OPTIMUM VENTILATION AND AIR FLOW CONTROL IN BUILDINGS

17th AIVC Conference, Gothenburg, Sweden, 17-20 September, 1996

VENTILATION IN HOUSES WITH DISTRIBUTED HEATING SYSTEMS

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Synopsis

The LTEE laboratory of Hydro-Québec, in collaboration with Canada Mortgage and Housing conducted an indoor air quality study involving 30 single family detached houses heated with electric baseboard heaters in the vicinity of Trois Rivières during the 1993-94 heating season. The houses were selected according to the measured air leakage at 50 Pa. so as to have a sample distribution similar to the distribution of air leakage of houses in the province of Quebec. The "source strength" of several air pollutants were calculated from measurements of ambient pollutant levels and total ventilation during a one-week test. In addition, the indoor CO_2 and humidity levels were recorded in eight of the houses continuously during the heating season.

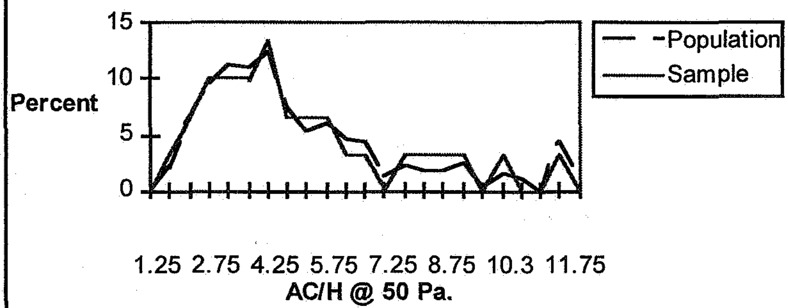
The level of CO_2 in the master bedroom was found to follow fairly closely the CO_2 level in other parts of the building including the basement (within about 200 ppm) except when the bedroom door was closed. With the room occupied and the door closed, CO_2 levels in the bedroom increased steadily during the night until morning, when the door was opened, to levels in excess of 3 500 ppm with one person, and in excess of 4 500 ppm with two persons. Model studies using the measured pollutant source strengths and measured equivalent leakage areas of the buildings indicated that the recommended health guidelines for airborne respirable solid particles (RSP's), CO_2 and formaldehyde are exceeded during periods of low total ventilation, coinciding with mild outdoor temperatures and low wind conditions. It was observed that kitchen and bathroom fans originally installed in some of these houses were not operated by the occupants for sufficiently long times to affect the quality of indoor air.

Various different methods of ventilating some of the houses were tested, including quiet replacement exhaust fans, mixing fans for indoor air, and a fresh air intake and mixing system. The effects of operating various air handling systems were monitored by keeping track of indoor CO_2 and relative humidity in the master bedroom, and occupancy in person-hours per day. Quiet replacement fans noticeably improved indoor air quality when these were operated over 50% to 100 % of the time. An area of remaining concern is the fact that exhaust only systems accentuate the negative pressure in the basement by raising the level of the neutral pressure zone in the building, and may enhance the flow of soil gases into the basement. A system which mixed indoor air between the basement and the main floor also reduced the average level of indoor pollutants. The system was designed to create a pressure difference between the main floor and the basement, causing a slight pressurization of the basement. A system designed to introduce 5 L/s of outdoor air and to mix it with 55 L/s of indoor air for tempering was installed to draw air from the hallway and deliver the mixed air into each of three bedrooms. This system was capable of maintaining CO_2 levels in the master bedroom below 1000 ppm with two occupants in the room and the door closed.

1. Introduction

Hydro-Québec initiated a study of air tightness and ventilation of residences to determine whether building air-tightness alone could be used as the determining criterion for air-tightening the building so as to improve energy efficiency. Using indoor air quality as a measure of building's ventilation performance, a field study was undertaken involving 30 houses heated with electric resistance baseboard heaters in the Trois-Rivières area. The houses were selected on the basis of their air leakage determined via a blower door test at 50 Pa. By design, the sample of 30 houses was selected to have a similar distribution of air leakage as a random sample of several thousand houses in Québec. Figure 1 illustrates the distribution of house leakage determined from a very large random sample of the population (Eval-Iso Programme /1/), and the distribution of leakage in the thirty house sample of houses selected. The average indoor air contaminant levels during a one-week period was determined in each of the houses, along with the average (total) ventilation during the same period.

Figure 1. Distribution of Air leakage (AC/H @ 50 Pa.)



Instrumentation and Measurements Made

The physical size and shape of each house was noted along with the leakage characteristics as determined via the fan pressurization method. During a one week period between December and March, air sampling kits as indicated on Table 1 were installed in each of houses for a period of one week to determine level of the air contaminants of interest:

Table 1. Air Contaminants Monitored and sampling Systems Used

Variable	Sampling System
Average air change rate	PFT tracer method. This method uses 1, 2, or 3 sources and several samplers per house for a 7-day period. The materials and analysis a carried out by Brookhaven National Labs in Long Island.
Indoor air particulates	Pumped occupational hygiene filter cassette for 7-day period (micrograms per cu.m)
Total VOC's:	Pumped special multi-absorption tube for 3-hour period(will identify 6 major components in percent of toluene equivalent)
Formaldehyde:	AQRI passive Dosimeter (tube with a lid) with +/- .02 ppm resolution
Radon:	Canadian Institute for Radiation Safety (CAIRS) pumped filter sampler for 7-day period
Carbon Dioxide and Water Vapour	YES 203 recorder in living room

The average contaminant levels along with the house volume and average ventilation rate for the test week were used to calculate the "source strength" of each airborne contaminant as follows: The source strength S is defined as:

$$S = L \times A \times V \qquad .....(1)$$

where: L = average contaminant level over a one-week period (mg/cu. m.)
A = average air change rate over a one week period (AC/H)
V = house volume (cu. m.)

Using the indicated units, S would be units of mg/hr.

The average air change rate for each house during the test week was determined using the PFT tracer method. The tests in the 30 houses were conducted sequentially in small groups due to the limited number of instruments available. Although the weather conditions during the determination of average air change rates would not have been identical for the group of tests, this is of no concern for the evaluation of pollutant source strength for air contaminants since the controlling factors are essentially independent of weather.

The results of these tests and calculations are tabulated on Table 2. On this table, the natural air change rate is expressed in litres/second. The accuracy of the source strength estimate is affected by the uniformity of diffusion of airborne pollutants throughout the entire building, and by the stability of the source strength of each contaminant over time. While it is known that some of the contaminants such as formaldehyde are released at a fairly steady rate by surfaces and that other contaminants such as carbon dioxide and some of the moisture are produced intermittently during occupancy or during certain activities, the average measurement during a one-week period is expected to capture a good representative sample of the pollutants which naturally occur in a house during a full week cycle.

Table 2. Source Strength of Airborne Contaminants in 30 Quėbec Houses

House #	Vol	Nat. Air Change	Occu-pancy	RSP	VOC's	Form.	Radon	CO_2	Moisture.
Units:	cu m	L/s	p-hr/day	mg/hr	mg/hr	mg/hr	µCi/hr	g/hr	g/hr
1*	444	14.8	102	4.42	21	3.54	11	59	259
2*	306	26.4	89	7.21	38	5.37	19	120	488
3	486	14.9	39	1.44	37	6.18	32	64	295
4***	505	19.6	83	1.41	120	8.61	28	107	
5	515	14.3	77	1.96	36	5.19	52	96	358
6*	517	14.4	69	3.83	16	5.28	41	61	342
7	487	13.5	55	1.12	19	3.35	29	36	239
8**	737	26.6	83	3.35	220	4.95	57	104	332
9	478	27.9	82	1.91	30	4.57	40	109	---
10	371	8.2	69	0.50	9	2.56	18	25	---
	513	34.2	74	7.39	86	10.75	25	105	---
12	412	22.9	63	2.06	7	3.55	33	149	---
13	504	81.2	121	7.60	58	7.55	175	139	---
14*	548	22.8	69	6.08	16	5.46	33	92	---
15	429	22.6	40	2.12	41	4.31	16	52	---
16	478	26.6	96	1.72	48	5.76	19	166	---
17	387	39.8	125	2.72	86	7.57	29	89	---
18	397	41.9	32	5.28	60	6.12	60	141	---
19	325	12.6	39	1.18	32	1.90	82	104	---
20	519	31.7	101	1.26	80	1.97	69	121	---
21*	270	15.0	39	0.59	38	4.38	22	47	---
22*	426	39.1	90	2.95	56	7.95	141	199	---
23*	441	22.1	80	3.41	198	2.34	111	64	---
24*	221	23.3	69	2.18	59	3.31	50	102	---
25	748	58.2	69	2.09	63	5.41	84	91	---
26*	444	27.1	24	---	39	3.6	78	44	---
27*	231	24.4	74	3.69	26	4.10	70	91	---
28	456	63.3	90	5.02	46	7.01	46	220	---
29*	418	19.7	59	2.34	21	3.93	313	96	---
30*	455	19.0	99	6.35	68	4.28	232	153	---
Means	449	27.6	73	3.21	55.9	5.03	67.1	102	330

* House where smoking takes place
** House with attached garage
*** Epoxy resin used in basement

Please note that the natural ventilation in AC/H is converted to a rate expressed in L/s (by multiplying by the internal volume of each house) for consistency of units in the evaluation of the source strength. The results are also presented graphically in the form of histograms for each contaminant on Figures 2 to 7.

3. Ventilation model and implied ventilation requirements

The source strength estimates can be used to determine the minimum ventilation required in order to maintain the air contaminant levels within the recommended maximum levels in all houses. Rearranging, equation (1) becomes:

Air change rate (A x V) = S / L in cu.m /hr ....(2)

This equation can now be used to calculate the minimum level of ventilation required in order to maintain the indoor pollutant level below the recommended maximum concentration, based on the source strength of the pollutant. By substituting for L with the maximum recommended pollution level for each contaminant in turn and inserting the observed corresponding source strength for each house into equation (2), we obtain the estimated minimum ventilation required in units of (cu. m/hour). By applying the factor (1000/3600), we convert the units of the answer to litres/second. The recommended guidelines for long term and short term exposure levels to the pollutants of interest are presented on Table 3 below. Taking the acceptable long term exposure levels indicated on Table 3, we have calculated the minimum ventilation levels in each of the houses in the study in L/s. The results are tabulated on Table 4

Table 3. Exposure Guidelines

Contaminant	Acceptable Long Term Exposure Range	Acceptable Short-term Exposure Range
Respirable Solid Particles < 2.5 µm mass median aerodynamic diameter	40 µg/cu m*	100 µg/cu m (1 hour)
Total Volatile Organic Compounds	0.2 mg/cu m for no irritation** 3 mg/cu m and above results in complaints from occupants*	
Radon	4 pCi/L (EPA, USA) 800 Bq/cu m*	21.6 pCi/L*
Formaldehyde	60 µg/cu m (0.05 ppm)*	120 µg/cu m (0.10 ppm)*
Carbon Dioxide	3500 ppm *(Health Canada) 1000 ppm (ASHRAE Std 62-1989)	

* Health Canada: "Exposure Guidelines for Residential Indoor Air Quality"

** ASHRAE Handbook of Fundamentals, 1993, p 37.7

The minimum ventilation level required to maintain the levels below the recommended guidelines has been calculated using equation (2) for each pollutant of interest and for each house. The results are presented on Table 4. It is interesting to note that the average amount of ventilation required for formaldehyde, RSP's and carbon dioxide (1000 ppm) are nearly identical at 22 L/s.

Fig. 2 Histogram of RSP Source Strengths

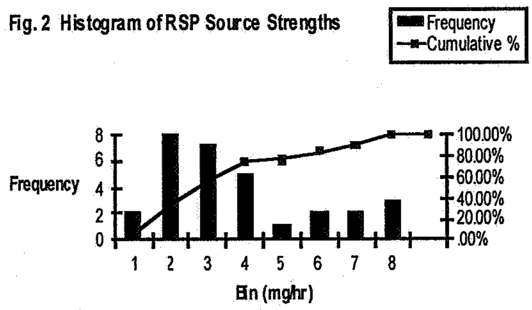


Fig. 3 Histogram of VOC Source Strengths

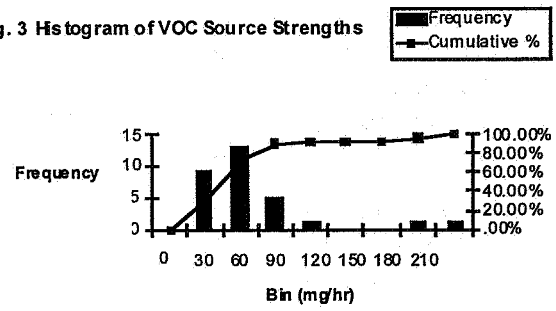


Fig. 4 Histogram of Formaldehyde Source Strengths

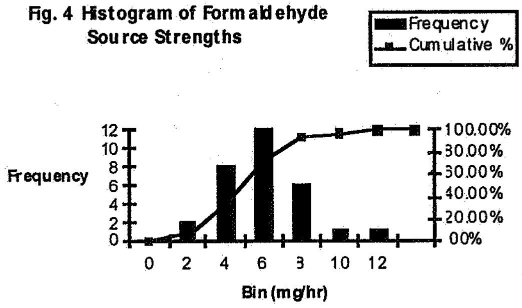


Fig. 5 Histogram of Radon Source

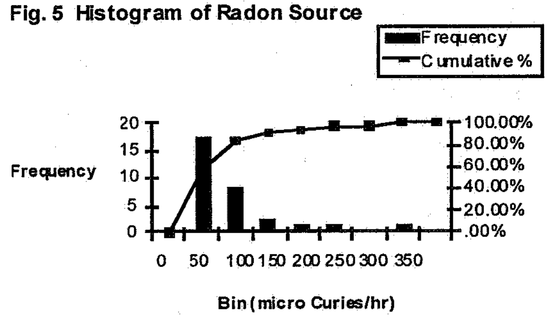


Fig. 6 Histogram of Carbon Dioxide Source Strength

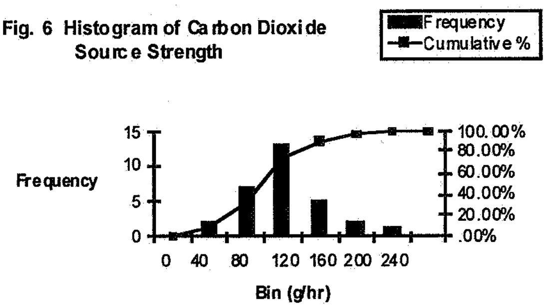
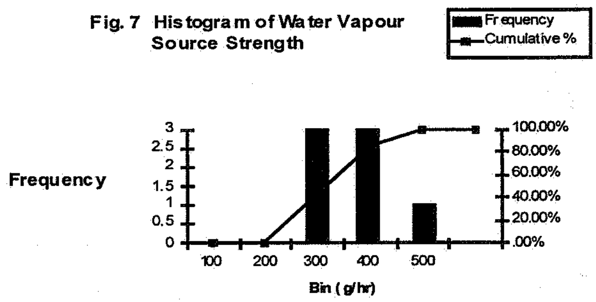


Fig. 7 Histogram of Water Vapour Source Strength



Ventilation Model

A ventilation model which was developed by CMHC, called AQ1, was used to estimate the natural ventilation during a one-week period in order to compare the results with the ventilation rates actually measured in eighteen of the houses during the 1993-4 winter field test. Once "calibrated" to a house, the ventilation model is capable of predicting the ventilation rate and pollutant levels on an hourly basis or on a monthly average basis from given house leakage characteristics, source strength information and weather data. The model has the capability of taking into account the use of ventilation equipment and wood-burning appliances by keeping track of schedules of equipment use. The method is more fully explained in Reference 2 (Appendix). The reliability of the model was tested by comparing simulation results against measured air change rates in the test houses measured during the one-week test employing the PFT tracer method. These results are presented graphically on Figure 8. The R-squared for the relationship between measured and calculated air change rates was 0.65, and the standard error of estimate was 0.1 air changes per hour.

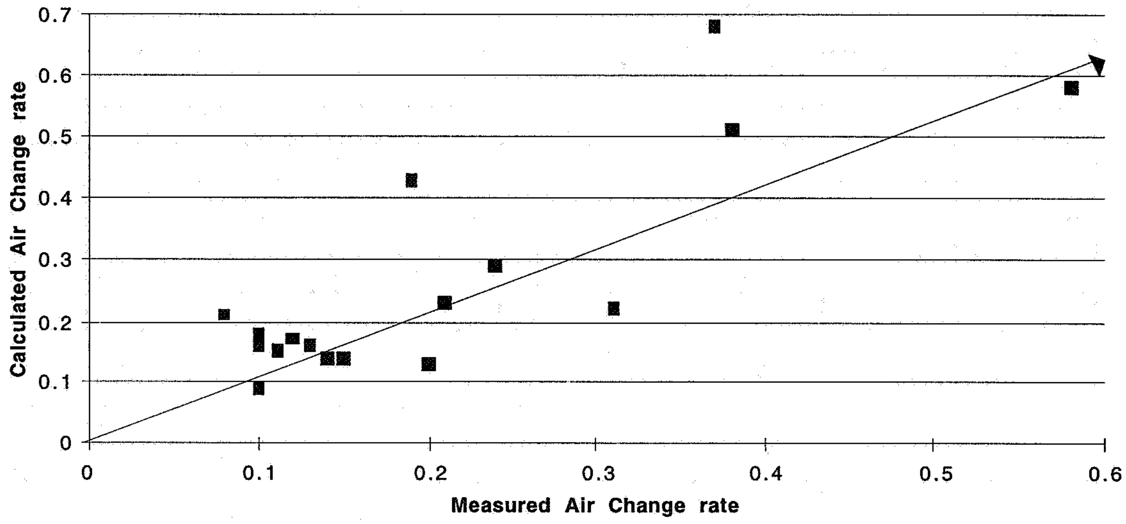
Table 4. Minimum Ventilation Required to Control Pollutants to within Recommended Levels in Litres/second

House #	RSP	VOC	Formald.	Radon	CO2 *	CO2 **	Limiting Pollutant
Limiting Level:	40 µg/cu m	3 mg/cu m	60 µg/cu m	4 pCi/L	3500 ppm	1000 ppm	
1	***31***	1.9	17	0.0	2.8	13	RSP
2	***50***	3.3	25	0.5	5.2	26	RSP
3	10	3.3	***29***	0.5	2.8	14	Formald.
4	10	11	***40***	0.5	4.7	23	Formald.
5	14	3.3	***24***	0.9	4.2	21	Formald.
6	***26***	1.4	25	0.5	2.8	13	RSP
7	7.6	1.9	***16***	0.5	1.4	7.6	Formald.
8	***23***	20	***23***	0.9	4.7	23	RSP/Form.
9	13	2.8	21	0.5	4.7	***24***	CO2 **
10	3.3	0.9	***12***	0.5	0.9	5.7	Formald.
11	***51***	8.0	50	0.5	4.7	23	RSP
12	14	0.5	17	0.5	6.6	***32***	CO2 **
13	***53***	5.2	35	2.4	6.1	30	RSP
14	***42***	1.4	26	0.5	4.2	20	RSP
15	15	3.8	***20***	0.0	2.4	11	Formald.
16	12	4.2	26	0.5	7.6	***36***	CO2 **
17	19	8.0	***35***	0.5	3.8	19	Formald.
18	***37***	5.7	29	0.9	6.1	30	RSP
19	8.0	2.8	9.0	0.9	4.7	***22***	CO2 **
20	8.5	7.6	9.0	0.9	5.2	***26***	CO2 **
21	4.2	3.3	***20***	0.5	1.9	9.9	Formald.
22	20	5.2	37	1.9	9.0	***43***	CO2 **
23	***24***	18	11	1.4	2.8	14	RSP
24	15	5.7	15	0.5	4.7	***22***	CO2 **
25	15	5.7	***25***	0.9	4.2	19	Formald.
26	---	3.8	***17***	0.9	1.9	9.4	Formald.
27	***26***	2.4	19	0.9	4.2	20	RSP
28	35	4.2	33	0.5	9.9	***47***	CO2 **
29	16	1.9	19	4.2	4.2	***21***	CO2 **
30	***43***	6.1	20	3.3	6.6	33	RSP
Mean	**22**	**5.2**	**23**	**0.9**	**4.5**	**22**	
Std Dev	**14.6**	**4.5**	**9.5**	**1.0**	**2.1**	**10**	

* Assuming the current Health Canada guideline of 3,500 ppm

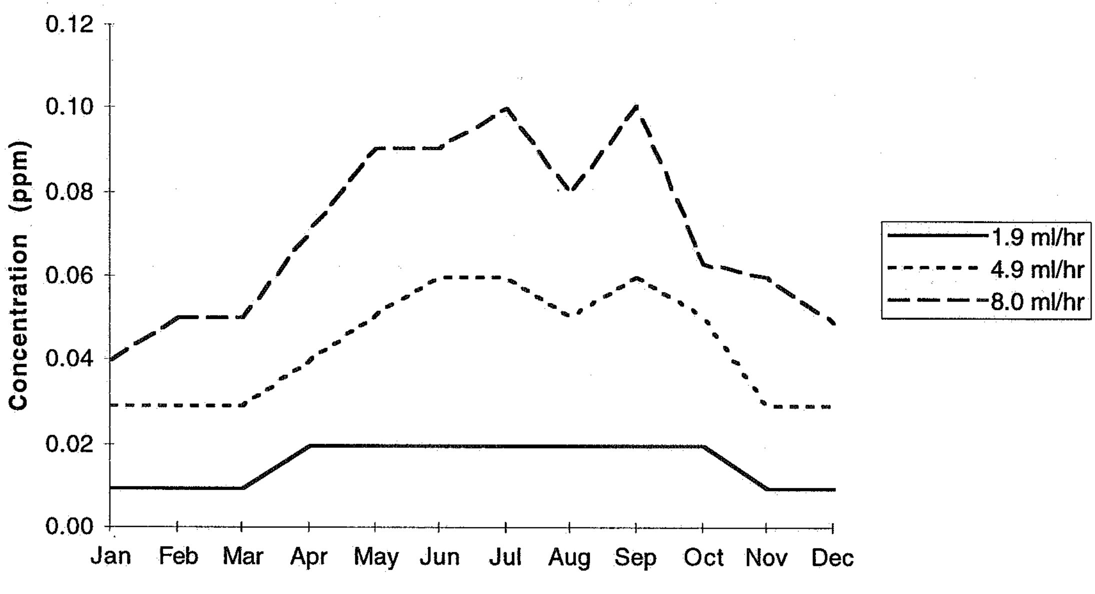
** Assuming the current ASHRAE recommended level of 1,000 ppm

Figure 8 Calculated vs Measured Air Change Rates



Using three different emission rates for formaldehyde covering the range found in the test houses, and weather data for Montreal, the AQ1 model was used to predict the average level of formaldehyde over an entire year in several houses. For example, using the air change rate of House #9, we show the effect of different levels of source strengths. Please refer to Figure 9. At the lowest formaldehyde source strength of 1.9 ml/h (2.2 mg/h), the formaldehyde level remained below 0.02 ppm, below the Health Canada long term exposure limit of 0.05 ppm (60 µg/cu m) Assuming the medium source strength of 4.9 ml/hr in the same house, the model predicts levels at or over 0.05 ppm from May to September and lower for the colder months. Only during the lowest ventilation periods during July and September and at the highest source strength encountered in the 30 houses (8 ml/hr), was the Canada short term exposure limit of 0.1 ppm reached in this house.

Figure 9 Projected Formaldehyde Concentration (ppm) in House #9 Montréal



4. Ventilation methods tested

Five different simple ventilation systems were operated and their effectiveness at reducing indoor pollutant levels was evaluated. Simultaneous carbon dioxide recordings in various locations were used along with occupancy records to determine the movement and dilution of the gas over time in each house. The systems could be turned on and off to permit evaluating the changes in indoor conditions. The results are presented very briefly in order of decreasing effectiveness from the points of view of efficacy and economy.

1. Outdoor air supply and mixing with indoor air for tempering, combined with return or supply of air in each bedroom plus a bathroom exhaust - Best system from point of view of comfort and economy.
2. Simultaneous outdoor air supply and exhaust (air exchange) and mixing with indoor air for tempering - air drawn from upper hallway, mixed air released into the basement - Good system, but may have to over-ventilate in order to control bedroom pollutant levels.
3. Two-fan recirculating system installed through the main floor: downflow is greater than upflow fan capacity to cause a slight pressurization of the basement. - System does not provide sufficient outdoor air, but helps diluting pollutants and reducing average levels.
4. Replacement exhaust fan of tolerable noise level; operated at high percent on-times. - Indications are that the effectiveness is about half of a balanced system due to lack of mixing of air within the house and short-circuiting of outdoor air through the fan.
5. Turbine Ventilation system - an open chimney system utilizing a 15 cm diameter insulated duct from the ceiling of the upper hallway, through the attic and roof to the outside, topped with a wind-driven revolving head to facilitate air flow under all wind conditions. This system has the reverse flow characteristics required, with minimum flow during the shoulder seasons and maximum flow during the coldest season. It tends to under-ventilate in mild weather and over-ventilate in cold, windy weather.

5. Movement and distribution of pollutants in a house

In houses without an air distribution system, pollutants such as carbon dioxide released by the occupants redistribute themselves by diffusion and by mixing with air in adjacent open areas. Continuous recording of carbon dioxide in several locations of a house can reveal the amount of redistribution which takes place naturally with doors open and closed. We found the method to be quite sensitive, and was capable of detecting the increase in carbon dioxide production by more people in the house, by the use of candles and by the open fermentation of beer and wine. Some of the more salient observations are summarized in this section.

Stratification within a Room

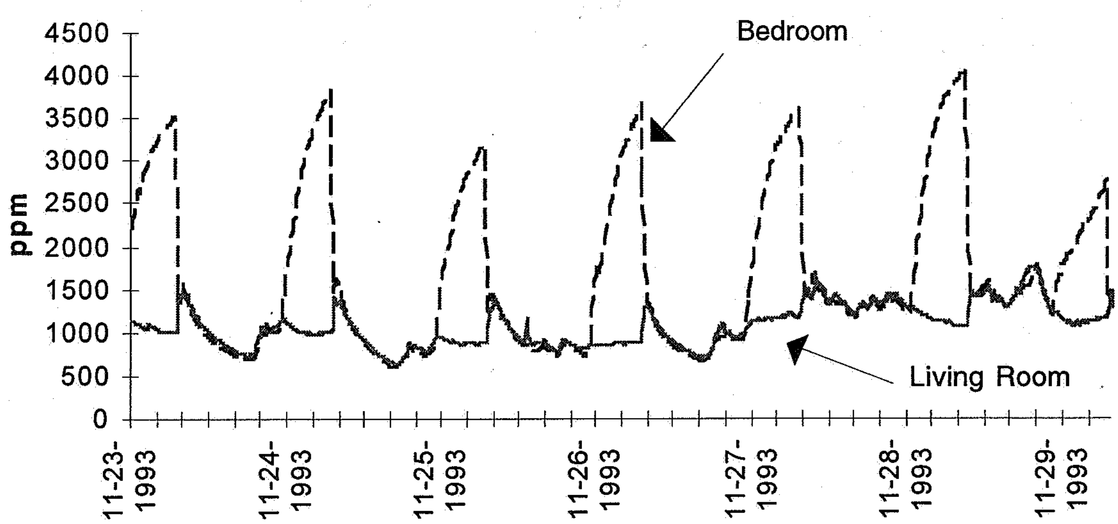
Recordings of carbon dioxide in occupied bedrooms (without an air distribution system) at three levels (floor, 80 cm from the floor and near the ceiling) indicate that there is a small difference in CO_2 levels between the floor and the ceiling while the room was occupied, the readings near the ceiling being higher by about 200 ppm while people were present in the room.

Difference in CO_2 Levels Between Rooms on Same Floor

Simultaneous records of CO_2 levels in the living room and master bedroom in house #3 (on the same level of the building, at table height) which had no air distribution system operating, indicate a difference of 300 to 400 ppm between the occupied and unoccupied room only during the sleeping hours, with the level in the occupied room being higher (bedroom door open). The rest of the time, while the occupants are moving about the house or are away, the room CO_2 levels are within about 50 to 100 ppm.

In House #5, the bedroom door was closed regularly during the night. There was no air distribution system operating in this house. The difference in CO_2 levels between the bedroom and living room increased steadily from the time that the door is closed around 11:00 p.m. until the door is opened around 7:00 am., with CO_2 levels rising to 4000 ppm by morning. Once the bedroom door is opened in the morning, it takes approximately 30 minutes for the CO_2 levels in the bedroom and living room to equalize. Please refer to Figure 10. During the day, while the occupants are away and the bedroom door is open, the levels in the bedroom and in the living room equalize.

Figure 10 Carbon Dioxide Levels in Different Rooms on the Same Floor, House #5



Difference In CO_2 Levels Between Basement And Main Floor

In houses where new ventilation systems had been installed, the carbon dioxide levels were recorded in the master bedroom, in the living room and in the basement for a period of several days. In House #4, where two fans had been installed through the floor at opposite ends of the house, blowing in opposite directions to mix basement and main floor air, there was an indistinguishable difference in carbon dioxide levels among the bedroom, living room and basement while the equipment was operating (third system described in Section 4)

In House #5, a new ventilation and air mixing system was ducted to each bedroom and to the hallway (first system described in Section 4). In this house, the occupants normally sleep with the bedroom door closed. While the system was operating, there was a small difference of between 100 and 200 ppm in the levels of CO_2 recorded in the bedroom, living room and basement. The occupants noted a marked improvement in air quality compared to the system being off and the bedroom door being closed, when CO_2 levels regularly rose above 4,000 ppm.

In house #8, where a balanced fresh air supply and exhaust system normally operates (second system in Section 4), there are virtually no differences in levels of CO_2 in the basement, bedroom and living room. With the ventilation system off, and the door to the basement in the normal "closed" position, the average CO_2 level in the basement was always lower than the levels on the main floor. The difference in CO_2 levels between upper level and basement ranged between 300 and 600 ppm. The difference in levels between the bedroom and living room were indistinguishable.

6. Conclusions

1. During the heating season, total ventilation (natural plus mechanical) is inadequate to maintain indoor pollutant levels below the recommended limits during mild weather in the majority of houses tested. During the coldest part of the season, total ventilation is adequate in about half of the houses. The main determining factors are pollutant source strength and building ventilation (operation of fire-places, exhaust equipment and window openings).

2. The main pollutants which determine the minimum ventilation required are formaldehyde, RSP's and CO_2 (when the maximum desired level of CO_2 is 1000 ppm). Since there are no guidelines for maximum TVOC's, no conclusions can be drawn from the observed source strengths of these contaminants.

3. The correlation between the measured air tightness of houses (ACH_{50}) and indoor air quality is very poor.

4. Carbon dioxide levels are directly dependent on the person-hours of occupancy, as well as on the use of candles. The local levels of CO_2 and humidity become elevated when the door of an occupied room is closed in cases where there is no air distribution system.

5. Modeling predicts that the worst indoor air quality will occur in spring through to fall. Air sealing and controlled ventilation together present a significant opportunity for winter peak demand reduction with a small increase in demand the rest of the year.

6. The stratification of carbon dioxide in occupied rooms demonstrates that there is value in mixing air within a building mechanically to improve air quality in the occupied areas.

Acknowledgments

This report is the compilation of an enormous amount of work carried out by the technical staff at LTEE, by the volunteers and their families who allowed us into their homes and faithfully recorded the needed information, and by other staff responsible for the field work and laboratory testing. We are grateful to CMHC for providing partial financial support of this study, and for their technical contribution to the AQ1 model study.

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