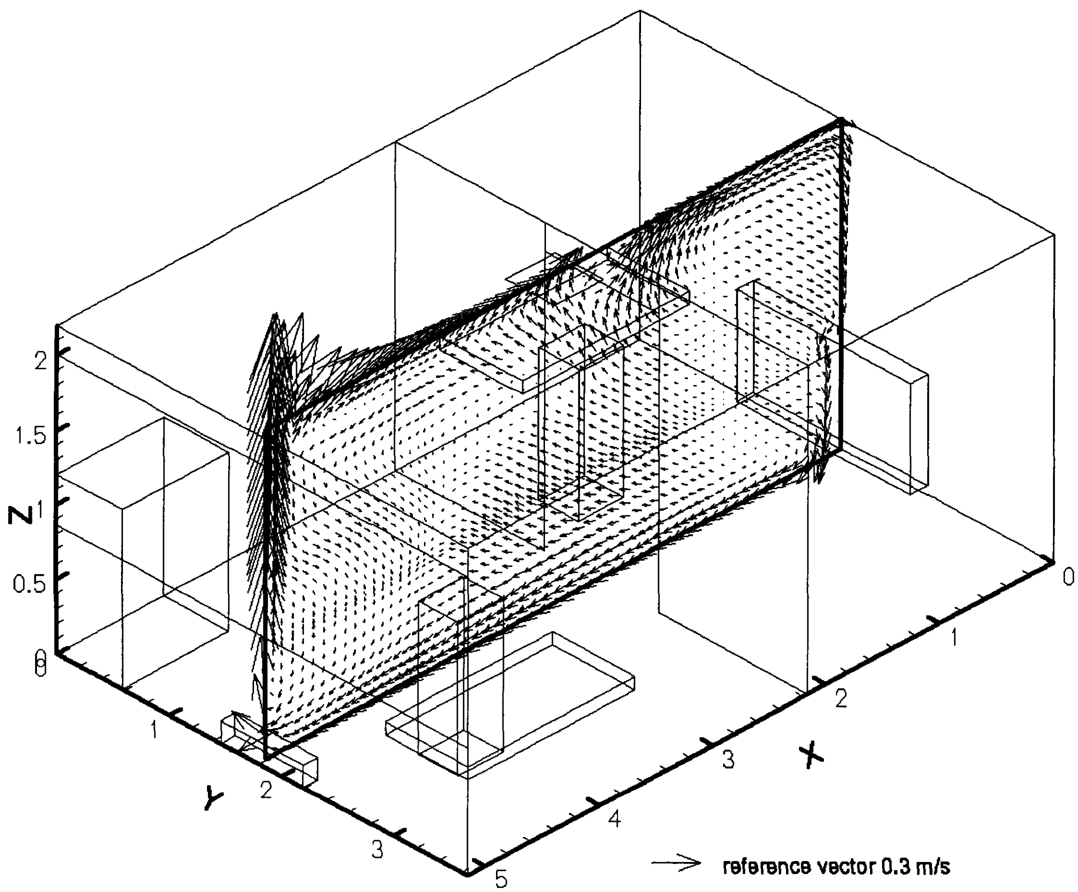


Figure 3.1.1.1 Velocity vectors along the centerline of the test chamber

The low velocity and temperature of the inlet air helps to set up a large temperature gradient throughout the two zones, shown in Figure 3.1.1.2. The gradient decreases further away from the diffuser due to the warming up of the air as it moves along the floor. The temperature gradient, coupled with the convector-generated vortex, produces a flow through the large opening (doorway). Near the floor, air from Zone A enters Zone B, and near the top of the doorway, the flow is reversed.

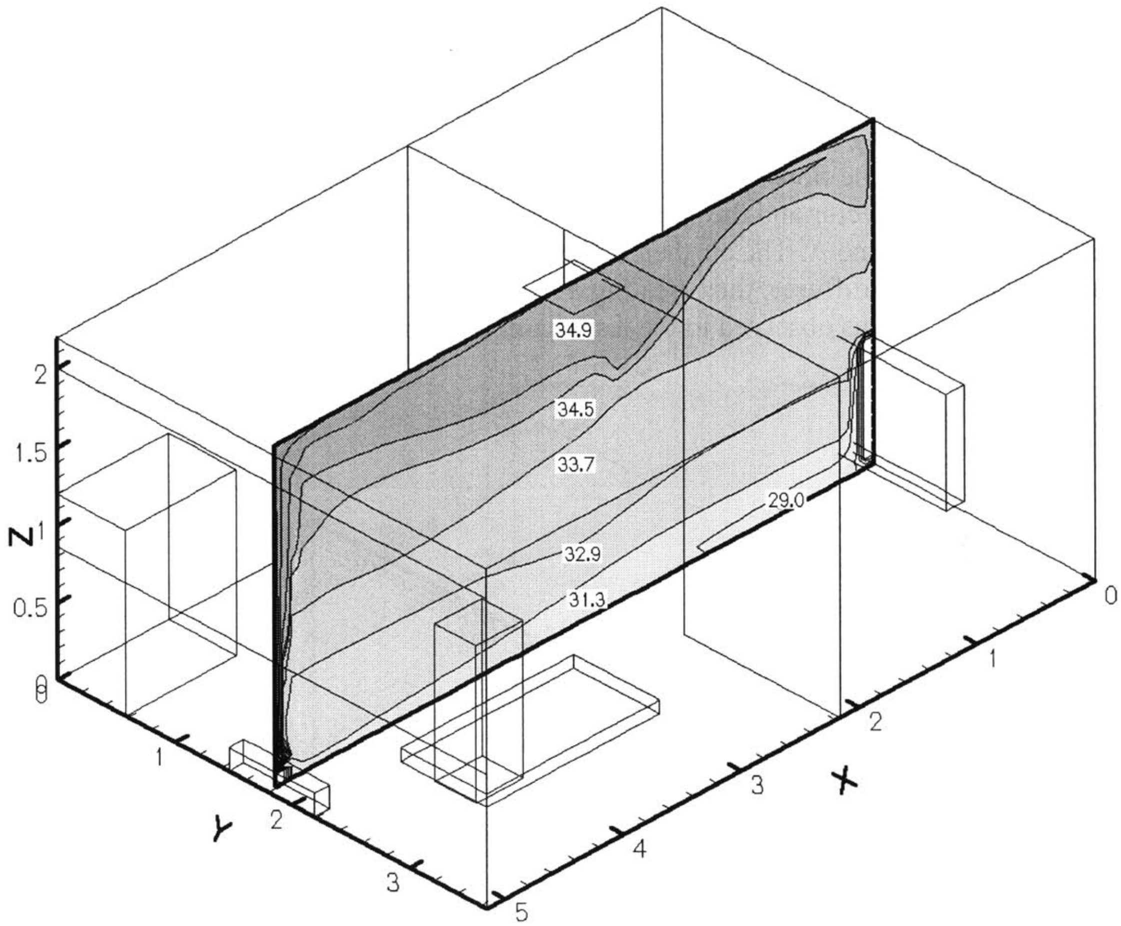


Figure 3.1.1.2 Temperature [°C] gradient through the mid-plane of the two zones

Due to the location of heated objects and the partition closing off much of the two zones from one another, the flow is clearly not two-dimensional. Thermal plumes are generated from the two occupants in a much weaker fashion than the convector as seen in Figure 3.1.1.3. Some recirculation regions are seen at the ceiling in the plane of the people. The outer portions of the window (not directly above the convector) have a slightly lower temperature, so we observe a downwash of air due to negative buoyancy shown in Figure 3.1.1.4. In fact, this happens on all the vertical walls, since the wall temperature is lower than that of the interior air.

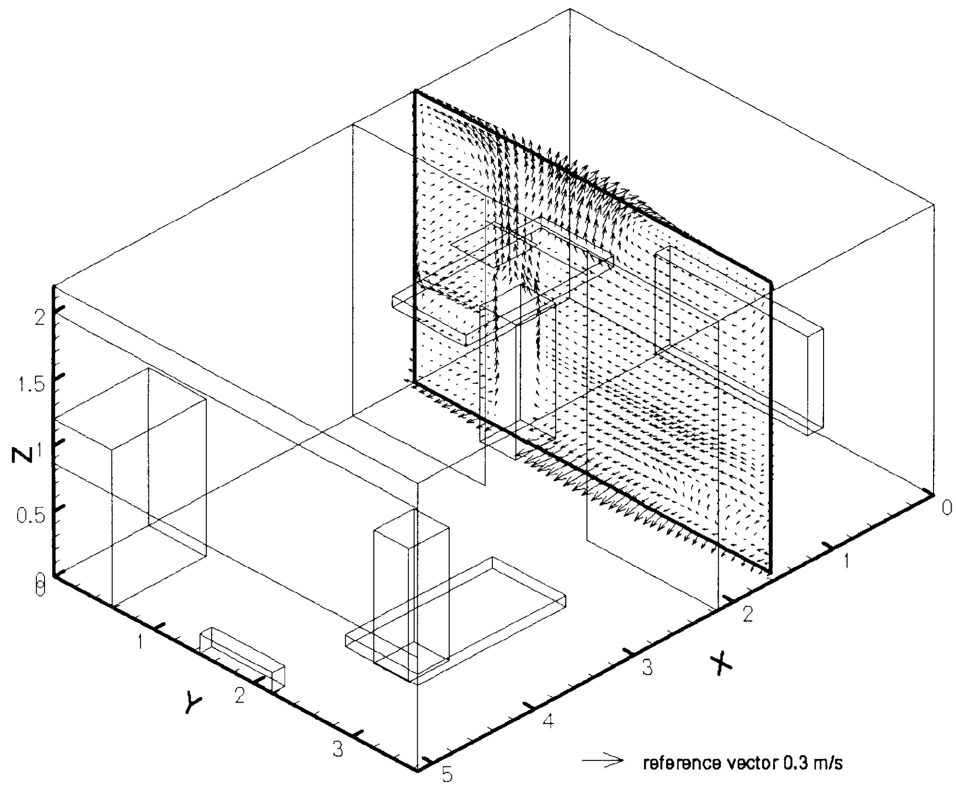


Figure 3.1.1.3 Velocity vectors showing a thermal plume generated through body heat

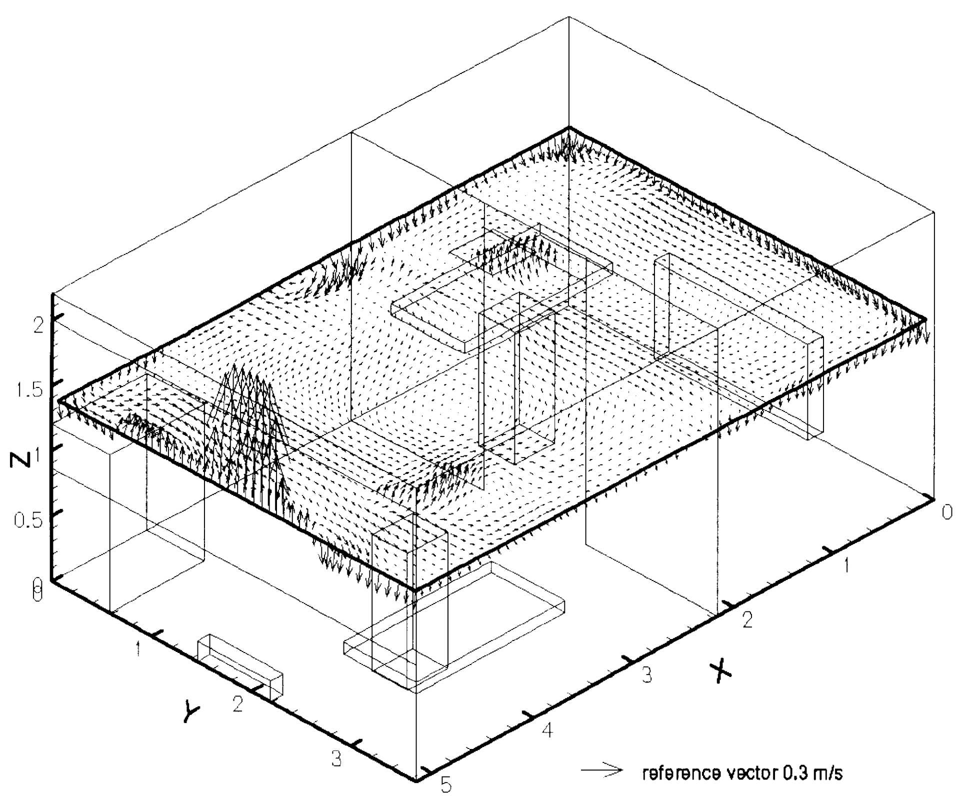


Figure 3.1.1.4 Velocity vectors showing downwash at the outer vertical walls and window

The temperature and tracer gas concentration data obtained from the experiment used for the comparison is shown in the tables below.

Table 3.1.1.1Experimental pole temperatures at location 1 in degrees Celsius

Height [m]	Pole1	Pole2	Pole4	Pole5	Height [m]	Pole3
2.22	35.73	35.83	38.15	37.77	2.22	36.89
2.1	35.61	31.03	37.78	36.95	2.032	36.98
1.7	35.18	32.19	36.25	36.21	1.7	36.09
1.3	34.29	35.02	34.64	34.67	1.3	34.78
0.9	33.50	33.97	33.12	33.12	0.9	33.76
0.5	31.75	35.20	31.63	31.63	0.5	31.76
0.1	29.57	29.84	30.90	30.55	0.1	30.56
0.05	28.73	29.27	30.69	30.25	0.05	29.32

Table 3.1.1.2 Experimental pole temperatures at location 2 in degrees Celsius

Height [m]	Pole1	Pole2	Pole4	Pole5	Height [m]	Pole3
2.22	36.01	36.52	38.08	39.66	2.22	36.54
2.1	35.68	30.70	37.51	36.77	2.032	36.55
1.7	34.52	31.86	35.79	35.59	1.7	35.77
1.3	33.70	34.26	34.40	33.90	1.3	34.21
0.9	32.89	33.52	32.64	32.71	0.9	33.33
0.5	31.14	36.25	31.43	31.18	0.5	31.32
0.1	27.97	28.41	29.70	30.17	0.1	29.90
0.05	27.20	28.14	29.45	30.47	0.05	28.52

Table 3.1.1.3 Steady-state experimental pole concentrations at location 1 in mg/m^3

Height [m]	Pole1	Pole2	Pole4	Pole5	Height [m]	Pole3
2.1	8.382	8.305	7.370	7.671	2.032	7.397
1.7	8.414	8.174	7.176	8.133	1.7	7.643
1.3	16.621	8.208	7.130	12.284	1.3	7.795
0.9	9.386	8.246	7.417	8.722	0.9	8.424
0.5	7.761	7.377	4.706	5.505	0.5	6.391
0.1	4.901	5.195	4.200	4.797	0.1	4.446

Table 3.1.1.4 Steady-state experimental pole concentrations at location 2 in mg/m^3

Height [m]	Pole1	Pole2	Pole4	Pole5	Height [m]	Pole3
2.1	7.919	7.593	7.853	7.612	2.032	7.320
1.7	8.313	7.794	8.122	7.579	1.7	7.649
1.3	8.016	7.918	8.480	7.887	1.3	7.596
0.9	10.044	9.579	8.100	7.507	0.9	8.356
0.5	7.009	6.496	4.794	5.287	0.5	6.370
0.1	4.802	4.532	4.603	4.629	0.1	4.466

Comparing the measured temperature values with that obtained through the CFD simulation, the general patterns are predicted well, with the values never erring much more than 10% off the experimental values as seen in Figure 3.1.1.5 and Figure 3.1.1.6. The high temperature gradients are difficult to obtain through simulations, most likely due to the turbulence model used. In this case, the k-ε RNG model is used; it, as in most k-ε turbulence models, has a difficult time predicting the size and location of recirculation zones. Due to the various heat source locations, in addition with the strong circulation produced by the convector, there may be circulation regions that cannot be defined by the computer simulation, thus reducing the potential temperature gradient. In general, the simulation underpredicts the experimental temperature gradient.

However, when looking at the pole data that are close to and in the same plane as the convector (poles 4 & 5 in location 2), the temperature near the ceiling is predicted well (as in pole 4) or overpredicted (as in pole5). This is due to the strong buoyancy effect of the convector, with higher velocities and strong flow patterns that are easier to match using computational methods.

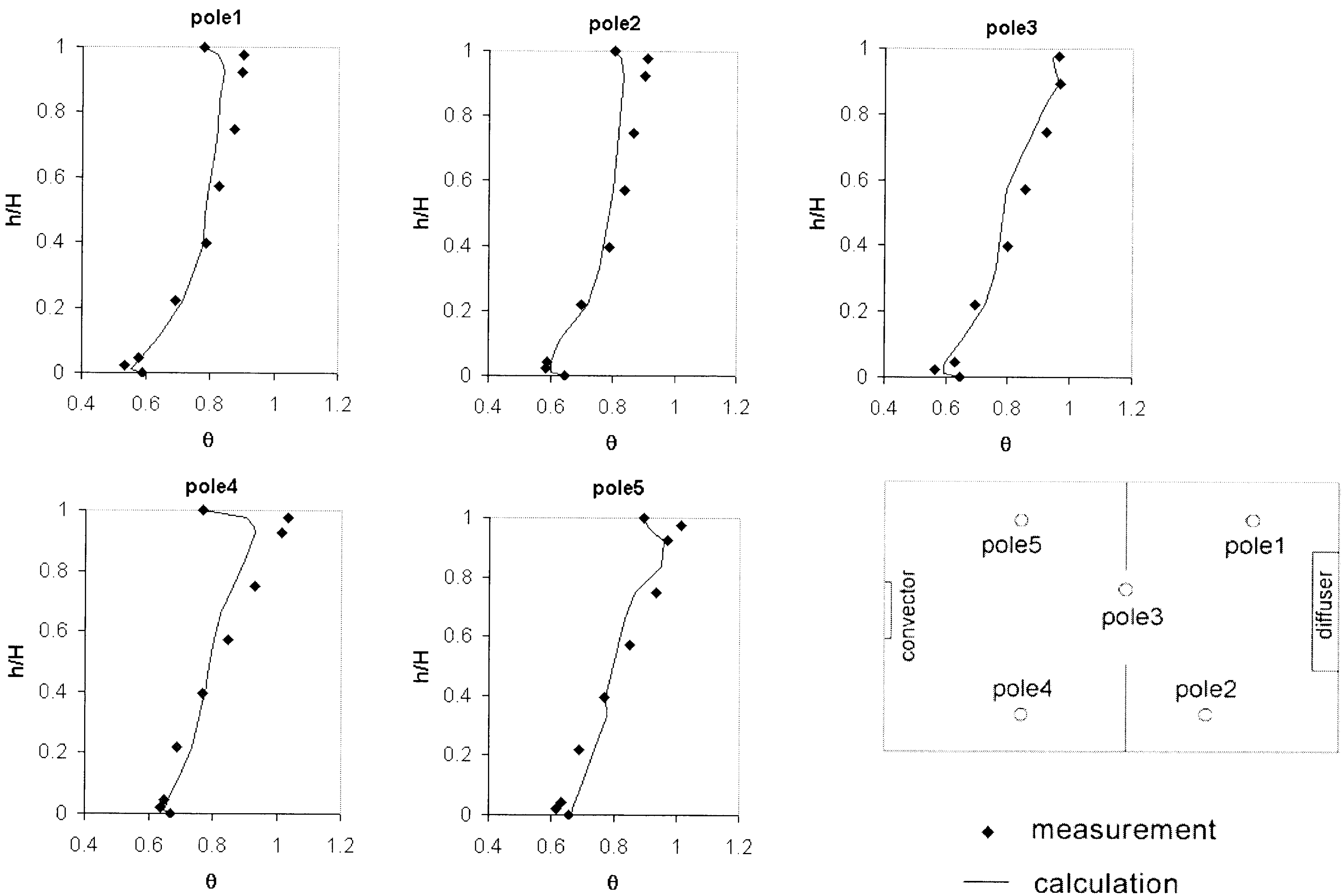


Figure 3.1.1.5 Pole temperatures at location 1 comparing experimental data to the CFD calculation. [h] is the height, [H] is the total room height , and $\theta = (T-T_{in})/(T_{out}-Tin)$, T_{in}=17.0°C, T_{out}=37.3°C.

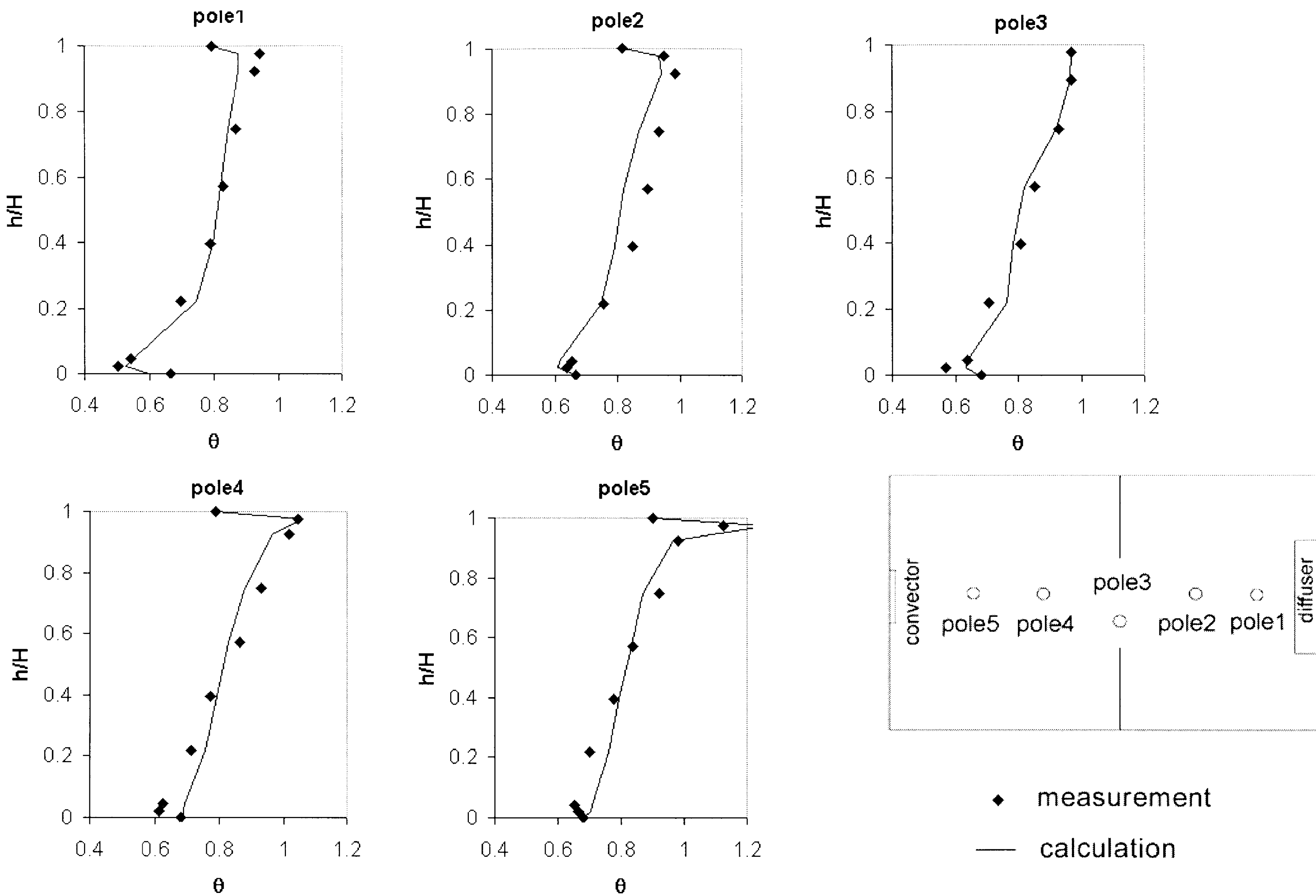


Figure 3.1.1.6 Pole temperatures at location 2 comparing experimental data to the CFD calculation. |h| is the height, |H| is the total room height , and θ= (T-Tin)/(Tout-Tin), Tin=17.0°C, Tout=37.3°C.

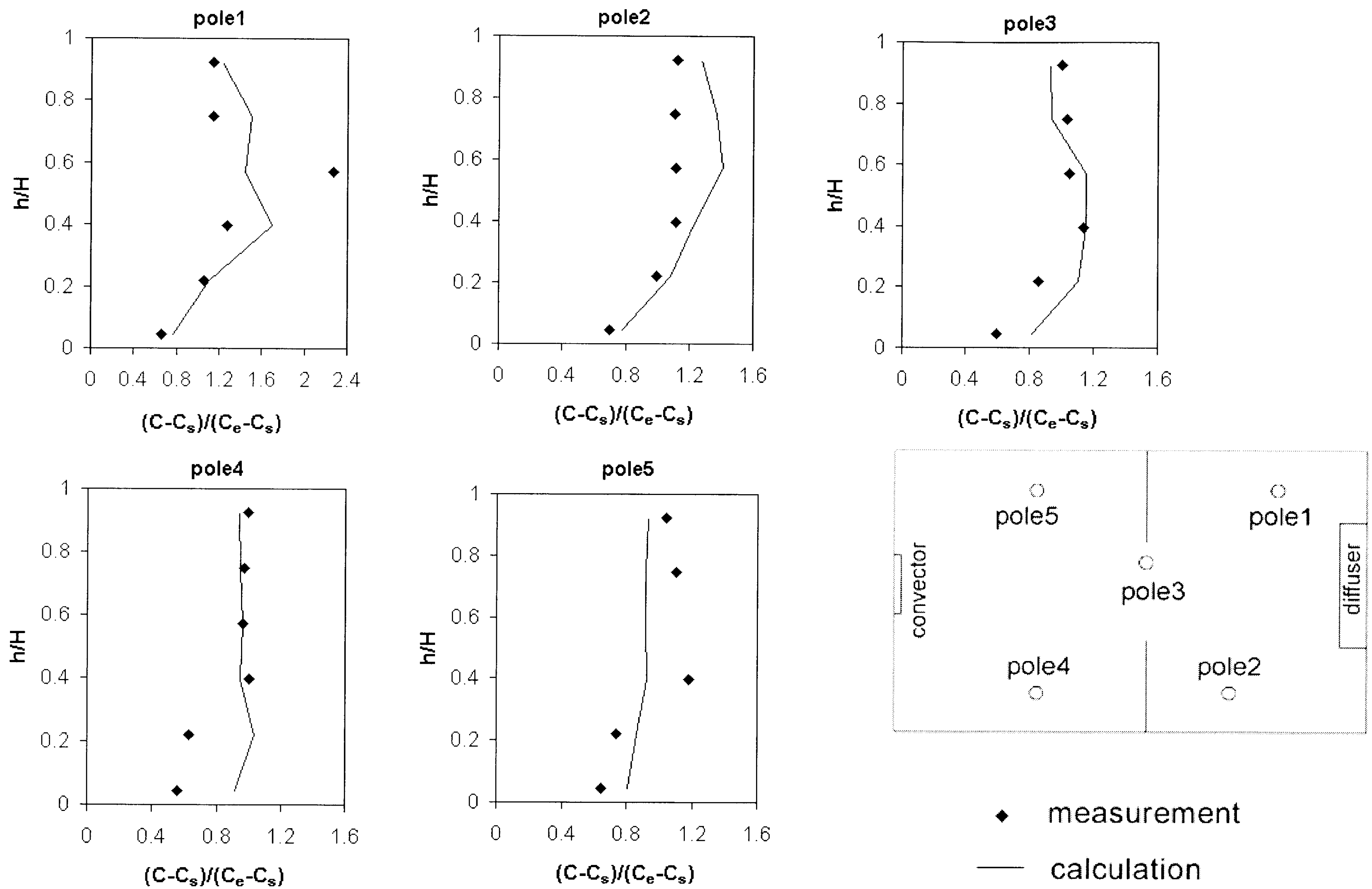


Figure 3.1.1.7 Pole concentrations at location 1 comparing experimental data to the CFD calculation. [h] is the height, [H] is the total room height , [C] is the measured concentration, [C_s] is the supply concentration, and [C_e] is the exhaust concentration, C_s=0.12mg/m^3, C_e=7.40mg/m^3.

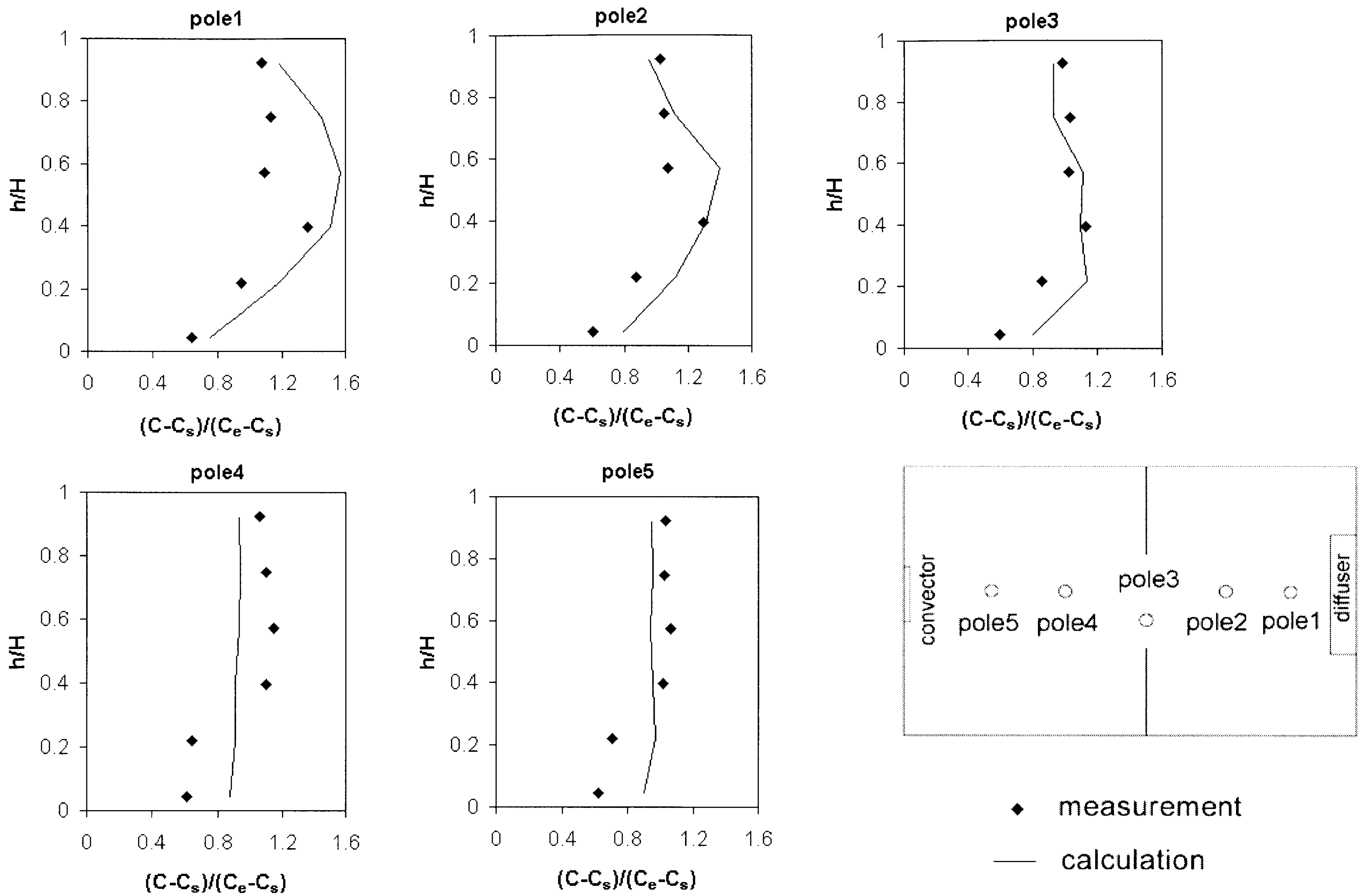


Figure 3.1.1.8 Pole concentrations at location 2 comparing experimental data to the CFD calculation. [h] is the height, [H] is the total room height , [C] is the measured concentration, [C_s] is the supply concentration, and [C_e] is the exhaust concentration, C_s=0.12mg/m^3, C_e=7.40mg/m^3.

Although the temperature shows good agreement between the experiment and the simulation, the agreement for the concentration is less (Figure 3.1.1.7 and Figure 3.1.1.8). The migration of tracer gas is highly dependent on the velocity, and thus flow pattern. In this case, due to the location and the amount of heat generated from the sources, in conjunction with the low flow rate, the flow is quasi-stable. This means that some regions exhibit stability, while other regions show somewhat chaotic motion. The combination of these two forces generates uncertainty when attempting to compare the two results.

The concentration gradient is not as well predicted in Zone B. This is because the convector generates natural convection that is very strong (when compared to the other convection forces), and generates somewhat chaotic motion. Also, there is a fair degree of small obstructions that are part of the data acquisition on the floor of the test chamber. This rough surface gives rise to zones of stagnation; a stagnation zone near the floor has a lower concentration since this air consists mainly low concentration air coming directly from the diffuser. Since there is a concentration gradient in Zone A where there is a region of lower concentration air near the floor, the effect tends to propagate into Zone B as it does in the experiment.

Table 3.1.1.5 and Table 3.1.1.6 spell out the percent differences at each of the pole heights at the two sets of pole locations for the SF_6 concentrations. Generally, the lower part of Zone A and the upper region of Zone B show the best correlations.

Table 3.1.1.5 Percent differences between the measured and computed data for SF_6 concentration at location 1

Height [m]	Pole1	Pole2	Pole4	Pole5	Height [m]	Pole3
2.1	3.2	7.7	-11.7	-15.9	2.032	-12.6
1.7	25.4	17.2	-8.2	-22.0	1.7	-14.8
1.3	-39.5	19.9	-6.1	-48.6	1.3	3.0
0.9	23.5	4.2	-11.4	-26.9	0.9	-4.0
0.5	0.2	2.6	55.8	9.9	0.5	22.1
0.1	11.8	6.4	54.3	18.8	0.1	32.0

Table 3.1.1.6 Percent differences between the measured and computed data for SF_6 concentration at location 2

Height [m]	Pole1	Pole2	Pole4	Pole5	Height [m]	Pole3
2.1	3.6	-13.1	-17.9	-14.6	2.032	-11.6
1.7	23.8	-0.2	-20.2	-13.1	1.7	-15.2
1.3	38.2	24.0	-23.9	-16.7	1.3	2.0
0.9	4.9	-4.6	-22.3	-13.7	0.9	-8.6
0.5	18.4	21.2	32.6	27.5	0.5	25.0
0.1	12.2	25.2	35.5	36.7	0.1	28.0

It is clear that certain locations lend themselves to more stable flow (Figure 3.1.1.9), as exhibited by a steady asymptote of the concentration history. In general, these locations are not within the plane of the diffuser and convector (poles in location 1), the two components of the experiment that generate the most convection. Pole4 in location 1 is the only exception, and actually produces the most stable concentration history of those recorded. Flow instability is seen in the mid-height region of the chamber as shown in Figure 3.1.1.10; this region is not dominated by the momentum caused by natural convection (from the convector) or the diffuser, lending itself to somewhat chaotic motion due to very low velocity.

Flow instability can also be a source of the measured data error. For all the tracer gas concentration data, the reported value is an average value over the time that the concentration becomes relatively steady. Thus for measurement locations that have high concentration fluctuations (as shown in Figure 3.1.1.10), the variation in the concentration value may be as high as 50%. Thus, there is a great uncertainty for the concentrations reported in the mid-height region of the test chamber.

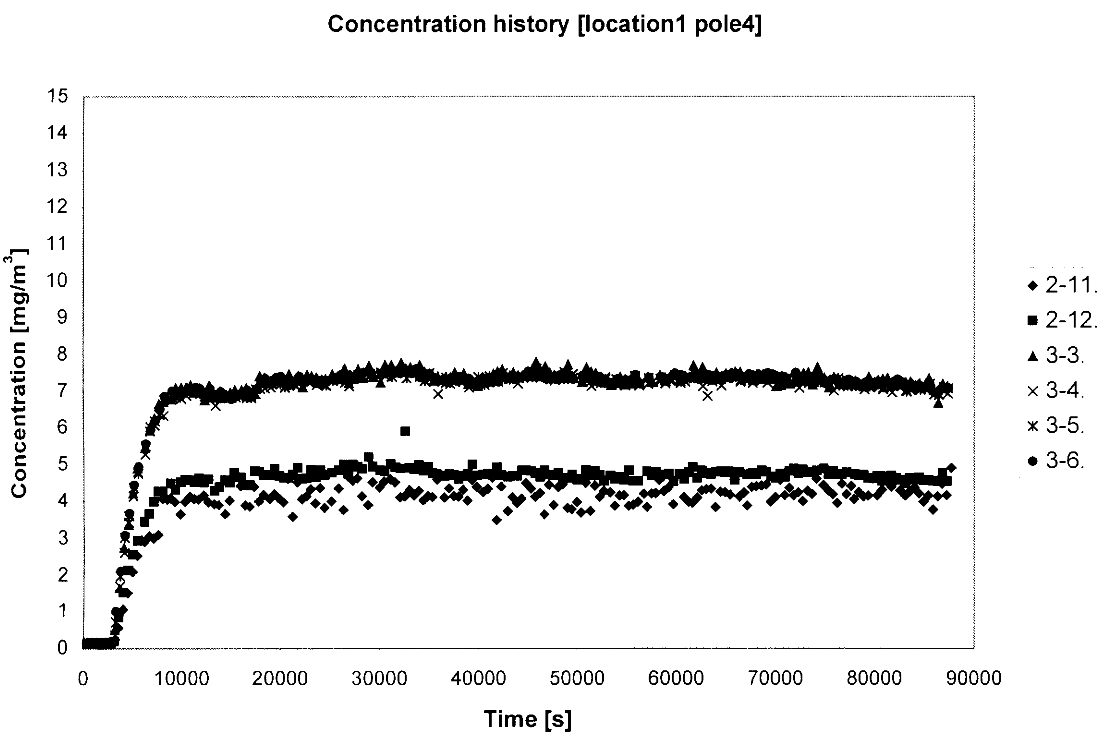


Figure 3.1.1.9 Concentration history at pole4 location1 indicating flow stability through the entire height of the chamber (all legends read from top [floor] to bottom [ceiling])

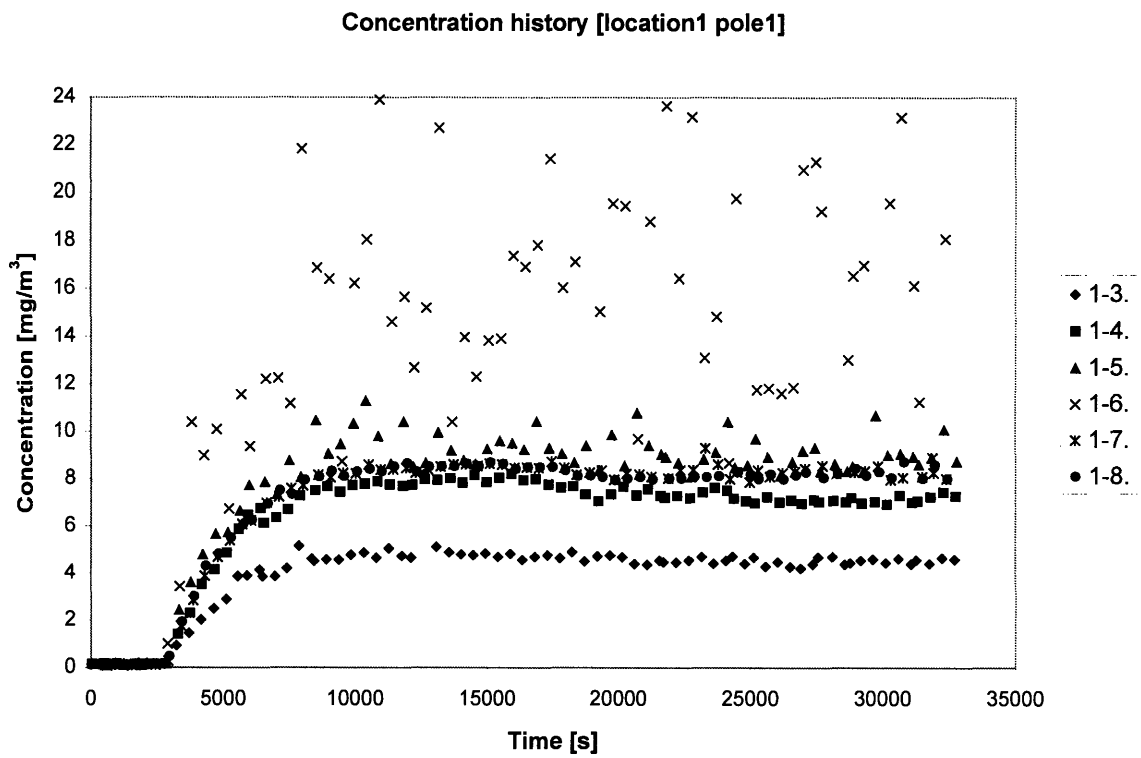


Figure 3.1.1.10 Concentration history at pole1 location1 indicating unstable flow in the mid-height region of the chamber

3.2 Displacement Ventilation Case

The displacement ventilation case is based on data acquired and reported by Chen [10]. It utilized the same test and climate chamber and data acquisition system. The test chamber is shown schematically in Figure 3.2.1. The displacement diffuser introduces air to maintain four air changes per hour, corresponding to a face velocity of 0.09 m/s due to a 10% effective area ratio. The summer case is assumed and the supply temperature was controlled to 17°C, while the adjacent window was kept between 27-28°C. The heat sources include six overhead lamps emitting 34W each, two person simulators at 75W each, and two computers at 108.5W and 173.4W at the Person1 and Person2 locations, respectively. Five movable poles acquire the data at nine locations in the test chamber, shown schematically in Figure 3.2.2. Temperature, velocity, and SF_6 concentrations are taken to ascertain the movement of the airflow and migration of the contaminant.

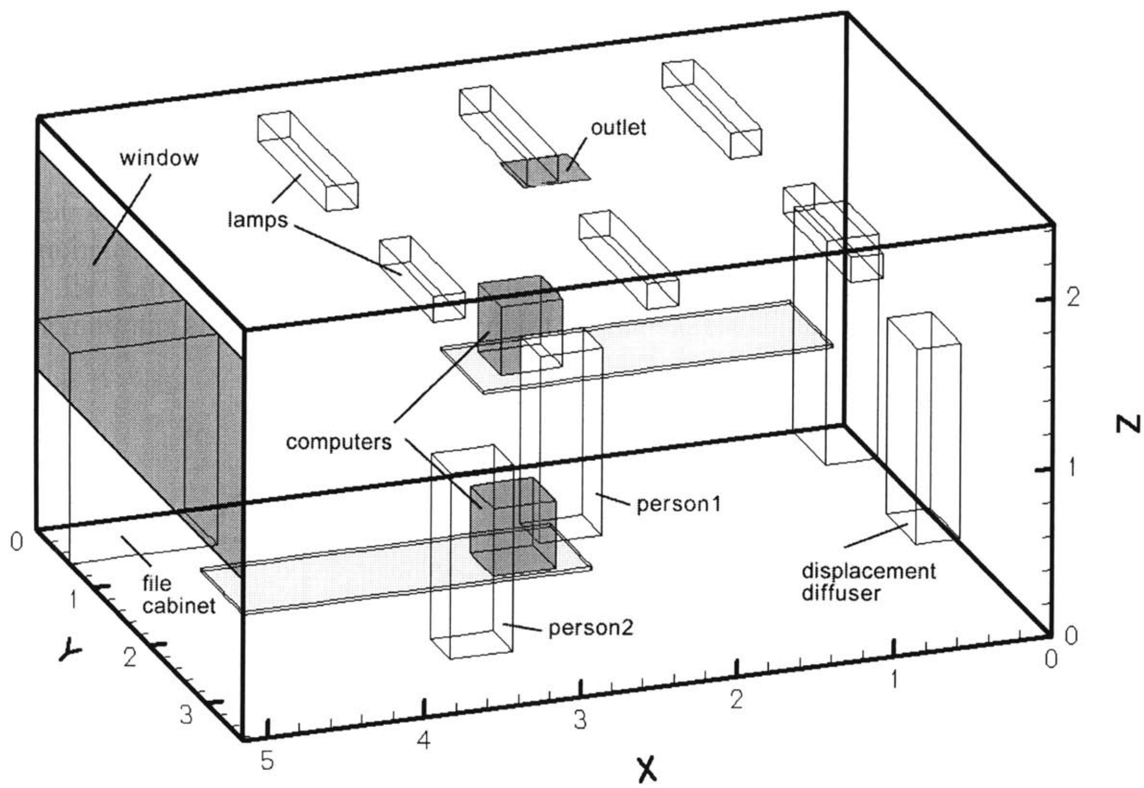


Figure 3.2.1 Schematic of displacement ventilation case test chamber setup including the diffuser, outlet, heat sources, people, and furniture

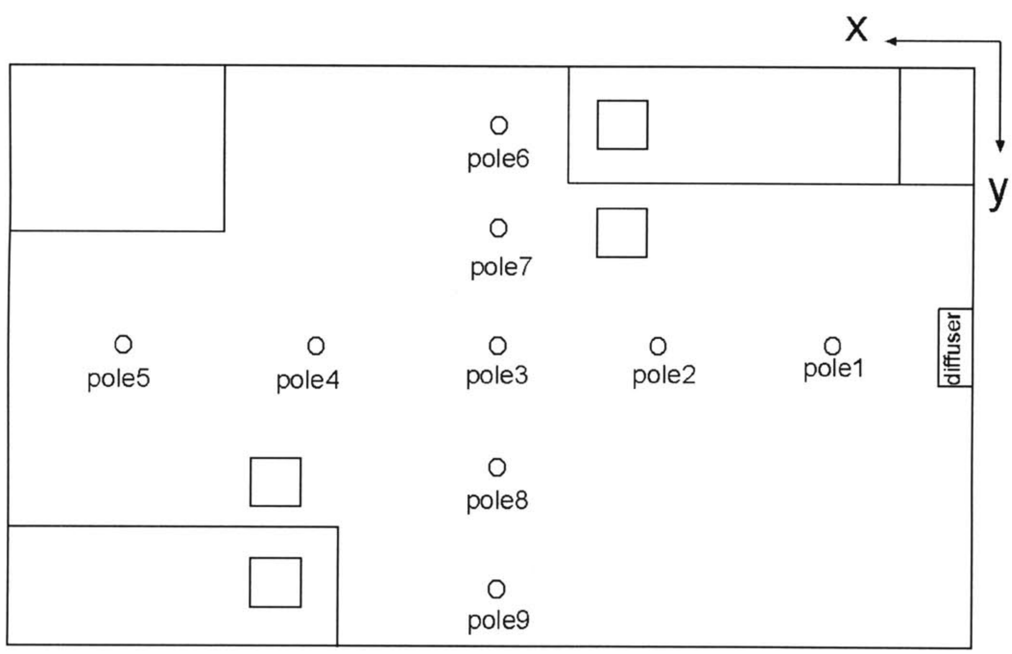


Figure 3.2.2 Schematic of the pole locations in plan

3.2.1 Results and Discussion

The flow pattern generated from the CFD simulation shows colder air introduced by the displacement diffuser sinking towards the ground (Figure 3.2.1.1). Due to the low level momentum, the throw of the jet is not very far, but it has enough momentum to push the air towards the opposite side of the test chamber. There is a large low-level recirculation zone that is created as the flow turns back towards the diffuser once it reaches the wall with the window. Low velocities are seen in the midheight region, as there is entrainment due to the exhaust.

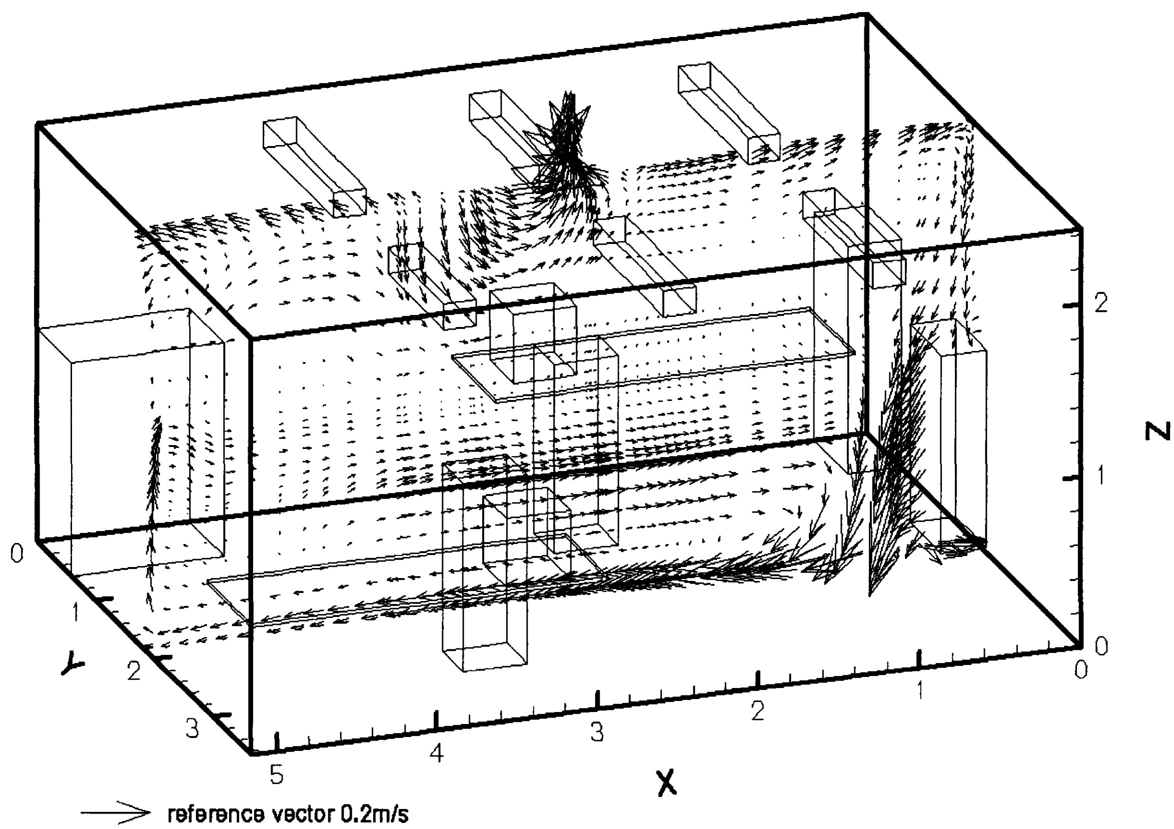


Figure 3.2.1.1 Velocity vectors through the centerline of the test chamber showing recirculation in the lower zone

A temperature stratification is clearly exhibited in Figure 3.2.1.2, which is an important reason that displacement ventilation is used in the first place, as the lower temperature tends to get heated up as it comes into contact with heat sources, thus rising due to buoyancy. The stratification is much more apparent closer to the diffuser than away from it, as the air near the floor gets heated up as it travels along it.

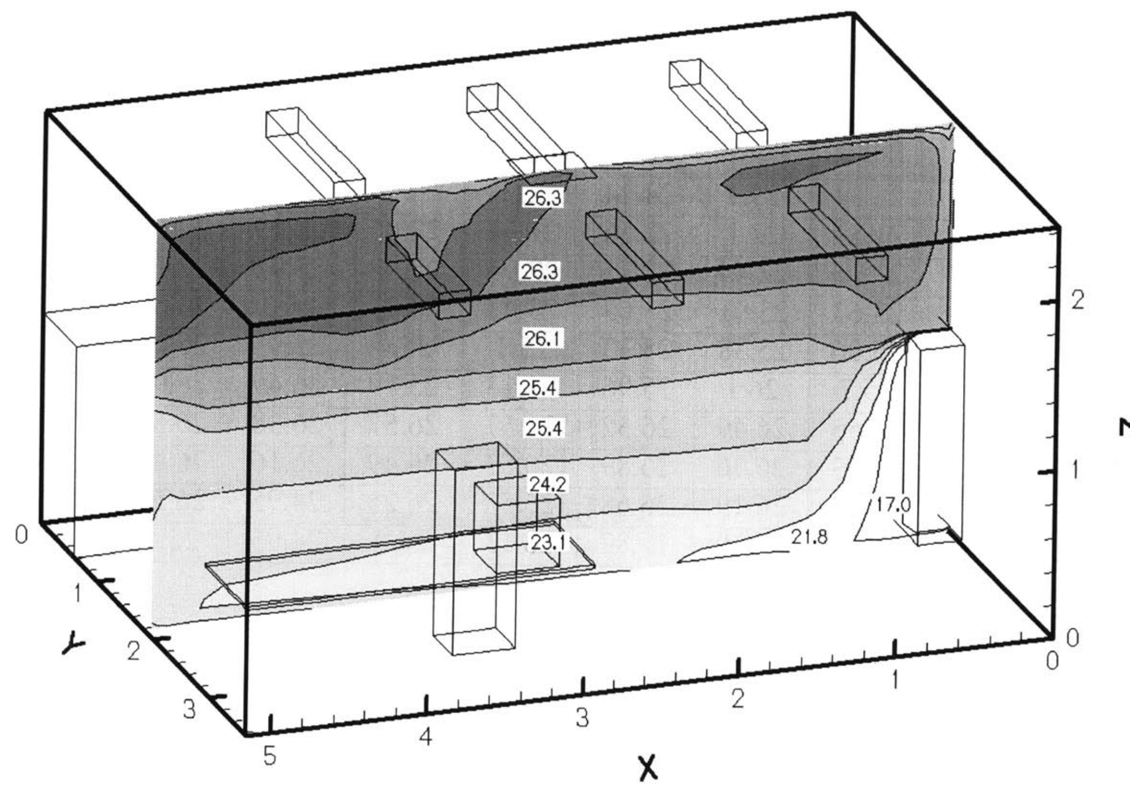


Figure 3.2.1.2 Temperature gradient [°C] through the centerline of the test chamber showing stratification

Table 3.2.1.1, Table 3.2.1.2, and Table 3.2.1.3 show the tabulated experimental data for temperature, velocity and direction respectively. Figure 3.2.1.3 shows the comparison between the experimental data to that obtained from the CFD simulation. The correlation is quite good, and the simulation is quite accurate at discerning the temperature gradients at the floor and ceiling. Clearly stratification is observed between the lower and upper zones.

Table 3.2.1.1 Experimental Pole temperatures for the displacement ventilation case

	Temperature [°C]								
Height [m]	Pole1	Pole2	Pole3	Pole4	Pole5	Pole6	Pole7	Pole8	Pole9
0	21.54	23.34	23.9	24.24	24.72	23.8	24.11	24.01	23.86
0.05	20.85	21.51	22.1	22.56	22.87	22.01	22.19	22.08	22.12
0.1	20.97	21.96	22.44	22.71	22.94	22.08	23.71	22.15	22.26
0.6	23.33	23.63	23.91	23.63	23.43	23.73	25.3	23.66	23.6
1.1	24.75	25.06	25.38	25.33	25.1	25.4	25.99	25.09	25.16
1.5	25.76	25.7	26.1	25.96	26.13	25.79	26.49	26.07	25.99
1.9	26.37	26.55	26.49	26.52	26.57	26.57	26.38	26.51	26.75
2.3	26.17	26.53	26.36	26.89	26.53	26.49	26.16	26.44	26.94
2.38	25.9	26.05	26.19	26.68	26.53	26.25	24.95	26.51	26.61
2.43	25.16	25.4	26.19	25.87	26.13	24.9	24.95	25.5	25.89

Table 3.2.1.2 Experimental pole velocities for the displacement ventilation case

	Velocity [m/s]								
Height [m]	Pole1	Pole2	Pole3	Pole4	Pole5	Pole6	Pole7	Pole8	Pole9
0.1	0.16	0.08	0.08	0.06	0.04	0.08	0.08	0.08	0.10
0.6	0.03	0.03	0.03	0.03	0.06	0.04	0.04	0.04	0.04
1.1	0.06	0.04	0.05	0.03	0.03	0.02	0.03	0.02	0.03
1.5	0.01	0.02	0.02	0.03	0.02	0.02	0.01	0.02	0.02
1.9	0.02	0.02	0.03	0.03	0.01	0.03	0.03	0.01	0.02
2.3	0.04	0.03	0.16	0.03	0.05	0.06	0.06	0.05	0.12

Table 3.2.1.3 Experimental pole concentrations for the displacement ventilation case

	Concentration [ppm]								
Height [m]	Pole1	Pole2	Pole3	Pole4	Pole5	Pole6	Pole7	Pole8	Pole9
0.1	0.037	0.047	0.052	0.066	0.065	0.037	0.034	0.041	0.037
0.6	0.061	0.075	0.061	0.072	0.070	0.054	0.046	0.052	0.046
1.1	0.282	0.300	0.257	0.290	0.249	0.153	0.133	0.213	0.209
1.5	0.452	0.562	0.521	0.379	0.447	0.309	0.546	0.424	0.324
1.9	0.521	0.574	0.560	0.337	0.334	0.295	0.373	0.303	0.265
2.3	0.521	0.559	0.401	0.356	0.339	0.329	0.402	0.426	0.304

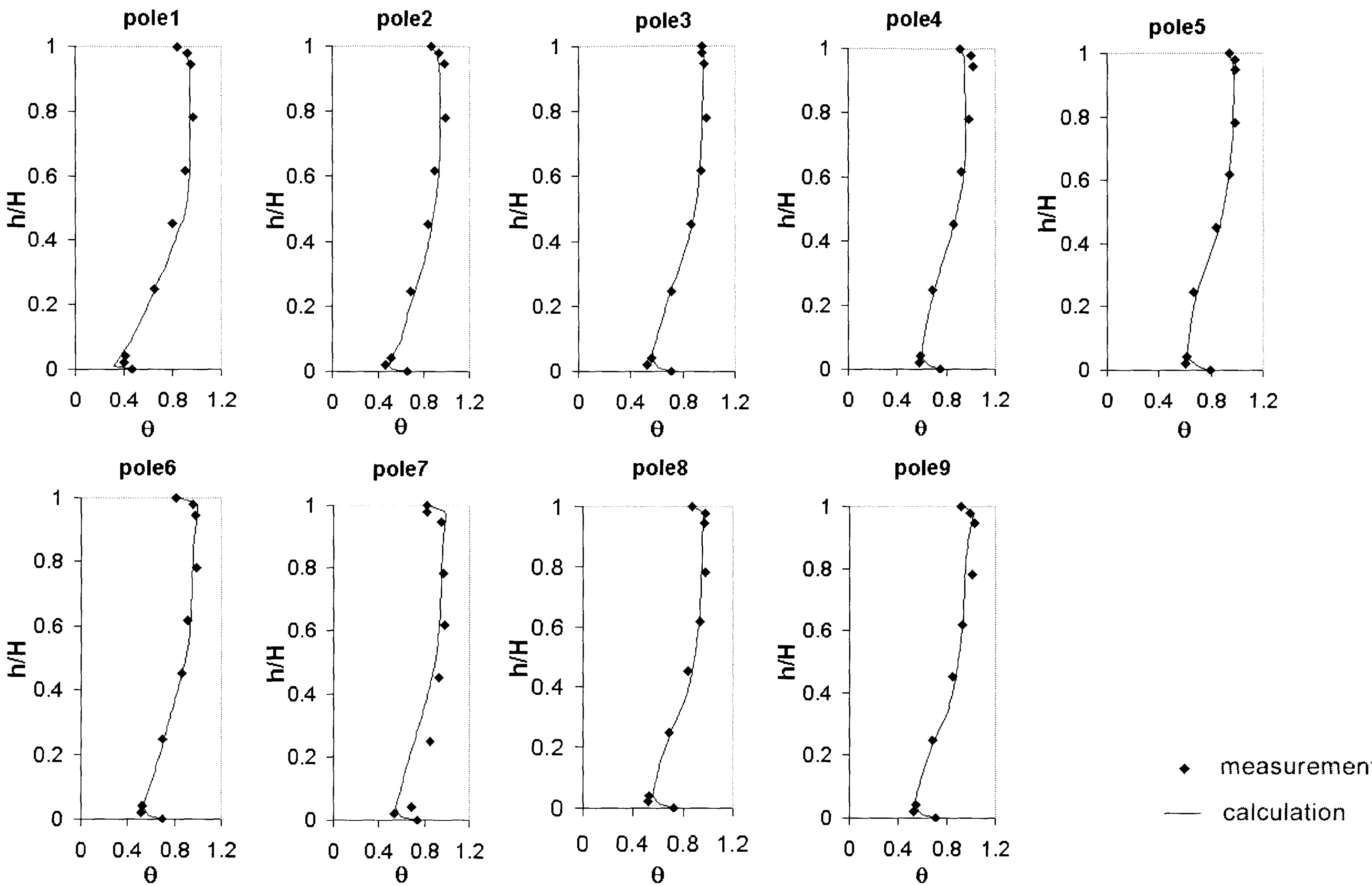


Figure 3.2.1.3 Pole temperatures comparing experimental data to the CFD calculation. [h] is the height, [H] is the total room height, and $\theta=(T-T_{in})/(T_{out}-T_{in})$, T_{in}=17.0°C, T_{out}=26.7°C.

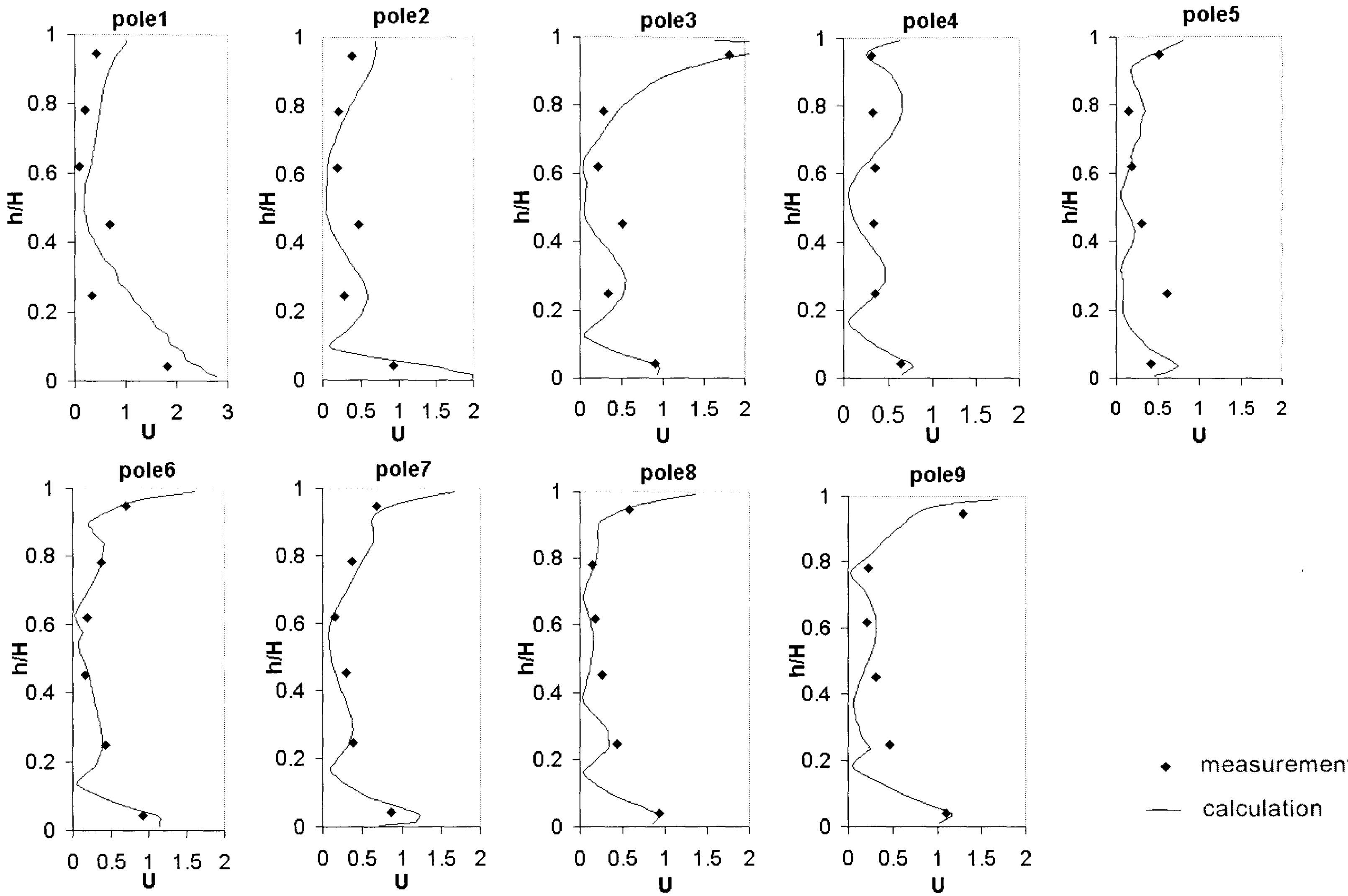


Figure 3.2.1.4 Pole velocities comparing experimental data to the CFD calculation. [h] is the height, [H] is the total room height, $U=u/u_s$, u_s=0.09m/s.

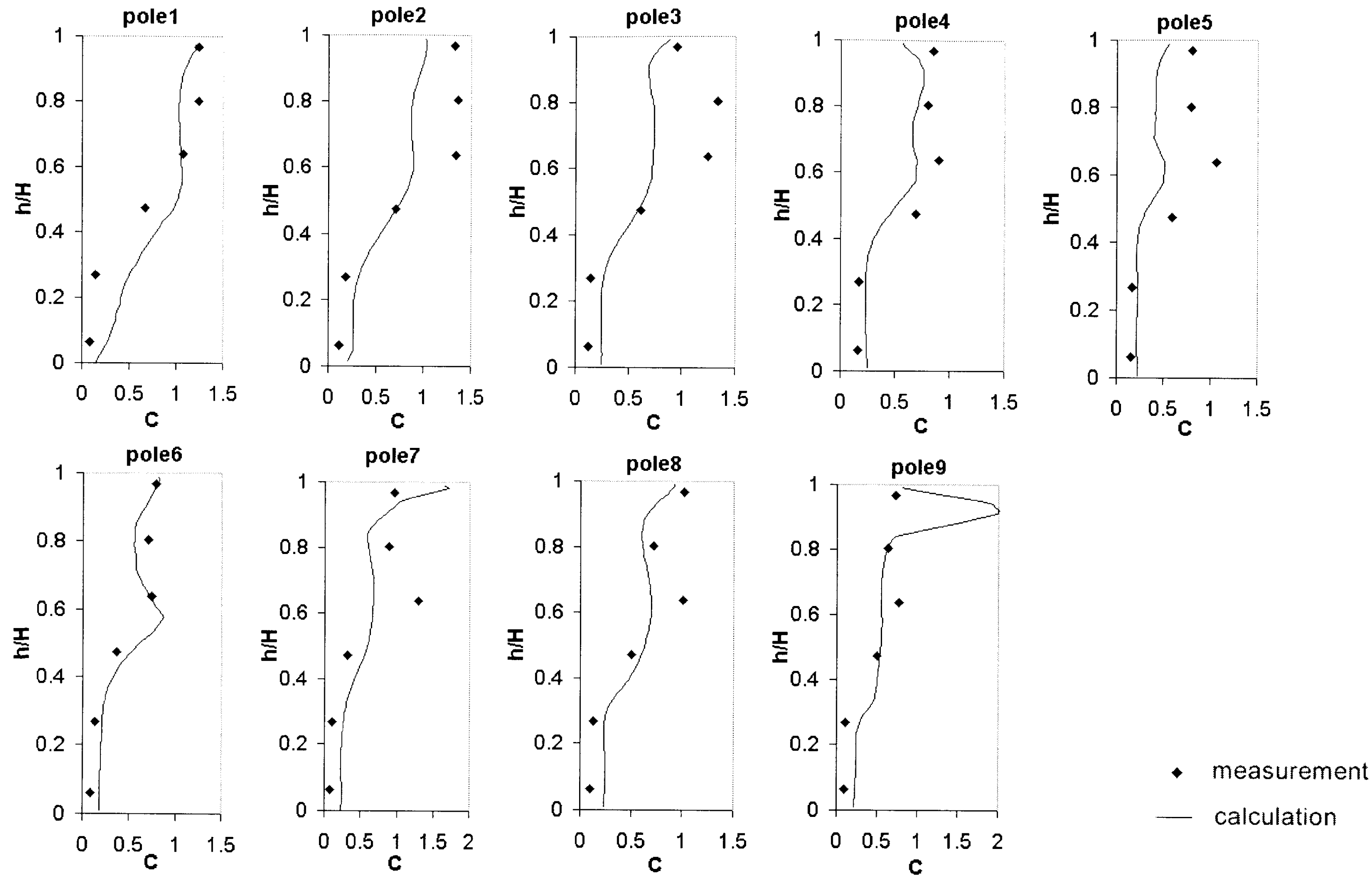


Figure 3.2.1.5 Pole concentrations comparing experimental data to the CFD calculation. [h] is the height, [H] is the total height, $C=(C-C_s)/(C_e-C_s)$, C_s=0ppm, C_e=0.42ppm.

There are discrepancies between the measured and computed data for the velocity and tracer gas concentration, shown in Figure 3.2.1.4 and Figure 3.2.1.5. The high sensitivity of the SF_6 concentration to the flowfield is one major cause for the difference, as the comparison for the very low velocities found in the room is inaccurate. The hot sphere anemometers can only measure to 0.1m/s; many of the pole values are clearly beyond this regime of accuracy. Observationally and characteristically, there is some agreement with the velocity comparison, in that the velocities near the floor are higher than in the middle portion of the room.

The computational method can predict the trend of tracer gas concentration, and shows that stratification of the gas, with the lower regions having a lower concentration than the upper regions. The accuracy is deemed to be acceptable.

3.3 Conclusion

In general, CFD can predict the airflow and concentration migration between two zones with good accuracy, and can thus be used to predict multizonal flow, displacement flow, and contaminant migration. The temperature gradients are very well correlated for the displacement case, and well correlated with very similar patterns though usually underpredicted especially near the ceiling for the low infiltration case. The concentration is predicted less accurately, especially in Zone B for the infiltration case, but the trends are mimicked. However, for this study, the accuracy is deemed to be acceptable, since the low ventilation rates and velocities, coupled with high heat sources contribute to flow instability.

4 Results of Cases in Winter

This section compares the quantitative and qualitative aspects for both ventilation systems. Discussion and analysis of the major aspects of methods of contaminant exposure are presented along with a comparison of the results to the international indoor air quality guidelines for pollutant concentrations.

4.1 Convector Cases

A very common method to heat an interior space is through the use of convectors, mostly though district heating devices. Normally located underneath or near windows, strong buoyancy is generated to counteract the negative buoyancy of cold infiltration air stemming from cracks around the window in addition to relieving the effects of a cold radiating window.

4.1.1 Bimodal Exhaust System with Convectors

The bimodal exhaust system utilizes a constant ventilation rate for the bathroom and WC exhausts, and a bimodal kitchen exhaust that varies between a base value of 45 m^3/h during normal operation and 120 m^3/h only when cooking as seen in Figure 4.1.1.1. Accordingly, the ventilation rate of the whole house jumps from 0.36 ACH to 0.67 ACH for 1.75 hours throughout the time that the family is at home.

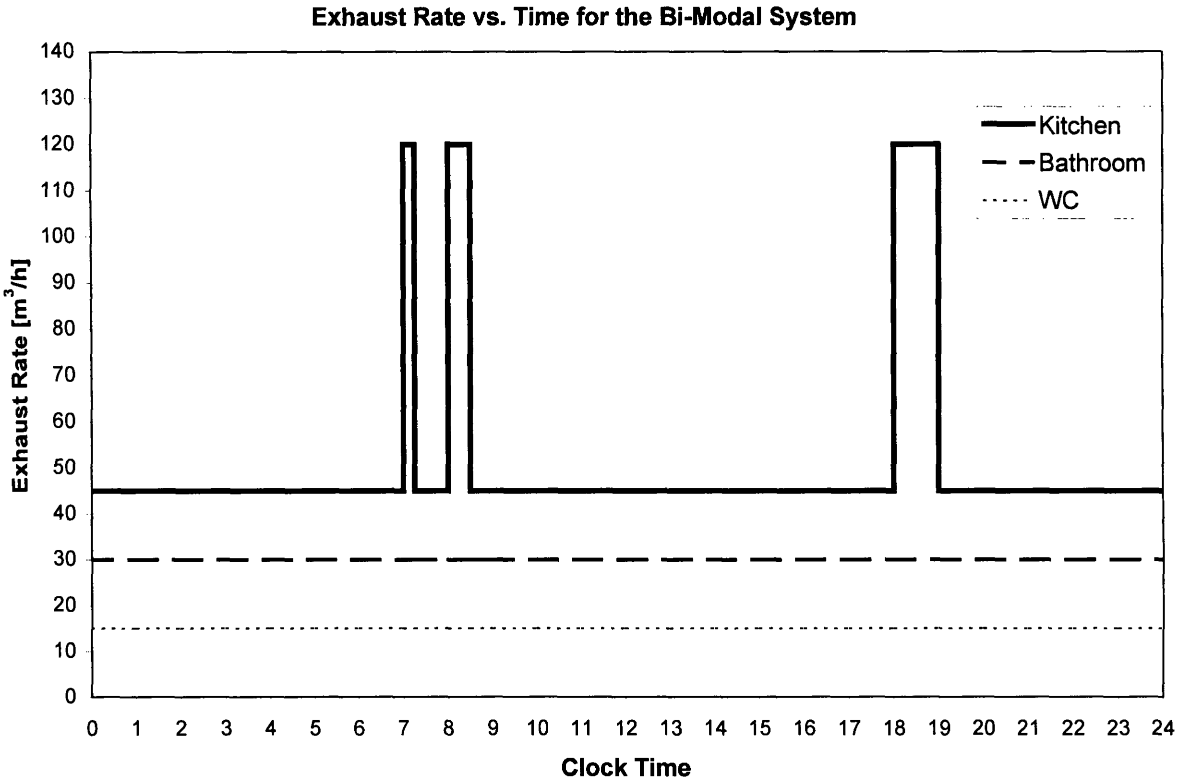


Figure 4.1.1.1 Exhaust rates for the bimodal system showing an increase of the kitchen exhaust rate when cooking and constant bathroom and WC exhaust

Due to the low ventilation rates (and thus small velocities) throughout the house, high degrees of stratification and body boundary layer are characteristic throughout the simulations (see Figure 4.1.1.2), resulting in low concentrations for the occupants that are considered vertical or upright (such as sitting or standing) as exhibited in Figure 4.1.1.3. The air surrounding the person can increase by as much as 3°C, and the temperature difference induces a positively buoyant flow that sweeps contaminants emitting from the facial region upward. This stratification leads to higher temperatures close to the ceiling, and since there is not a lot a mixing (inherent to the fact of stratification), air from the lower part of the room is "cleaner" than that of the upper part, which means that it has a lower concentration of contaminants. The buoyant flow induced by the body boundary layer draws breathing air from this "cleaner" reservoir.

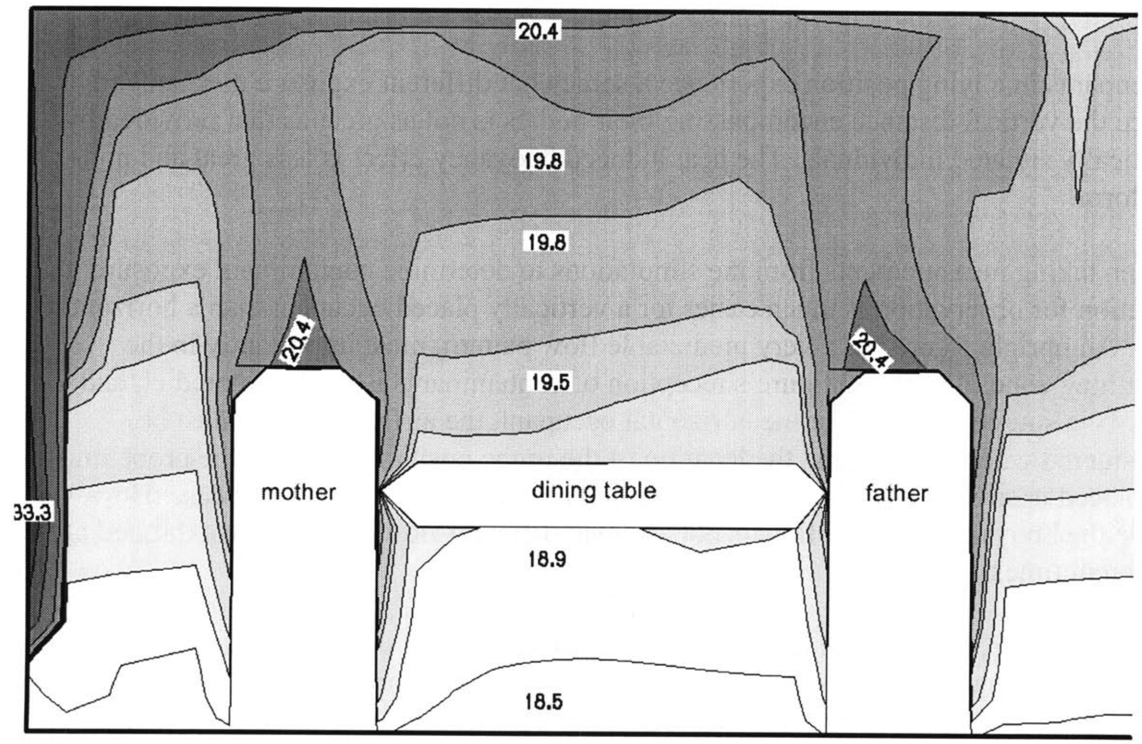


Figure 4.1.1.2 Typical room temperature [°C] contours showing vertical stratification and thermal plumes

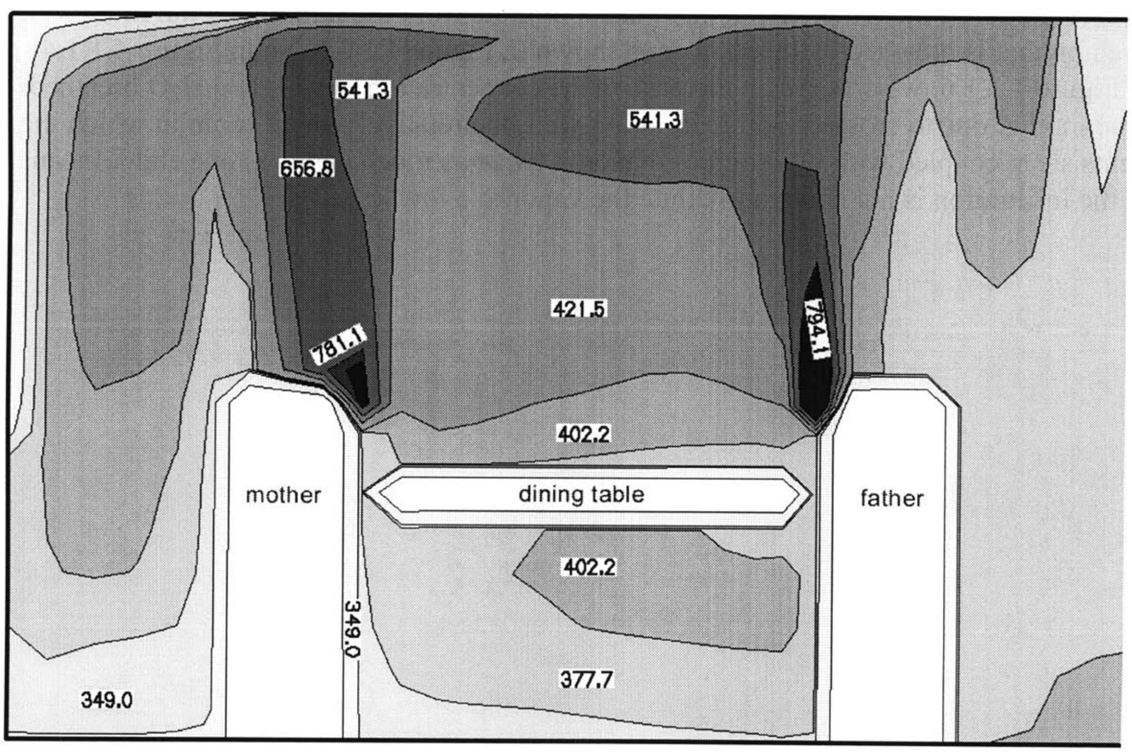


Figure 4.1.1.3 CO_2 concentration [ppm] contours showing the vertical concentration stratification due to buoyancy

Occupants in a lying position experience a somewhat different exposure mechanism, since the vertical distance encompassing their bodies is not as great as that provided by vertically situated individuals. The heat induced buoyancy effect is less great and non-uniform.

When taking measurements from the simulations to determine contaminant exposure, the location for observation is much easier for a vertically placed occupant than a horizontal one. An upright figure has a very predictable flow pattern, most importantly in the breathing zone. A reclined figure's reception of contaminants is harder to predict, and may be a source of error. For the horizontal occupant, the airflow pattern must be considered when determining the location of the probe position. Always, the probe must be placed upstream of the location of the facial region, just as in a vertical case. However, since the buoyancy induced flow is not as great, different flow patterns are exhibited at different times.

In Figure 4.1.1.4 we can see the most striking difference that occupant location plays on exposure through the change in concentration value for the parents while they sleep between 23.00-07.00h. The mother breathes in CO_2 of about twice the concentration that the father breathes. Due to the only heat source located on the south side of the room (not seen in the section), heat induced flow creates a strong circulation region in a south to north (clockwise) direction along the ceiling, impinging on the northern wall of the room and turning down to allow a north to south direction near the occupants. Since the mother is located south of the father, the contaminants migrate from the father's mouth into the air region that is breathed by the mother as shown in Figure 4.1.1.5. So in Figure 4.1.1.4 and Figure 4.1.1.6, we observe an increase in the concentration of CO_2 and H_2O breathed by the mother due to cross-contamination. As well, the relatively small room in which the parents sleep coupled with two sources that emit twice as much vapor as one child, means that the infiltration is not enough to dilute the vapor to a low level.

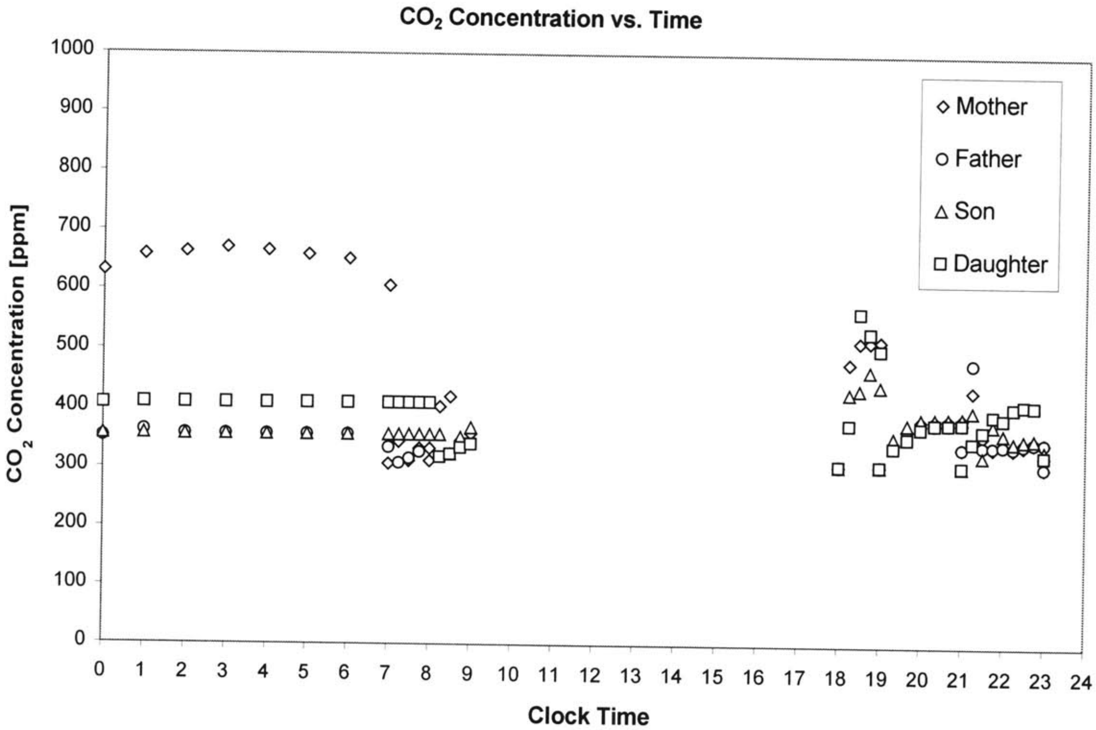


Figure 4.1.1.4 CO_2 concentration vs. time for the bimodal system showing increases during cooking and eating, and cross-contamination resulting in a higher exposure for the mother

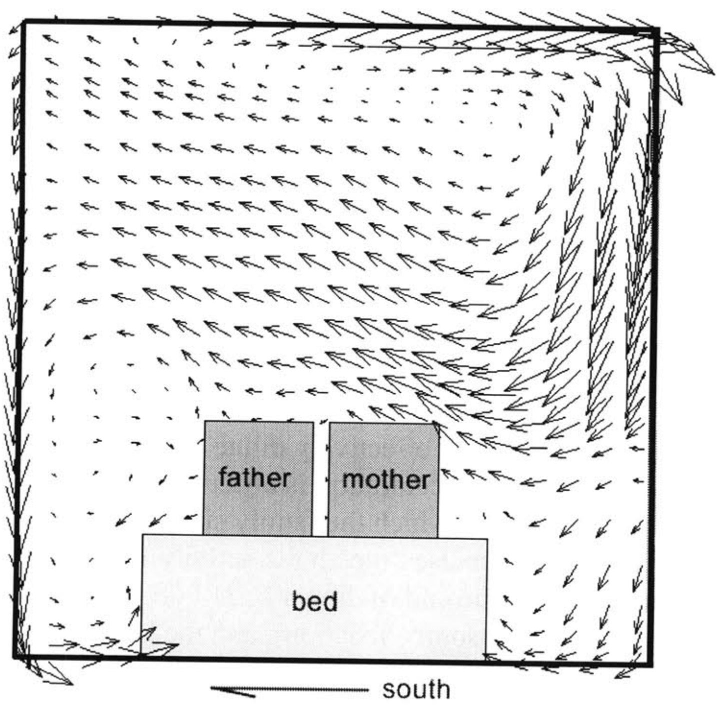


Figure 4.1.1.5 Airflow pattern in the parents' bedroom showing the method of cross-contamination

Differing locations for the children between 21.00-22.00h shows another example of location sensitive exposure; the children are at their desks reading (upright), and go to bed (reclined) starting from 22.00h. A change in the concentration of CO_2 is observed until a quasi-equilibrium point that extends throughout the night and into the morning, where the CO_2 breathed by the daughter is higher in the reclined than upright position, and switched for the son. This effect is also observed when tracking H_2O (Figure 4.1.1.6). Since the childrens' room doors are closed, there is very little interaction between those rooms and those of the other parts of the house, so that the parents' exposure to CO_2 is not affected by the childrens' location, for example.

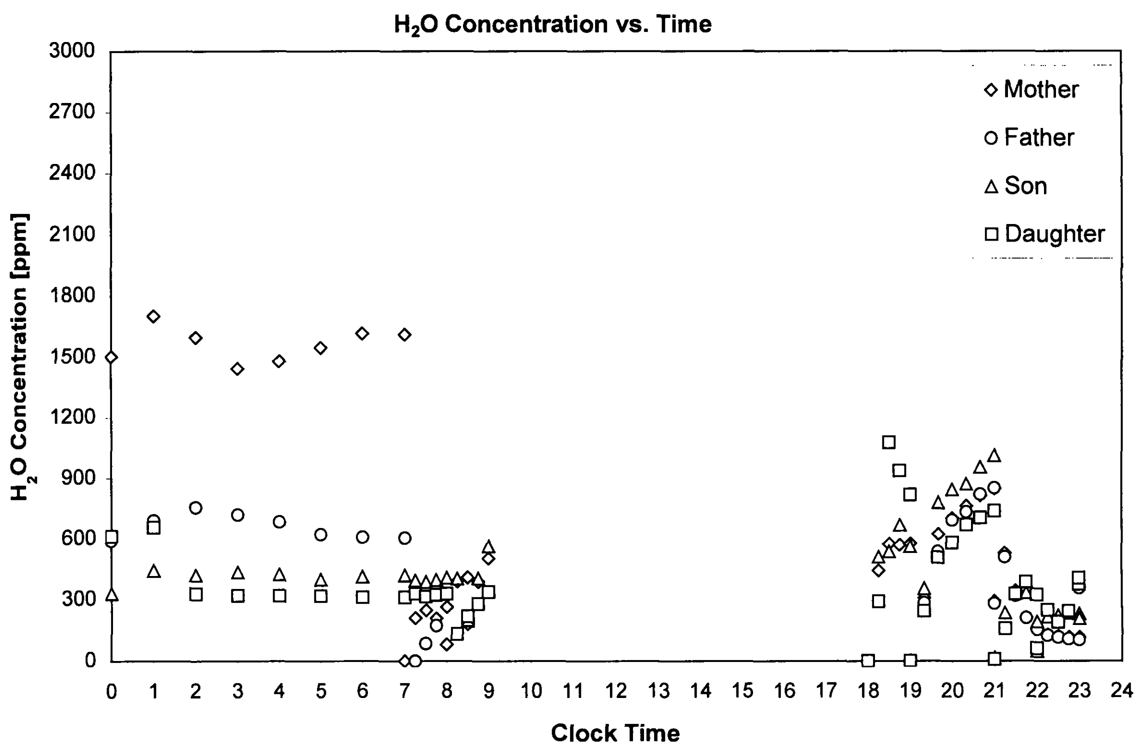


Figure 4.1.1.6 H_2O concentration vs. time for the bimodal system showing increases during dinner and cross-contamination resulting in a higher exposure for the mother

Dinner is another period during which infiltration cannot effectively dilute the water vapor that accumulates. The large spike in the vapor concentration is observed in Figure 4.1.1.6 Figure 4.1.1.6. The close proximity with which the family sits, coupled with an increase in the flux of water vapor (due to increased metabolic activity while eating) increases the vapor concentration right until the end of dinner at 21.00h. Infiltration contains the vapor to the living room (the source location), and the kitchen and bathroom (the extraction location). After dinner, the children return to rooms that have been diluted to ambient conditions. The vapor levels in the living room return back to stable conditions after about an hour due to ventilation and stratification. During dinner, the CO_2 concentration also rises, but peaks off to a quasi-equilibrium level after the first hour of dinner.

Observing the results to find the effectiveness of the kitchen exhaust as a local extract device for the mother, we can see that it is quite effective in curtailing exposure to cooking contaminants when coupled with the body thermal boundary layer. To see the effects of local ventilation, we must look at the pollutants associated with cooking (CO and NO_2) in Figure 4.1.1.7 and Figure 4.1.1.8. For CO, the concentration rises 64.8% during 18.00-19.00h when she cooks dinner. During this same time, the NO_2 concentration increases by 15.8%. The discrepancy is due to the fact that the CO source strength at the stovetop is 4.5 times that for NO_2, and that the ambient concentration of CO is 1.8 times greater than for NO_2.

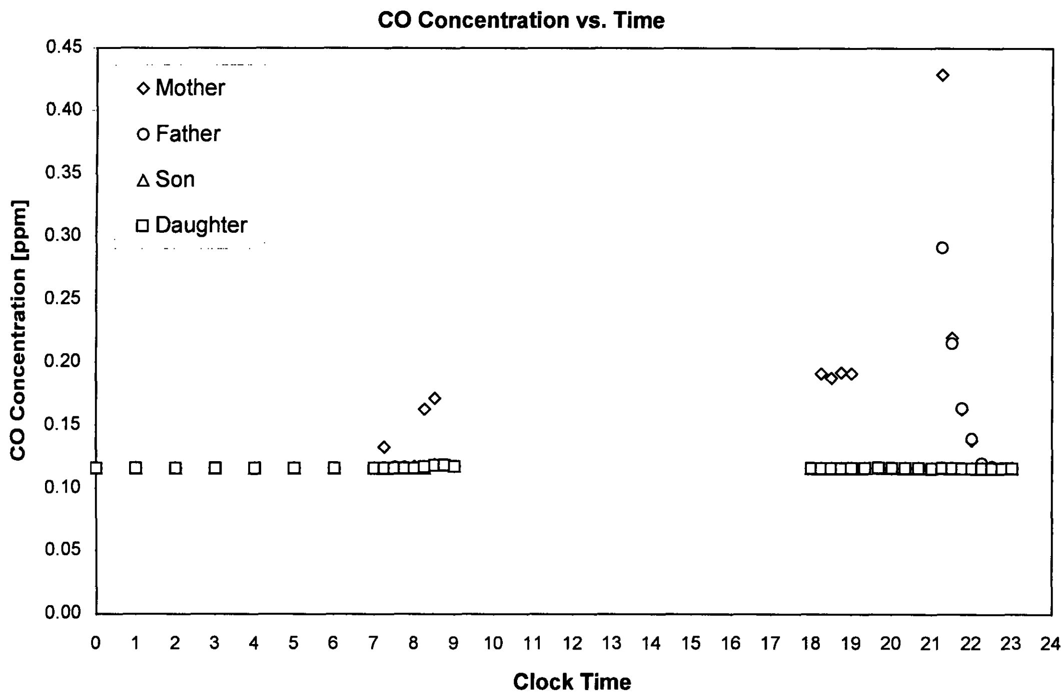


Figure 4.1.1.7 CO concentration vs. time for the bimodal system showing increases of concentration that the mother breathes during cooking, and a sharp spike when the father smokes

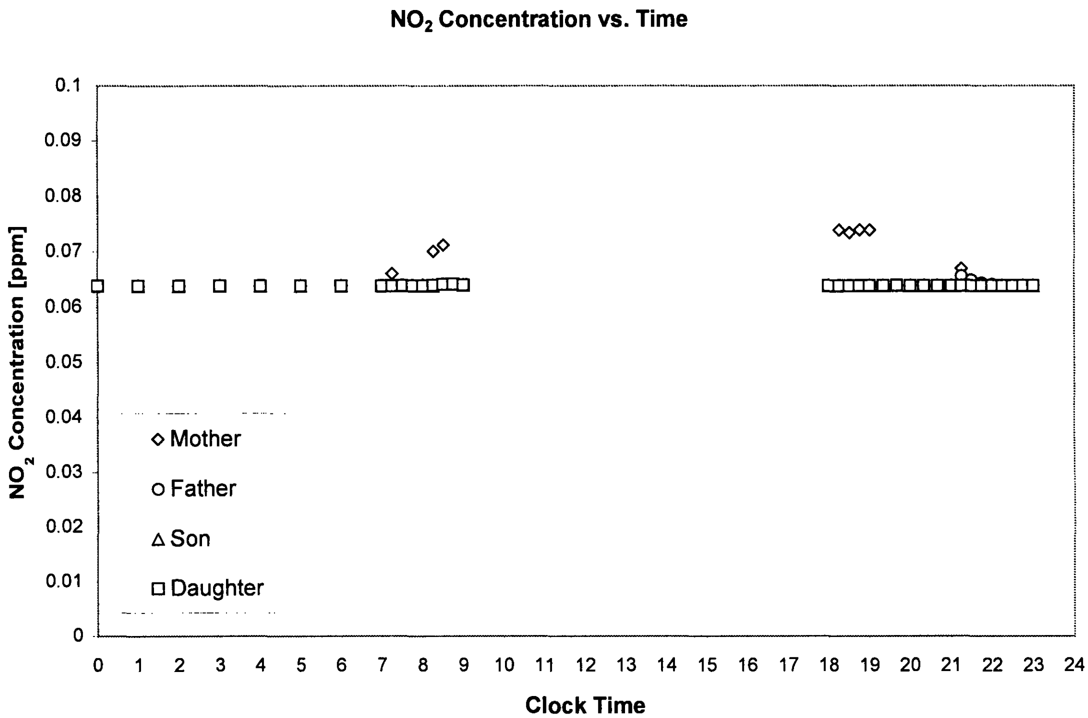


Figure 4.1.1.8 NO_2 concentration vs. time for the bimodal system indicating when the mother cooks and the father smokes

The kitchen exhaust proves to be quite effective for the mother during cooking when she stands directly in front of it. Migration of the cooking pollutants NO_2 and CO is contained with the use of the kitchen exhaust. Only localized escape of the contaminants is seen from the slight elevation of the concentration of air that the mother inhales (see Figure 4.1.1.9). Because of the heat produced at the stove surface, the range exhaust performance is enhanced by buoyancy capture, where a large density difference induces high degrees of natural convection to sweep contaminants toward the exhaust [Figure 4.1.1.9]. As well, this confluence incurs entrainment of the surrounding air, helping to prevent dispersion and diffusion of these contaminants.

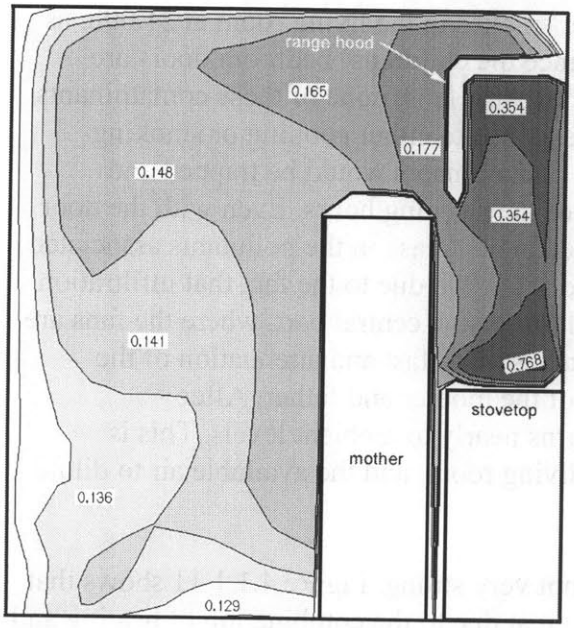


Figure 4.1.1.9 Escape of CO from the range hood exhaust at the end of cooking dinner showing that the exhaust rate is not high enough to capture all of the cooking contaminants

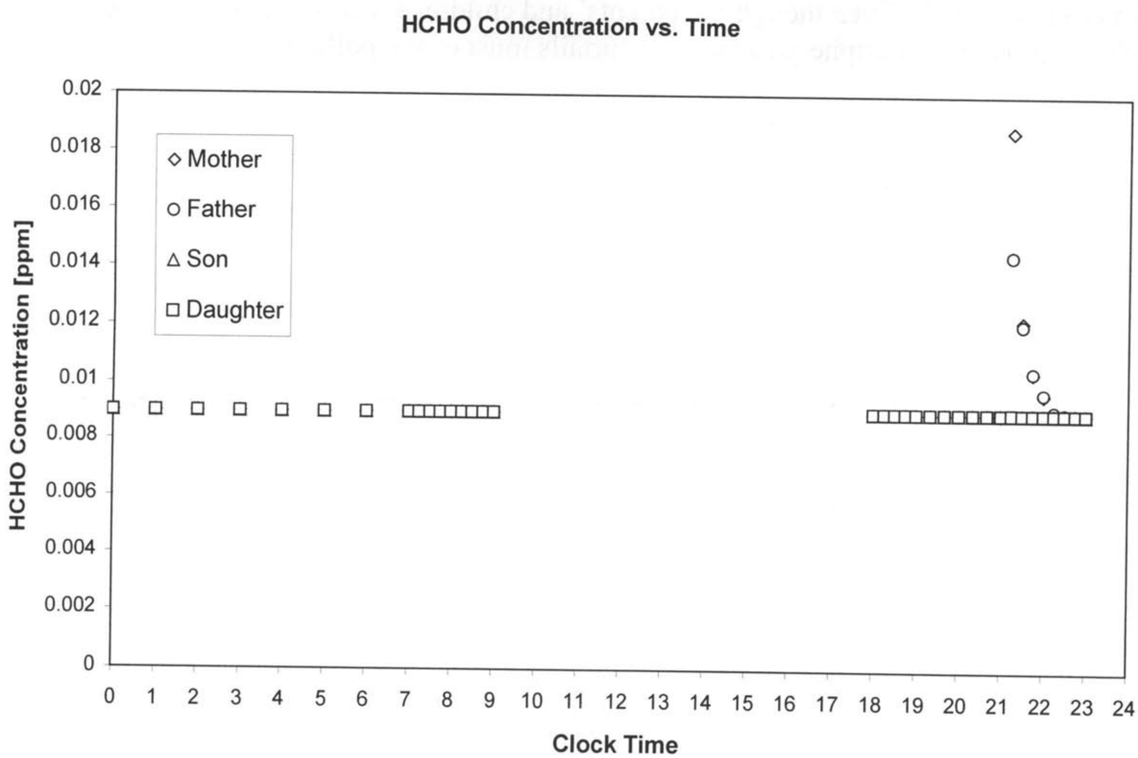


Figure 4.1.1.10 HCHO concentration vs. time for the bimodal system that indicates the time that the father smokes

Definitive spikes are observed when the father smokes in the living room at 21.00h, as seen in Figure 4.1.1.8, and Figure 4.1.1.10. Since the childrens' bedroom doors are closed, and infiltration is induced through the exhaust fans, none of these contaminants ever gets into their rooms and are thus never exposed to either cooking or smoking contaminants. This is very fortunate for these contaminants would be trapped and breathed in by the occupants for the duration of the sleeping hours. Even with the door open, the parents' bedroom exhibits no appreciable increase in the pollutants associated with smoking once they are ready to go to bed at 23.00h due to the fact that infiltration induces airflow from the perimeter of the building to the central part, where the fans are located. The dispersal of smoking contaminants is quite fast and attenuation of the pollutants is good around the breathing zone of the mother and father. After approximately an hour, the concentration returns nearly to ambient levels. This is attributable to the rather large volume of the living room, and the available air to dilute these contaminants.

Room to room migration of contaminants is not very strong. Figure 4.1.1.11 shows that CO migration outside the kitchen is not very great due to the combination of heating and ventilation conditions. The pollutants stay only within the hallway and move into the bathroom and WC, where additional exhausts are located. The vapor concentration at the end of dinner can be seen in Figure 4.1.1.12; migration from the living room (a room without ventilation) occurs only to the rooms with exhaust fans (i.e. the kitchen, bathroom, and WC). Even though the parents' and childrens' bedroom doors are open, infiltration from the periphery to the core curtails must of the pollutant migration.

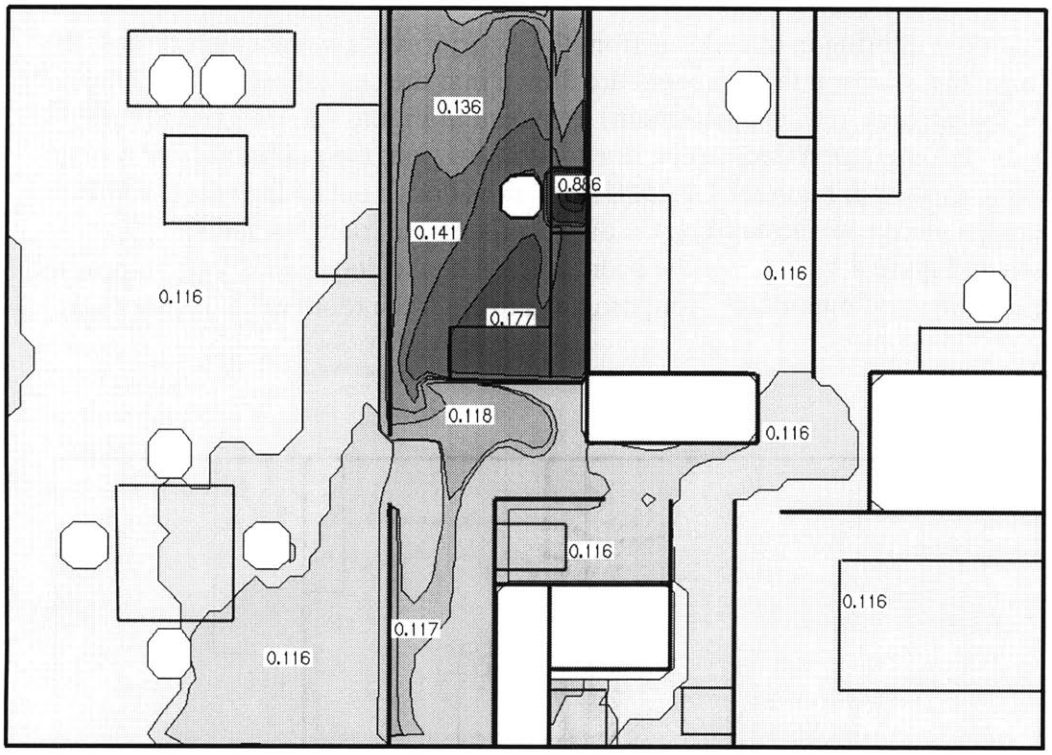


Figure 4.1.1.11 CO concentration gradient at the end of cooking with bimodal ventilation showing the incomplete exhaust of cooking contaminants, but minimal migration out of the kitchen

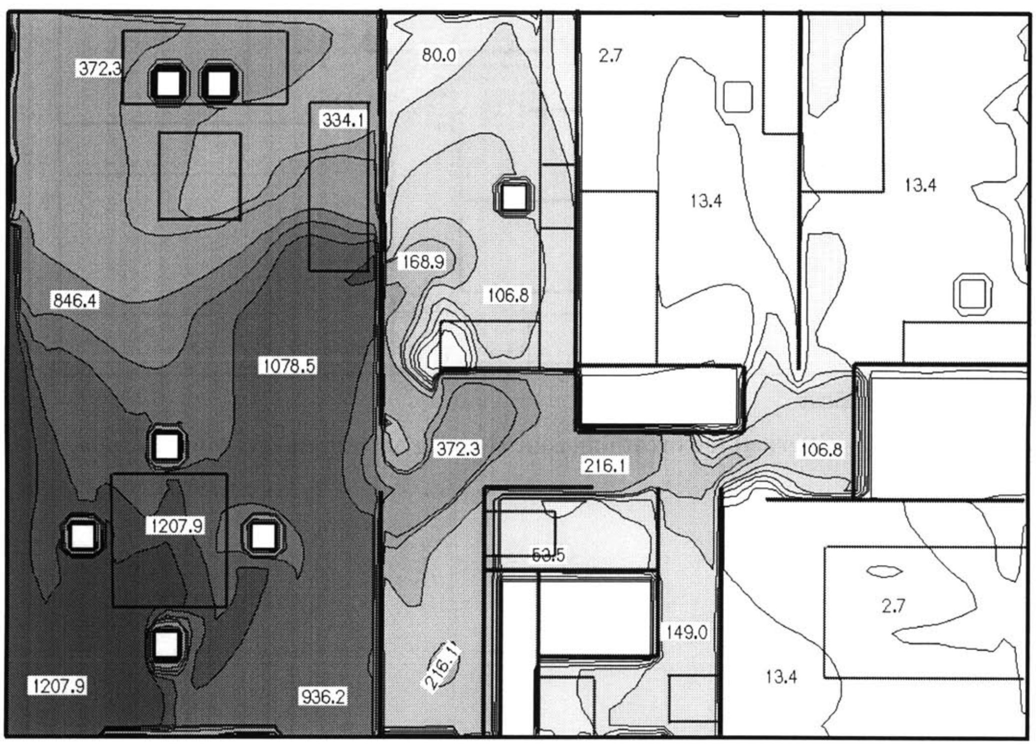


Figure 4.1.1.12 Vapor concentration gradient at the end of dinner with bimodal ventilation showing migration of pollutants only towards rooms with exhausts

Since infiltration will bring in outside air from the exterior walls to the exhaust fans, the pollutants from the rooms in the periphery are drawn into the central region of the house (made up of the kitchen, WC, and bathroom) as shown in Figure 4.1.1.13 and Figure 4.1.1.14. Although migration does occur, due to stratification, the pollutants still remain near the ceiling as seen in Figure 4.1.1.15. Colder air is drawn out of the room, while warmer (perhaps more contaminated air) is displaced into the room, as shown schematically in Figure 4.1.1.16. For the bedrooms, since the door gap is located near the floor, there is little to no opportunity for pollutants to enter the room once the doors are closed.

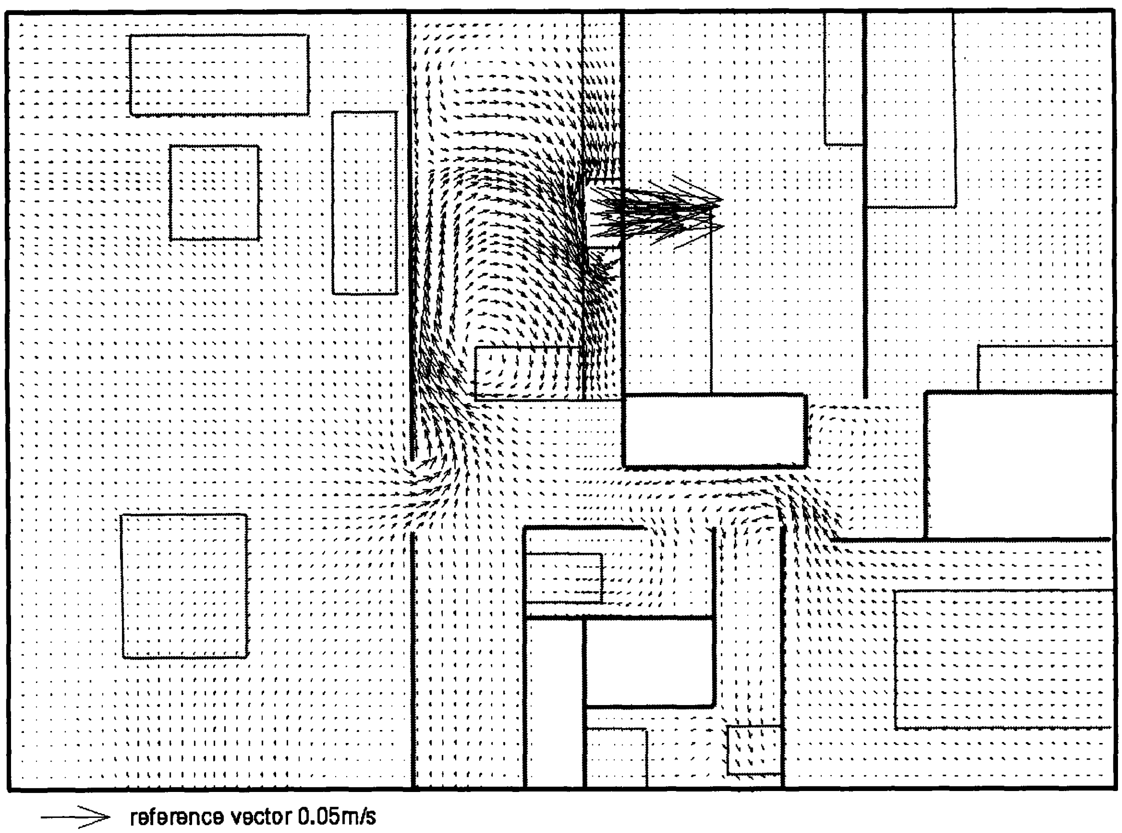


Figure 4.1.1.13 Main airflow pattern at the breathing zone showing air movements towards rooms with exhausts

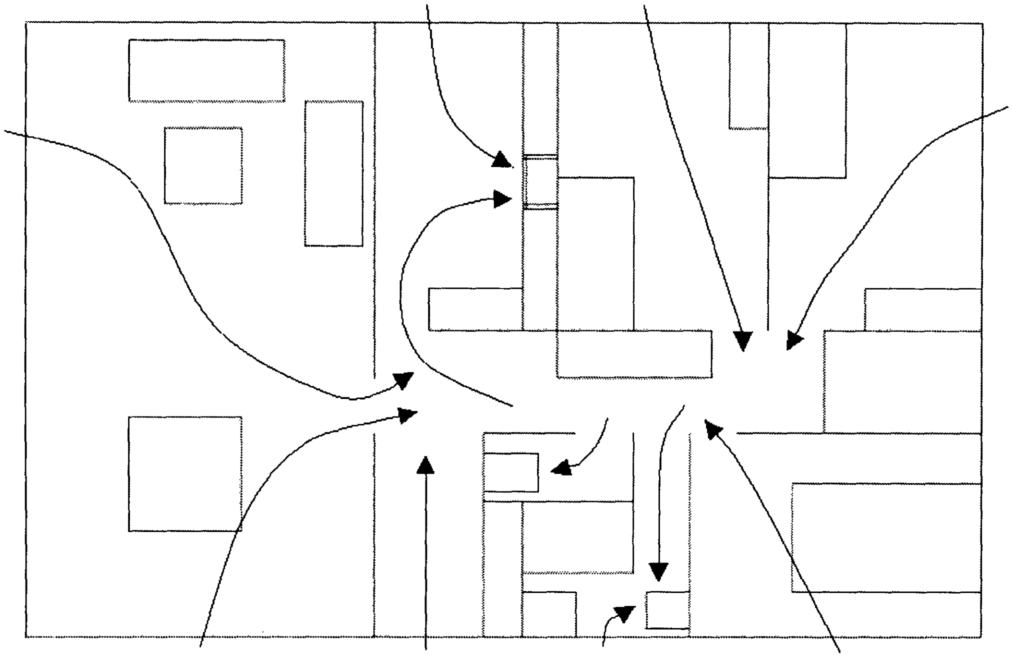


Figure 4.1.1.14 Schematic adaptation of main airflow pathways due to mechanical exhaust and infiltration

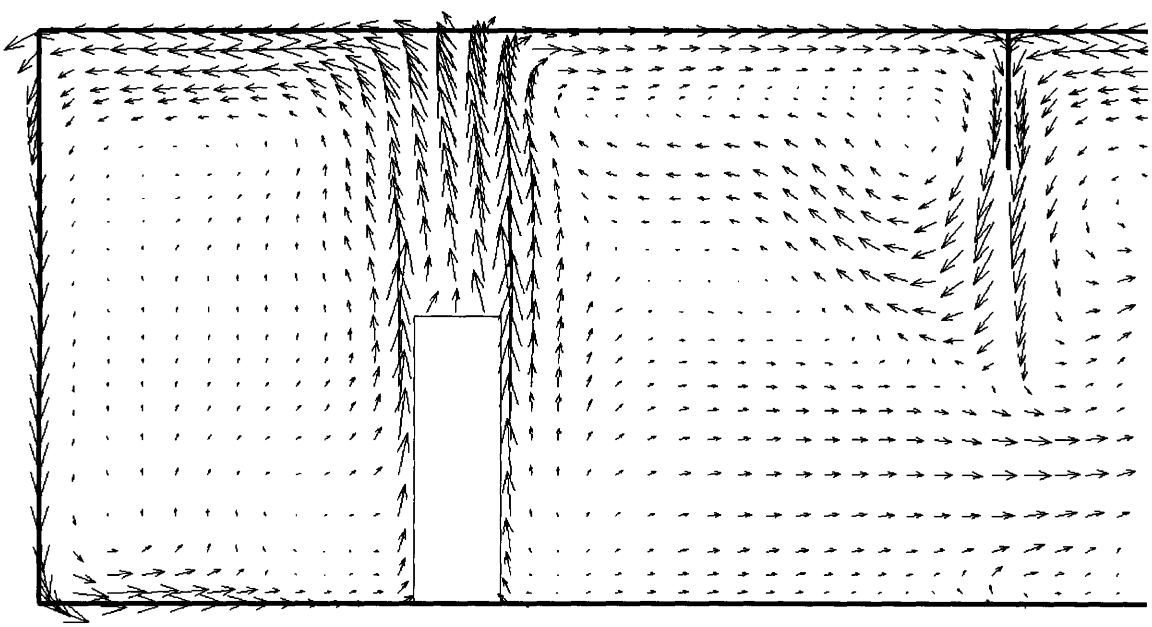


Figure 4.1.1.15 Simulation view showing that thermal plumes greatly affect room airflow patterns at the doorway while producing recirculation zones (color represents temperature)

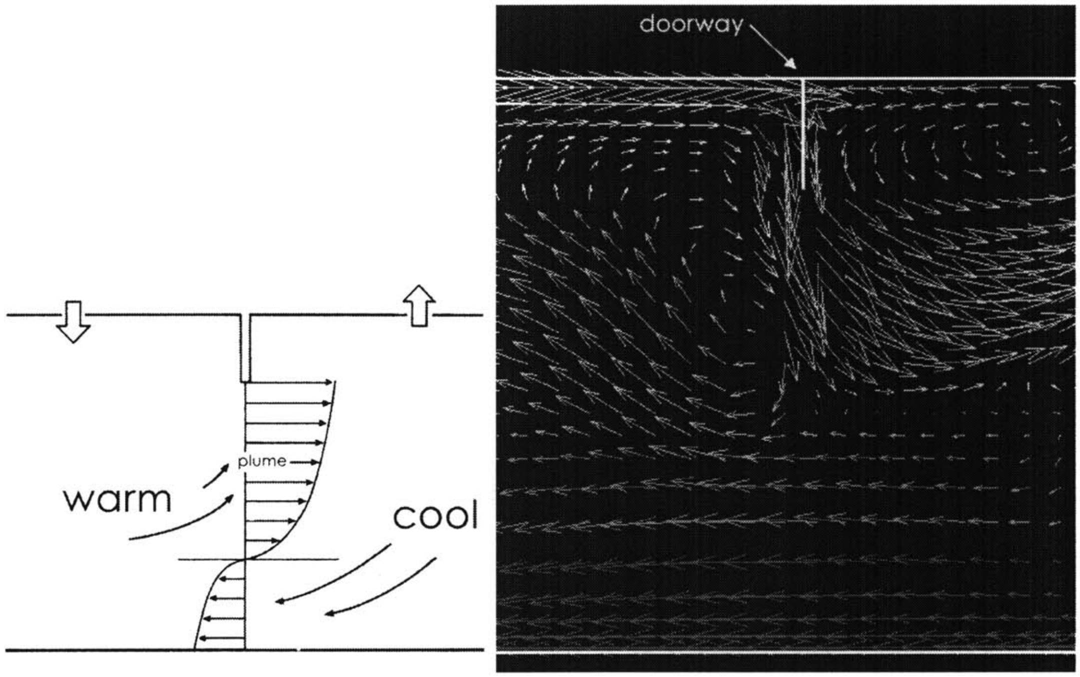


Figure 4.1.1.16 Schematic and simulation view of buoyancy driven flow through a large opening

It is quite noticeable that heated objects have quite a profound impact on the flow patterns in the planes that they intersect (see Figure 4.1.1.15). Since the flows are dominated by buoyancy, heated objects (i.e. convectors) or people will cause large plumes to rise to the ceiling. The impinging jet onto the ceiling will result in a recirculation vortex that is quite strong relative to the quiescent surrounding air. Even if they are quite far away from entities such as doorways or walls, they can still have an impact on the flow, if they are in the same plane.

Since buoyancy dictates the airflows, contaminant concentrations recorded are highly dependent on the location, since small changes in temperature or position can greatly affect the concentration value. Thus probe locations should be chosen in a way that embodies much of the characteristics of room location and other conditions. Even within rooms, aggregations of pollutants may occur due to certain boundary and ventilation conditions. These conditions should then be encapsulated or reflect the contaminant migration and thus personal exposure.

Differences in exposure for occupants with similar schedules come about mainly due to variations in the spaces that they occupy. Much of the exposure to contaminants for the daughter while she sleeps occurs due to a recirculation region that forms near the wall seen in Figure 4.1.1.17. Since she sleeps with her head toward a wall, buoyant flows rising due to body heat will encounter a large circulation induced by the convector on the opposite side of the room. When the residual momentum of this plume reaches the opposite wall (where the head is located), it forces a stream downward along the wall. The contaminants are caught in this recirculation zone to elevate the concentrations of CO_2 and H_2O. The son's room has a different location of the convector, so the large buoyancy-driven vortex shapes exposure in somewhat of a different way shown in Figure 4.1.1.18.

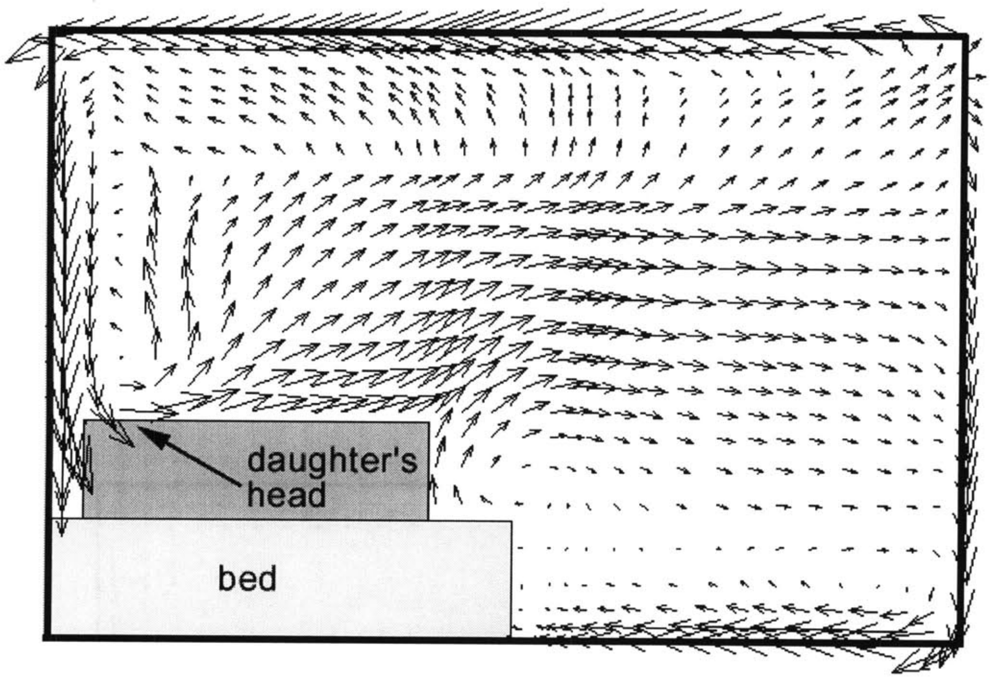


Figure 4.1.1.17 Recirculation around the daughter's head as she sleeps due to convector generated circulation and a body heat induced thermal plume

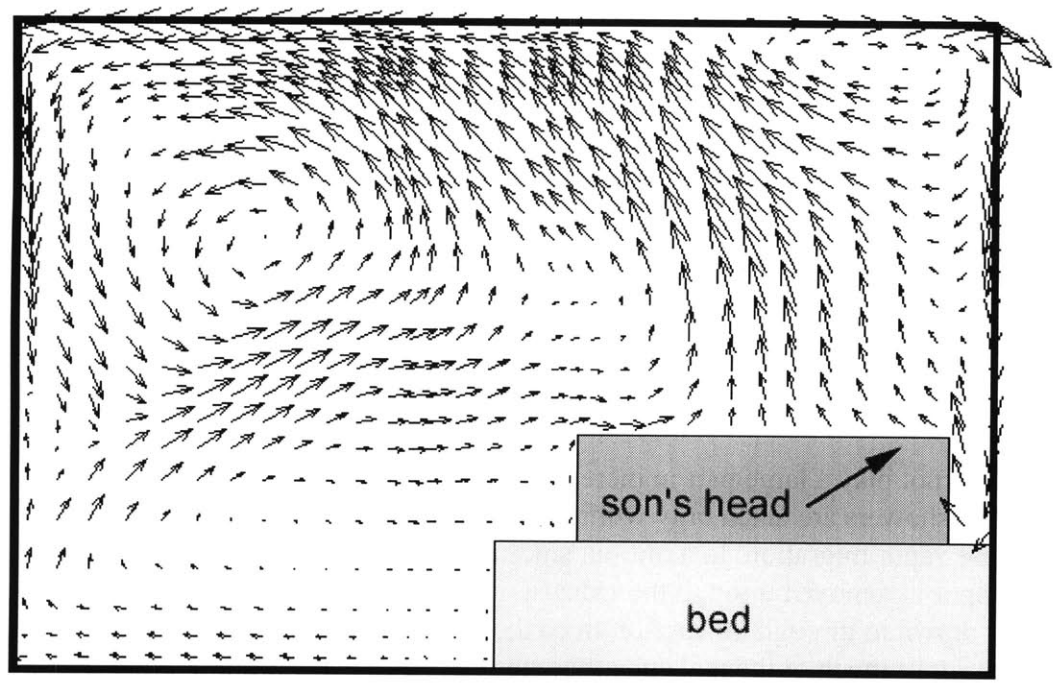


Figure 4.1.1.18 Buoyant removal of contaminants as son sleeps

The heat from the convectors induces the major room-wide circulation as seen in Figure 4.1.1.19. As the buoyant flow rises to the ceiling, the impinging jet then follows the ceiling towards the opposite wall, where it turns into a downward flow. Of course objects near the floor inhibit the flow of this large vortex, but since the convector emits a lot of heat, it is one of the biggest driving factors for convection within the rooms. Especially in rooms with closed doors, the buoyancy induced flows play a much bigger role in air circulation than from that contributed through low-pressure (exhaust) induced infiltration. However, large rooms experience less of an effect of the heat sources as small rooms, since the large volumes will tend to dissipate any of the effects. It is good idea to encourage occupation near these sources, as the buoyancy will tend to increase the stratification effect of the contaminants, as well as place them closer to a heated source during the colder seasons.

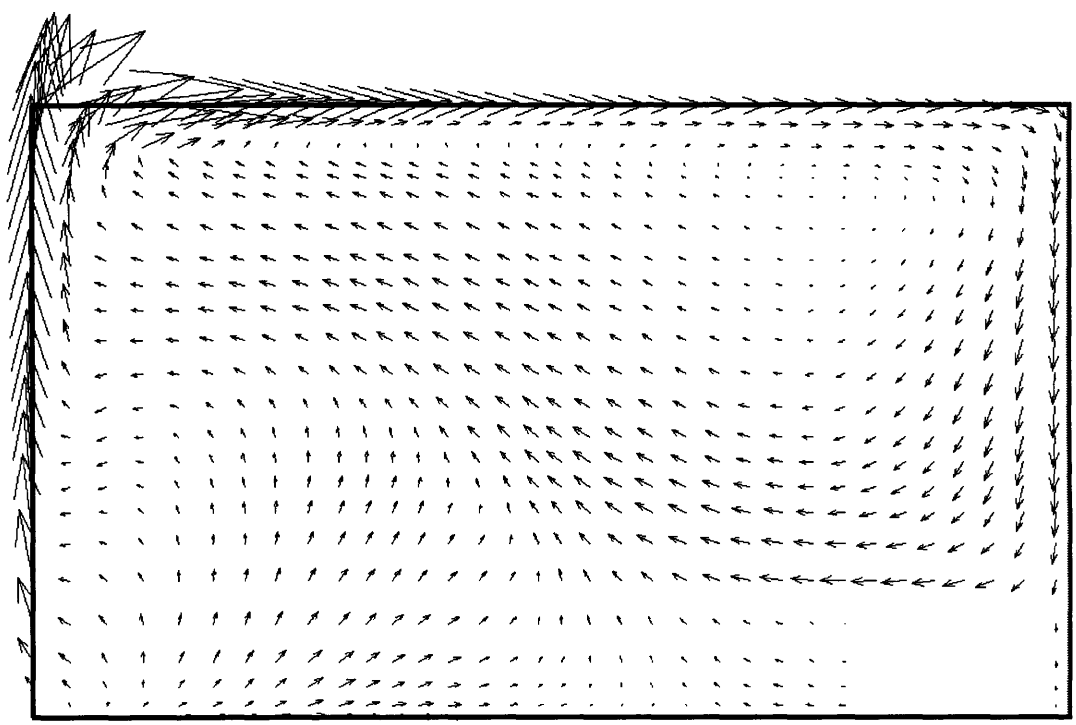


Figure 4.1.1.19 Room-wide circulation generated by buoyantly induced flow

The shower does not play a large part in increasing the amount of vapor found in the house. Since the showers are taken only within a two-hour window in the morning, there is less chance of vapor migration. In addition, since the door is closed during showering, much of the vapor is removed through the exhaust, as well as being diluted from an increase of air drawn in through infiltration from the bathroom window. This occurs since the door is closed, so much of the makeup air comes through the infiltration rather than a large reservoir of the hallway. This phenomenon is observed in Table 2.4.1.3, where the ACH for the bathroom increases (due to increased infiltration) once the family begins showering. The closed door greatly restricts the ability for the bathroom exhaust to have an influence of drawing air from the adjacent hallway. The evaporative process that take place after showing (such as from towels) was not taken into consideration.

4.1.2 Relative Humidity Controlled Exhaust System with Convectors

The relative humidity controlled system is one that varies the exhaust rate based on the relative humidity. A minimum ventilation rate is used when the relative humidity at the exhaust is less than 30%. Between 30%-70% humidity, the exhaust runs at a linear variation between the minimum and maximum value. Above 70% humidity, the fans exhaust at the maximum rate. Although the relative humidity of the outdoor air is taken to be at 50%, since it is a typical winter day and the temperature is 0°C, the humidity ratio is still quite low ($2\frac{g_{water}}{kg_{dry-air}}$). Although the bimodal ventilation system differs from the humidity controlled system (during the winter season) only during cooking and showering (18.00-19.00h and 07.00-08.30h), it still makes a slight difference on personal exposure, since contaminant exposure is highly dependent on the indoor airflow patterns, which are linked to the rates of exhaust.

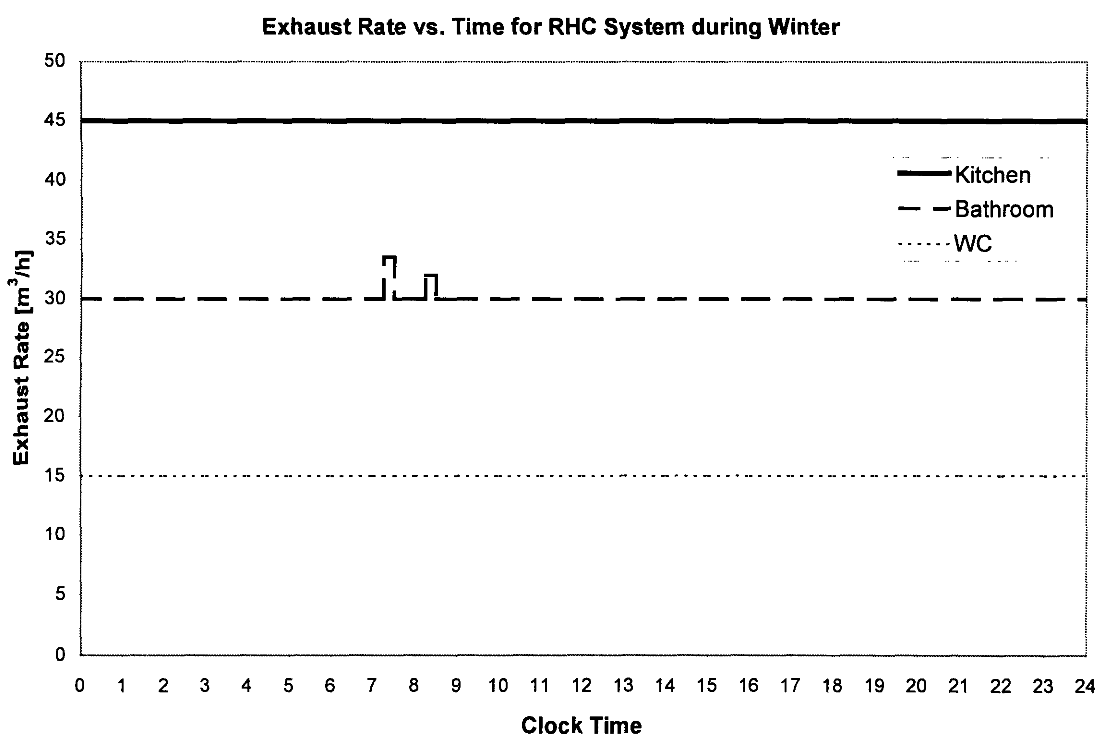


Figure 4.1.2.1 Exhaust rates for the RHC system, noting a slight increase of the bathroom exhaust when showering

The RHC system exhausts at the default low rate if the relative humidity remains below 30%. Since the simulations assume a winter outdoor environment, the humidity inside the house only exceeds the threshold limit near the exhaust fans when the family showers in the morning. When the family sits together for dinner, the vapor concentration and humidity does increase (see Figure 4.1.2.2), but since there is a large volume of the living room space to dilute the vapor with dry outdoor air, by the time it reaches the exhausts, the humidity levels are low. In addition, since the stovetop creates thermal plumes that migrate towards the kitchen exhaust, the increased temperature of the air further reduces the relative humidity of the air as it reaches the fan. Generally, the comparison between the RHC and bimodal system under these conditions is very similar. In all subsequent charts that feature the comparison between two systems, the legend provides the conditions of the plotted data, with the first word in parentheses describing the heating system, and the second word describing the ventilation system.

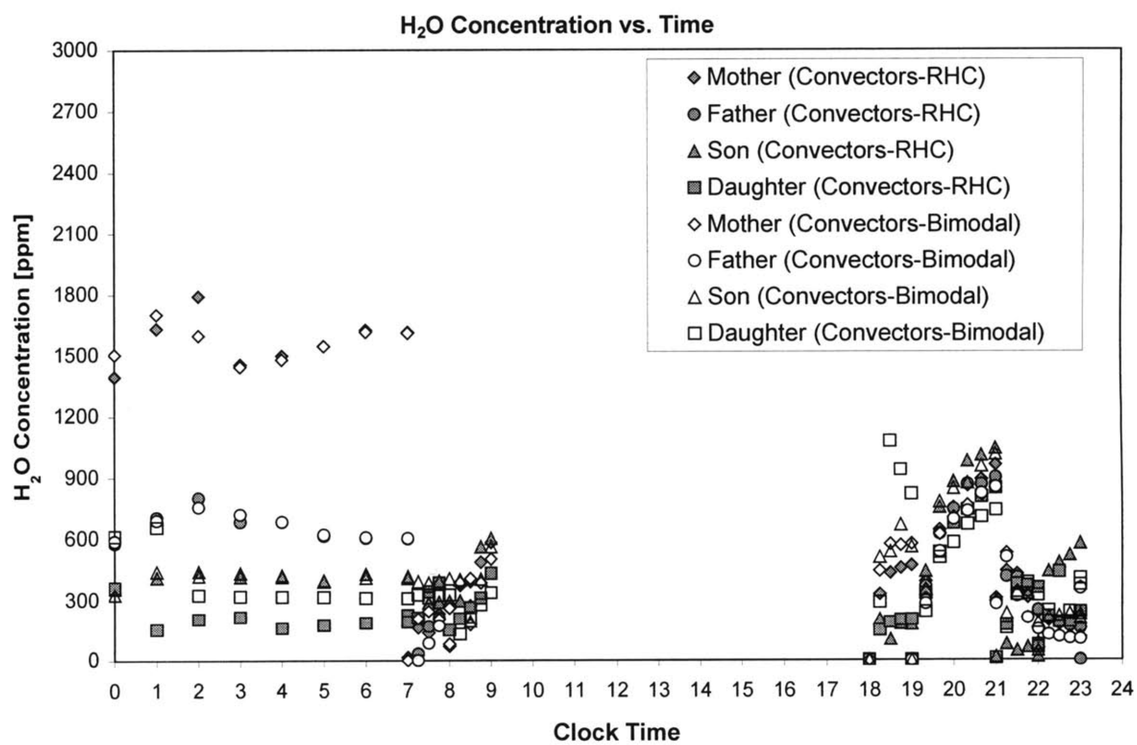


Figure 4.1.2.2 H_2O concentration vs. time for the RHC system revealing when the family eats and cross-contamination for the mother

Although the humidity controlled system does change the exhaust rate of the bathroom extract during showering in the morning, due to the relatively small volume compared with the heat emitted from the convector, the relative humidity exceeds the 30% threshold by less than 10% relative humidity. Thus the exhaust rate at the bathroom only provides marginal effects on mitigating contaminant exposure. And since the door is closed during showering, migration of vapor out of the bathroom is still kept at a minimum.

The difference in exposure due to the airflow patterns can be objectified by the dramatic difference between the CO_2 concentrations for the two ventilation systems, despite the fact that all many other conditions are equal. Comparing the values in Figure 4.1.2.3, there are some differences in the indoor concentrations, mainly during the cooking and eating of dinner.

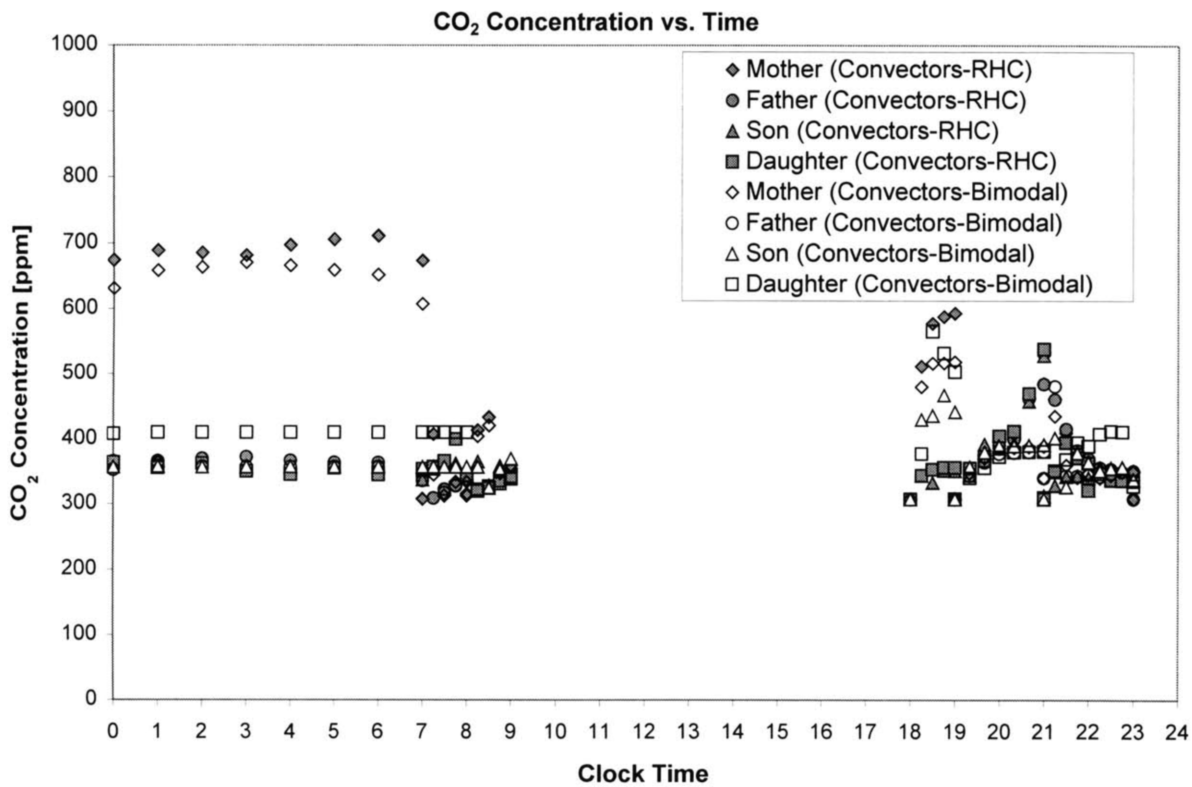


Figure 4.1.2.3 CO_2 concentration vs. time for the RHC system showing cross contamination for the mother and indicating the gathering of the family as they eat dinner

The reduced fan rate clearly does not help decrease the exposure of the mother to the contaminants during cooking, so the concentrations of combustion by-products is higher for the RHC system compared to the bimodal system as seen in Figure 4.1.2.4.

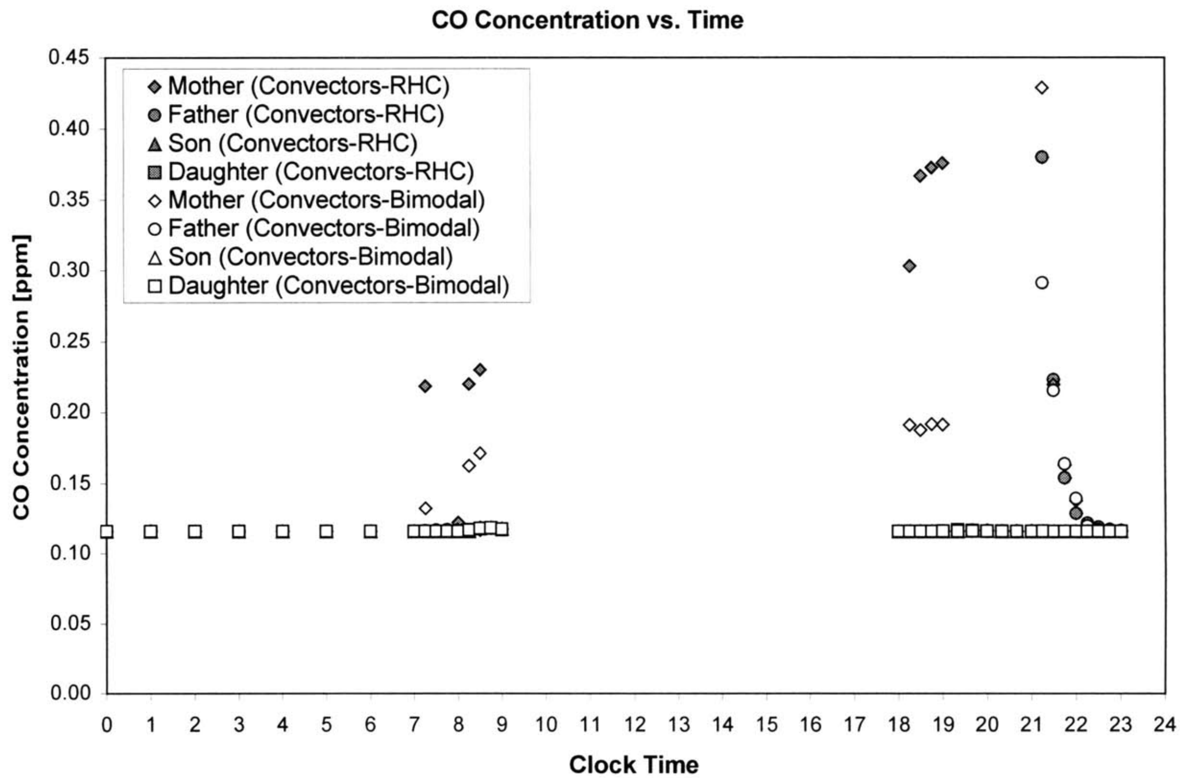


Figure 4.1.2.4 CO concentration vs. time for the RHC system revealing when the mother cooks and the father smokes

We can see that the effects of a lower exhaust rate by comparing the CO concentration gradients of Figure 4.1.2.5. With the same scales of for the concentrations, much more CO escapes from the stovetop (as expected) for the RHC system that the bimodal system, and that the kitchen concentration is elevated. Fortunately, the migration of CO out of the kitchen is not very great, even with a lower exhaust rate. For water vapor, the comparisons of Figure 4.1.2.6 reveal that the mother's exhaled vapor remains in the kitchen and migrates into the living room, to elevate the overall vapor concentration. Again, migration to the bedrooms is still curtailed through the exhaust locations at the core of the house.

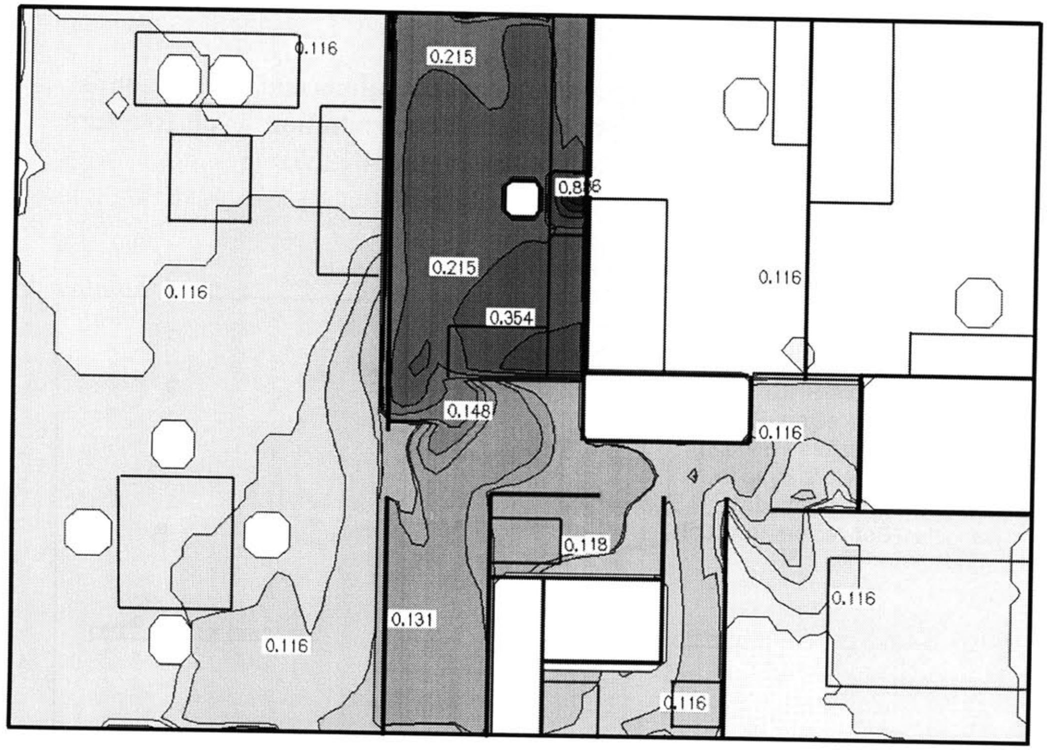


Figure 4.1.2.5 CO concentration gradient at the end of cooking with humidity controlled ventilation showing an increase in concentration levels over the bimodal system, but still limited migration to the other rooms

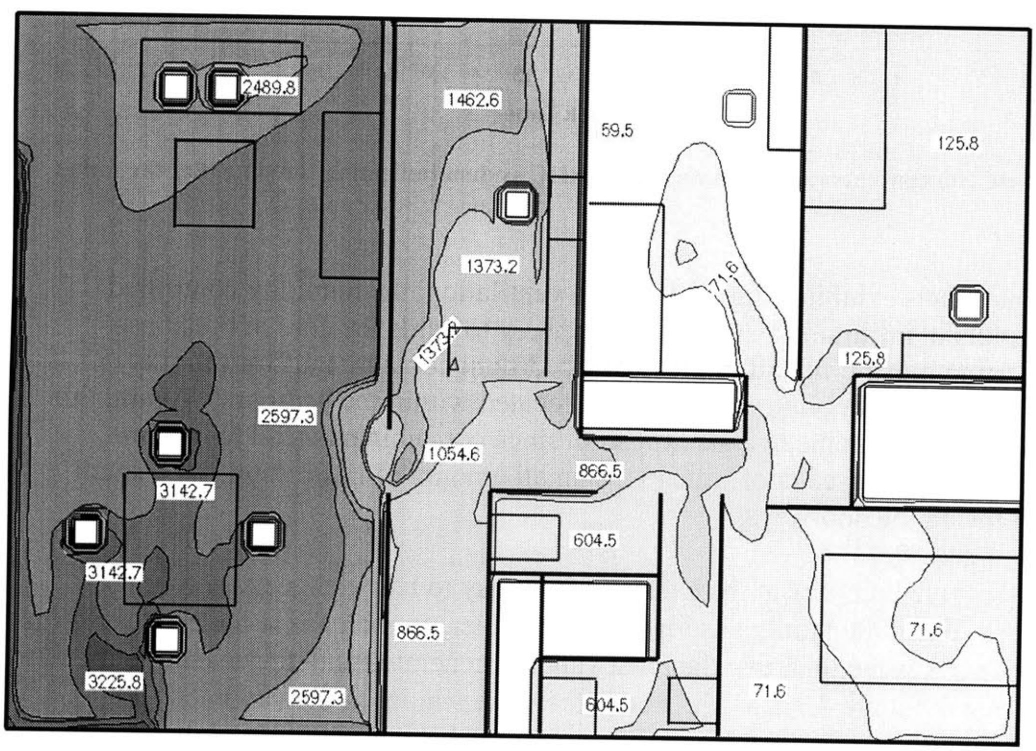


Figure 4.1.2.6 Vapor concentration gradient at the end of dinner with humidity controlled ventilation showing elevated concentration in the dining area/living room by similar patterns of migration compared with the bimodal system

During the time that the father smokes, the pollutant concentrations and attenuation is still generally similar. Both ventilation systems cause the concentration levels to return back to stable conditions after about an hour as seen in Figure 4.1.2.7.

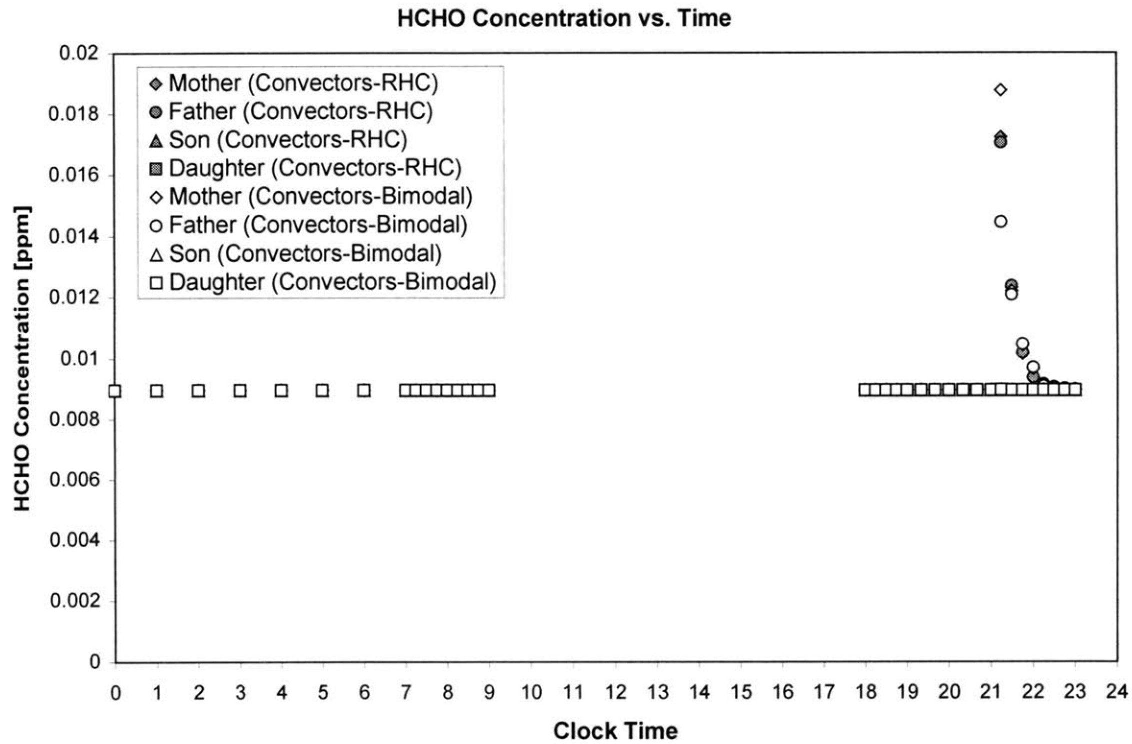


Figure 4.1.2.7 HCHO concentration vs. time for the RHC system indicating the time that the father smokes

Due to similar effects exhibited during bimodal ventilation, the humidity controlled exhaust still pulls in infiltrated air from the periphery towards the core of the house, thereby mitigating most, if not all of the out of bedroom contaminant sources (i.e. contaminants generated by sources that are not located within the bedroom). Again, this plays a profound effect on the overall exposure, since contaminants tend to become trapped in rooms with closed doors due to the small amount of infiltration and a small opening underneath the doorways.

Tracking the relative humidity at the exhausts, it is easy to tell when certain types of activities occur. When the family sits together for dinner, an increase in the exhaust RH is observed, since this is the time that the most vapor is generated and dispersed into the exhausts as seen in Figure 4.1.2.8. The trends are quite similar to the vapor concentrations when there is a source in the room with the exhaust fan, and the high peaks during showering can clearly be seen. Times of cooking can be discerned in the RH at the kitchen exhaust since they are so low (due to the high heat of the stovetop). Otherwise, general trends in vapor concentration throughout the house are mimicked by the exhaust concentrations in a damped form in that peaks and troughs in the concentrations lag slightly behind when actual events occur.

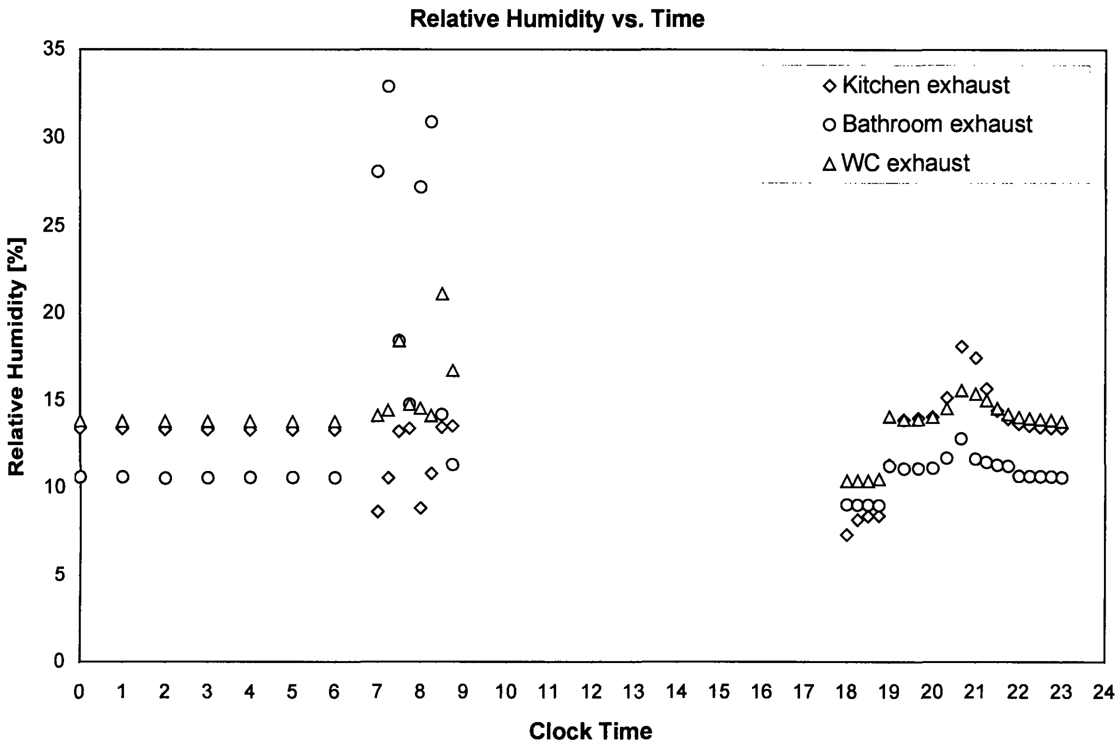


Figure 4.1.2.8 Relative humidity at the exhausts throughout the day that increases as different activities take place throughout the day, most notably showering in the morning hours

Generally, the RH seen at the exhausts correlate to each other when there are no sources of vapor in the room. The RH rises and falls during the same periods of time, and at a similar relative magnitude. As the door to the bathroom is opened after showering, since there is a higher concentration of vapor, it migrates into the WC, elevating the relative humidity at the exhaust. We can see some difference in the performance of the exhausts relative to their location, as the kitchen exhaust experiences a greater increase the RH relative to the other fans during dinner, since this is the closest exhaust location to the dining area.

There are some differences between the two systems in terms of both the indoor air quality and the use of energy, as higher exhaust rates for longer durations incurs more electricity usage to heat up a larger amount of cold infiltration air. As a first estimation, the bimodal exhaust system consumes more energy compared to the RHC system, for this winter situation only. The difference in exposure is reviewed in the following section. While energy usage was not tackled in this phase report, it is an important factor that must be taken into consideration when designing the heating and ventilation systems.

4.1.3 Balanced Ventilation with Bimodal Exhaust System and Convectors

The balanced system is fundamentally different from the bimodal or the RHC system since it provides inlets for semi-conditioned fresh air. Incoming air is heated slightly or passed through a heat recovery system to 13.3°C at a rate of 22.5m^3/h through diffusers located directly in the bedrooms. All the makeup air is through infiltration. As the bimodal exhaust system is employed, all other conditions are the same.

Very striking in the context of airflow patterns dictating the method of exposure, we see that when the father smokes in the living room, an initial spike of high concentration is seen at 21.00h, which then begins to decay (Figure 4.1.3.1). At about 22.00h, a shift in the flow pattern increases the concentration of the combustion contaminants breathed. This is most likely caused by the balanced ventilation diffuser that is located just to the west of where the mother and father sit in the living room. The concentrations then take on a totally different trajectory, and exposure is fundamentally changed.

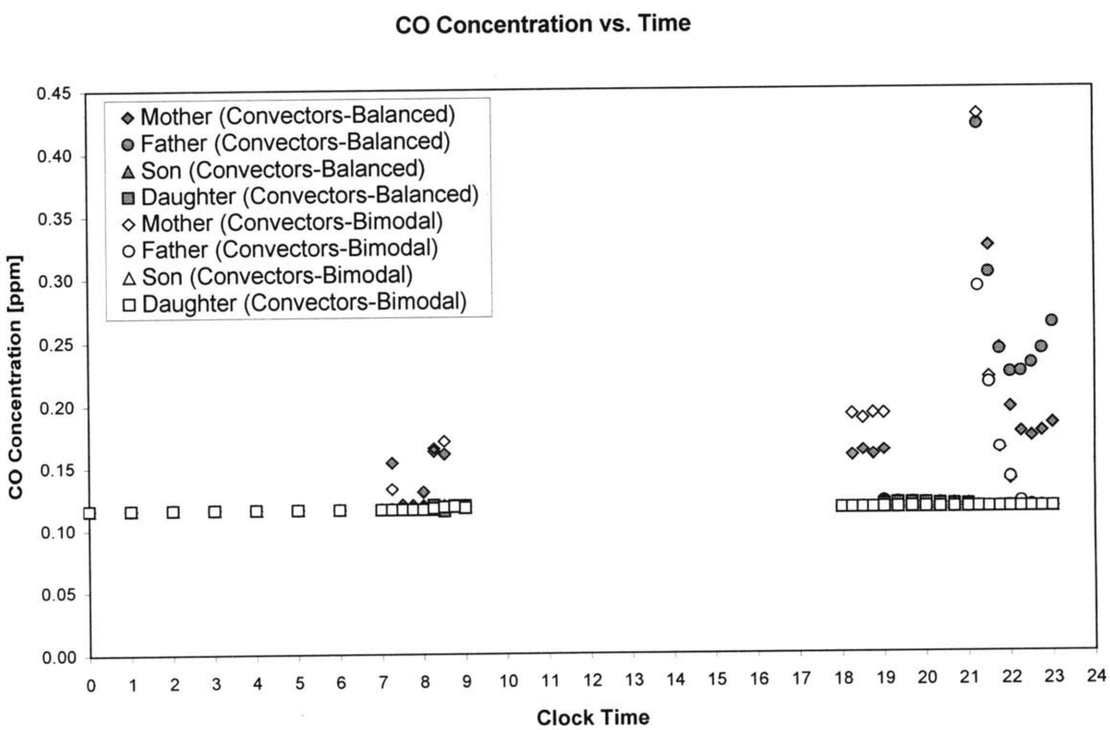


Figure 4.1.3.1 CO concentration throughout the day showing a different trajectory for the parents at 21.00h

Good correlations can be seen when comparing the concentrations of CO_2 for the balanced and bimodal ventilation systems as seen in Figure 4.1.3.2. We observe that there is slight cross contamination for the parents while they sleep, however, with the balanced ventilation, the method of contamination is reversed. The father now breathes in higher concentrations due to a shifting flow pattern, most likely attributable to the placement of the balanced ventilation diffuser.

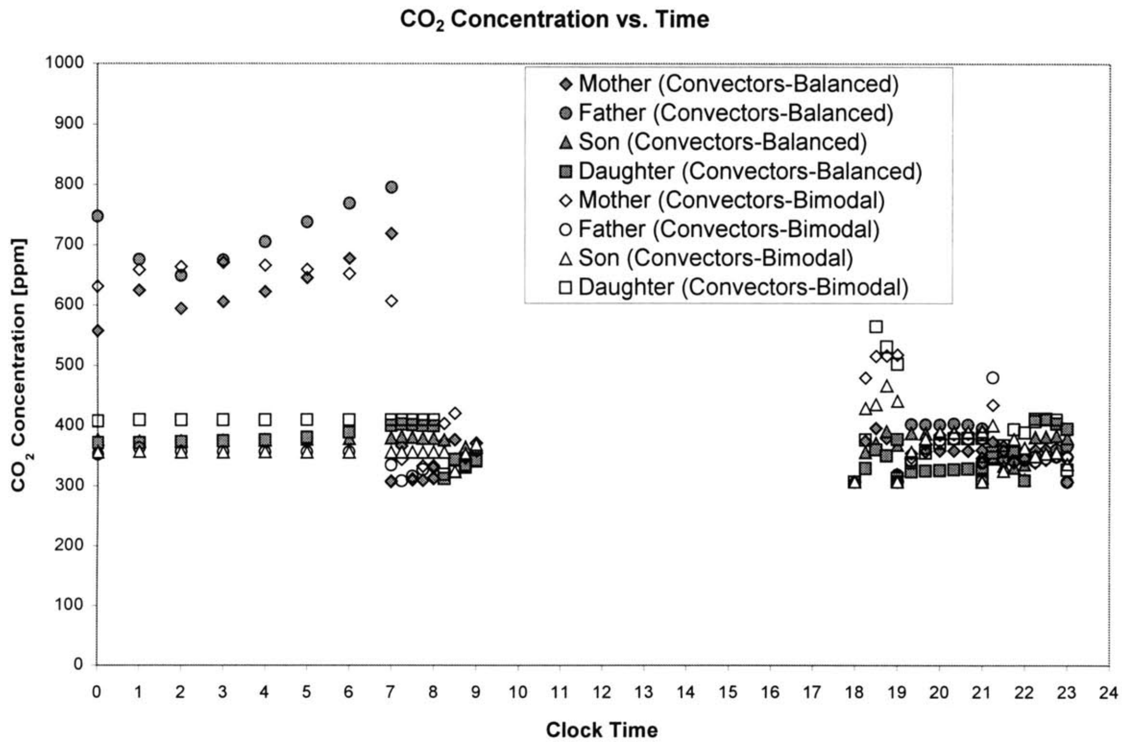


Figure 4.1.3.2 CO_2 concentration history showing slight cross contamination for the parents while they sleep

Also, a reduction in the kitchen window infiltration (26.7% with respect to the Convectors-Bimodal case) increases the effectiveness of the kitchen exhaust hood by reducing cross ventilation flow that sweeps the contaminants outside of the hood before it gets exhausted as shown in Figure 4.1.3.1 and Figure 4.1.3.3. The off-center shift of the vectors and contour show that some of the CO has escaped into the kitchen space. However for Figure 4.1.3.4 showing the same section for the Convectors-Balanced case, a higher concentration is observed between the stovetop and the range hood, and the centered vectors and contour make note of a more efficient capture method.

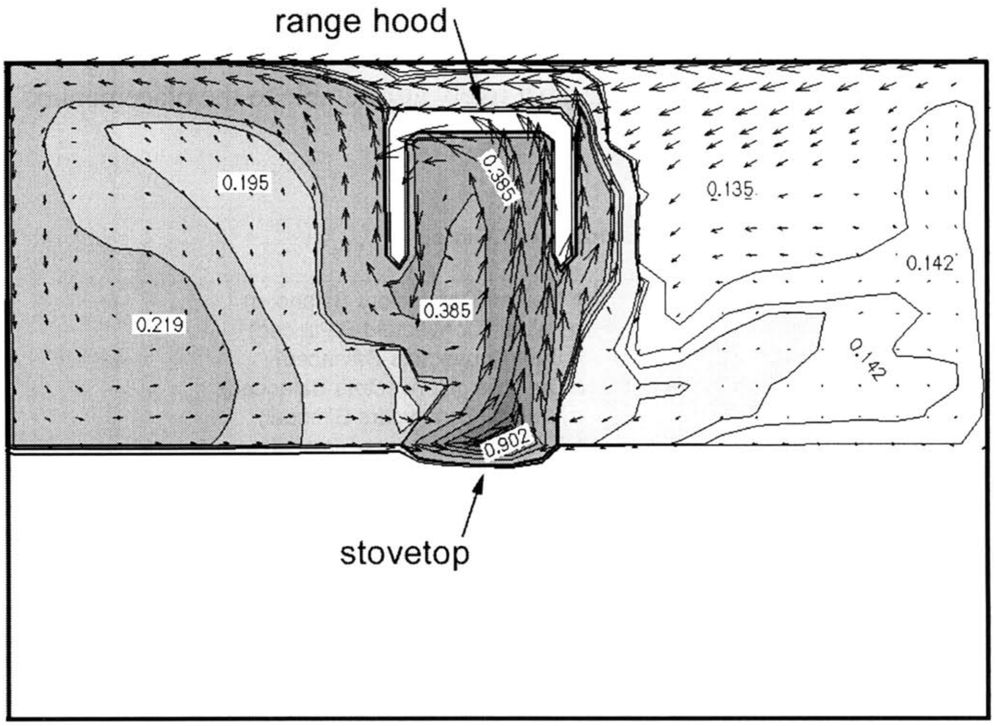


Figure 4.1.3.3 Velocity field and CO concentration after cooking in the plane of the stovetop and range hood for the Convectors-Bimodal case

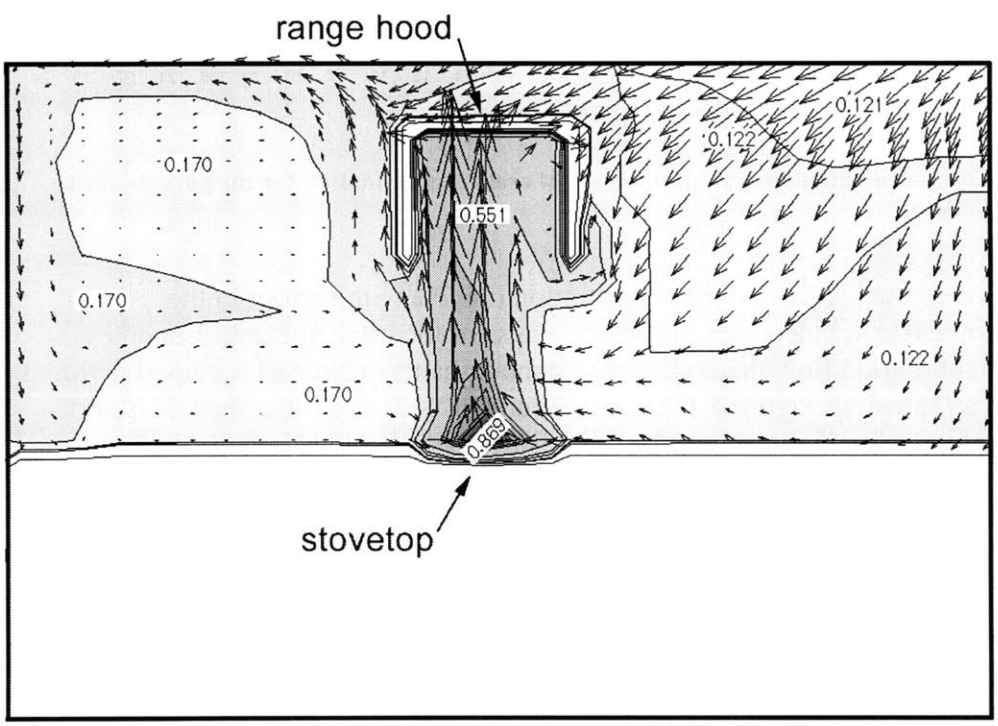


Figure 4.1.3.4 Velocity field and CO concentration after cooking in the plane of the stovetop and range hood for the Convectors-Balanced case

Slight changes in the flow pattern change the trajectory for both bioeffluents while the parents sleep. However, stratification is still a dominant phenomenon within the space, since the colder inlet air drops down from the ceiling height where the diffusers are located towards the floor. There is not much momentum in the inlet air, and thus it sheets down close to the wall, impinging on the floor while spreading out. Strong convectors still produce large room-wide circulations, although their flow is somewhat hindered by the inlets, which are usually located quite close to the windows in each room.

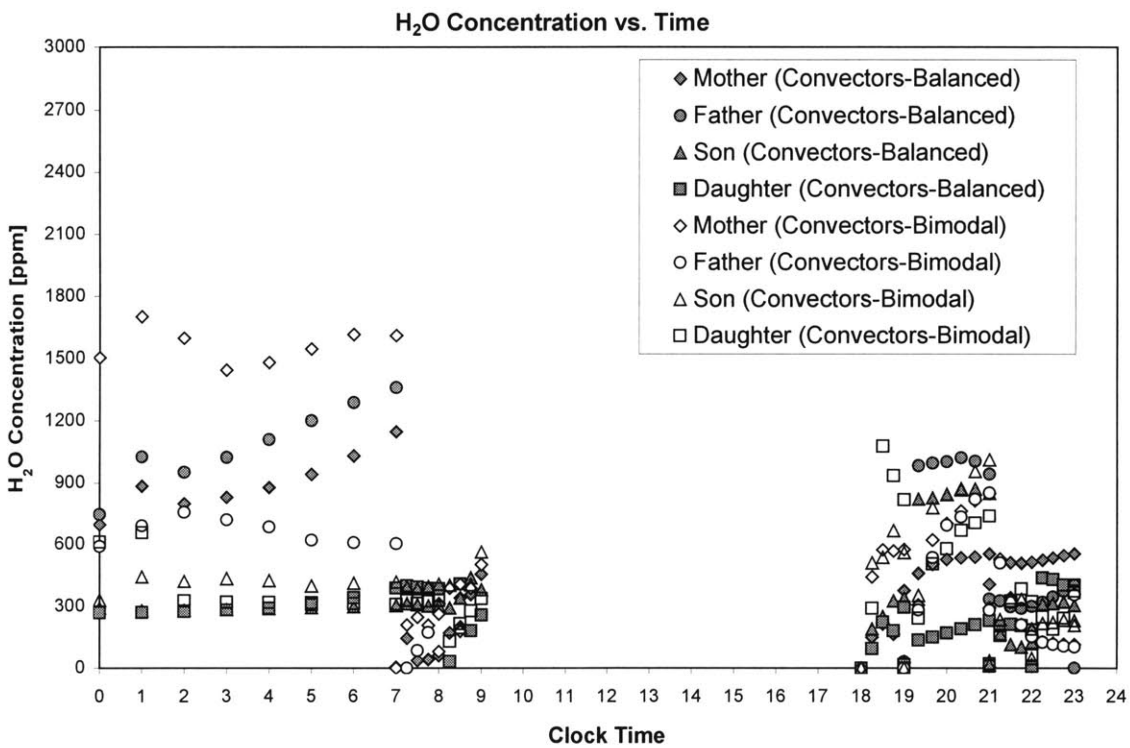


Figure 4.1.3.5 Water vapor concentrations throughout the day

Despite the differences in the method of air introduction, the cumulative exposure is not changed dramatically. There is an increase in the combustion contaminants due to the change in the pattern in the living room to increase the concentration of the contaminants that the parents breathe. But since this happens for only about one hour in the fifteen total that they spend indoors, the effect is quite small.

4.1.4 Exposure

Pollutant exposure is a metric by which we can understand the cumulative effects of contaminant concentration on the occupant. To do this, exposure is calculated by

1. Multiplying the pollutant concentration that an occupant breathes by the time step
2. Adding these values up throughout the day

Table 4.1.4.1 and Table 4.1.4.2 show the exposure for each of the occupants to all the contaminants. The childrens' exposure is well correlated for CO, NO_2, and HCHO, and mildly correlated for CO_2 and H_2O for the bimodal system case. The latter two pollutants are somewhat different due mainly to the differences in exposure during sleeping, where the different room geometries and boundary conditions had a large effect on how the air flowed throughout the rooms. In both cases, the father experiences less CO_2 and H_2O exposure than the mother due to cross-contamination with the mother (which artificially inflates her exposure) due to the heating conditions. The cross contamination is reversed for the balanced system, as reflected in Table 4.1.4.3. In addition, he is home for two and a half hours less than the other family members. Since almost half of the indoor occupation occurs when sleeping, this is the largest time during which any difference in exposure will accumulate towards a discrepancy.

The mother is exposed to more of the pollutants associated with combustion since she is closest to the stovetop during cooking. Also, when the father smokes, there is a slight degree of cross contamination, so she experiences an elevated exposure to HCHO when compared to the father.

Table 4.1.4.1 Exposure during indoor occupancy for bimodal exhaust system with good agreement between the son and daughter and showing the effects of cross contamination for the mother

	Mother [ppm/15hr]	Father [ppm/12.5hr]	Son [ppm/15hr]	Daughter [ppm/15hr]
CO_2	7439	4391	5196	5790
CO	1.87	1.53	1.71	1.71
HCHO	0.138	0.128	0.132	0.132
NO_2	0.95	0.80	0.94	0.94
H_2O	13940	6587	6053	5764

Table 4.1.4.2 Exposure during indoor occupancy for RHC system showing high correlation for the son and daughter and how cross contamination affects the mother's exposure

	Mother [ppm/15hr]	Father [ppm/12.5hr]	Son [ppm/15hr]	Daughter [ppm/15hr]
CO_2	8790	5174	5821	5943
CO	2.05	1.54	1.71	1.71
HCHO	0.135	0.117	0.132	0.132
NO_2	0.97	0.80	0.94	0.94
H_2O	13840	6550	6086	3930

Table 4.1.4.3 Exposure during indoor occupancy for balanced system showing high correlation for the son and daughter and how cross contamination affects the father's exposure

	Mother [ppm/15hr]	Father [ppm/12.5hr]	Son [ppm/15hr]	Daughter [ppm/15hr]
CO2	7157	7513	5492	5530
CO	1.99	1.66	1.72	1.72
HCHO	0.139	0.122	0.132	0.132
NO2	0.95	0.77	0.94	0.94
H2O	8858	10105	4968	3979

The values of Table 4.1.4.4 and Table 4.1.4.5 show the percent increase of indoor pollutant exposure over breathing the ambient conditions for the same period of time. As stated before, there are no standards for vapor, so those results are excluded. The closed bedroom doors effectively shut out combustion contaminants for the children as seen by the very low CO, NO_2, and HCHO percentages. The combination of buoyancy and velocity capture is apparently not enough to lower the amount of CO_2 to which the mother is exposed, as the stove source strength is quite strong. The father is exposed to greater amounts of CO and HCHO due to his smoking habits, but not as much as the mother for NO_2. This is again due to the fact that the stove emits a larger portion of NO_2 over the duration of cooking periods compared with that for the smoking condition. It must be noted that the exposure for the father consists only of second-hand smoke (side-stream) and not primary smoke. If this were included, his exposure would be considerably larger.

Table 4.1.4.4 Percent increase in exposure over ambient (outdoor) conditions for the bimodal system

	Mother	Father	Son	Daughter
CO_2	64.1	14.3	14.6	27.7
CO	9.2	0.1	0.1	0.1
HCHO	4.1	5.2	0.0	0.0
NO_2	1.3	0.1	0.0	0.0

Table 4.1.4.5 Percent increase in exposure over ambient (outdoor) conditions for the RHC system

	Mother	Father	Son	Daughter
CO_2	74.3	19.7	16.1	18.4
CO	19.7	6.3	0.1	31.1
HCHO	2.1	4.5	0.0	0.0
NO_2	3.6	0.1	0.0	0.0

Figure 4.1.4.1 show the increase in exposure over the ambient (outdoor condition) for the two ventilation conditions. Clearly, the RHC system is not effective in removing CO_2. Generally for the other pollutants (those associated with cooking and smoking) however, the bimodal ventilation system fares slightly worse in terms of overall exposure.

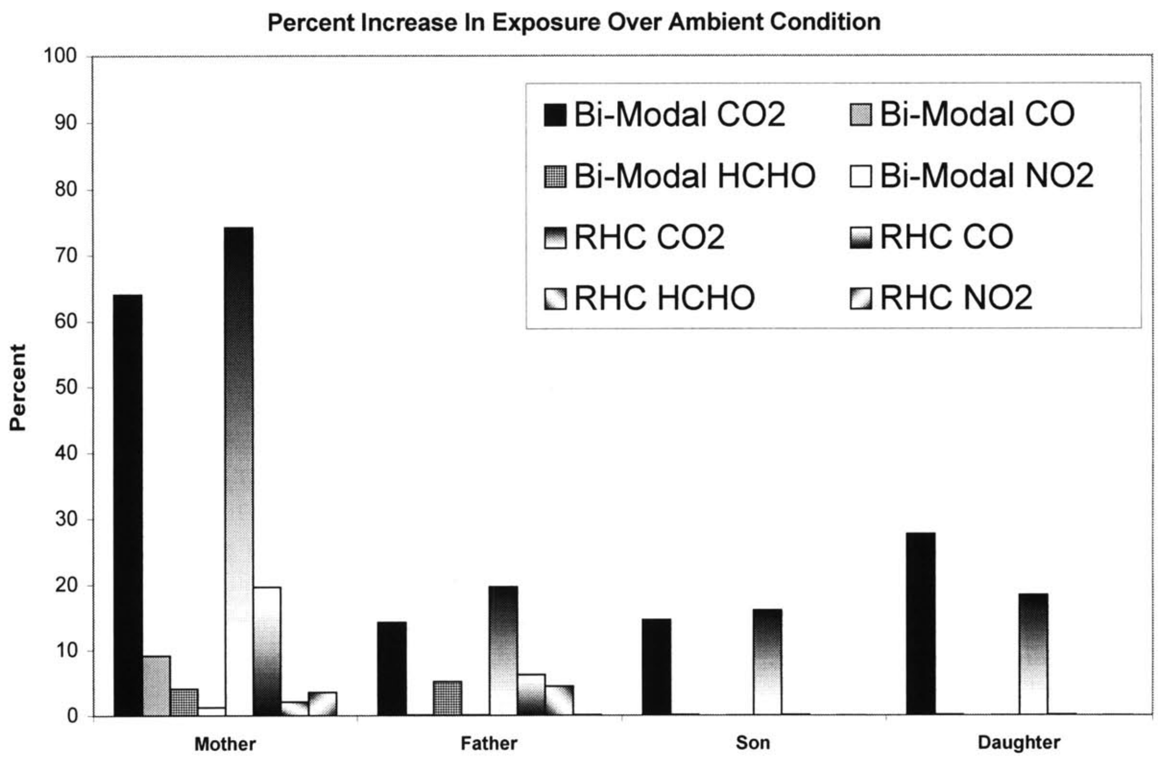


Figure 4.1.4.1 Increase in exposure for each occupant for the two ventilation conditions

The mother experiences greater exposure to contaminants associated with bio-effluents and cooking. It is reasonable to understand that the lower exhaust rate during times of cooking for the relative humidity based system allows more contaminants to escape the range hood compared to the bimodal system.

The comparison of water vapor exposure is seen in Figure 4.1.4.2. Clearly, there is good correlation for the vapor exposure levels for the mother, father, and son. All of the difference in the vapor exposure for the daughter is due to a slightly different flow pattern in the bedroom that causes a change for the duration of the time she sleeps. The difference in vapor exposure clearly reifies the effects that changing flow patterns have on personal exposure.

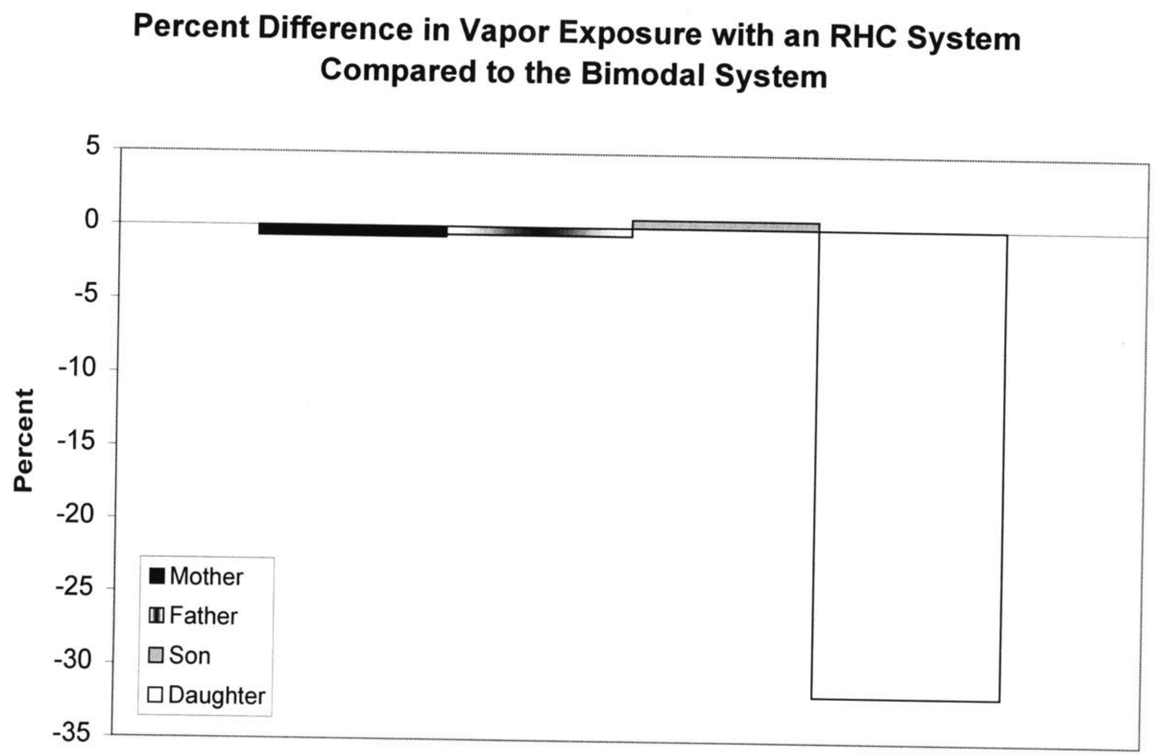


Figure 4.1.4.2 Percent difference in vapor exposure with an RHC system compared to the bimodal system

Comparing the RHC system with respect to the bimodal system, Table 4.1.4.6 shows that in general, the systems work mainly the same. Again this is attributable to the fact that the bimodal system has an increased ventilation rate only for the periods of cooking. Overall, the differences are less than 20%, with the father and mother having the highest difference between them during the time that they sleep due to slight shifts in the airflow pattern. Generally from the results, we can say that the RHC system performs less effectively to remove contaminants than the bimodal system under these winter conditions.

Table 4.1.4.6 Percent differences for the total exposure with the RHC system relative to the bimodal system

	Mother	Father	Son	Daughter
CO_2	18.2	17.8	12.0	2.6
CO	9.6	1.0	0.0	0.0
HCHO	4.1	14.1	0.0	0.0
NO_2	2.3	0.0	0.0	0.0
H_2O	-0.7	-0.6	0.6	-31.8

The differences between the bimodal and balanced system, however outwardly different, do not impose much variation in terms of exposure, shown in Table 4.1.4.7. As typically seen, the combustion contaminants are within a 10% threshold of value differences, while the bioeffluents exhibit a greater difference. Certainly for CO_2, only the father experiences a drastic increase due to the reversal of cross-contamination. And divergent water vapor trajectories account for the differences for H_2O. At this point, we can conclude with marginal confidence that the balanced system is more effective than the RHC system (under these specific winter conditions) to reduce contaminant exposure.

Table 4.1.4.7 Percent differences for the total exposure with the balanced system compared to the bimodal system

	Mother	Father	Son	Daughter
CO_2	-3.8	71.1	5.7	-4.5
CO	6.5	9.1	0.4	0.3
HCHO	0.7	-4.2	0.0	0.0
NO_2	-0.1	-0.1	-0.1	-0.1
H_2O	-36.5	53.4	-17.9	-31.0

4.2 Heated Floor Cases

This section shows the results stemming from the calculation of contaminant exposure in the Mozart house with a heated floor (HF) in the living room and either bimodal or relative humidity controlled ventilation. These results are then compared to the corresponding results of the convector only case to show the relative effectiveness and impact the heated floor has on pollutant transport, room air temperature, and contaminant exposure.

Comparing the bimodal heated floor case to the results derived from the bimodal case with just convectors, the occupational exposure is generally the same. Since the family sits in the living room (where the heated floor is located) for only a short period of time (two and a half hours for the children, three and a half hours for the parents, or 17% of the time for the former, 23% for the latter) relative to the time they stay in the rest of the house, the effects of the heated floor are minimal. Due to the dislocation of the heated floor to the other rooms that contain convectors, the localized effects of the changes in exposure due to the floor are only seen in the living room; these effects are still only slight. The characteristics of the dynamics of the heated floor are:

- The living room is warmer than the other rooms since the large floor area is maintained at 23.5°C
- Large room circulations caused by the convectors are not present, thus reversing the major circulation caused by downwash at the cold walls and negative buoyancy from the inlet air at the windows
- The effects of the thermal body boundary are smaller, since the lower room temperature is raised, thus reducing the temperature difference, inhibiting positive buoyancy
- Stratification is less pronounced
- Attenuation of smoking pollutants is similar for the convector only case

It is of importance to note the change in general flow patterns when the convectors are not in place. The room-wide circulations that occur with the convectors in place are not present in the heated floor case. Instead, a uniform heating of the floor warms the air, and the room-wide convections are now dominated by the colder walls and the cold inlet air. Since the convectors were originally placed beneath the windows to counteract the negative buoyancy of the outside air entering the house, there is no strong counteracting force. The heated floor inhibits this to some degree, but since the heat is evenly distributed along the whole floor area (and not localized beneath the windows), downwash occurs in the plane of the windows, exactly opposite of the convector only case, as shown in Figure 4.2.1.

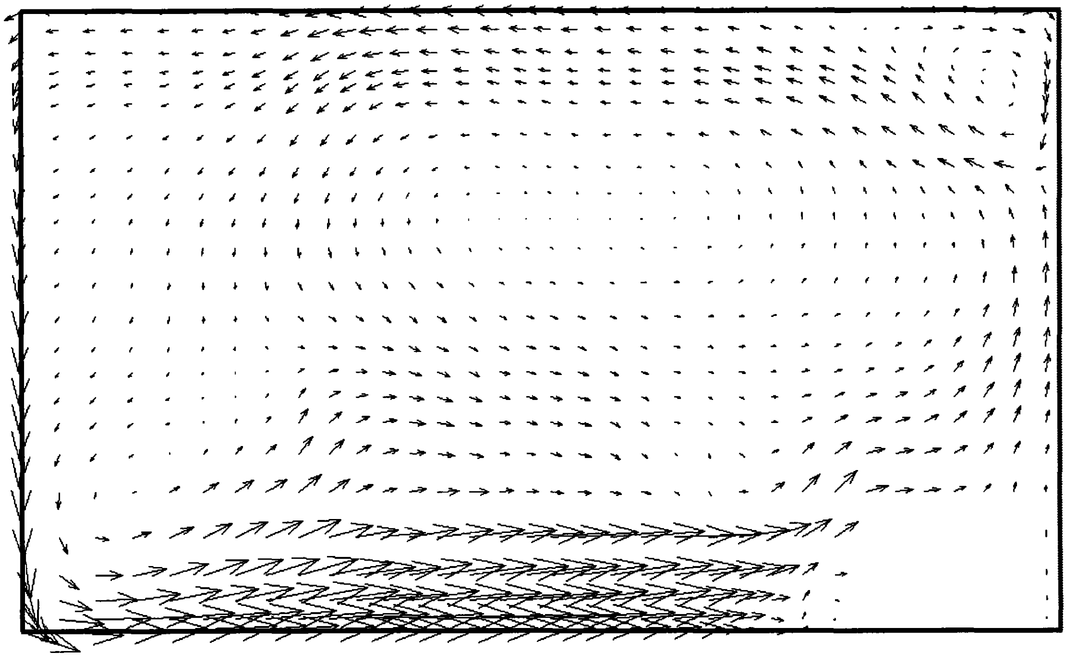


Figure 4.2.1 Reversal of large circulation due to the lack of convectors counteracting negative buoyancy

In addition, due to the higher living room temperature, there is a greater amount of large-opening flow caused by stack effect exhibited in Figure 4.2.2. This in turn increases the exchange allowed between the living room and the rest of the house, which occurs significantly during dinner. With this large outflux of high concentration contaminants such as CO_2 and water vapor, the exhaust fans at a low setting are not enough to effectively expel these contaminants before migration into other rooms. Since the bedroom doorways of the son and parents are at the end of the corridor, more of the contaminants migrate to these two rooms as compared to the daughter's bedroom. The bathroom and WC fans do pull in some of the pollutants, but the concentrations are so high and the stack effect so great that migration is not impeded. The migration of CO_2 and vapor to the son's bedroom is important, since the door is closed when he returns to the room after dinner. These accumulated pollutants are then trapped within the room and the son breathes in a higher concentration than in the convector-only case.

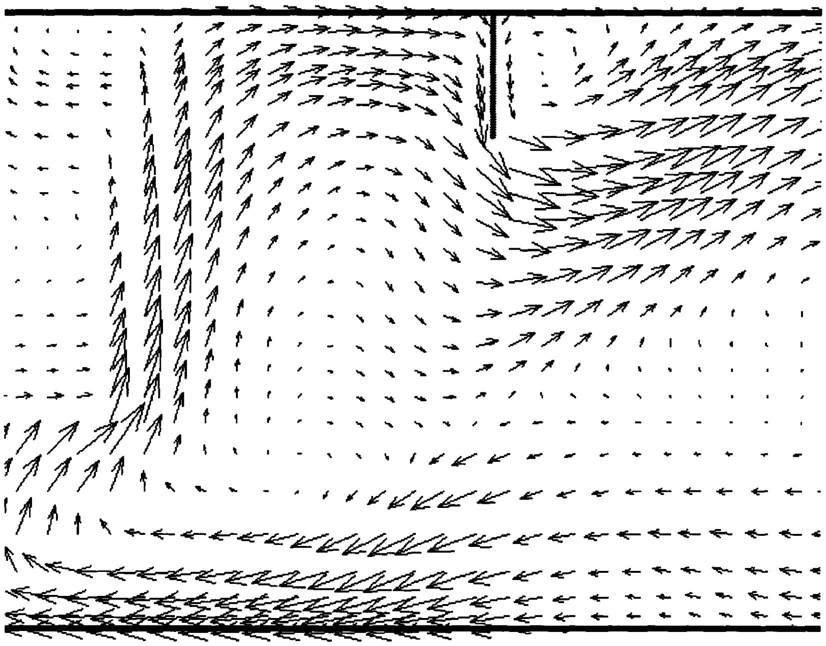


Figure 4.2.2 A higher average temperature in the living room prompts a larger flow exchange through the doorway cause by stack effect

Uniform heating of the living room floor decreases the stratification effect for both temperature and contaminant concentrations as seen in Figure 4.2.3 and Figure 4.2.4. Thus if it the case that the whole house were conditioned using a heated floor, the levels of pollutants that the occupants breathe will be elevated, since the lower parts of the rooms have a higher concentration than in previous cases. Stratification does still occur, but to a lesser degree than the convector only case. This is due to the uniform heating of the living room floor, which has a higher temperature than the air immediately above it. Since the family stays in the living room for a short period of time, although the concentrations are increased, over the course of the day, it doesn't affect the exposure greatly.

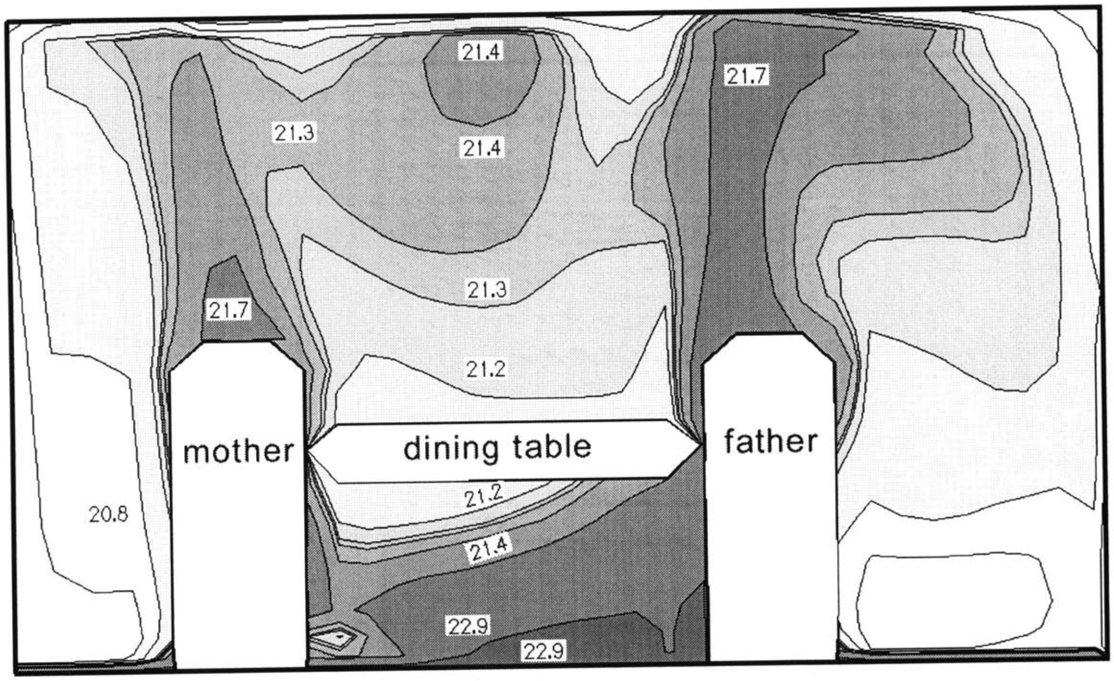


Figure 4.2.3 A section through the living room showing a decreased temperature stratification due to the heated floor

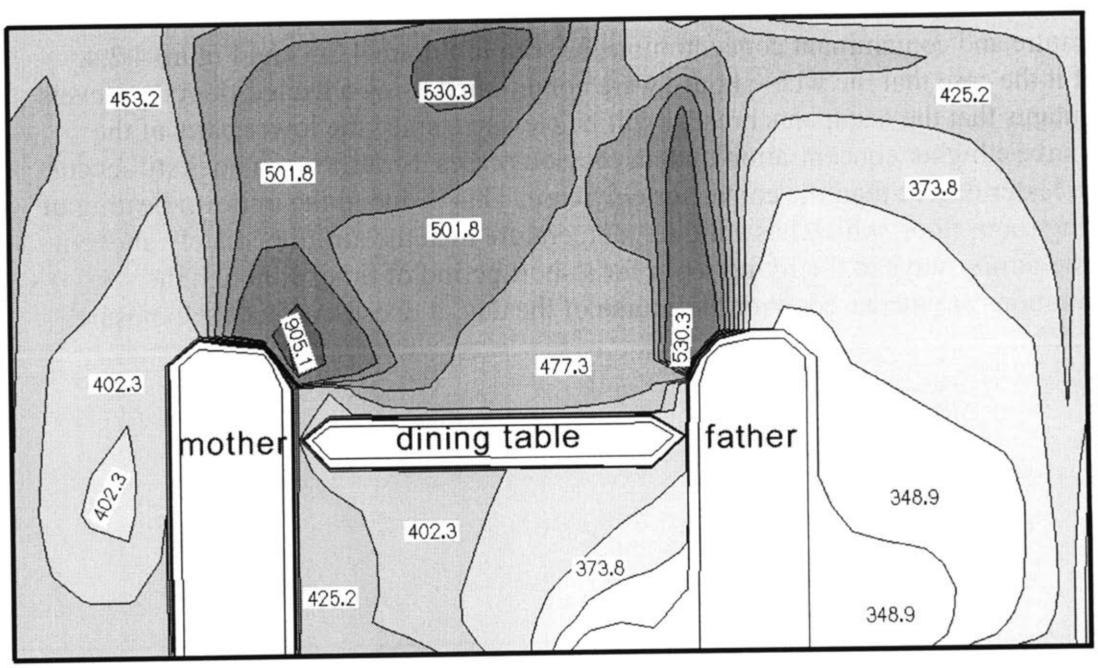


Figure 4.2.4 A decreased temperature stratification induces a weaker CO_2 stratification

The following sections deals with the data and analysis of the heated floor with both bimodal and relative humidity controlled ventilation. The results are compared respectively with the convector only cases with bimodal and RHC ventilation conditions that were discussed previously.

4.2.1 Bimodal Exhaust System with Heated Floor

The first of the heated floor cases consists of the living room floor of uniformly distributed temperature. A Clim2000 simulation was performed by Philippe Aude (Table 2.3.2.2) to determine that the floor temperature is 23.5°C. The rest of the rooms are conditioned with convectors. Bimodal ventilation was used in this first case, and all other boundary and source conditions are the same as the base case (bimodal ventilation with convectors in all rooms for winter conditions), as reported in section 4.1.1.

Comparisons of the room air concentrations between the heated floor case and the convector only case with bimodal ventilation show that the differences are only slight, as seen in Figure 4.2.1.1 and Figure 4.2.1.2. For CO in Figure 4.2.1.2, we can see that the father breathes a higher concentration of the smoking contaminants, due to the lack of convector located on the west wall of the base case. Without the large room circulation that occurs from this placement, the mother and father breathe air with the same concentration of contaminants. However, since attenuation is good, this effect has little impact on the overall exposure of the father.

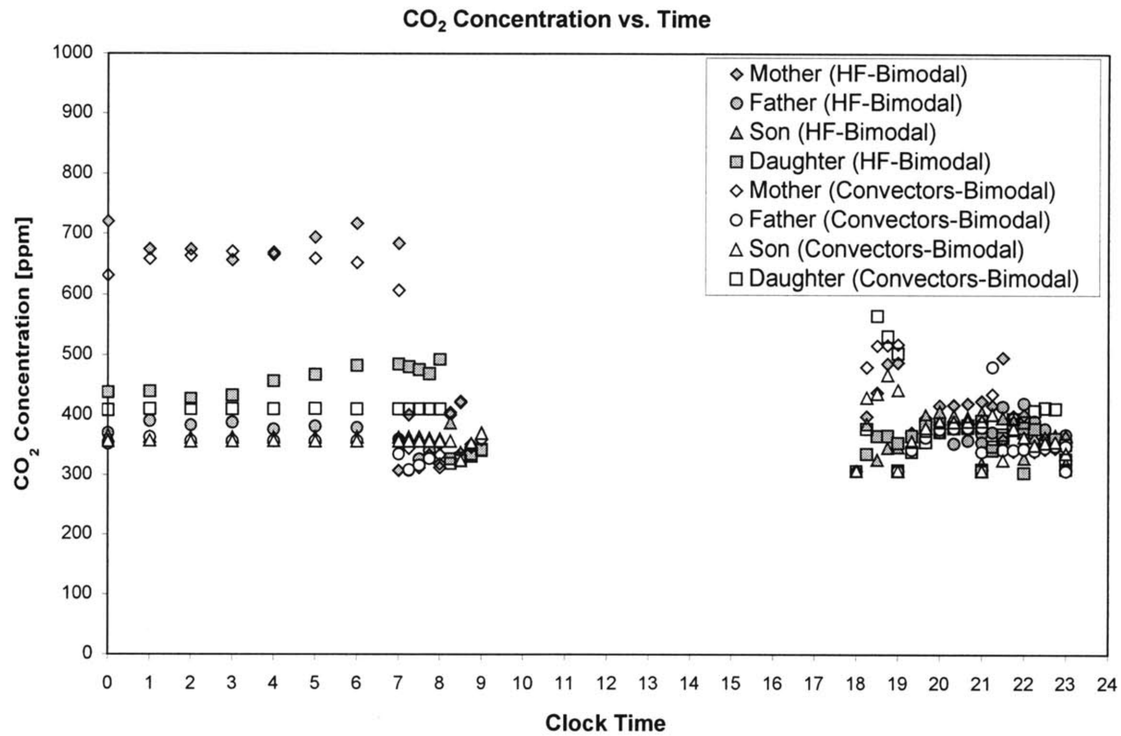


Figure 4.2.1.1 CO_2 concentration history for the family comparing the heated floor and convector case, both with bimodal ventilation

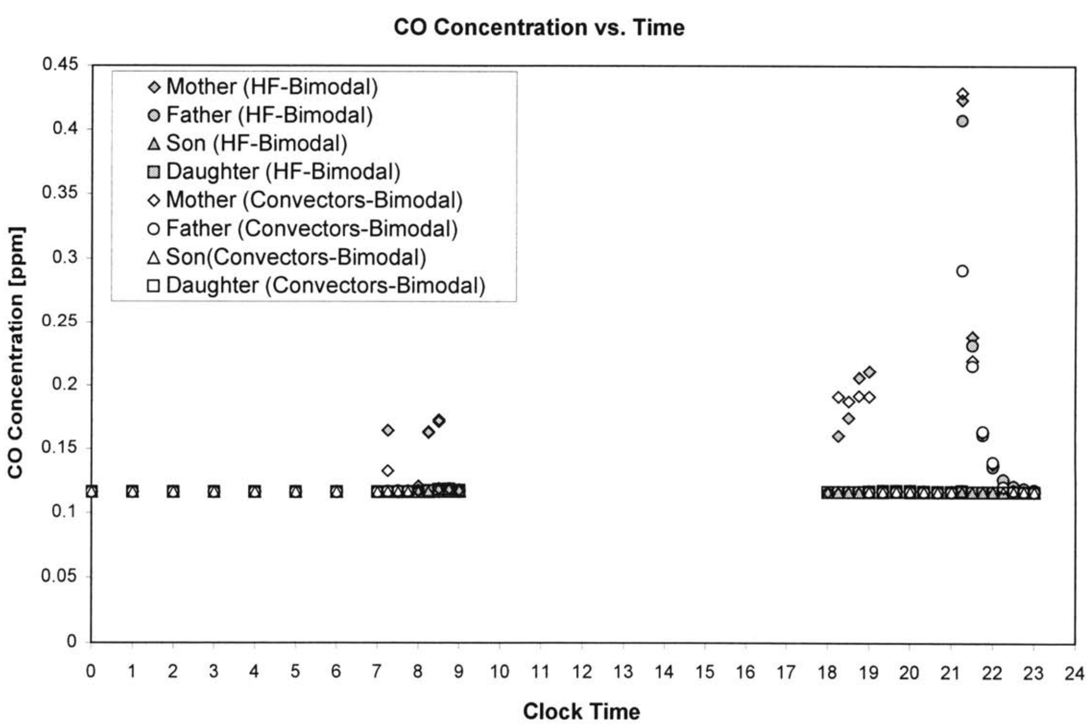


Figure 4.2.1.2 CO concentration history for the family comparing the heated floor and convector case, both with bimodal ventilation

There is clearly a divergence of breathed vapor concentration for the family during dinner, and for the parents during sleeping as seen in Figure 4.2.1.3. This difference is attributable to a slightly differing flow pattern throughout the night that greatly affects the breathed concentration in conjunction with the weak stratification effect. For the time interval spanning dinner, this can be a direct impact from the heated floor and the lack of living room convectors, as witnessed by an increase in concentration for the whole family with HF heating. However, during sleeping there is an uncertainty, since the heated floor is quite far away and insulated from the parents' bedroom due to the closed door. However, since this is the fifth hour of simulation, slight differences in flow pattern accumulated over this interval can mean drastic changes. In addition, the convector power was reduced to 410W, which also changes the flow somewhat.

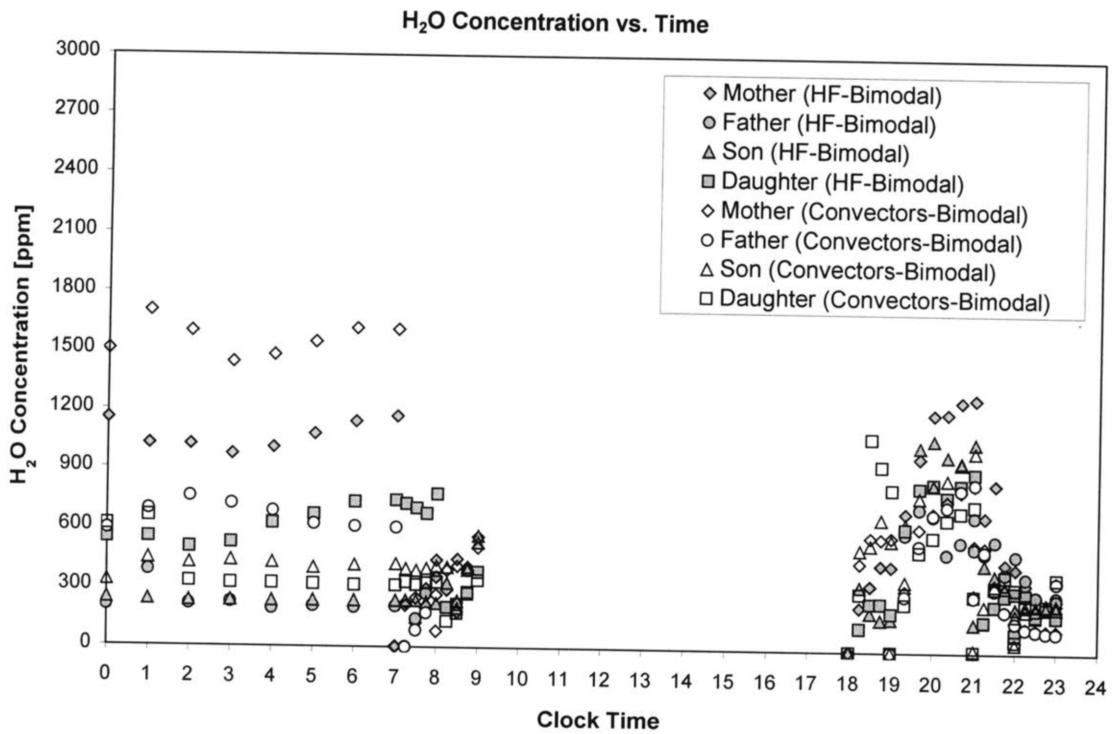


Figure 4.2.1.3 Water vapor concentration history comparing the heated floor case to the convector only case, both with bimodal ventilation

Previously (in the convector only cases), the convector power was set at 750W as an oversight to the Clim2000 data supplied. The room convectors for the heated floor cases were thus reduced in power with recognition to the information provided by Philippe Aude. However, we can see that this has relatively little impact on the comparison of the two heating systems, with the exception for water vapor, although it is not conclusive that this is the main contributing factor for the discrepancy. This is mainly due to the fact that the source values for water vapor are so high in comparison to the other pollutants types that small changes in the flow or boundary conditions are more highly visible.

4.2.2 Relative Humidity Controlled Exhaust System with Heated Floor

The second of the heated floor cases utilizes a relative humidity controlled ventilation system to determine whether or not a passively controlled system would be effective in removing contaminants associated with occupation. Again, due to the simulated winter case, the exhaust rates at each of the three locations remains the same, except for the bathroom exhaust which increases due to water vapor from the shower.

The comparison of the relative humidity controlled exhaust system is actually similar to that of the convector only case. Again this is due to the relatively short time that the family stays in the living room, where the boundary conditions are different.

Figure 4.2.2.1 shows the exhaust rate at the kitchen, bathroom and WC over the duration of the day. Only the bathroom exhaust increases in the morning when the occupants shower. Between 07.00-07.30h, the mother and father shower, with the exhaust rate increasing over the two fifteen minute intervals. The same thing happens when the son and daughter shower between 08.00-08.30h.

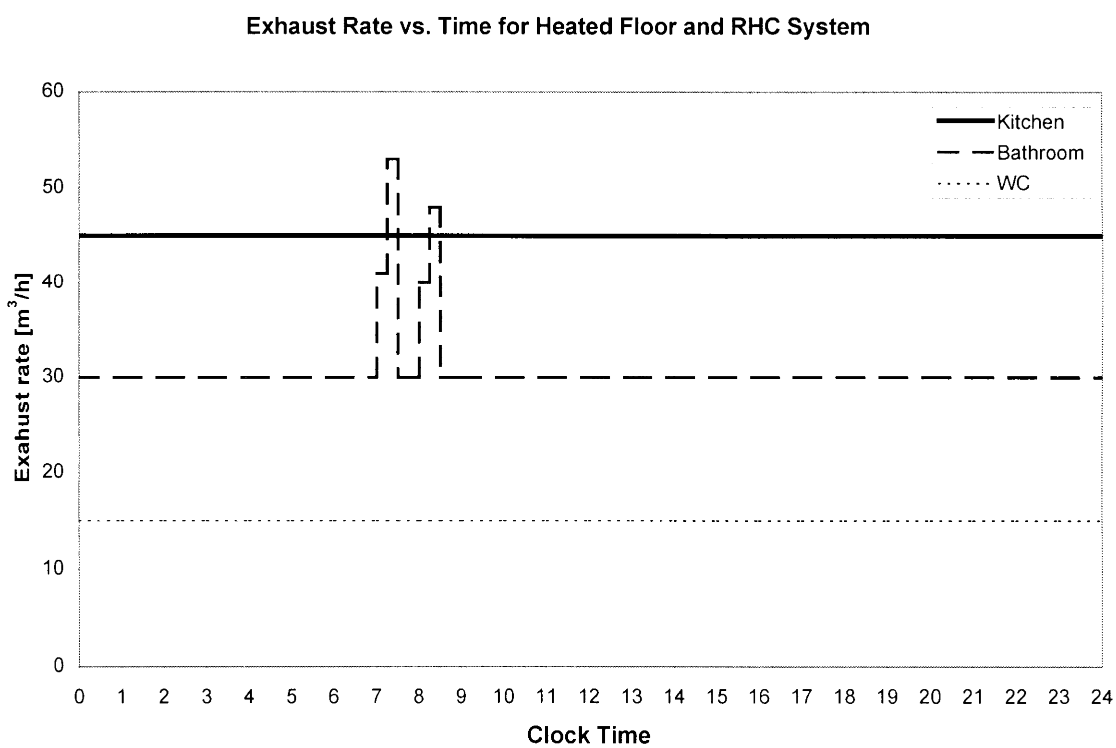


Figure 4.2.2.1 Exhaust rates for the RHC system with a heated floor in the living room, noting an increase of the bathroom exhaust when showering

Comparing the concentration histories over the course of the day for the heated floor case and the convector only case both with an RHC system, we can see from Figure 4.2.2.2 and Figure 4.2.2.3 that the differences are slight, and exhibit similar patterns.

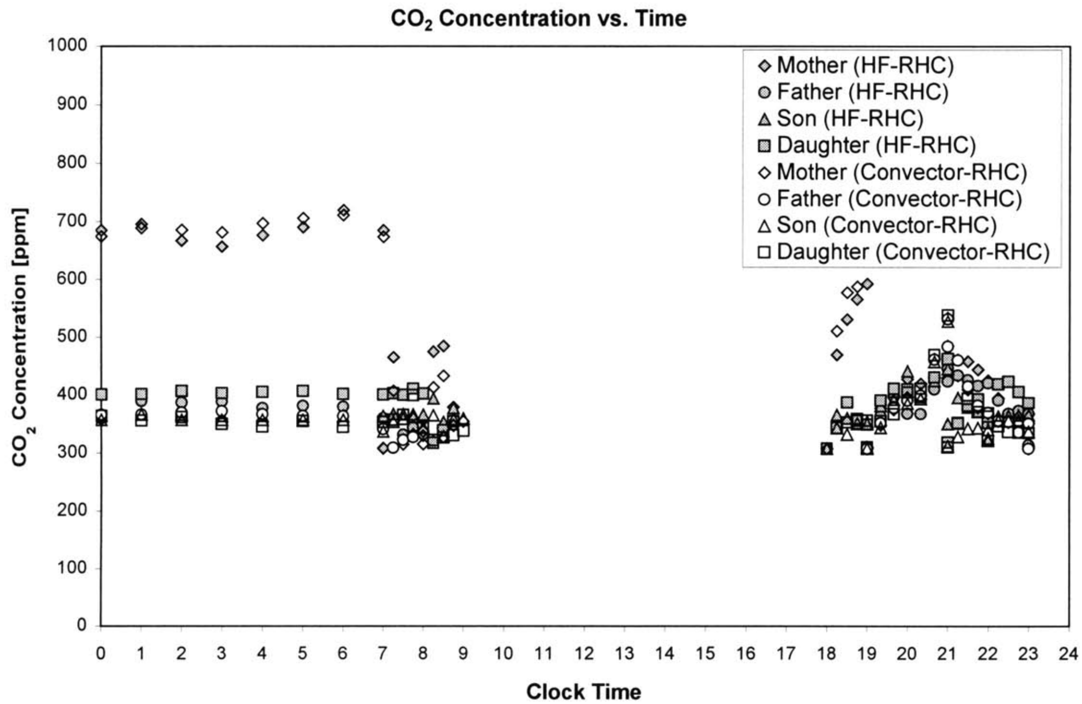


Figure 4.2.2.2 CO_2 concentration history for the family comparing the heated floor and convector case, both with relative humidity controlled ventilation

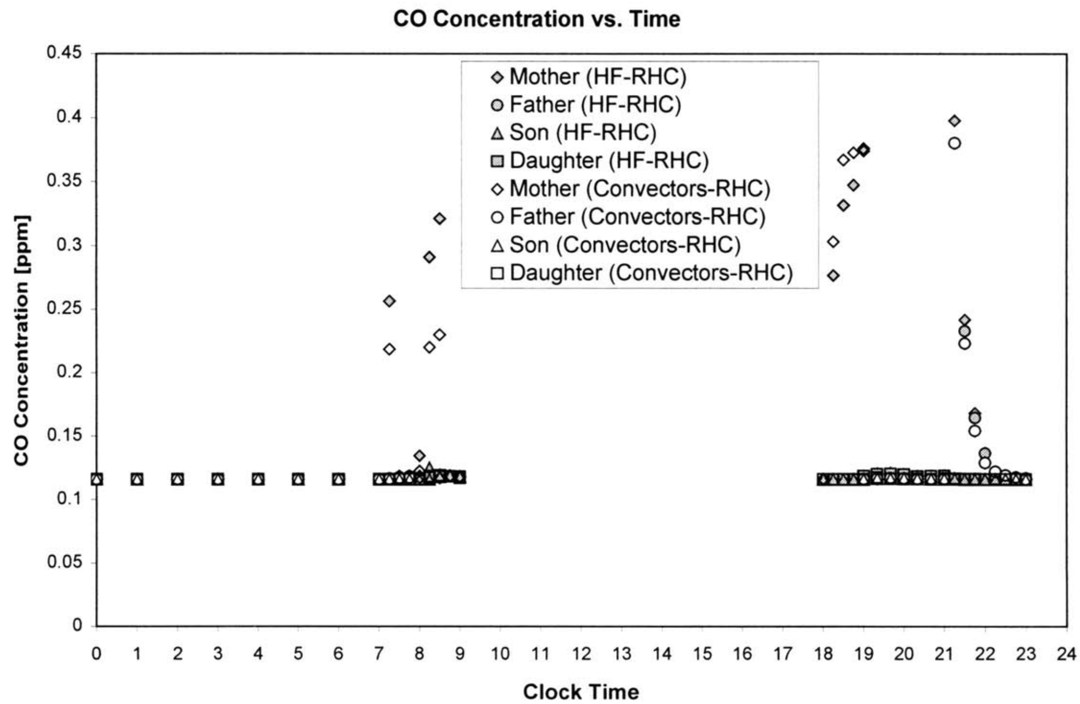
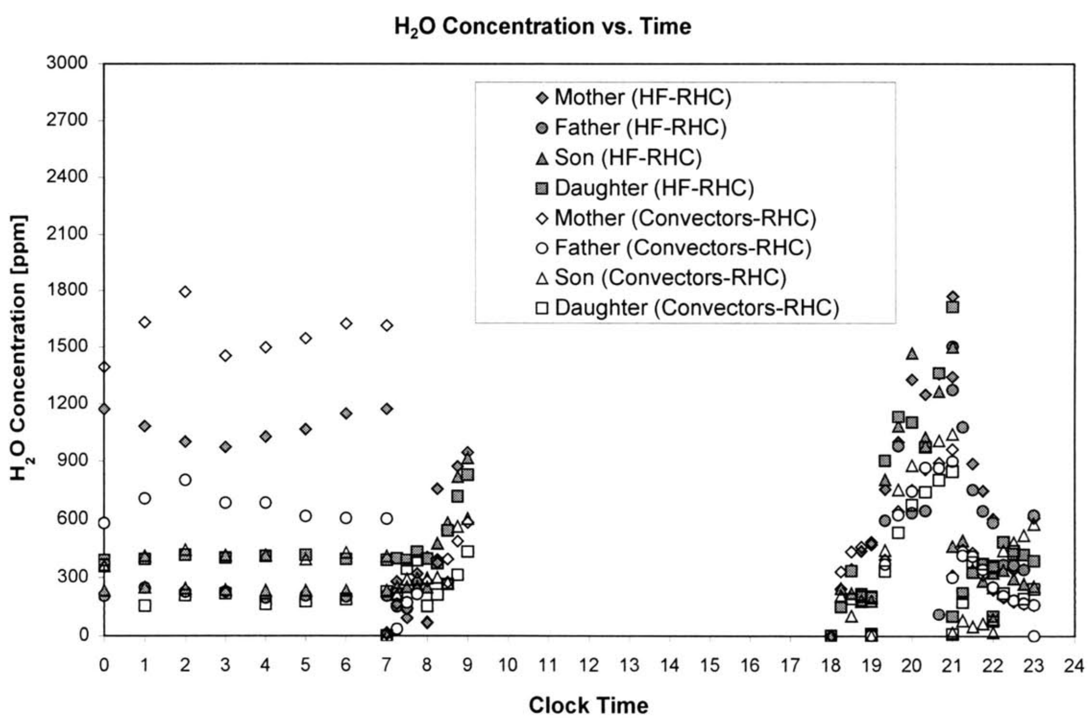


Figure 4.2.2.3 CO concentration history for the family comparing the heated floor and convector case, both with relative humidity controlled ventilation



4.2.3 Exposure

Cumulative exposure differences between the heated floor case and the convector only case with bimodal heating shows are not very great. Comparative charts for the CO_2, CO, and H_2O differences between the two cases are shown in Figure 4.2.3.1 and Figure 4.2.3.2. From Table 4.2.3.1 we can see that comparing the total exposure for each individual and for each contaminant. The mother sees a difference of about 19% for CO_2 as compared to the convector only case. Since the mother historically experiences the greatest change from the varying heating and ventilation conditions, this is to be expected. However when considering a 10% simulation error, the difference is small. Especially looking at the combustion contaminants (which are most potent), the only time the percent differences reach above 10% is for the father for HCHO. Again, this is due to the different heating condition of the living room where smoking takes place. With the base simulation error, the exposure difference is of the same scale as the mother.

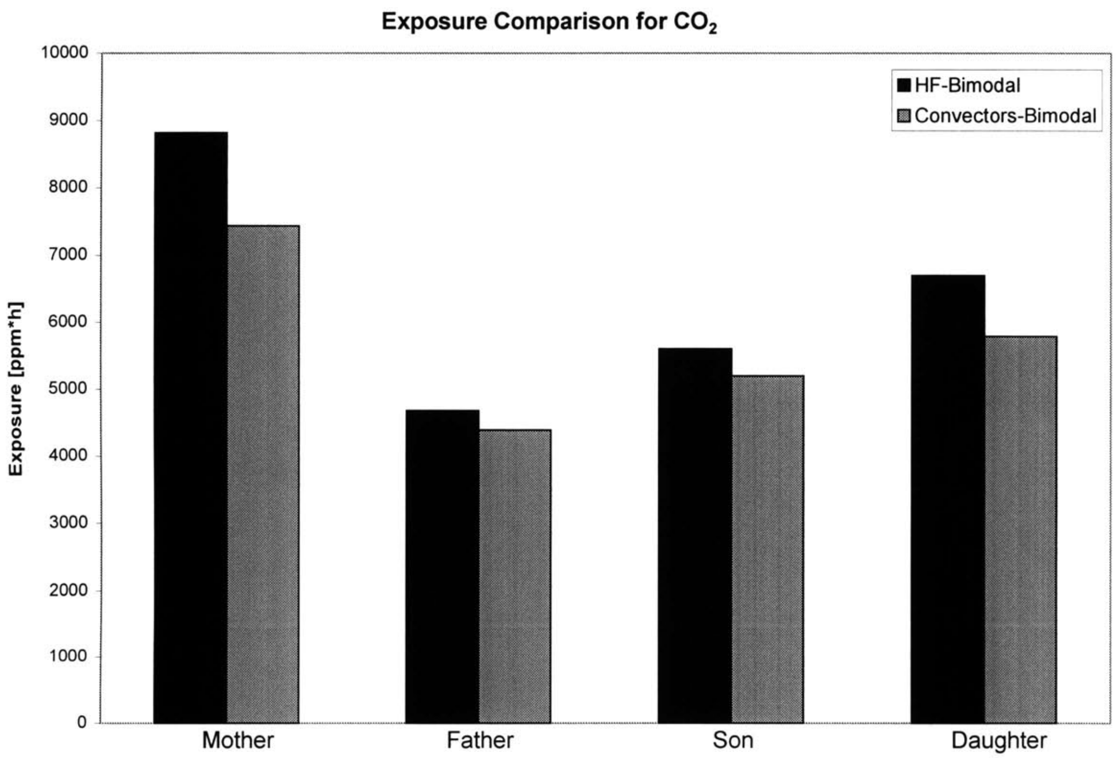


Figure 4.2.3.1 The cumulative daily exposure to CO_2 does not differ much between the heated floor and convector only case when using bimodal ventilation

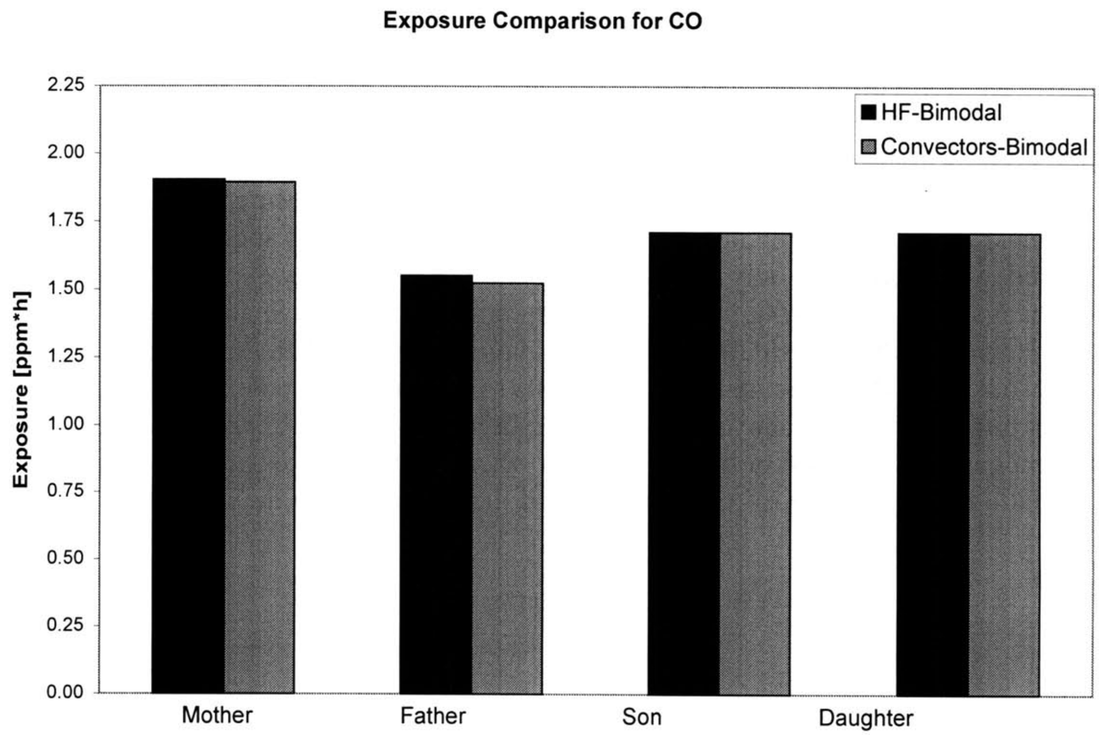


Figure 4.2.3.2 The cumulative daily exposure to CO differs negligibly between the heated floor and convector only case when using bimodal ventilation

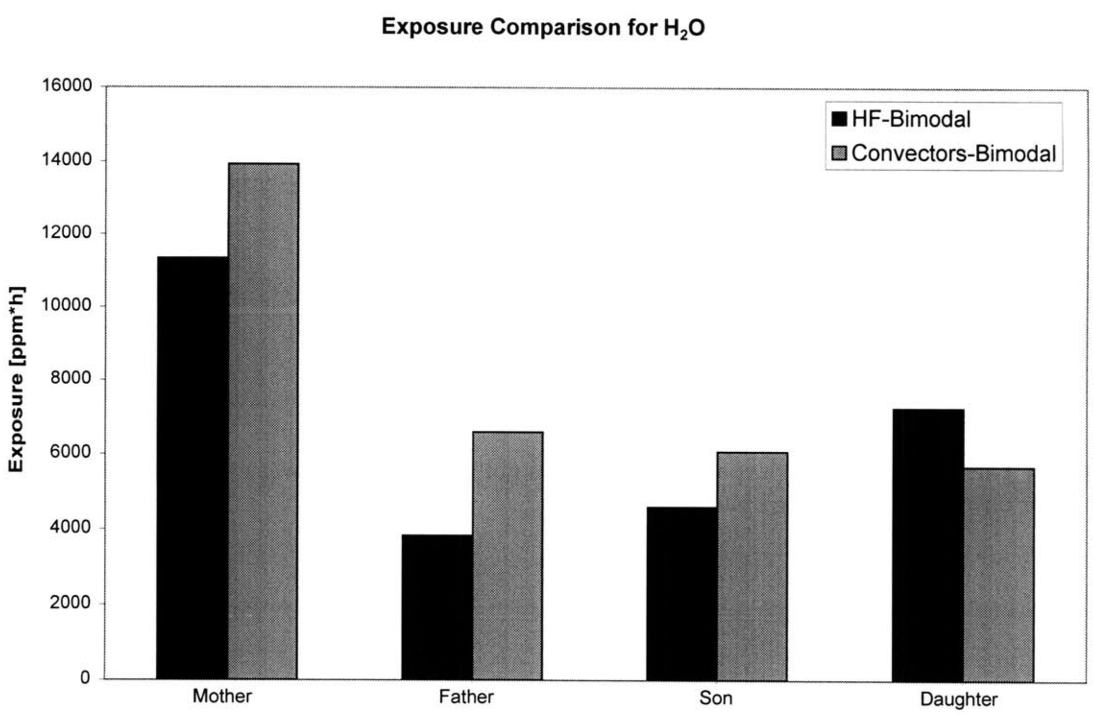


Figure 4.2.3.3 The cumulative daily exposure to water vapor shows larger differences due to the strength of the sources and the contaminant's subjection to changing flow patterns

Table 4.2.3.1 Percent differences of the heated floor case compared to that obtained with heating only from convectors, both with bimodal ventilation

	Mother	Father	Son	Daughter
CO_2	18.5	6.6	7.8	15.8
CO	0.4	1.8	0.0	0.0
HCHO	7.9	17.3	1.7	1.7
NO_2	0.0	0.0	0.0	0.0
H_2O	-18.6	-41.8	-24.2	27.7

The greatest differences are from the comparison of water vapor for the two cases. This is attributable to the relatively high source strengths, in addition to the high dependence of airflow patterns. A strong sign of vapor exposure dependence on other more external factors is seen when occupants with similar schedules (mother/father, son/daughter) have similar correlations for other concentrations, and not for H_2O.

We can thus conclude that the heated floor with a bimodal exhaust system neither significantly aids nor detracts from the effectiveness of the combination of the heating and bimodal ventilation system to remove common household contaminants under typical winter conditions.

Comparing the accumulated effects of the difference in heating systems in Figure 4.2.3.4 and Figure 4.2.3.5, the differences for combustion contaminants is less than for bioeffluents. This is due to the fact that the heated floor is contained in the living room only, and doe not have as large an effect in changing the occupational exposure as a difference in ventilation system.

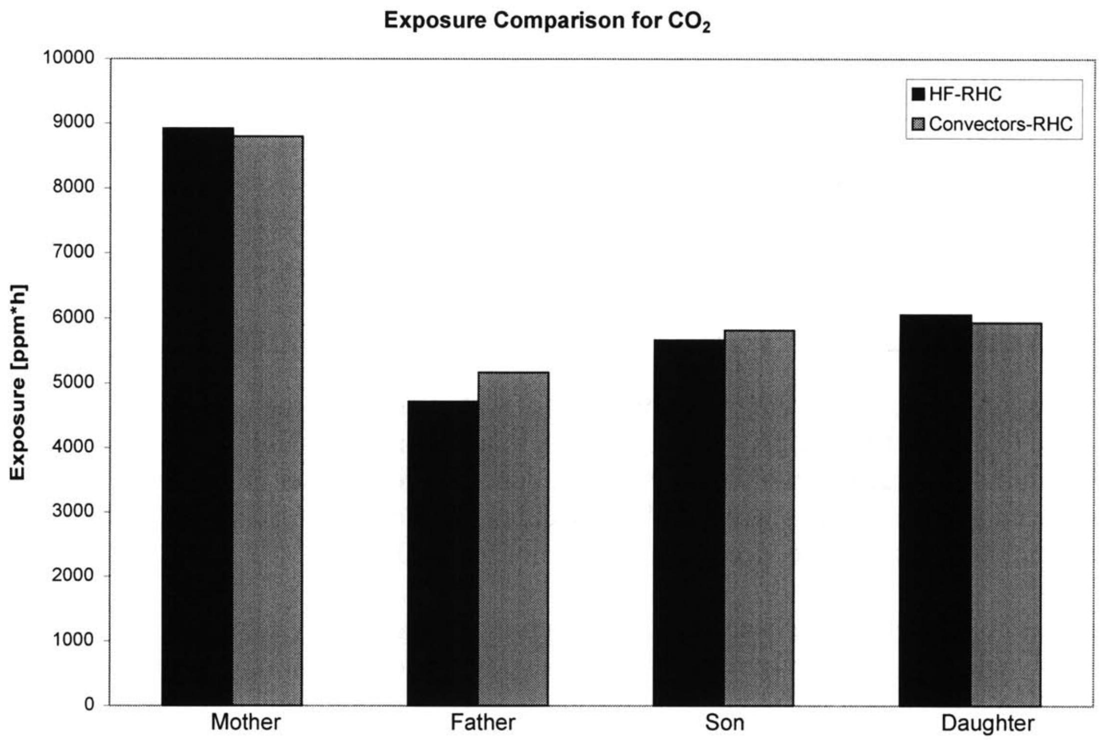


Figure 4.2.3.4 The cumulative daily exposure to CO_2 does not differ much between the heated floor and convector only case when using RHC ventilation

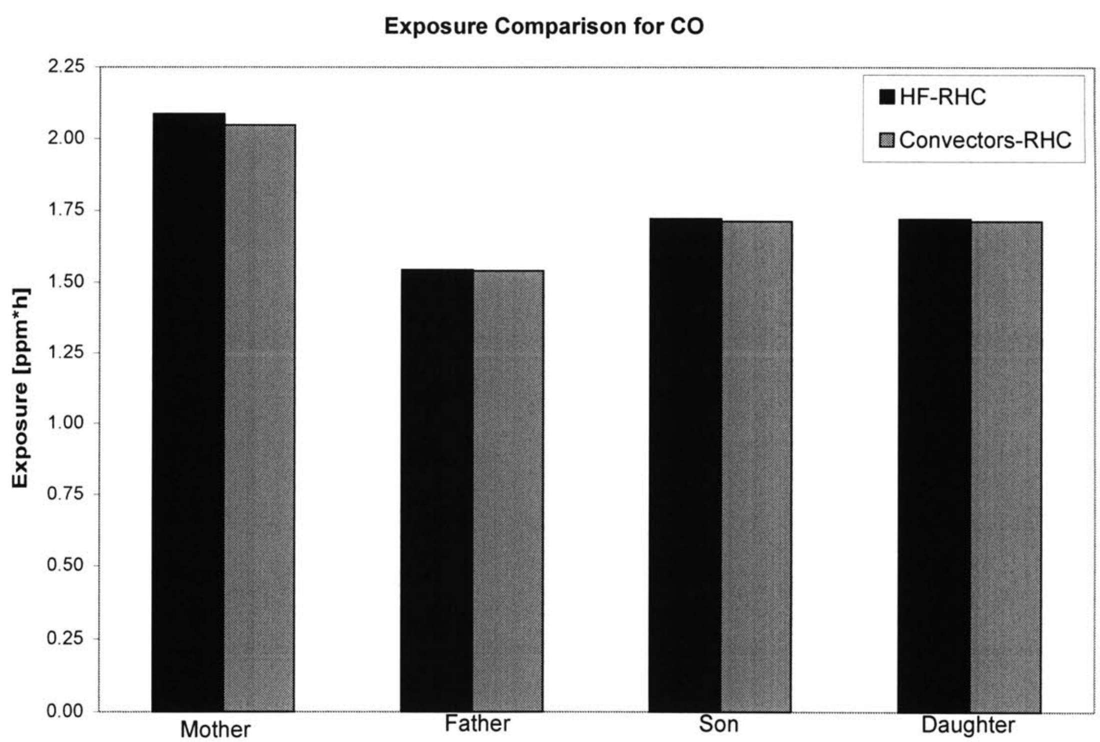


Figure 4.2.3.5 The cumulative daily exposure to CO does not differ much between the heated floor and convector only case when using RHC ventilation

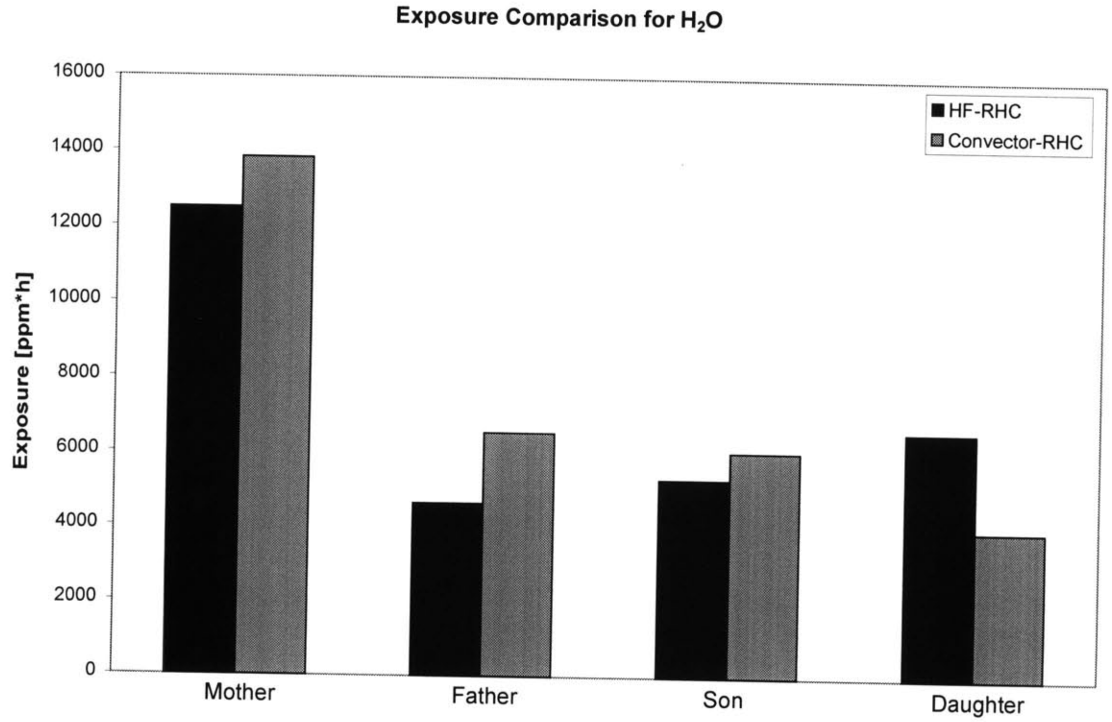


Figure 4.2.3.6 The cumulative daily exposure to H_2O between the Heated Floor and Convectors cases with RHC ventilation

Below we find the tabulated percent differences between the heated floor case and the convector only case for RHC ventilation. All values except for water vapor are below 10%, thus falling within the range of computational error. The differences in the vapor comparison are similar for the bimodal case, and are described above.

Table 4.2.3.2 Percent differences of the heated floor case compared to that obtained with heating only from convectors, both with RHC ventilation

	Mother	Father	Son	Daughter
CO_2	1.4	-8.8	-2.6	2.0
CO	1.9	0.3	0.5	0.4
HCHO	0.6	8.6	1.7	1.7
NO_2	-0.6	-4.8	0.1	0.1
H_2O	-9.7	-29.2	-12.3	66.8

Figure 4.2.3.7 shows the relative humidity at each of the three exhaust locations. Only during showering in the morning does the humidity ever exceed 30%, the threshold for the change in the bathroom exhaust rate. The kitchen humidity is low when the mother

cooks between 18.00-19.00h and in the morning. During the family dinner, the humidity increases, until the children go back to their rooms following the meal at 21.00h.

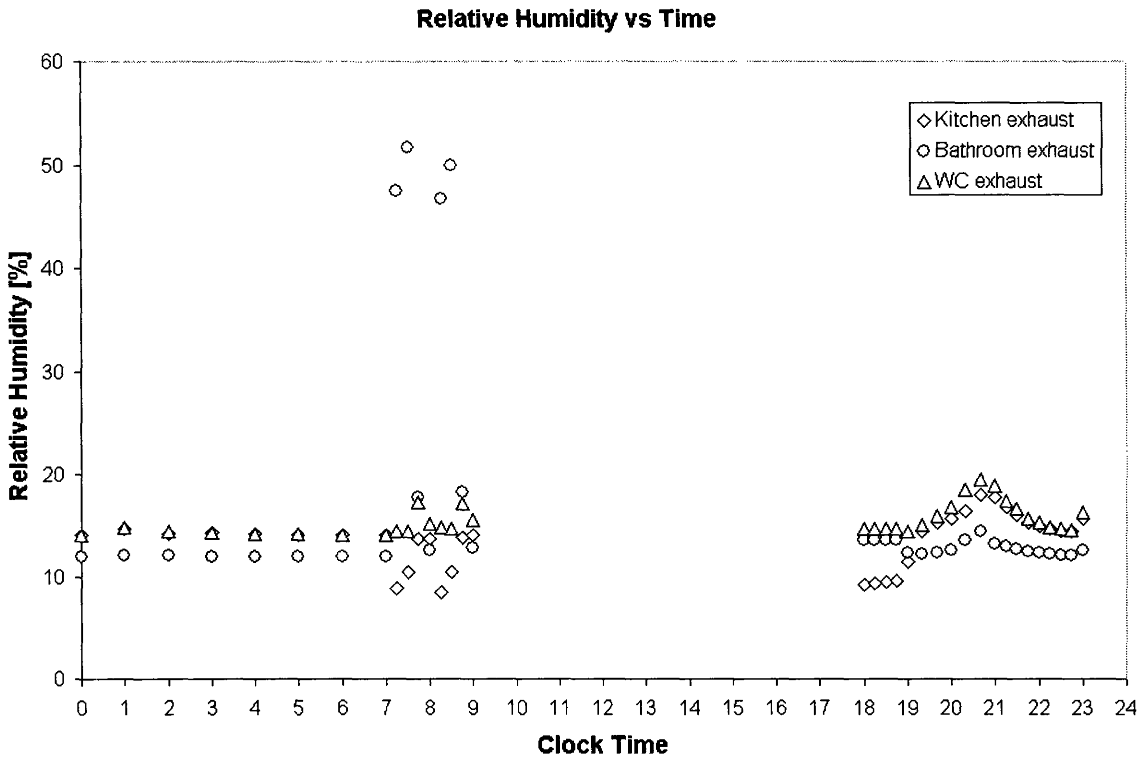


Figure 4.2.3.7 Relative humidity at the exhausts throughout the day that increases as different activities take place throughout the day, most notably showering in the morning hours

The heated floor, although a fundamentally different method of heating compared to convectors, does not alter the occupational exposure when coupled with the relative humidity controlled ventilation system. There are differences when looking at water vapor, but since the most critical aspects of exposure come from toxic gases, we find that the different heating system causes less than a 10% discrepancy, within the bounds of simulation error.

5 Results of the Cases in Summer

The driving force behind the simulation of the summer is to see the effect of stratification without the benefit of cool infiltration air and strong convective heating systems. Stratification is greatly reduced because of unfavorable conditions. In certain situations, this means that more migration of contaminants tends to occur, as well as higher exposure, as the pollutants mix vertically within the space. This means that previously "cleaner" air below the breathing zone might be more concentrated with pollutants. Also, the more humid air should trigger the RHC system to an increased ventilation rate compared with the winter scenario.

Migration through closed doors still does not occur for the peripheral zones. However, slight amounts of diffusion bring in small amounts of pollutants into these rooms from remote sources. This is due to the fact that migration does occur in the hallways, which leads to a higher concentration there as compared to the winter cases. A higher concentration allows a better opportunity for diffusion to occur.

One of the most striking features about the summer condition when comparing the respective ventilation conditions during the winter is that the high convector circulation created in the parents' bedroom does not occur in the summer. Since there are not any strong heating sources, room-wide circulation is generated by mainly due to the thermal plumes induced by the room occupants. Relatively cooler infiltration air (at 25°C) also produces a downwash at the windows. These two factors, although present in the winter case, become dominant in the summer cases due to the lack of strong heating sources.

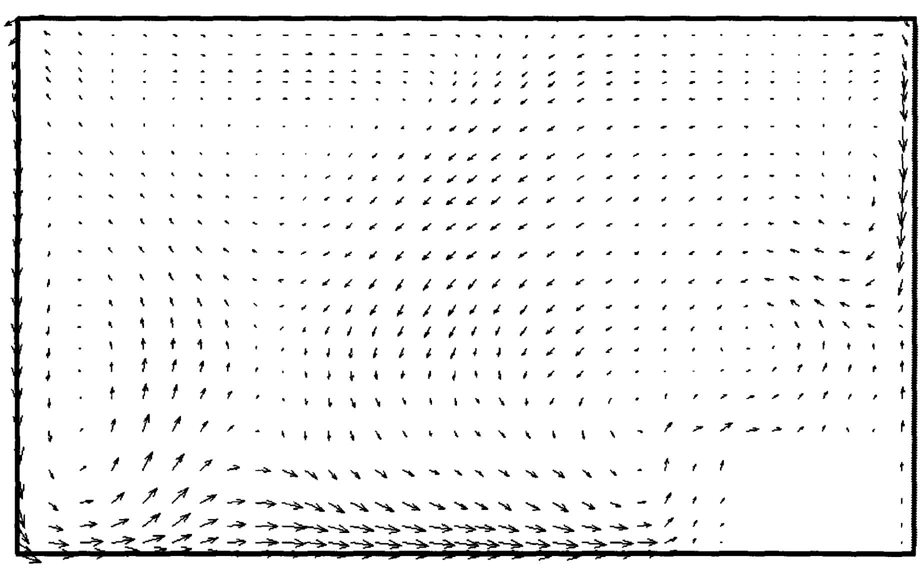


Figure 5.1 No room-wide circulation is seen due to a lack of strong heat sources (convectors)

In this regard, cross-contamination which is clearly seen in the winter case is not present in the summer. Nearly equitable bio-effluent concentrations are seen throughout the period that the parents sleep for both summer cases.

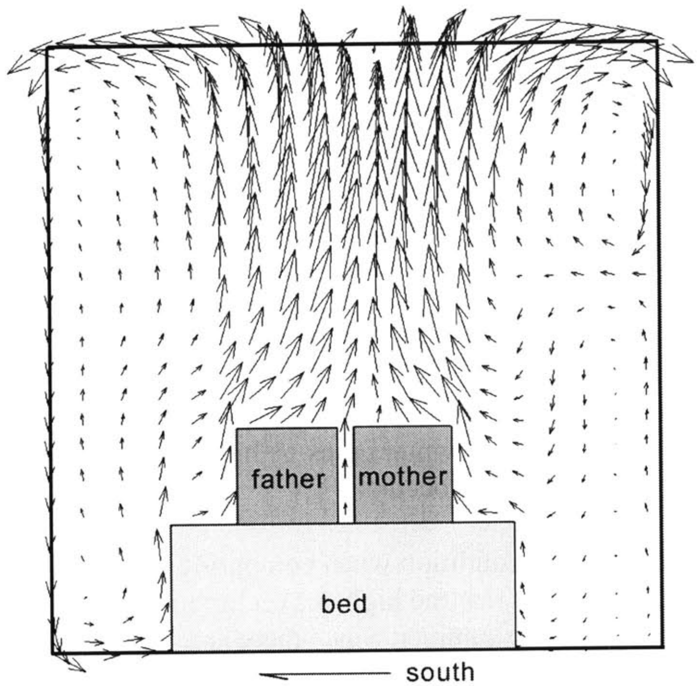


Figure 5.2 No cross-contamination is seen when the parents sleep

A similar phenomenon can also be seen in the childrens' bedrooms when they are sleeping. The recirculation region at the daughter's head in the bimodal winter case is not generated. Instead, since the occupants are the main source of heat in the rooms, the children, in a prone position, create a plume that generally removes the contaminants in their vicinity. However, due to a lack of stratification, only buoyant contaminant removal may not be enough to stave off a high concentration of breathed air as vertical mixing of contaminants tends to increase the exposure.

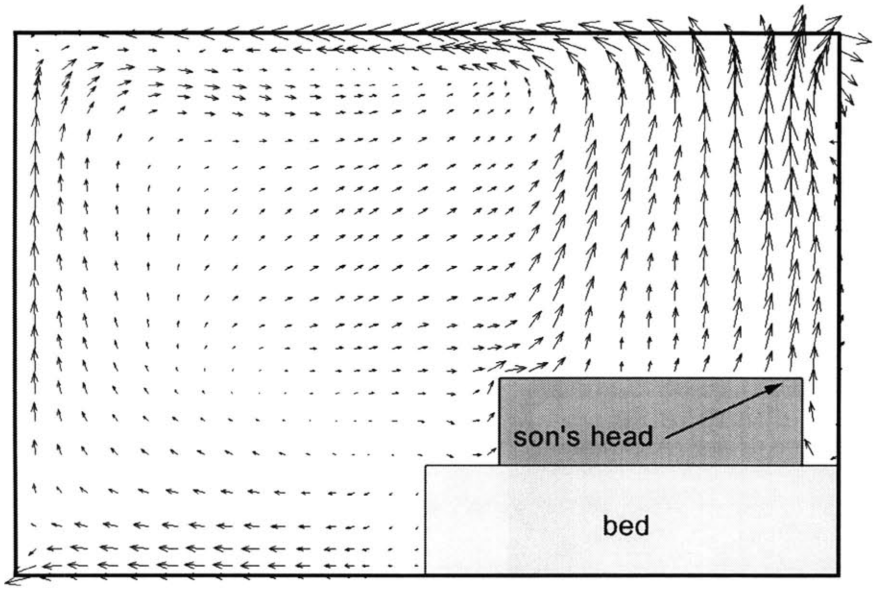


Figure 5.3 Buoyant removal of contaminants as the son sleeps

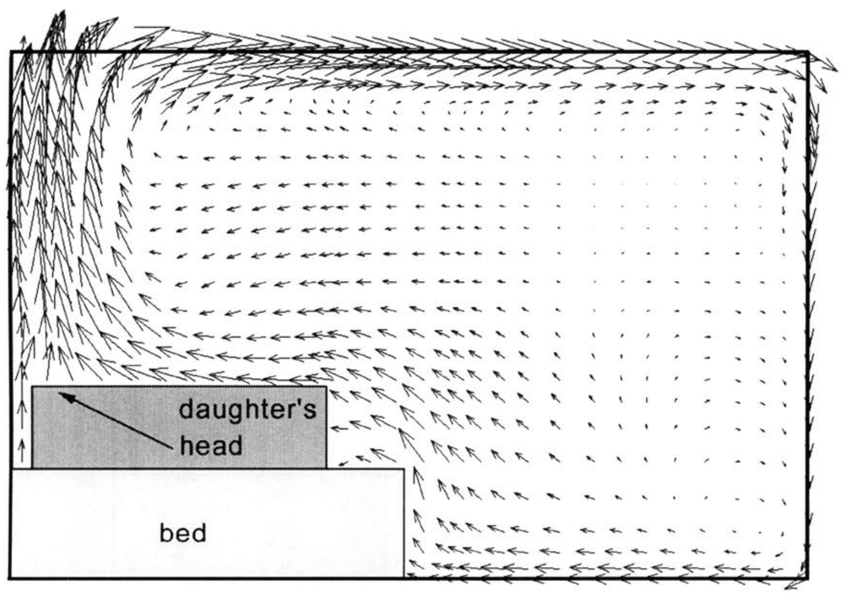


Figure 5.4 No recirculation region is found above the daughter's head as she sleeps

Indeed, there is a deconstruction of stratification during the summer, seen in Figure 5.5. Stratification only occurs to a slight degree in the rooms that are occupied, and to the highest degree around the vicinity of the person or people. When the room is unoccupied, there is a nearly uniform temperature field, with exceptions at the walls which are slightly warmer than the air. Since concentration gradients are associated most highly with the velocity field, and buoyancy is the dominant flow inducing mechanism, a loss of stratification generally indicates a loss of contaminant stratification as well (Figure 5.6).

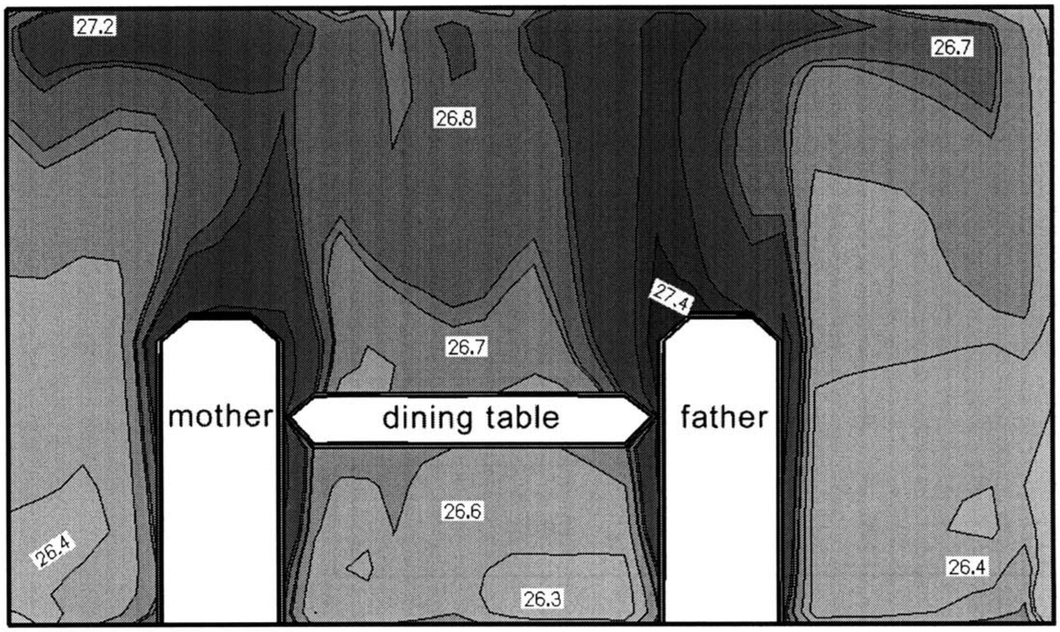


Figure 5.5 A slight temperature stratification is found in rooms that are occupied

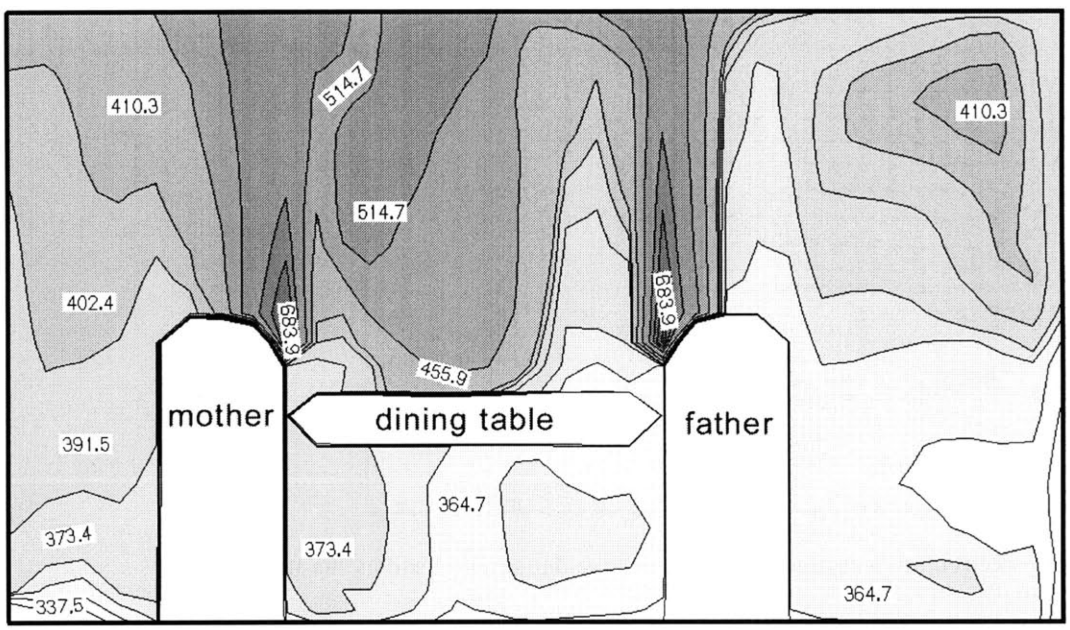


Figure 5.6 The slight temperature gradient is not enough to induce a pollutant stratification (CO_2 concentrations shown here)

For all the cases, water vapor was not included in the ambient condition (the infiltration air) since during the humid summer, increases in the concentration of water vapor would be masked by the very high ambient concentrations.

Comparisons between the summer cases must be done in the following pairs:

- Summer-Bimodal vs. Convectors-Bimodal
- Summer-RHC vs. Summer-Bimodal

The first pair is comparable since the differences between them are the use of convectors in the winter, and a change in the ambient/boundary conditions. The difference in outdoor temperature does not affect the comparisons, since the outdoor air is always lower than indoor. This means that there is always a negative buoyancy effect near the windows that is consistent throughout the seasons. The second pair directly evaluates the ventilation system performance when little to no stratification is present.

The Summer-RHC case cannot be compared well with the winter cases (bimodal or RHC), since there are two major competing factors to change the results: difference in stratification, and continuously high extract rates. These are two fundamentally different indoor phenomenon that makes it difficult to compare side by side. However, comparing the summer-RHC case to the summer-bimodal case is possible, since the different extract rates is the only difference between them (stratification effects are similar). The exposure differences between each of these two pairs of data helps to determine whether stratification or a higher ventilation rate is more effective in reducing indoor occupant exposure.

Temperatures throughout the house are almost vertically uniform for each room. Thermal body buoyancy still plays a role in the method of occupational exposure, though due to a lower stratification, the lower air is not a clean as in the winter cases.

Rooms in which occupants are not present experience an upwash at the walls caused by buoyancy, since the wall temperatures are warmer than the infiltration air. In the rooms where there are people, the thermal plumes raise the temperature in the upper part of the room appreciably enough so that there is a downwash at the walls, since the wall temperature is no longer cooler than the temperature of the air in the upper zones. This stratification only occurs in rooms that are occupied, however slight.

The slight stratification that occurs in occupied rooms changes the dynamics of room to room interaction, thus changing the mechanism for interzonal pollutant transport. Figure 5.7 and Figure 5.8 shows the change in flow pattern as there is a shift in the occupancy scenario. When the room is occupied, the small degrees of stratification then induce natural convection that displaces warmer air near the ceiling with cooler air at the floor level. The large opening flow in an unoccupied room becomes dominated by the extraction devices located outside the room.

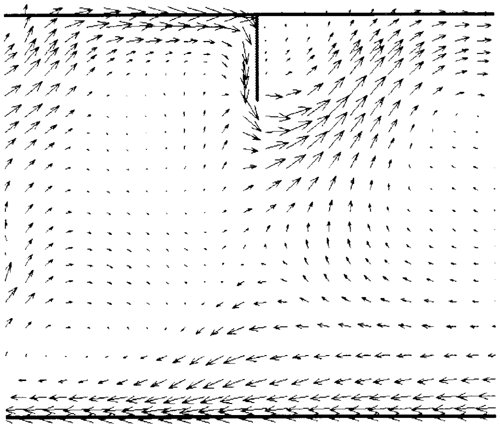


Figure 5.7 Mechanism of room to room exchange when occupants are present in the room

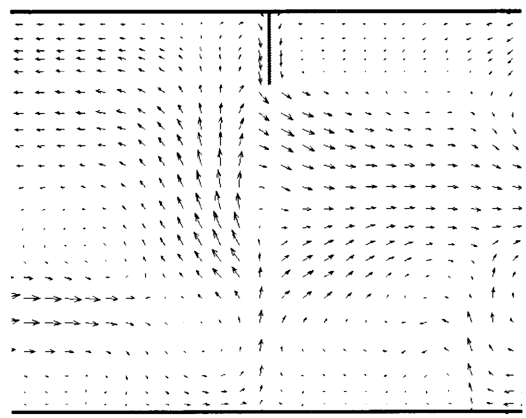


Figure 5.8 A different method of room to room exchange is seen when the occupants leave the room

5.1 Bimodal Ventilation under Summer Conditions

This summer case setup is similar to the bimodal case under winter conditions (base case). The differences are:

- Outdoor temperatures in the summer are 25°C as opposed to 0°C in winter
- No convectors or heated floors are used in the summer

The rates of exhaust are the same in the summer case as the winter case, and are shown in Figure 4.1.1.1.

The effects of a lack of stratification in the summer can be seen in Figure 5.1.1 for the parents and children in the form of an elevated CO_2 concentration. Also, due to the equitably divided thermal plume between the aggregation of the parents (shown in Figure 5.2), cross-contamination is not observed, and the concentration of the breathed air is about the same. Local variations and small shifts in the flowfield contribute to the minor discrepancies between the two. Again, the sleeping period is crucial to the overall personal exposure to contaminants associated with bioeffluents, due to its relative duration with respect to the total time indoors.

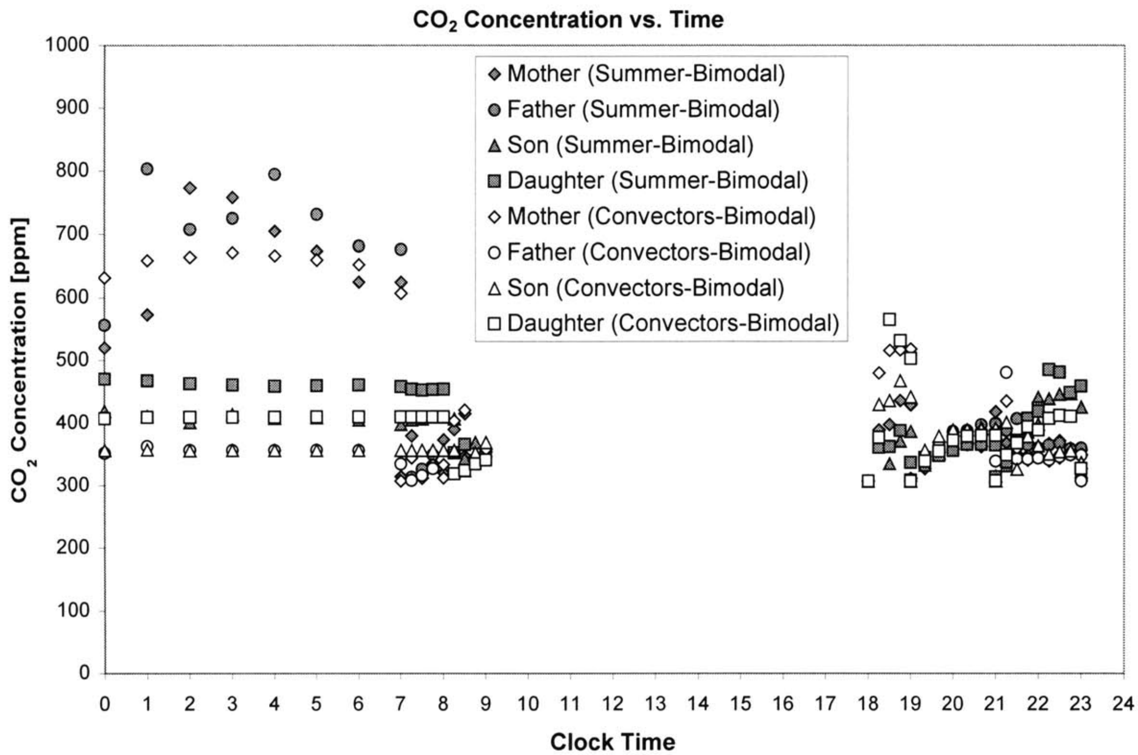


Figure 5.1.1 CO_2 concentration history comparing the summer and winter (base) cases with bimodal ventilation

When evaluating the difference between the winter case with bimodal ventilation and convective heating with the corresponding summer case, the peak values for smoking contaminants is higher in the winter than the summer as shown in Figure 5.1.2. However, attenuation to a normal level is about twice as long for the summer case as the winter case. The concentration path for the winter attenuation after smoking follows exponential decay, while during the same period, the summer cases exhibit more of a linear decay. During 21.00-23.00h when the effects of smoking are most prevalent, the difference in CO exposure for this two-hour period for the parents is approximately 11%, while for the other contaminants the value is less. When taken over the course of the whole day, these are small differences.

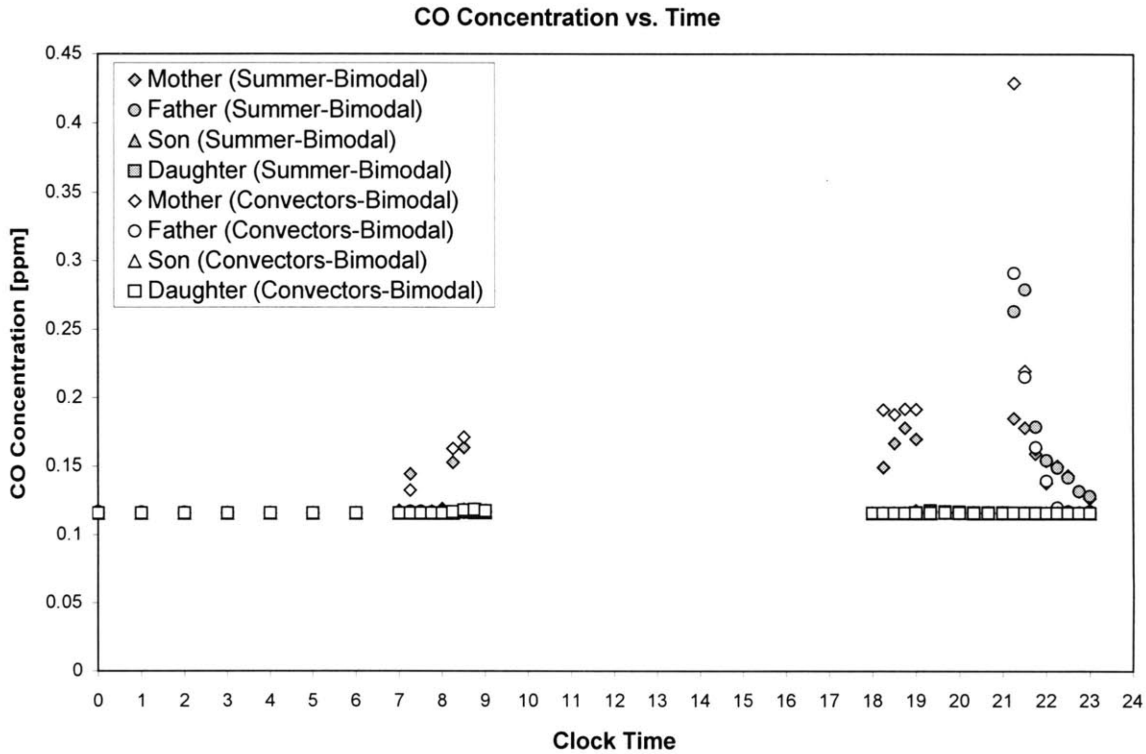


Figure 5.1.2 CO concentration history for the summer case with bimodal ventilation and the winter case with bimodal ventilation and convective heating

Indeed the effects of stratification is clearly seen when the parents breathe in water vapor during sleeping. For both cases, the accumulation of vapor steadily accumulates within the room throughout the night, but whereas the higher concentration of air remains near the ceiling for the winter case, an even and incremental increase in the concentration is seen at all vertical levels. The concentration history of water vapor is somewhat anomalous, in that the data trends are not the same or similar to that found for CO_2. The winter case produces a higher concentration breathed in by the family during the most critical and lengthy periods of the day (sleeping, dinner, and after dinner).

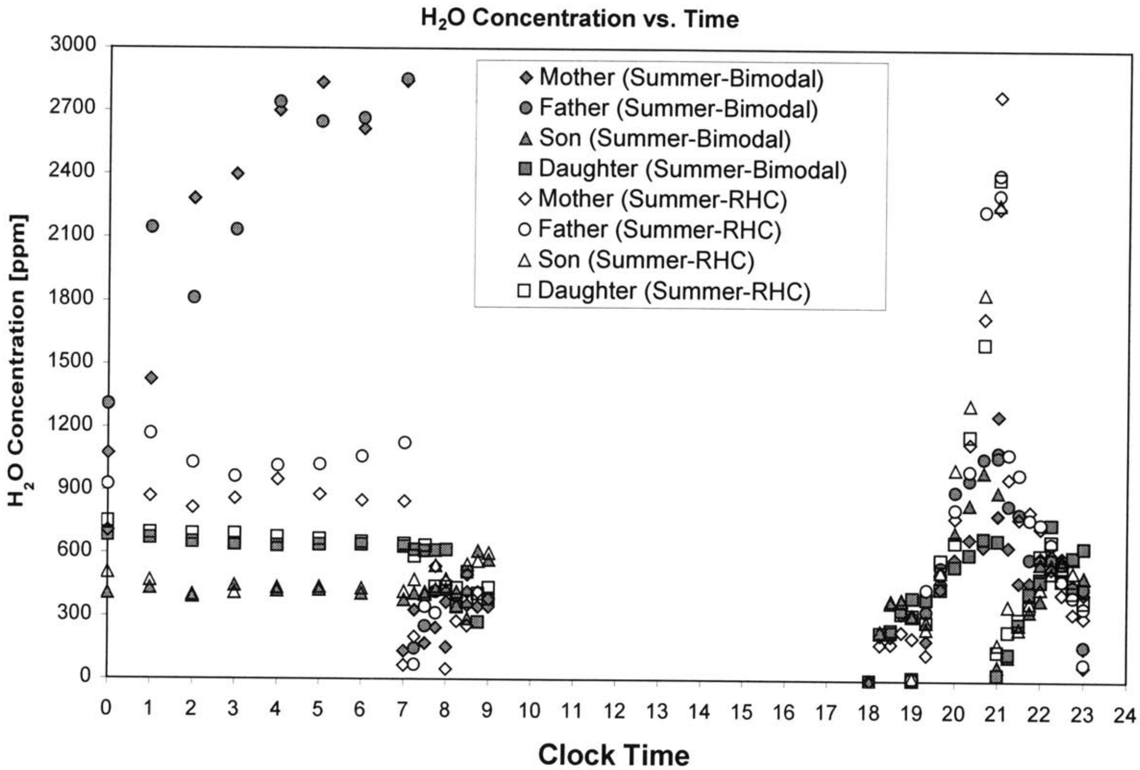


Figure 5.1.3 Water vapor concentration history for the summer case with bimodal ventilation and the winter case with bimodal ventilation and convective heating

Except for the mother, we see a decrease or equilibrium of contaminant exposure for each of the family members when comparing the winter to the summer case with bimodal ventilation as shown in the following figure. The greatest discrepancy is the vapor exposure. Clearly for all cases, the water vapor concentrations will impart the greatest deviation when making comparisons, since the source values are much higher than any other pollutant. Thus seemingly small differences in the flow pattern or boundary conditions are magnified greatly when the concentration values are taken, thus causing the biggest difference.

5.2 Relative Humidity Controlled Exhaust System

The setup of the Summer-RHC case is the same as the Winter-Convectors-RHC case except:

- Outdoor air comes in at 25°C with a humidity ratio of $15.5 \frac{g_{water}}{kg_{dry-air}}$
- No convectors or heated floors are used in the summer

The fluctuation of the exhaust rates is shown in Figure 5.2.1. Since the outdoor temperature and humidity are high, the exhaust fans for the bathroom and the WC are on the highest rates for the duration of the day. For the kitchen range hood, the rate decreases when cooking dinner and breakfast, since the additional heat supplied by the stovetop reduces the humidity found at the exhaust; otherwise the kitchen exhaust is always on the high setting. This is a marked difference and important to note when observing the differences with the Winter-Convectors-RHC case, where all the exhaust rates were at the lowest rate for the entire day.

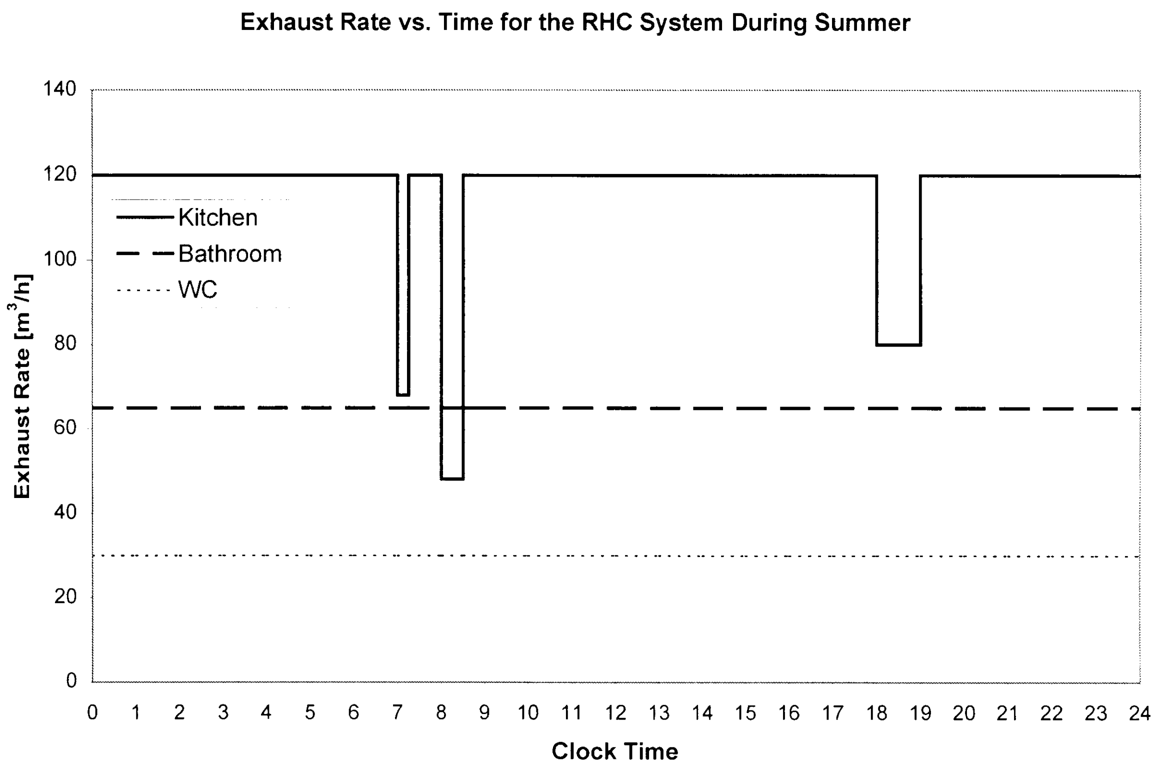


Figure 5.2.1 Exhaust rates for the Summer-RHC case

The RHC system does not help reduce daily exposure when the mother cooks breakfast and dinner. Since the stove directly underneath the kitchen exhaust produces a large thermal plume, due to buoyancy and velocity capture of the hood, the exhausted air is hot, thus reducing the relative humidity. This is quite detrimental when cooking, as it generates a lot of contaminants for the twelve percent of the time that it occurs.

The greatest difference between the Summer-Bimodal and RHC cases is the values of water vapor concentration. During sleeping, the high exhaust rate helps to curb the buildup of vapor in the parents' bedroom, while marginally changing what happens in the childrens' bedrooms.

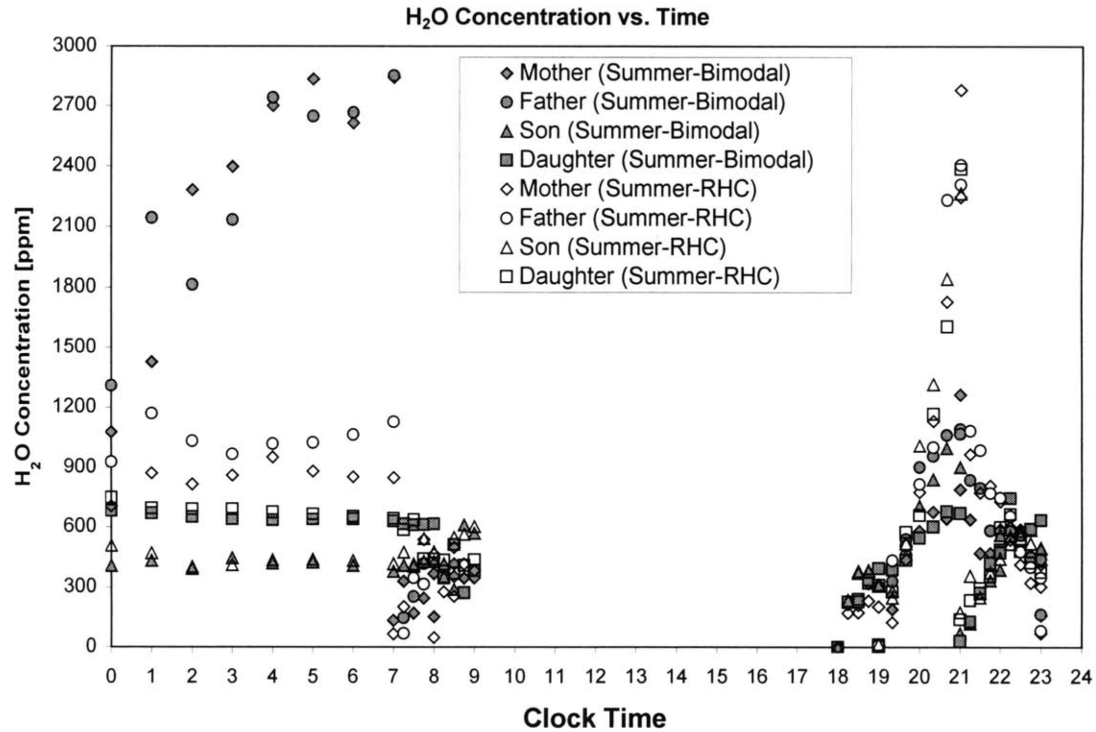


Figure 5.2.2 Water vapor concentration history comparing the summer cases with bimodal and RHC ventilation

When looking at smoking contaminants, the increased ventilation rates does not help all that much to reduce the amount of combustion contaminant exposure during this time comparing the summer cases with bimodal and RHC ventilation. This is attributed to the fact that the living room has the largest volume of all the rooms, and thus is more insulated with regard to an increased exhaust rate when it comes to the changing dynamics that are associated with it. However, when comparing cooking contaminants, the RHC system is inferior due to the lowered rates caused by the heated stovetop as seen in Figure 5.2.3. With that, migration of cooking contaminants should be larger with the RHC system than the bimodal system, but is not the case due to the changing dynamics of large opening flow. While cooking, there are no occupants in the living room, which means that thermal stratification is lower than usual. Without the temperature gradient, only low levels of room to room exchange occur, when contrasted with cases where the lower levels have a lower temperature than that in the upper regions of the room.

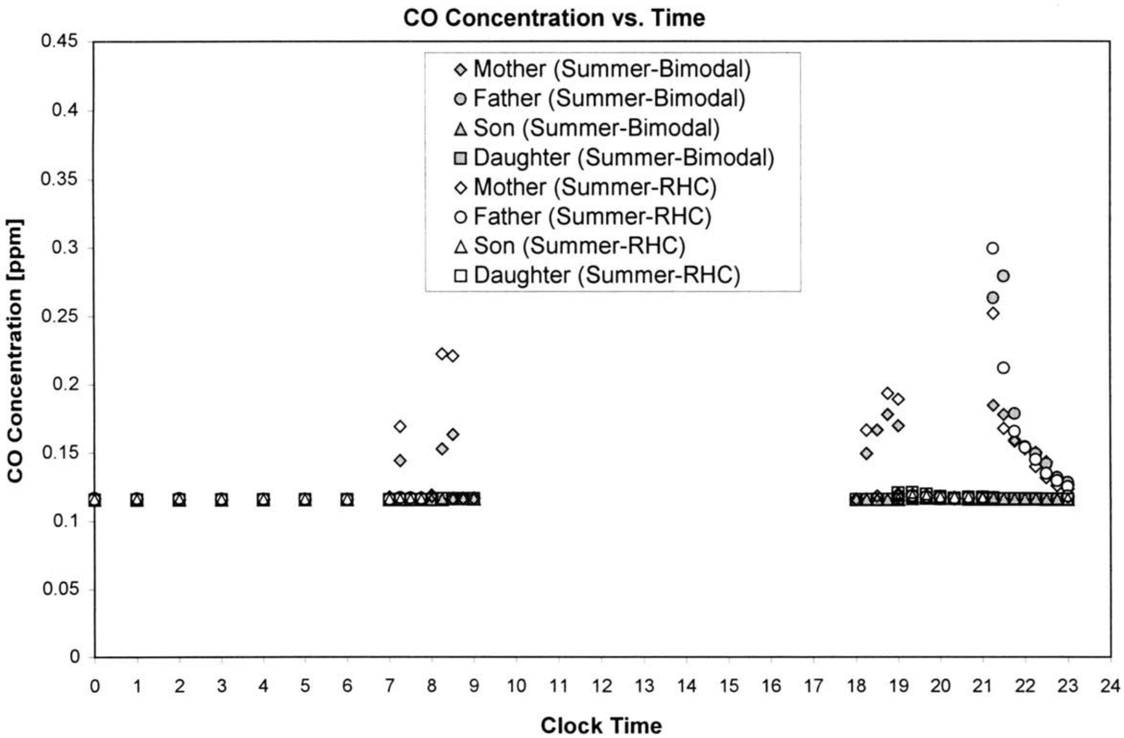


Figure 5.2.3 CO concentration history comparing the summer cases with bimodal and RHC ventilation

It just so happens that the large opening flow under no temperature stratification is effective in curbing migration for this particular set of occupational scenarios. While the mother cooks, there is no migration of cooking pollutants into the living room, which would normally happen since the door is open. While the family eats, there is an accumulation of water vapor due to the congregation of the family in a relatively dense space, while they emit a larger amount of vapor due to increased metabolism. But since the people are relatively significant heat sources in the summer, large opening flow now occurs, removing contaminants from the living room into the rooms with exhaust and the bedrooms. It is quite fortunate that the family does its activities in tandem, that is, they all eat and sleep at similar times, and the children fortuitously close their doors together when dinner is being cooked and the father smokes.

Comparing the two summer cases, it is clear from Figure 5.2.2 and Figure 5.2.4 that the high ventilation rate during the night reduces the concentration of both CO_2 and water vapor in the parents' bedroom. For the children, the benefits are less pronounced; the differences are either slight or ephemeral.

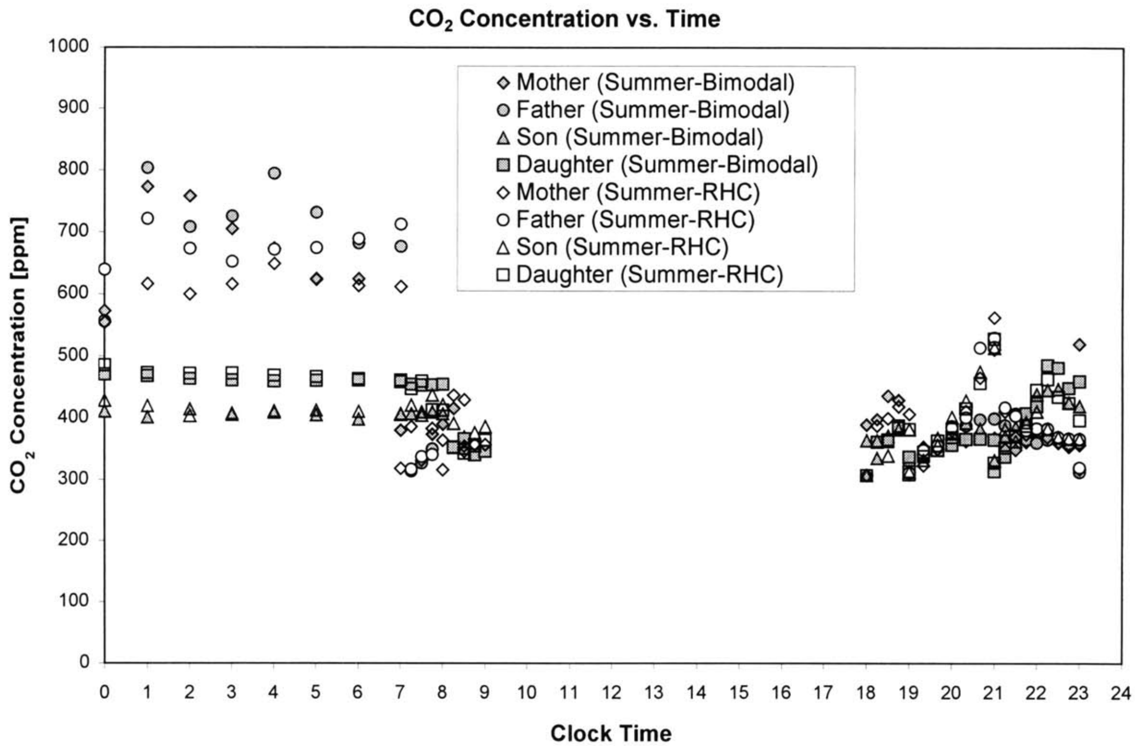


Figure 5.2.4 CO_2 concentration history comparing the summer cases with bimodal and RHC ventilation

5.3 Exposure

When comparing the winter-convectors-bimodal case to the summer-bimodal case, small differences in the boundary conditions can have a dramatic effect on the concentrations, and thus the exposure. A change in the outdoor temperature and heating condition causes dramatic changes in the concentration of vapor breathed, especially during sleeping. Decreases in exposure are seen for the family (except the mother), but only to a relatively moderate amount for the combustion contaminants, since the source strengths are not nearly as high. The father experiences a very large decrease in CO_2 exposure, due to the lack of circulation within the room, and thus equal distribution of the pollutant during sleeping. Differences for other non-vapor exposures are within the threshold of a 10% error.

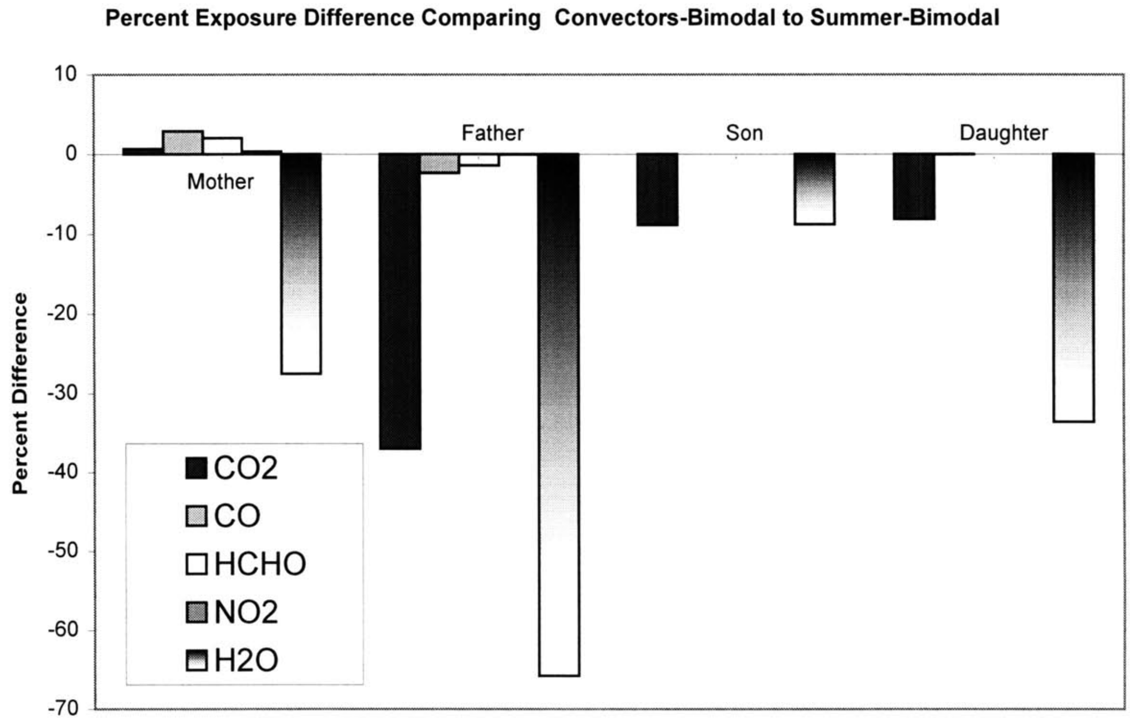


Figure 5.3.1 Exposure differences comparing the Summer-Bimodal case to the Winter-Convectors-Bimodal case

For this particular Summer-RHC case when the fans are on high for 87.5% of the time, the global ventilation rate is 123.6% over bimodal ventilation in the base mode, distributed unevenly throughout the house depending on location to the exhausts, door positions, etc. When comparing the two summer conditions armed with this fact, it is clear that an increased ventilation rate does not work as effectively as imagined to remove household contaminants as shown in Figure 5.3.2. Again, the differences in H_2O concentrations are markedly large due to the relatively strong source strengths compared with other contaminants. All other pollutants, including the telling CO_2, has a difference in exposure less than 10%.

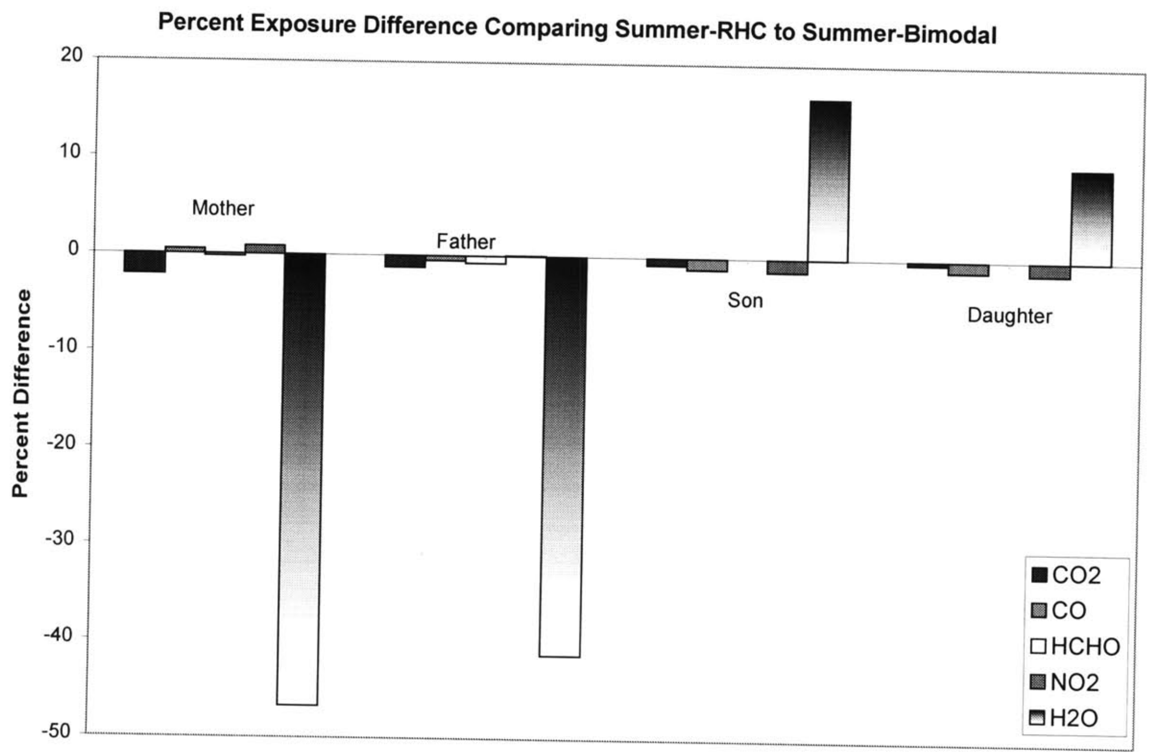


Figure 5.3.2 Percent differences for each indoor pollutant comparing the Summer-RHC case to the Summer-Bimodal case

It is possible to evaluate and compare the relative efficiencies of two exposure curbing techniques of thermal/concentration stratification and increased ventilation rates. The Convectors-Bimodal case compared to the Summer-Bimodal case shows the effectiveness of thermal stratification due to the cold infiltration air in addition to the strong convective heat sources, while the ventilation systems are equal. The summer cases are comparable since only their ventilation rates differ.

Taking the sum of the percent differences in exposure (for all four occupants) between the Convectors-Bimodal vs. Summer-Bimodal and Summer-RHC vs. Summer-Bimodal, Table 5.3.1 shows that in general, the increase in ventilation is slightly better in reducing indoor exposure. However, it must be stressed that these results are for case specific solutions to exposure, and may not necessarily be applied to all situations.

Table 5.3.1 Sum of the percent differences between the two sets of comparison cases

	Convectors-Bimodal vs. Summer-Bimodal	Summer-RHC vs. Summer-Bimodal
CO_2	-53.3	-4.5
CO	0.5	-2.3
HCHO	0.6	-1.0
NO_2	0.3	-1.7
H_2O	-135.6	-62.0

Looking at the average of the percent differences between the two sets of comparisons, the trends are similar. The stratification effects are dominant for the winter case to reduce the exposure for the bioeffluents, and the combustion contaminants are negligibly different.

Table 5.3.2 Average of the percent differences between the two sets of comparison cases

	Convectors-Bimodal vs. Summer-Bimodal	Summer-RHC vs. Summer-Bimodal
CO_2	-13.3	-1.1
CO	0.1	-0.6
HCHO	0.2	-0.2
NO_2	0.1	-0.4
H_2O	-33.9	-15.5

6 International Ventilation and Exposure Standards

This study attempts to link exposure to occupancy throughout the house. In addition, the exposures to the pollutants will be compared with some international standards to determine whether or not the indoor air quality is indeed good enough. The standards usually employ either a ventilation rate or an exposure limit. Certainly the latter provides a more stringent requirement, but the former offers a sense of universality to be applicable to almost any situation.

For many countries, there are standards for proper ventilation by which official and unofficial building codes are based. They usually prescribe a minimum air change rate in the residence (which can also be expressed in a normalize form of a volume flow rate of fresh air), or a limit to the concentration to which a person should be exposed. Leaky buildings with high infiltration waste a large portion of building energy, as well as increase the risk of poor thermal comfort due to drafts and reduce envelope durability due to condensation damage.

Fundamentally, infiltration and ventilation have similar functions; they both provide means by which indoor contaminant concentrations may be reduced. The main difference between these two mechanisms is that infiltration is an uncontrolled phenomenon, whereas ventilation is controlled based on occupant thresholds. Although ventilation standards or recommendations are in place, there is usually no specific requirement for the installation of mechanical ventilation; only when natural ventilation does not provide adequate purging of contaminants does mechanical ventilation become a necessity.

When mechanical ventilation is necessary, there are requirements for the minimum airflow rates. Since the aggregations of contaminants are produced based on occupation, ventilation standards reflect this fact. These ventilation flow rates are specified for outdoor air, which is assumed to be of good quality; if it is not of sufficiently good quality, as seen in a later section, the outdoor air has a large impact on the indoor environment. These ventilation values also reflect an assumption of perfect mixing within the space. Ventilation effectiveness then brings an additional influence to bear on the quality of the indoor air. Table 6.1 shows a variety of standards with regard to residential ventilation based on a floor area of 100m^2.

Table 6.1 International ventilation standards for housing based on a floor area of 100m^2 [49] [50]

Country (Standard)	General (whole dwelling)	Bedroom (10 m^2)	Kitchen (7 m^2)	Bathroom (5 m^2)
Canada (CSA Standard F326)	0.3 ACH	5 l/s (single) 10 l/s (double)	30 l/s (continuous) 50 l/s (intermittent)	15 l/s (continuous) 25 l/s (intermittent)

France (CSTB)	0.5 ACH	N/A	12.5-25 l/s	8.3-16.6 l/s
Netherlands (NEN 1087)	N/A	10 l/s	21-28l/s	14 l/s
Norway (BF)	N/A	N/A	22 l/s	16 l/s
Sweden (SBN 1980)	0.5 ACH	N/A	10 l/s	10 l/s
Sweden (National Building Code)	N/A	N/A	15 l/s	10 l/s
Switzerland (SIA 380)	N/A	N/A	22-33 l/s	17 l/s
UK (Building regulations)	N/A	3-8 l/s (single) 6-16 /s (double) (Scotland) 6 l/s (single) 12 l/s (double) (London)	30 l/s (Scotland) 7 l/s (London)	10 l/s (not London)
U.S. (ASHRAE 62-1999	0.35 ACH, not less than 15 cfm (8 l/s) per person	N/A	100 cfm (50 l/s) (intermittent) 20 cfm (12 l/s) (continuous)	50 cfm (25 l/s) (intermittent) 20 cfm (10 l/s) (continuous)

In the U.S., there are two paths toward compliance for acceptable indoor air quality according to ASHRAE Standard 62-1999. The first method, known as the Ventilation Rate Procedure (VRP), is to impose a required fresh air rate for each occupant in a space. The Indoor Air Quality Procedure (IAQP) is the second method, whereby an acceptably specified level of contaminant concentration is prescribed. Although the VRP is supposed to guarantee acceptable indoor air quality, it is deemed a more indirect approach towards compliance.

Generally, there are not guidelines for the bedroom, and the kitchen ventilation rate is approximately twice that of the bathroom. France and Sweden have the most stringent whole house ventilation standard, while Canada has the strictest recommended bedroom, kitchen, and bathroom ventilation rate. However, most of the kitchen and bathroom ventilation rates are quite similar in magnitude.

As the alternative to setting ventilation rates, indoor air quality standards that are based on guidelines for maximum room air concentrations are more rigorous compared to a fresh air rate designation, since it absolutely takes into account any sources that might exist either generated indoors, or brought in from the outside air. These standards are based upon the epidemiological effects of health, and are not normally concerned with subjective effects such as odors or mild irritation.

Typically, concentrations of one tenth the values for the threshold limit value (TLV) are used for concentrations in order to provide a minimum of complaints in residential, office, school or other similar environments [50]. Guidelines published by organizations like the U.S. Occupational Safety and Health Administration (OSHA) typically express concentrations on the basis of time-weighted average (TWA) over an 8-hour day and a forty-hour workweek. The U.S. OSHA standards are quite lax, since the standards are only guidelines for the workplace, whereas the time spent in a house often exceeds 100 hours per week.

Table 6.2 Pollutant guidelines published by the U.S. Occupational Safety and Health Administration 1999 [51]

Pollutant	Industrial workplace standard	Comments
CO_2	9000mg/m^3 (5000ppm)	TWA, 8 hours
CO	55mg/m^3 (50ppm)	TWA, 8 hours
HCHO	1 ppm (8 hours) 5 ppm (15 min)	TWA-Permissible exposure limit Short term exposure limit
NO_2	9 mg/m^3 (4.68 ppm)	Concentration cannot be exceeded

Table 6.3 Pollutant guidelines published by the Canada Department of National Health and Welfare 1987 [49]

Pollutant	Acceptable short term exposure range	Acceptable long term exposure range
CO_2	N/A	6300 mg/m^3 (<3500 ppm)
CO	<11 ppm (8 hours) <25 ppm (1 hour)	N/A
HCHO	N/A	0.12 mg/m^3 (0.1ppm)
NO_2	<0.48 mg/m^3 (<0.25 ppm) (1 hour)	<0.1 mg/m^3 (<0.05 ppm)

Table 6.4 Pollutant guidelines published by the National Ambient-Air Quality Standards (U.S. EPA) 1997 [52]

Pollutant	Acceptable short term exposure range	Acceptable long term exposure range
CO	9 ppm (8 hours) 35 ppm (1 hour)	N/A
NO_2	N/A	0.053 ppm (annual arithmetic mean)

Table 6.5 Pollutant guidelines published by the American Conference of Governmental Industrial Hygienists 1995 [53]

Pollutant	Short term (15 min)	Long term TLV
CO_2	54,000 mg/m^3 (30,000 ppm)	9000 mg/m^3 (5000ppm)

Table 6.6 Pollutant guidelines published by the World Health Organization for air quality 1999 [54]

Pollutant	Short term	Long term (TWA)

CO	100 mg/m^3 (90 ppm) (15 min)	10 mg/m^3 (10 ppm) (8 hours)
HCHO	0.1 mg/m^3 (0.08 ppm) (30 min)	N/A
NO_2	0.2 mg/m^3 (0.10 ppm) (1 hour)	0.04 mg/m^3 (0.02 ppm)

Table 6.7 Pollutant guidelines recommended by AHRAE Standard 62-1999 [50]

Pollutant	Short term	Long term
CO	40 mg/m^3 (35 ppm)(1 hour)	10 mg/m^3 (10 ppm)(8 hours)
NO_2	0.26 mg/m^3 (0.14 ppm)(24 hours)	N/A

Although carbon dioxide has not been known to cause serious health damage, CO_2 is commonly used as a barometer for the indoor environment. Without a specific association of CO_2 and indoor air quality, it has been used as a basis for the perception of indoor environmental qualities for comfort and irritations.

There are obviously differences in standards between short term and long-term exposure ranges for acceptable concentration. Exposure attempts to assess the cumulative levels of contact with contaminants, and show the epidemiological effects when humans become the receptor for this accretion of pollutants over a period of time. It is yet unclear whether or not high concentrations at short exposures are more detrimental that continuous exposure over a long period of time.

Since people spend about 90% of their time indoors, it is important to understand the basis for ventilation in terms of total exposure, where humans become a receptor for contaminants on a time-based limit. Health safety organizations have attempted to put a limit on the amount of time indoor occupants are allowed to be exposed to certain contaminants based on both short term and long term time periods. Therefore, for this study, the most rigorous concentration-based IAQ guidelines will be used for the exposure comparison, as outlined in Table 6.8. The value for long term exposure should ever exceed that for the short term, so for the case of HCHO, the short and long term values are equal.

Table 6.8 Pollutant concentration limits used for exposure comparison that encompasses the most stringent requirements

	Short Term (15 min)	Long Term (>8 hours)
CO_2	5000 ppm	5000 ppm
CO	25 ppm	9 ppm
HCHO	0.08 ppm	0.08 ppm
NO_2	0.10 ppm	0.02 ppm

6.1 Comparison of Results to International Standards

Since carbon dioxide is generally not considered to be a toxic substance, the standards provide some generosity with the values for exposure. Water vapor is not considered a contaminant at all so there are no guidelines. Thus over-exposure for the family for these contaminants is never achieved.

Due to stratification and the body thermal boundary layer, the concentration limits for CO and HCHO were not exceeded.

For NO_2, the ambient condition exceeds the WHO guidelines of 0.026ppm. Therefore, the long-term exposure condition is exceeded, as the assumed ambient condition for the simulations performed was 0.064 ppm. The short term limit was not exceeded.

Few standards related to indoor air quality have been established with require compliance by law, but guidelines have been established for building implementation as recommended by Haghighat [55].

7 Sources of Error

Within the use of CFD, the simulation results are certainly not infallible. In fact, there are a number of reasons that seemingly similar conditions between the cases produce such markedly dissimilar results. These sources of error are generated by both the user of the computational tool as well as the assumptions and conditions of its usage. Three major forces in contributing to sources of error are

- CFD simulation
- CFD modeling
- Measurement location

CFD simulation errors are on a more global scale. These account for errors in how the computation tool is used, as well as the approximations for the equation solutions. Using a quasi-steady discretization technique imparts inevitable error. This is of course dependent on the coarseness of the discretization. The method described in the research approach section was chosen to provide the most accurate solution in a minimum of time, taking into consideration the changes in occupational position and activity. It is clear that airflow patterns are not steady throughout the house for the whole duration of each period; thus it should also be the case for each time-step. A greater number of time-steps for each time period would produce a more accurate result at a cost of higher computation time.

Although the grid is quite large (dense), it is of usual practice to make the grid finer near objects such as heat sources and walls. A fine grid ensures that the boundary and source conditions are well calculated within the simulation program. This was not done in these cases, since the grid size was already large. Employing this technique would have increased the grid number, and thus significantly lengthening the calculation time to an undesirable degree.

An across the board simulation error of 10% is thus assumed due to the simulation error. Mostly this includes the approximations of the program to sole the Navier-Stokes equation and the quasi-steady discretization method, in addition to any user-input error that may have occurred along the way.

CFD modeling errors are how approximations of real life are considered using a computational tool. For instance, the simulation does not take into account the opening or closing of doors or the movement of people within the house. This may actually have a great impact since these motions greatly help to stir up the air immediately surrounding the person or the doorway, and may fundamentally change the flow patterns.

The simulation assumes a calm wind condition during the winter and summer season, and no superimposition of wind or stack effect is included with the mechanical ventilation. Clearly this is not representative of all the situations that may occur throughout the time that the family stays inside the house over the course of a year. Seasonal temperature variations and changing wind direction will cause different effects on personal exposure, sometimes good, and sometimes bad.

Component efficiencies (exhausts, convectors, etc.) are assumed to be at 100%, meaning that they work perfectly all the time. In reality this is not the case, as there may be occupational influences over these devices. For instance, the kitchen exhaust may be completely turned off due to the noise, where it should be set for a low exhaust rate. Thus incorrect usage or improper installation was not considered.

The measurement location is a source of error that is based on subjective consequences. During the times that the occupants sleep, changing or different flow patterns indicate the values of the breathed concentrations. When the occupants are in an upright position, due to the low ventilations rates, the dominant flow in the breathing region is from buoyancy. Thus only an upward motion of the air is seen, and the locations are taken confidently, based on Brohus [14] and Murakami's [14] data. Due to the relatively long length of the body in the vertical orientation, buoyancy overpowers any sort of lateral flow.

When sleeping, the prone position offers no such consistency. Mainly this is due to the fact that the major length of the heating surface is in a horizontal position. There is not a lot of vertical surface to generate a uniform upward flow, so lateral flows readily disturb the air in the breathing zone. Since buoyancy does not dominate this condition, other factors have a greater influence on the airflow, though it is difficult to say which is the most influential. The measurement location attempts to "lead" the air, meaning that the location is upwind of the facial region as shown schematically in Figure 7.1. These locations are chosen in attempt to follow uniformity, but may not always be the case.

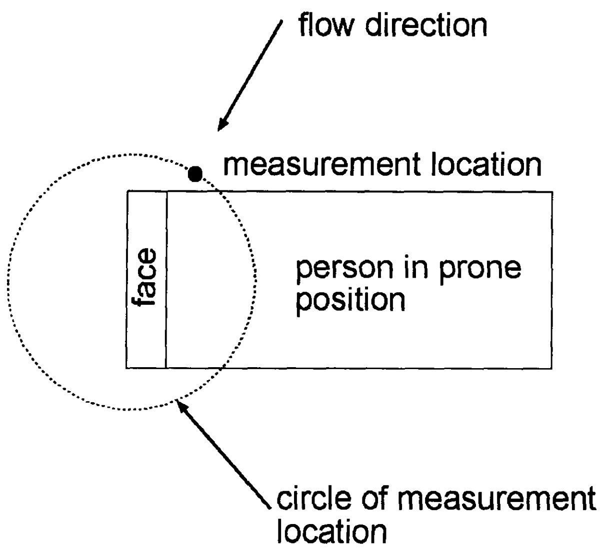


Figure 7.1 Schematic of measurement location

It should be noted that errors within each simulation are cumulative, in that errors in the solution for airflows or concentrations in the first step propagate to the next time step and the next time period. For occupants that stay in a room with closed doors for many time steps (e.g. the children stay in their room with the door closed for ten hours, or sixteen time steps), the aggregation of errors may eventually become noticeably large.

8 Conclusions and Recommendations

This thesis evaluates the physical phenomenon of airflows and occupational exposure in a single-family house under various ventilation, heating, and climactic conditions using CFD. To ensure that the numerical technique was being properly applied, the program was validated with experimental data to acquire confidence in the use of the tool. Comparisons of each of the combinations of systems are presented, based on the breathed concentrations of a family of four (two parents and two children) under typical occupational conditions throughout a normal day. The cumulative exposure is then measured against a set of international ventilation and exposure standards to verify the effectiveness of the systems.

CFD is a necessary tool used to investigate and evaluate airflows and concentration migration throughout a space. It is a tool that can be specifically harnessed to obtain a detailed understanding of localized phenomenon that might otherwise be lost in mathematical equations and other such generalizations.

A number of ventilation, heating, and seasonal conditions have been documented here, and the exposure comparisons for the combination of systems and conditions have variable results. The three ventilation types consisted of a bimodal system that cycles between two exhaust rates based on whether or not someone is cooking, a relative humidity controlled system that increases the ventilation rate based on the relative humidity at the exhaust, and a balanced system that inputs semi-conditioned air directly into the bedrooms coupled with a bimodal extraction system. The two heating types include convectors in all the rooms, and a combined heated floor and convector system. The climactic conditions simulated are the winter and summer, where the outdoor temperatures are 0°C and 25°C respectively. Many of the results are the same, although the method of exposure is somewhat different in some respects.

Comparing the ventilation systems, the RHC system does a poorer job of exhausting contaminants in winter, and thus allowing more exposure to the occupants. In the summer, this exhaust strategy does not help during cooking, due to the heat generated from the stovetop. Since RHC ventilation is highly seasonally dependent, it is not a recommended method for mechanical ventilation.

Looking at the big picture, exposure to combustion contaminants never exceeds 10% above the exposure due to breathing ambient air for the bi-modal system, and doesn't reach above 20% for the RHC system. Comparisons between the systems with each other also show that combustion contaminant exposure is quite small. These values are within or close to the 10% simulation error.

Stratification and the body thermal boundary layer prove to be quite effective in reducing the amount of exposure to contaminants, and is seen (in the context of these cases evaluated) to be more effective than a higher ventilation rate. This phenomenon is set up most effectively in the winter in rooms with strong convective heat sources, and is not as effective with the heated floor. However, even the weak effects found during the summer condition are enough to curb excessive exposure to combustion contaminants.

The time periods that call for the most amount of ventilation is

1. During cooking
2. When the family aggregates together for dinner
3. When smoking
4. When in a closed room for an extended period of time (e.g. sleeping)

Since the family spend the most time sleeping while they occupy the house, the reduction of exposure would be most effective during this time period. However, since the exhausts are located remotely and the doors are closed when sleeping, another method of localized ventilation should be implemented to achieve such a reduction. Since centralized exhausts help to reduce contaminant migration by drawing air in from the peripheral bedrooms to the house core, opening the doors to increase the coupling of the bedrooms to the exhausts, but conflicts with privacy.

Airflow patterns have a direct impact on personal exposure. It is in this realm that is difficult to control when designing the heating and ventilation systems; often, there is instability or fluctuations in the flow pattern over time. However, for cases of high stratification and strongly induced thermal body boundary layers, these fluctuation effects are less influential.

Doors should be left closed whenever possible, as peripheral room infiltration will provide a higher pressure in the room than at the extract room. A small door opening (under the door) prevents most, if not all contaminants from migrating and accumulating in the closed rooms. The recommendations for the door positions during various occupational conditions are shown below:

Door closed:

- Contaminant source and an extract in the room (kitchen, bathroom with shower)
- Interior has already nearly reached ambient conditions (parents' bedroom before sleeping)

Door open:

- Contaminant source in the room but no extract (bedrooms, living room)
- Contaminant source was previously in the room but has been removed: to help dilute the buildup (childrens' bedrooms)
- No source in room but has an extract (bathroom, WC)

For all the cases, the bioeffluents should be used to evaluate the indoor air quality rather than the combustion contaminants. Although their measurement is important to determine whether or not international standards are being upheld, their source strengths are usually too small to be a good indicator.

There is obviously a link between IAQ and energy, in that they are often diametrically opposed; assurance of good IAQ often has a penalty of higher energy use. This is especially the case for mechanical extract systems used during the cold seasons for which the makeup air is only infiltration. Not only is more electricity used to power the fan at a higher exhaust rate, but more heating of the occupied space is necessary. Although this tradeoff is not evaluated, it is a necessary and important aspect in the determination of the success of the ventilation system.

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