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Modeling Contaminant Exposure in a Single-Family House

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Keywords Computational fluid dynamics (CFD), Indoor air quality, Contaminant exposure, Stratification, Ventilation system performance

Abstract

This study simulated occupational exposure to household contaminants in a single-family house under different ventilation, heating, and climatic conditions using computational fluid dynamics (CFD). The contaminants studied are CO_2 and CO. This investigation assesses the exposure over the day for a generic occupational schedule of four family members. Characteristically, high degrees of contamination as well as thermal stratification were found during the winter months, where low ventilation rates mimic displacement ventilation. This leads to lower contaminant exposure of the occupants, compared to a situation with completely mixed air. The stratification effect is more efficient at curbing exposure than increasing the global ventilation rate for the cases evaluated.

Introduction

Since residential housing traditionally relies on infiltration in part to provide adequate ventilation (ASHRAE, 1997), tighter building construction for energy conservation standards (ASHRAE Standard 119, National Building Code of Canada 1995) may reduce the amount of available fresh air. This decrease in fresh air is a subject of concern as health issues becomes more sensitive. Mechanical ventilation is increasingly being implemented to respond to and mitigate these trends to reduce the risk of overexposure to indoor pollutants. Nevertheless, the ventilation rate is rather low and fresh air may not mix well with indoor air. The actual breathed concentration of indoor contaminants may be different from the mean value. Thus, it is necessary to conduct a detailed study to estimate the actual exposure so that the overall performance of building ventilation system can be accurately evaluated.

Indoor airflows are quite complex and the transport of contaminants is highly dependent on the airflows. Stratifications or non-uniformities often exist in the

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distribution of pollutants (Hyldgarrd, 1994), complicating the determination of the pollutant exposure of the occupants. In order to understand the impact, computational fluid dynamics (CFD) is an ideal tool, as it provides insight into the distribution of contaminants, while providing a degree of foresight into predicting the flows in unbuilt spaces. Though it takes great effort to perform, this method provides a clear understanding of pollutant transport and personal exposure.

This paper demonstrates how CFD was used to evaluate the performance of two heating systems, two cooling systems and three ventilation systems in summer and winter to help curb the accumulation of contaminants within a single-family house. The evaluation criteria are the concentration and occupational exposure to CO_2 and CO, common household contaminants emitted as byproducts of human metabolism, gas cooking, and smoking.

Research Approach

Case Setup

This investigation studied contaminant exposure in a generic, small single-family house with a floor area of 100 m^2 and a height of 2.5 m occupied by four people as shown in Figure 1. Furniture was included as it normally affects the airflow throughout the house (Etheridge and Sandberg, 1996) and the location of occupants within the room (e.g. sleeping on a bed elevates the body). These factors were included to closer approximate reality. Inside the house, the bedroom and bathroom doors were open, unless the room was occupied; all other doors were left open. The closed doors had a gap between the bottom of the door and the floor, which weakly coupled the rooms to the hallway.

Each person moves about the house throughout the day, and performs a variety of daily activities according to Table 1. Table 2 represents the average pollution sources of CO_2 and CO as well as vapor sources used in this study, which were generated by humans (bioeffluents), combustion (smoking and gas stove cooking), or the ambient (CO_2).

This study used three ventilation (extract) devices: above the kitchen stove and in the bathroom and WC. The ventilation devices were operated in the following modes:

- Bimodal extraction: kitchen range hood cycled up from a low to high rate only when cooking
- Relative humidity controlled (RHC) extraction: each device varied the extract rate based on the relative humidity found at the exhaust
- Balanced ventilation: outdoor air was partially conditioned and supplied directly into rooms at a low flow rate

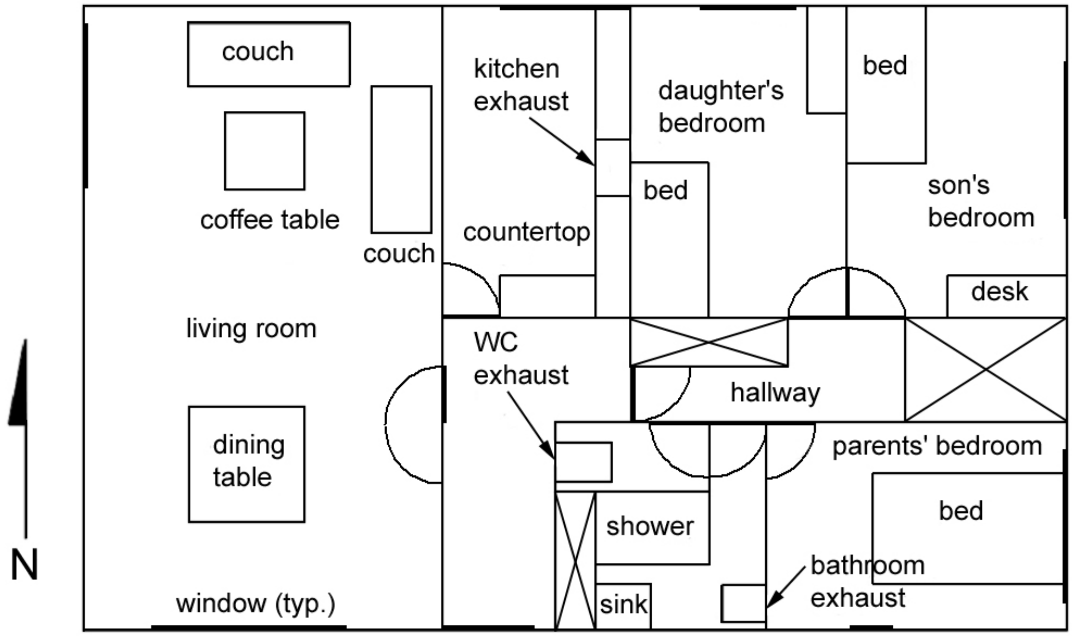


Figure 1 The house plan with furniture

Table 1 Person's activity throughout the day [1: kitchen 2. living room 3. son’s bedroom 4. daughter’s bedroom 5. parents’ bedroom 6. bathroom]

<table>
<tr><th>Hour</th><th>Mother</th><th>Father</th><th>Son</th><th>Daughter</th></tr>
<tr><td>18h00-19h00</td><td>Cooking (1)</td><td>Not home</td><td>Studying (3)</td><td>Studying (4)</td></tr>
<tr><td>19h00-21h00</td><td>Eating Dinner (2)</td><td>Eating Dinner (2)</td><td>Eating Dinner (2)</td><td>Eating Dinner (2)</td></tr>
<tr><td>21h00-21h15</td><td>Reading (2)</td><td>Smoking (2)</td><td>Studying (3)</td><td>Studying (4)</td></tr>
<tr><td>21h15-22h00</td><td rowspan="2">Reading (2)</td><td rowspan="2">Reading (2)</td><td>Studying (3)</td><td>Studying (4)</td></tr>
<tr><td>22h00-23h00</td><td rowspan="6">Sleeping (3)</td><td rowspan="6">Sleeping (4)</td></tr>
<tr><td>23h00-07h00</td><td>Sleeping (5)</td><td>Sleeping (5)</td></tr>
<tr><td>07h00-07h15</td><td>Cooking (1)</td><td>Showering (6)</td></tr>
<tr><td>07h15-07h30</td><td>Showering (6)</td><td rowspan="2">Eating Breakfast (2)</td></tr>
<tr><td>07h30-07h45</td><td rowspan="2">Eating Breakfast (2)</td></tr>
<tr><td>07h45-08h00</td><td rowspan="4">Not home</td></tr>
<tr><td>08h00-08h15</td><td rowspan="2">Cooking (1)</td><td>Sleeping (3)</td><td>Showering (6)</td></tr>
<tr><td>08h15-08h30</td><td>Showering (6)</td><td rowspan="2">Eating Breakfast (2)</td></tr>
<tr><td>08h30-09h00</td><td>Reading (2)</td><td>Eating Breakfast (2)</td></tr>
</table>

Table 2 Pollution source strengths

	Outside [ppm]	*Gas cooking [g/kJ]*	*Cigarette Smoking [g/s]*	*Shower [g/person]*	*Adult awake (asleep) [g/s]*	*Child awake (asleep) [g/s]*
CO_2	300	0.045	0.00065	0	0.0099 (0.0066)	0.0066 (0.0022)
CO	0.116	0.00005	0.00011	0	0	0

	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

Table 3 describes the ventilation rate at the exhausts based on the occupational parameters. For the relative humidity controlled system, the ventilation rate was at minimum value when the relative humidity was lower than 30%, changed linearly between the minimum and maximum values when relative humidity varied between 30% and 70%, and was set at maximum value when relative humidity is higher than 70%. Generally, the ventilation in the house varied between 0.36ACH to 0.86ACH, which seems very low. However, the paper shows that the indoor air quality, with indicators such as CO_2 and CO levels, is still acceptable according to ventilation standards

Table 3 Exhaust flow rates for the bimodal and the relative humidity controlled systems

Systems	*Modes*	*Kitchen*	*Bathroom*	*WC*
Bimodal	Normal flow rate [m^3/h]	45	30	15
	Cooking flow rate [m^3/h]	120		
Relative humidity controlled	Minimum flow rate [m^3/h]	45	30	15
	Maximum flow rate [m^3/h]	120	65	30

The balanced ventilation system was the most complex of the three; each of the three bedrooms and the living room was supplied with semi-conditioned outdoor air from diffusers at a constant rate of 22.5m^3/h at 13.3°C in both summer and winter. Due to the limitations of the bimodal exhaust, there was a mass flow imbalance during cooking when the exhaust rate increased. Thus for all the cases, outside air makeup was introduced through the windows. Since the extraction rates were small, the whole window area was assumed to be an inlet, and the induced face velocity was quite small.

In addition to the ventilation systems, four types of heating and cooling systems were concurrently evaluated under winter heating and summer cooling conditions, as summarized in Table 4:

- Convectors in all rooms (Convector case)
- Heated floor in the living room, convectors in all other rooms (HF case)
- Split system cooling devices located in the living room and bedrooms (Split case)
- Refrigerated floor located throughout the house (RF case)

Table 4 Cases evaluated

Season	*Ventilation System*	*Conditioning System*
Winter	Bimodal	Convectors
		Heated Floor
	Relative humidity controlled	Convectors
		Heated Floor
	Balanced	Convectors
Summer	Bimodal	None
		Split System Cooling
		Refrigerated Floor
	Relative humidity controlled	None

For space heating in the winter, room convectors were situated underneath a window to counteract cold makeup air drawn in from outside as well as negative buoyancy (downdrafts) due to the colder window surface. The heated floor in the living room was uniformly kept at 23.5°C. Wall, ceiling, and floor temperatures were assigned based on the energy simulation results from CLIM2000, developed by Electricité de France (Guyon et al., 1999). The simulated occupied zone had a temperature between approximately 17.5-21ºC in the winter cases, while the outside temperature was at 0°C and 50% relative humidity.

The split cooling systems were located in the living room and the three bedrooms, inputting recirculated air at 13.3°C and 18.3°C respectively during the summer. Since the split systems only provide cooled recirculated air, the bimodal exhaust with inlet makeup provided the fresh air, therefore maintaining the same ventilation rates for fresh air as the base case (bimodal ventilation with convectors). The refrigerated floor case consisted of a chilled floor over the entire house maintaining interior temperatures between 20-23°C. The ambient outdoor air conditions were at 25°C with a relative humidity of 78%.

Simulation Tool

To evaluate the performance of the ventilation, heating and cooling systems in terms of indoor air quality, this investigation required an accurate and informative assessment of contaminant exposure in a single-family house. Simple tools, such as jet formula, manufacturers' catalog data, and multi-zone/nodal modeling, cannot provide sufficiently accurate and reliable information. Comparisons with a single-zone perfect mixing model, exposure differences may be as high as 25% for CO_2 and 54% for CO throughout the day for a similar situation (Huang and Chen, 2000). Although lab or on-site experimental measurements could be used, as detailed in a book edited by Spengler et al. (2000), the technique to measure the exposure is very expensive and time consuming. The CFD method seemed most appropriate for this study.

CFD solves a set of partial differential equations for the conservation of mass, momentum, energy, and species concentrations, which govern the transport phenomena in the house. Since airflow in the house is turbulent, the CFD method used a turbulence model (the renormalized-group k-ε model from Yakhot et al. (1992)) to reduce the computing costs. With the turbulence model, the velocity, temperature, and contaminant concentration transport can be described by the following unsteady time-averaged Navier-Stokes equations:

$$\frac{\partial(\rho\Phi)}{\partial t} + div(\rho V\Phi - \Gamma_{\Phi,eff} \cdot \nabla\Phi) = S_{\Phi} \quad (1)$$

Where

ρ = air density

Φ = 1 for mass continuity

= V_j (j = 1, 2, 3) for three components of momentum

= k for turbulent energy

= ε for the dissipation rate of k

= T for energy transport

= C_i for contaminant concentration i

V = velocity vector

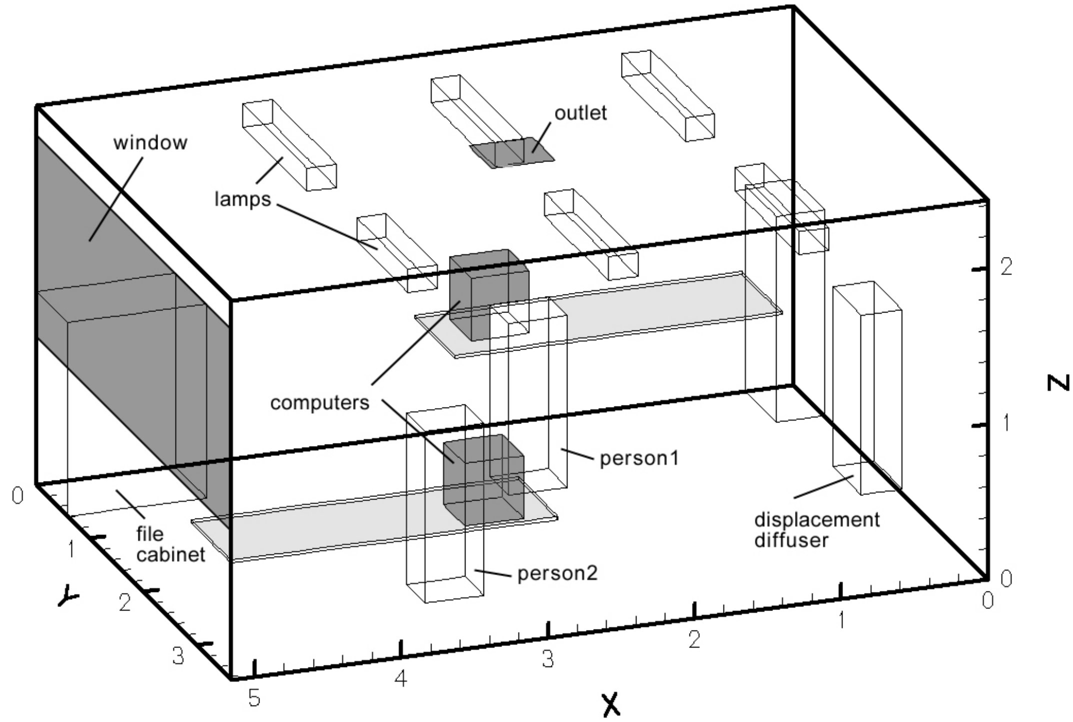
$\Gamma_{\Phi,eff}$ = effective diffusion coefficient

S_{Φ} = source term

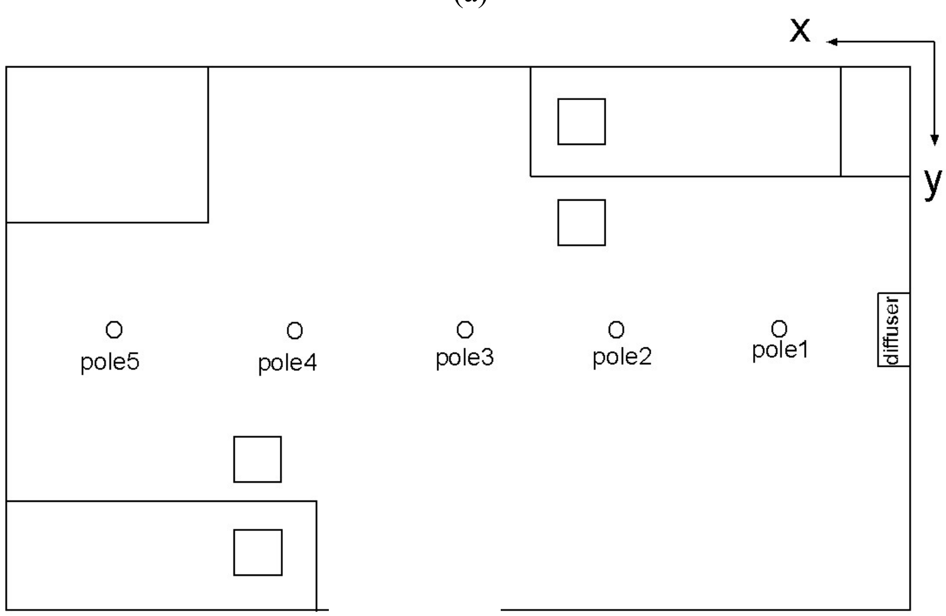
Many textbooks have detailed the CFD theory, such as Wilcox (1993) and Versteeg and Malalasekera (1995). The governing equations can be closed with appropriate thermo-fluid boundary conditions at all the boundaries such as air inlets, outlets and wall surfaces. The values of velocity, temperature, kinetic energy, the dissipation rate of kinetic energy, and species concentration (passive scalar) are therefore set at the boundaries.

A commercial CFD program (CHAM 1999) was used in the investigation to solve the time-dependent conservation equations together with the corresponding boundary conditions. The program uses discrete non-uniform computational cells to simulate the indoor space, and the equations are solved using the SIMPLE algorithm and the hybrid differencing scheme (Patankar 1980). The simulations were executed to convergence; the largest mass conservation discrepancy was less that 0.1%.

According to ASHRAE (Chen and Srebric, 2002) the CFD program has to be validated by the user before it can be applied as a tool for further studies. This investigation utilized the data from a displacement ventilation case (Yuan et al., 1999) that exhibited similar flow characteristics as that in the house. Although the ventilation rate for the displacement ventilation case was much higher than that for the house case, the most important parameters that govern the flow characteristics are Reynolds number and Grashov number. The highest velocities in both the displacement ventilation and the single-family house cases were around 0.3 m/s making the Reynolds number the same. The temperature difference in both cases was again close to each other, thus the corresponding Grashov number was the same. In addition, the flow was stratified in both cases. Therefore, if we could correctly predict the airflow in the displacement ventilation case, it is safe to assume that we could also correctly predict the airflow in the house.



(a)



(b)

Figure 2 Schematic of displacement ventilation case and the measuring pole locations in plan

The data for the displacement ventilation case was obtained in a test chamber, shown schematically in Figure 2(a). The displacement diffuser introduced air to maintain 4ACH, corresponding to a face velocity of 0.09 m/s due to a 10% effective area ratio.

The summer case was assumed and the supply temperature was controlled to 17°C, while the window temperature was between 27-28°C. The heat sources included six overhead lamps emitting 34W each, two person simulators at 75W each, and two computers at 108.5W and 173.4W. The data of air temperature, air velocity, and SF_6 concentrations that was used to simulate a contaminant was acquired at five locations in the chamber, shown schematically in Figure 2(b).

Figure 3 shows the comparison between the experimental data to that obtained from the CFD simulation in the mid-section of the room (poles 1 through 5). The correlation is good, and the simulation is accurate at discerning the temperature gradients at the floor and ceiling. Clearly there is stratification between the lower and upper zones.

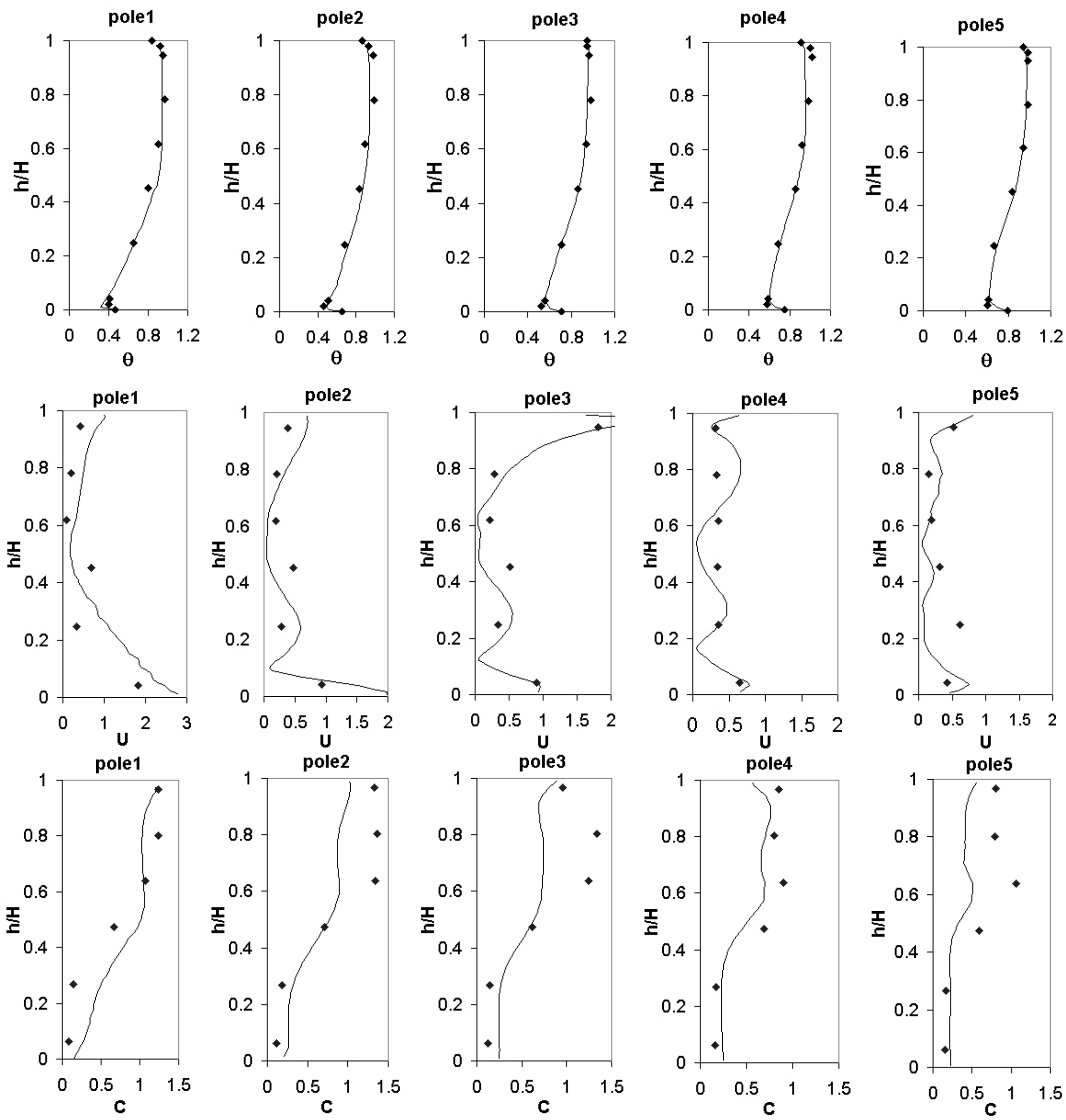


Figure 3 Comparison of predicted (solid line) and measured results (point) for normalized temperature (θ), velocity (U), and concentration (C) profiles at five different locations along the mid-section of the room. h is height from the floor and H is room height.

There are discrepancies between the measured and computed data for the air velocity and tracer gas concentration. Due to the very low velocities (0.01m/s-0.16m/s) found in the room, the flow field variation caused differences in the reported velocities. The hot-sphere anemometers used to acquire the data are sensitive up to 0.1m/s; many of the pole values were beyond this regime of accuracy, but within the range of uncertainty. Differences in SF_6 concentration were therefore observed, due to the dependency of the gas to the flow field. 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. CFD predicted the trend of tracer gas concentration, and showed that stratification of the gas, with the lower regions having a lower concentration than the upper regions. The accuracy is deemed to be acceptable.

Despite of the similarity of the flow regime between the room with displacement ventilation and the house, there are two major differences. First, the displacement ventilation case was steady state, while the flow in the house was unsteady over the day. This investigation broke up the day into a number of periods according to the schedule, as described in Table 1. Within each of these time periods, the flow was considered to be steady. This technique is considered quasi-dynamic, which implies a time dependency from one period to another, but within each period the flows were treated as being in steady state. It is not quite a fully transient situation, but a hybrid that utilizes the results of the previous time period as the initialization for the new time period.

Secondly, the house was much larger in size than the environmental chamber. If the same grid density were used for the house for the quasi-dynamic simulation, the computing time would take weeks to complete. The current study used a coarse grid distribution of 95 x 63 x 24 = 143,640 grids. A nearly uniform grid scheme was adopted due to the complexity of the house layout in order to capture as much relevant information as possible. An obvious question is whether the coarse grid could achieve grid independent results. Yuan et al. (1999) calculated the displacement ventilation case by using three grid resolutions: 72x66x36, 48x44x24, and 29x30x19. The results with the two finer grids were almost identical. The coarser grid, which had the same density as the one used here for the whole house, yielded a difference of around 10%. This level of accuracy provides sufficient insight into the nature of the patterns and flows of the contaminants, and thus meaningful solutions can be extracted with the coarse grid resolution. Hence, the grid distribution was used for the study.

Exposure Measurements

The detailed CFD results can provide the contaminant data at appropriate locations for the exposure assessment. With the small ventilation rates at a low temperature throughout the house, typical CFD results in Figure 4 show a high degree of stratification and body boundary layer in the house. The stratification resulted in low concentrations for the occupants that are considered vertical or upright (such as sitting or standing) as exhibited in Figure 5. The air surrounding the person increased by as much as 3°C, and the temperature difference induced a positively buoyant flow that swept contaminants emitted from the facial region upward. Since there was not a lot a mixing (inherent to the fact of stratification), air from the lower part of the room was “cleaner” than that of the upper part, which means that it had a lower concentration of contaminants. The buoyant flow induced by the body boundary layer drew breathing air from this “cleaner” reservoir. Despite a lower ventilation rate, the flow phenomenon was therefore very close to displacement ventilation, which was why this study used the experimental data from the displacement ventilation case to validate the CFD program.

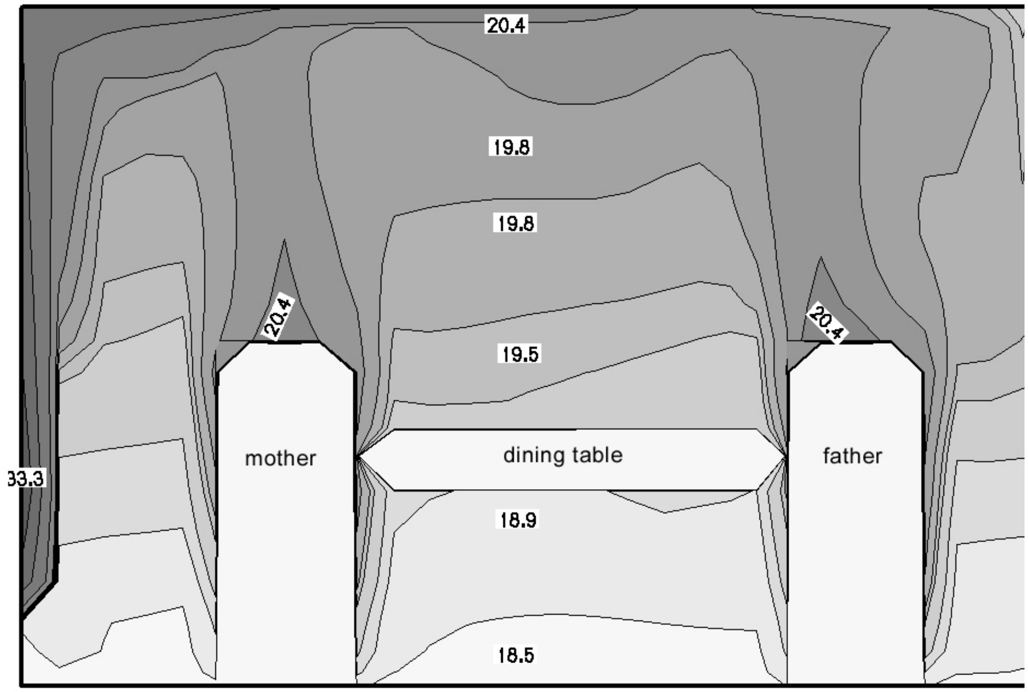


Figure 4 Typical room temperature [°C] contours showing vertical stratification and thermal plumes (bimodal-convectors case)

Conventional exposure assessments place sensors at a few locations in a house. The measurements do not take the buoyancy effect into account. Therefore, the measured exposure dosage may not be same for cases with stratified flows. The use of CFD results provides us a better means to measure the exposure. In fact, the impact of buoyancy effect on exposure has been observed by other studies. For example, Nielsen (1992) found that thermal buoyancy from metabolic heat generated by the occupants induces a boundary layer of fresher air that clings to the body as it travels upward to the breathing zone. The inhaled air has a different concentration from the ambient air at the same height. Since natural convection is dominant in the study, exposure is influenced by entrainment in the human boundary layer (Bjørn and Nielsen, 1996). CFD simulations by Murakami and Kato (1997) validate the necessity of taking measurements for contaminant concentrations below the general breathing zone. Therefore, the present investigation obtained the pollutant data below the facial region as suggested by those studies, as cleaner air tends to be transported upwards to the breathing orifices.

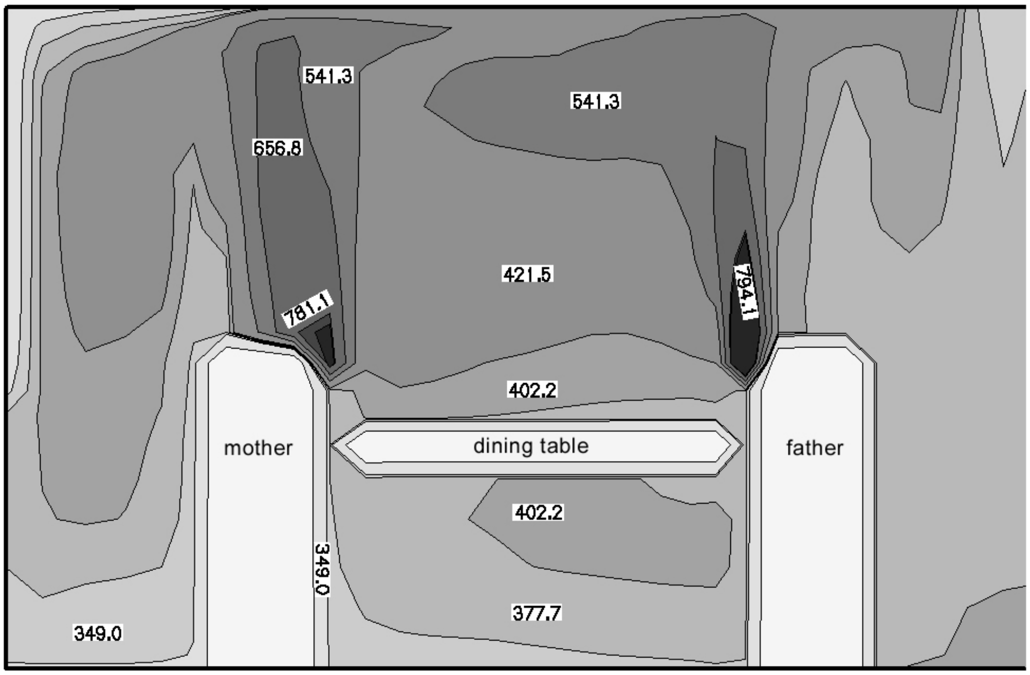


Figure 5 CO_2 concentration [ppm] contours showing the vertical concentration stratification due to buoyancy (bimodal-convectors case)

Results and Discussion

Contaminant Distribution in the House

Armed with a validated CFD program and the method to extract pollutant data in the house, this investigation assessed the performance of different ventilation, heating, and cooling systems. We will first show the results generally applied to all the cases studied and then summarize the similarities and differences among the cases.

This section shows the results for the base case (bimodal ventilation with convectors under winter heating conditions). Although other cases may have slight different results, the trend of the contaminant distribution looks similar. Figure 6 indicates that room-to-room migration of contaminants is not very strong. CO migration outside the kitchen was not great due to the combination of heating and ventilation conditions. The pollutants stayed only within the hallway and moved into the bathroom and WC, where additional exhausts are located. Migration from the living room (a room without ventilation) occurred only to the rooms with exhaust fans (i.e. the kitchen, bathroom, and WC). Although the parents and children's bedroom doors were open during dinner, air movement from the periphery to the core curtailed most of the pollutant migration. For the bedrooms, since the door undercut was located near the floor, there was little opportunity for pollutants to enter the room once the doors were closed.

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

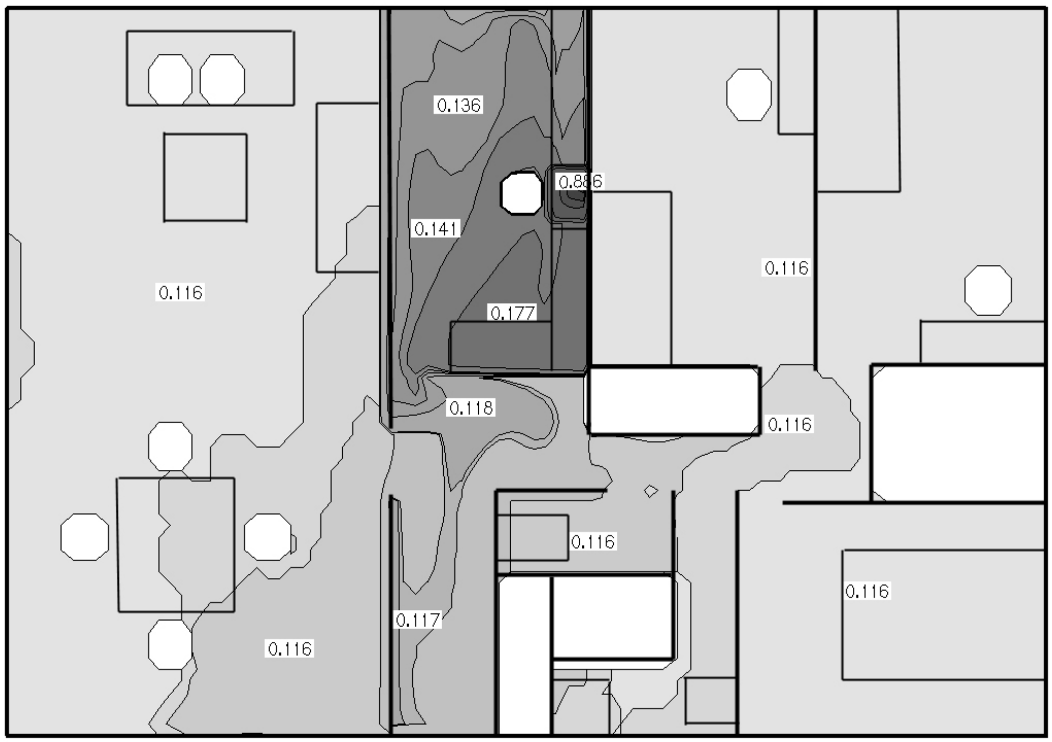


Figure 6 CO concentration gradient at the end of cooking with bimodal ventilation showing the incomplete exhaust of cooking contaminants, but minimal migration out of the kitchen

Since buoyancy dictated the airflows, contaminant concentrations recorded were highly dependent on the location, since small changes in temperature or position greatly affected the concentration value. Thus probe locations to extract pollutant data were chosen to embody much of the characteristics of room location and other conditions. Even within rooms, aggregations of pollutants may have occurred due to certain boundary and ventilation conditions. These conditions were then encapsulated to reflect the contaminant migration and thus personal exposure.

In addition, the CFD results illustrate that the kitchen exhaust proved to be quite effective for the mother during cooking when she stood directly in front of it, as shown in Figure 7. Migration of the cooking pollutant (CO) was contained with the use of the kitchen exhaust. Only localized escape of the contaminants was seen from the slight elevation of the concentration of air that the mother inhales. Because of the heat produced at the stove surface, the range exhaust performance was enhanced by buoyancy capture, where a large density difference induced high degrees of natural convection to sweep contaminants toward the exhaust. As well, this confluence incurred entrainment of the surrounding air, helping to prevent dispersion and diffusion of these contaminants. The mother was exposed to more of the pollutants associated with combustion since she was closest to the stovetop during cooking.

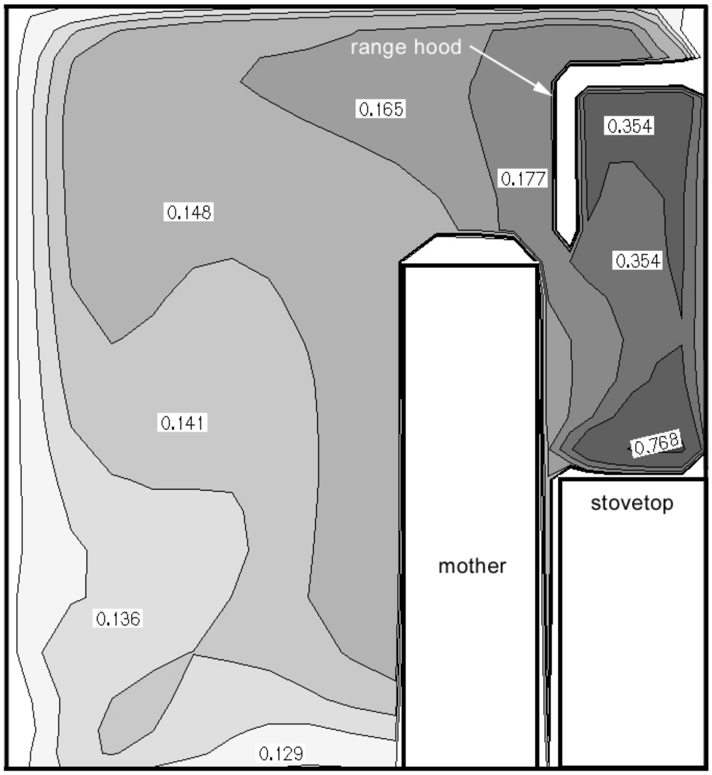


Figure 7 Section slice showing escape of CO from the range hood exhaust

Contaminant Distribution Histories

With the contaminant concentration distribution, we can determine the contaminant concentration an occupant breathed in a particular location. Since the position of the occupant varied with time in the house, it was necessary to know the contaminant concentrations to which the occupant was exposed over time.

This investigation evaluated the contaminant distribution exposure histories by the occupants for the nine cases as shown in Table 4. The winter cases were mainly marked by the effect of stratification, and the large heat sources that drove both the localized and global airflow patterns. This season is commonly thought to provide a poor indoor air quality since the windows are normally closed throughout the season, without any specific codes mandating fresh air input into the inhabited spaces.

Base Case or Bimodal system with convectors in the winter (Bimodal-Convectors)

Figure 8 shows the concentration of CO_2 each of the occupants breathed throughout a typical day. The most striking difference that occupant location played on exposure was the change in concentration value for the parents while they sleep between

23h00-07h00. The mother breathed in CO_2 of about twice the concentration that the father breathed. The heat source located on the south side of the room (not seen in the section) induced flow that created a strong circulation region in a south to north 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 was located south of the father, the contaminants migrated from the father's mouth into the air region breathed by the mother as shown in Figure 9. So we observe an increase in the concentration of CO_2 breathed by the mother due to cross-contamination (Figure 8). As well, the relatively small room in which the parents slept coupled with two sources that emitted twice as much as one child, means that the mechanical ventilation was not enough to dilute the bioeffluents to a low level. The CO_2 level in any space of the house at any time was lower than 810 ppm, which is below the threshold of indoor air quality standards (1000 ppm). Hence the air quality is acceptable.

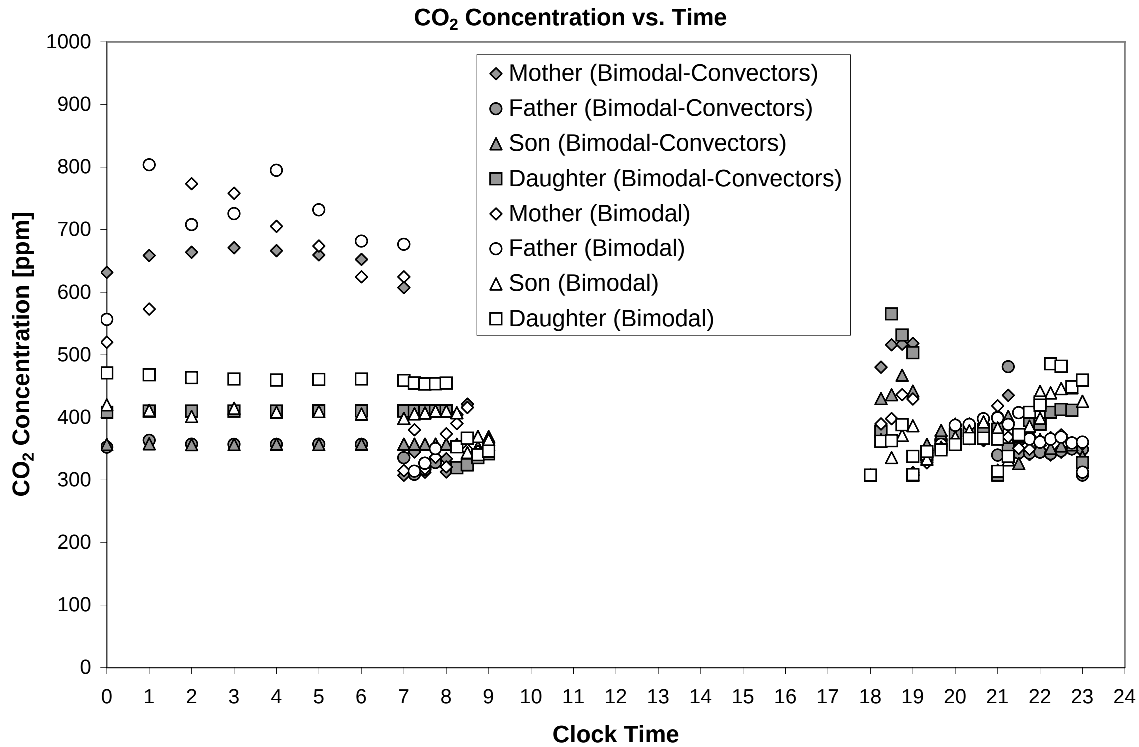


Figure 8 CO_2 concentration history comparing the base (winter) and summer cases with bimodal ventilation

Observing the results to find the effectiveness of the kitchen exhaust as a local extract device for the mother, it was quite effective in curtailing exposure to cooking contaminants. Nevertheless, Figure 10 shows that the CO concentration still rises 64.8% during 18h00-19h00 when she cooked dinner.

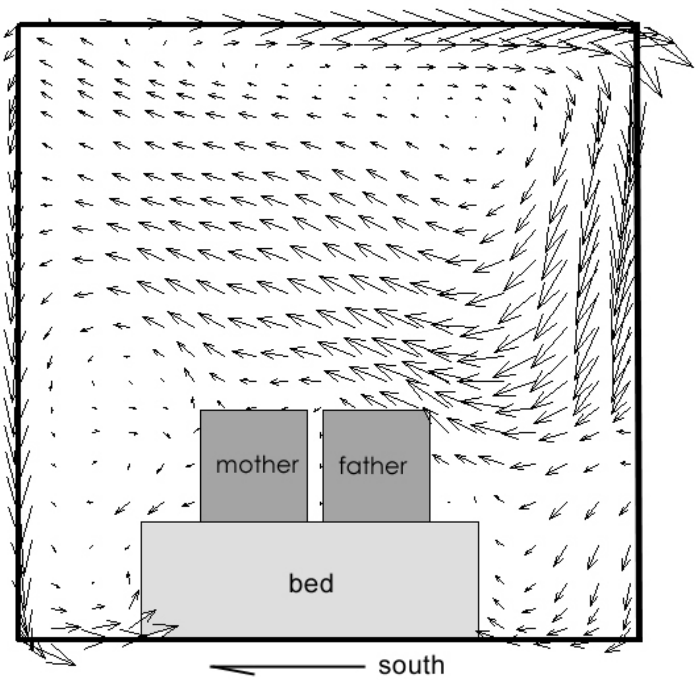


Figure 9 Airflow pattern in the parents' bedroom showing cross-contamination

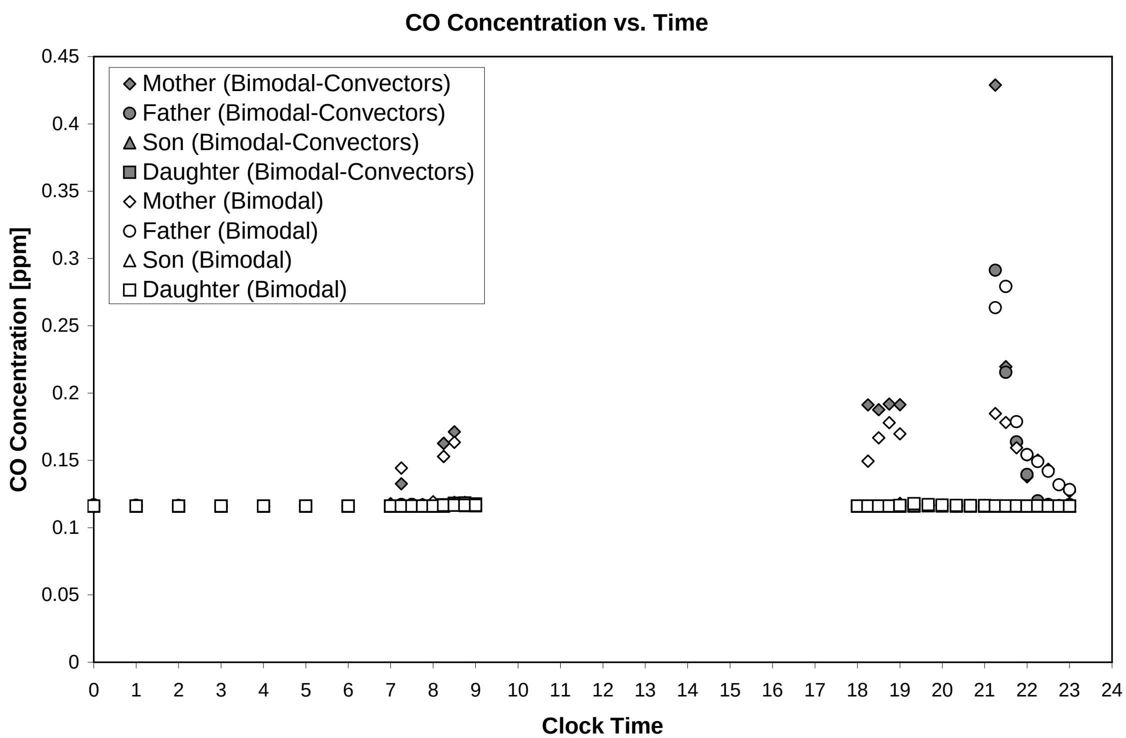


Figure 10 CO concentration history comparing the base (winter) and summer cases with bimodal ventilation

Figure 10 also indicates a sharp spike of the CO concentration exposed to the parents when the father smoked a cigarette (at 21h00) in the living room. The children were in their bedrooms so that the impact of the smoke on them was minimal.

Bimodal system with heated-floor in the winter (Bimodal-HF)

Comparing the bimodal heated-floor case to the base case, the exposure is generally the same. Since the family sat in the living room (where the heated floor is located) for only a short period of time, the effects of the heated floor were minimal. We observe the following differences:

- The living room was warmer than the other rooms since the large floor area was maintained at 23.5°C
- Large air circulations caused by the convectors were not present, thus reversing the major circulation caused by downwash at the cold walls and negative buoyancy from the cold air from the windows
- Stratification was less pronounced

Uniform heating of the living room floor decreased the stratification effect for both temperature and contaminant concentrations. Thus, there were elevated levels of pollutants that the occupants breathed, since the lower parts of the rooms had a higher concentration than in previous cases. Stratification did still occur, but to a lesser degree than the base case. This was due to the uniform heating of the living room floor, which had a higher temperature than the air immediately above it.

Relative humidity controlled system with convectors in the winter

The case of relative humidity controlled exhaust with convectors had minimum flow rate if the relative humidity remained below 30%. Since the simulations were for winter heating, the humidity inside the house only exceeded 30% near the exhaust fans when the family showered in the morning, as the outdoor humidity ratio was very low. In addition, since the stovetop created thermal plumes that migrated towards the kitchen exhaust, the increased air temperature further reduced the relative humidity as the air reached the fan. The relative humidity controlled and bimodal ventilation systems under these conditions had similar results.

Some differences in the indoor concentrations existed during the cooking and eating of dinner. The reduced fan rate during these periods increased the exposure of the mother to the contaminants, so the CO concentration was higher for the case of relative humidity controlled exhaust with convectors compared to the base case.

Relative humidity controlled system with heated floor in the winter

If heated floors were used instead of convectors in the winter, the exhaust rate remained the same except for the bathroom exhaust, which increased due to water vapor from the shower. Comparing the concentration histories over the course of the day for relative humidity controlled with heated floor and with convectors, the differences are slight, and exhibit similar patterns.

Balanced system with convectors in the winter (Balanced-Convectors)

Generally speaking, the balanced-convectors case yielded the same results as the base case. There were good correlations when comparing the concentrations of CO_2 for the balanced-convectors case and the base case. There was slight cross contamination for the parents while they slept, however, in the balanced-convectors case, the method of contamination was reversed. The father breathed in higher concentrations due to a shifting flow pattern, attributable to the placement of the balanced ventilation diffuser.

One major difference was when the father smokes in the living room, an initial spike of high concentration was seen at 21h00, which then decayed (as seen in Figure 10) in the base case. At about 22h00, a shift in the flow pattern in balanced-convectors case increased the concentration of the combustion contaminants breathed caused by the balanced ventilation diffuser that was located just to the west of where the mother and father sat in the living room. The concentrations then took on a totally different trajectory, and exposure was fundamentally changed.

The evaluation of the summer cases in this study was to determine the flow patterns that were exhibited through the incorporation of a cooling system. It was also pertinent to compare the effects of the seasonal climatic changes on the exposure.

In general, rooms in which occupants were not present experience an upwash at the walls caused by buoyancy, since the wall temperatures were warmer than the interior air during the summer. In the rooms where there were people, the thermal plumes raised the temperature in the upper part of the room appreciably enough so that there was a downwash at the walls, since the wall temperature was no longer warmer than the temperature of the air in the upper zones. This stratification occured slightly during the summer.

Bimodal system in the summer (Bimodal)

The effects of a reduced stratification in the summer can be seen in Figure 8 for the parents and children in the form of an elevated CO_2 concentration. Indeed, stratification only occurred to a slight degree in the rooms that are occupied, and to the highest degree around the vicinity of the occupant. When the room was unoccupied, the temperature field was nearly uniform, with exceptions at the walls that were slightly warmer than the air. Since concentration gradients were associated most highly with the velocity field, and buoyancy was the dominant flow inducing mechanism, a loss of stratification generally indicated a loss of contaminant stratification as well.

The smaller stratification in the summer than in the winter means higher concentrations at lower levels, leading to a higher exposure, especially during sleeping. Due to the lack of circulation within the room, there was a relatively equal distribution of the pollutant while the parents slept, nearly eliminating cross-contamination. Local variations and small shifts in the flow field contributed to the minor discrepancies between the two. Again, the sleeping period was crucial to the overall personal exposure to contaminants associated with bioeffluents, due to its long duration with respect to the total time indoors.

The peak values for smoking contaminants were lower in the summer than the winter as shown in Figure 10. However, attenuation to a normal level was about twice as long for the summer case as the winter case (approximately one hour). The concentration path for the winter attenuation after smoking followed exponential decay, while during the same period, the summer cases exhibited more of a linear decay.

Bimodal system with split cooling in the summer (Bimodal-Split) and
Bimodal system with refrigerated floor in the summer (Bimodal-RF)

There was not much difference between the summer cases with and without cooling systems in terms of contaminant concentration levels. This was mostly due to the fact that the major influencing factors surrounding the method of exposure was not overcome through the use of these cooling techniques.

Relative humidity controlled system in the summer

Since the outdoor humidity was high, the exhaust fans for the bathroom and the WC were on the highest rates for the duration of the day. The kitchen range hood fan was on the highest setting for 87.5% of the time, and decreased when cooking since the high heat from the stovetop reduced the relative humidity (at the same humidity ratio). The global ventilation rate increased to 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 bimodal and relative humidity controlled cases, an increased ventilation rate did not work as effectively as imagined to remove household contaminants. Both pollutants, including the telling CO_2 concentrations, had a difference in exposure less than 10%.

Exposure Analysis

With the contaminant concentration histories obtained from the previous section, it was possible to calculate the pollutant exposure, a metric indicating the cumulative effects of contaminant concentration on the occupants. This investigation calculated the exposure by

- Multiplying the pollutant mass concentration that an occupant breathes by the inhalation rate; sleeping inhalation rate was reduced to 2/3 of rate when awake
- Adding these values up throughout the day to get a cumulative daily dose over the fifteen hours the occupants were in the house.

Taking a global perspective, comparing the exposure differences to a common condition allows the complete evaluation of system performance. In this case, the ambient condition was used as a reference, which is the case if the family breathes only outdoor air. Averaged over the exposure for the entire family, the percent increase ranged from about 30% to 60% over the ambient condition for CO_2, with the summer cases at about the same level between 55%-60%, as shown in Figure 11. This is perhaps indicative of the ability of the stratification effect to impact exposure, since summer time stratification was weaker than in the winter due to the lower vertical temperature gradient. Figure 12 shows the CO levels for all the occupants in the house. Except for the mother, the trend of exposure to CO was similar to CO_2. The high exposure of the mother was due to her stay in the living room while the father smoked. Generally speaking, the CO concentration was very low in the house. If the father quit smoking, the health impact due to exposure to CO would be minimal.

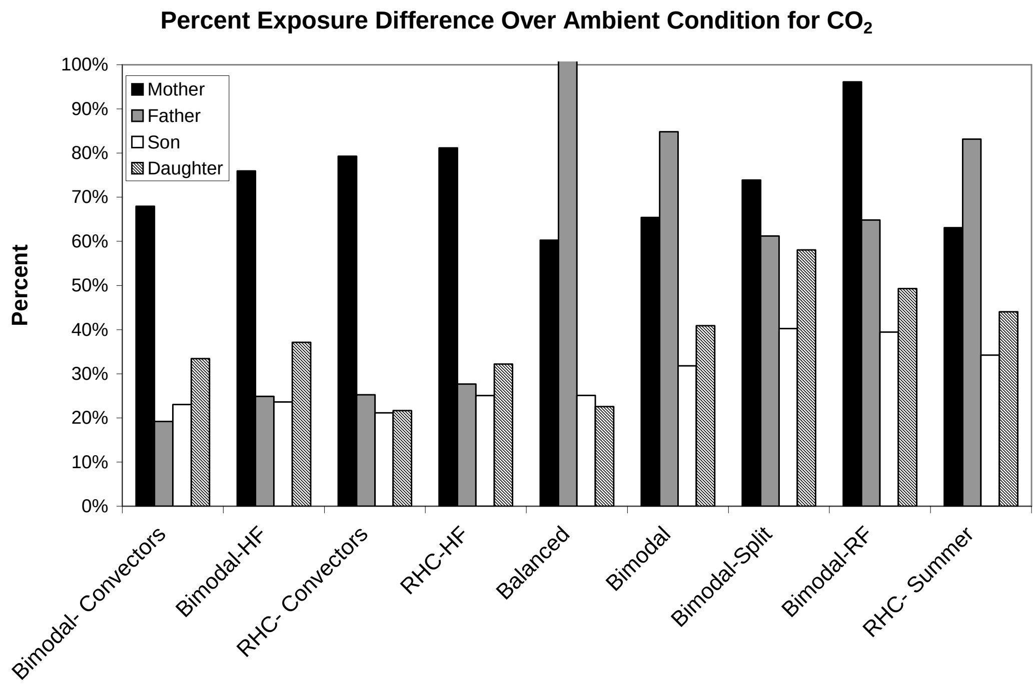


Figure 11 Percent exposure (relative) difference for the family over the ambient (outdoor) condition for CO_2

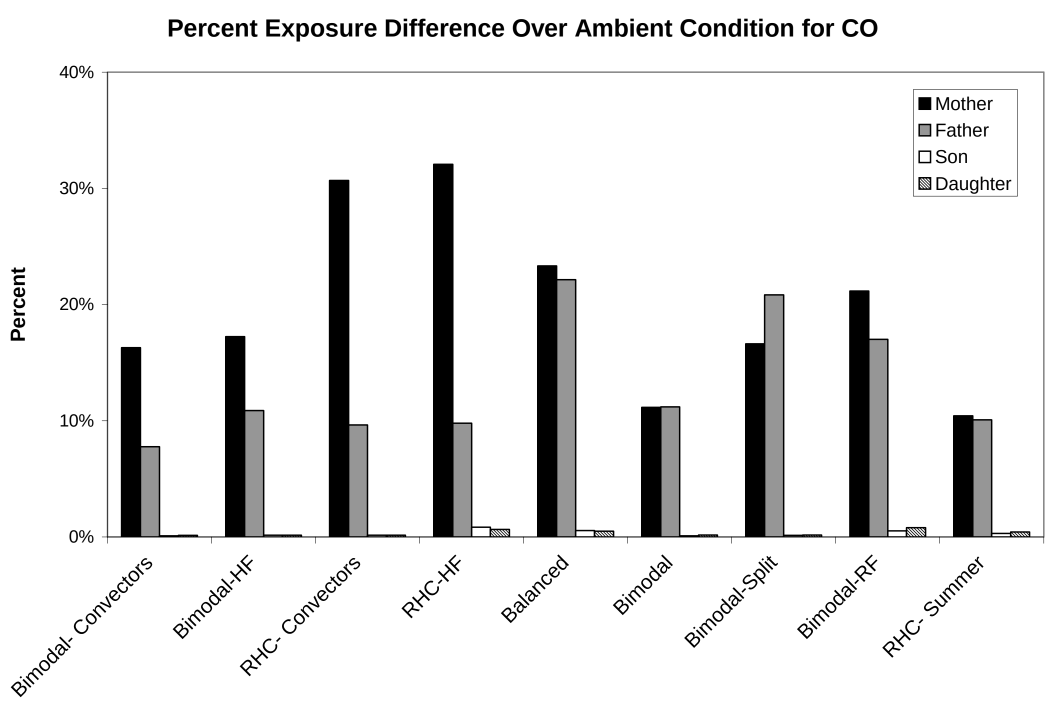


Figure 12 Percent exposure difference for the family over the ambient (outdoor) condition for CO

Figure 11 and Figure 12 shows the percent increase in exposure to CO_2 and CO compared to the ambient condition. They reveal that the convector case in winter with bimodal ventilation produced the most favorable indoor conditions with respect to CO_2 exposure, when averaged over the family members. For CO, there was generally a low amount of exposure, with the bimodal-convector, bimodal (summer) and relative humidity controlled (summer) cases showing the lowest family-averaged exposure values. It must be considered, however, that CO is a much more highly toxic contaminant than CO_2, and only side-stream exposure to CO was included in these simulations (i.e. direct inhalation of cigarette smoke by the father was not incorporated).

Although in each time step the differences between the values of breathed contaminants between the occupants were small, exposure over the whole day reveals that there were marked differences in the accumulated breathed contaminants based directly on the location and activity of the people, and ventilation quality within the house.

Conclusions

This paper evaluated the physical phenomenon of airflows and occupational exposure to contaminants in a single-family house using CFD method. To ensure that the numerical technique was properly applied, the CFD program was validated with experimental data to acquire confidence in the use of the predictive tool. The cases studied were for various ventilation conditions (bimodal, relative humidity controlled, and balanced ventilation), in combination with heating (convectors and heated floor), cooling (split system and refrigerated floor) and climatic conditions (summer and winter seasons). Comparisons of each of the combinations of systems were presented, based on the breathed contaminant concentrations of a family of four (two parents and two children) under typical occupational conditions throughout a normal day. The cumulative daily exposure was then calculated to verify the effectiveness of the systems.

The study used CFD as a new tool to measure exposure to contaminant concentrations in a house. The results show that CFD can be specifically harnessed to obtain a detailed understanding of localized phenomenon that might otherwise be lost in simpler calculations and measurements used in exposure studies.

The exposure for the entire family was about 30% to 60% higher over the ambient condition for CO_2 in the winter and between 55%-60% in the summer. Nevertheless, the CO_2 level in any space of the house at any time was lower than 810 ppm, which is below the threshold of indoor air quality standards (1000 ppm). In the winter, stratification and the body thermal boundary layer that works like displacement ventilation reduced the amount of exposure to contaminants. The displacement effect was more effective than a higher ventilation rate for these specific cases. The exposure trend of the family to CO was generally similar to CO_2. The CO concentration was very low in the house, but if the father quit smoking, the health impact due to exposure to CO would be minimal.

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