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QUANTIFYING THE EFFECT OF INFILTRATION ON CONTAMINANT CONCENTRATIONS FOR DIFFERENT EMISSION SCENARIOS

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ABSTRACT

Current building codes and construction practices are delivering increasingly airtight residential buildings. This is beneficial in terms of reducing energy demand but is increasingly linked to adverse health effects.

This paper examines the natural supply of outside air to Quebec City dwellings and examines the concentration of contaminants for various occupancy scenarios. Using local weather data and measured envelope leakage data the requirement for additional mechanical ventilation to meet existing standards is assessed. The contaminant concentrations are compared to a mechanical system delivering the fresh air at rates prescribed in the model national building code.

Additionally the energy implications of excessive infiltration and additional mechanical ventilation are quantified.

INTRODUCTION

Emphasis has been given to increasing the airtightness of buildings as a mechanism to reduce energy required to heat and cool the air infiltrating into buildings (ASHRAE 2004a, 2004b, 2004c). Envelope airtightness has reached a level whereby mechanical ventilation is required to achieve acceptable indoor air quality. Therefore, in order to save conditioning energy costs, energy must now be spent to introduce and circulate air within buildings. A successful natural solution would not require this energy.

This paper focuses on residential buildings where the requirement for mechanical ventilation often gives little credit for infiltration nor provides mechanisms to easily assess natural ventilation options (ASHRAE 2004b). The assessment is based on field data collected for buildings in the Quebec City area.

This paper sets out to examine relationships between contaminant concentrations and ventilation rates. The aim of the ongoing work is to enable easier assessment of natural ventilation to further reduce the energy load associated with infiltration and ventilation without compromising indoor air quality.

METHOD

Infiltration rates have been calculated for houses in the Quebec City area using data collected by the EnerGuide For Houses program (NRCan 2007). Climate data representative of Quebec City was used to model each house for a year.

Several algorithms exist to calculate infiltration rates from basic qualitative and quantitative descriptive data for houses (ASHRAE 2005). Recent work (Reardon 2007) compared the availability of data for Canadian houses and that required for available models. It concluded that the best approach for Canada was to use the EnerGuide for Houses database and the single-cell Shaw model (Shaw 1987).

The essence of the Shaw model is that the infiltration rates due to stack pressure and wind effect are calculated individually and then combined according to superposition of their driving pressures to produce a total infiltration rate. The key input parameters are: wind speed, ambient temperature, internal temperature, neutral pressure ratio and data from a blower door test (coefficients C and n from the curve fit). The model is now elaborated.

Stack-effect driven infiltration is modeled by the equation below:

$$I_S = 0.5\ (C/V)\ (h/H)\ (T_{in}-T_{out})^n \qquad (1)$$

Where:

0.5 factor has the units $[m^3 \bullet s \bullet Pa^n)/(L \bullet hr \bullet K^n)]$,

I_S = infiltration air change rate due to stack effect [ac/hr],

C = house flow coefficient from curve fit of the leakage test data $[L/(s \bullet Pa^n)]$,

V = internal volume of the house including basement $[m^3]$,

h = height above grade of the neutral pressure level [m],

H = height above grade of the upper ceiling of the house [m],
T_{in} = indoor air absolute temperature [K],
T_{out} = outdoor air absolute temperature [K], and
n = house flow exponent from curve fit of the leakage test data.

Shaw suggests that for a house without a flue h/H = 0.64, and for a house with a single 127 mm dia. flue h/H = 0.86, based on the data set used to develop this model. A later study (Reardon 1989) with measured NPLs in a larger number of houses has provided a guide for NPL=0.6 for houses without an open flue and 0.7 with an open flue.

The form of the curve fit to the leakage test data (from a fan depressurization measurement of the envelope airtightness of the house, following CGSB 1986), that is used to determine the flow coefficient and flow exponent is the power law curve:

$$Q_m = C\,(\Delta P)^n \quad (2)$$

Where:
Q_m= measured flow rates [L/s], and
ΔP= measured pressure difference across envelope [Pa].

Wind driven infiltration is modeled by the equation below:

$$I_W = 0.4\,(C/V)\,U'^{2n} \quad \text{Exposed} \quad (3)$$

$$I_W = 0.7\,(C/V)\,U'^{n} \quad \text{Shielded} \quad (4)$$

Where:
0.4 factor has units $[(m^3 \bullet Pa^n \bullet s^{2n+1})/(L \bullet hr \bullet m^{2n})]$,
0.7 factor has units $[m^3 \bullet Pa^n \bullet s^{n+1})/(L \bullet hr \bullet m^n)]$,
I_W = infiltration air change rate due to wind [ac/hr], and
U′= windspeed measured at height of 20m on-site [m/s].

The combined infiltration due to both stack-effect and wind is modeled by combining these two component infiltration rates using n-quadrature to effectively superpose the pressures created by these two physical phenomena, since the two component infiltration rates do not simply add, due to the non-linear relationship between driving pressure and driven flow rate. The combined model equation is:

$$I_{WS} = F\,(I_S^{1/n}+I_W^{1/n})^n \quad (5)$$

Where:
I_{WS} = total combined infiltration air change rate [ac/hr],
F = an empirical factor defined by the following:

$$F = 1 \text{ for } 0 \le (I_{sml}/I_{lrg}) < 0.1 \quad (6)$$

$$F = 0.8\,(I_{sml}/I_{lrg})\text{-}0.1 \text{ for } 0.1 \le (I_{sml}/I_{lrg}) \le 1.0 \quad (7)$$

Where:
I_{sml} = the smaller of the two components I_S and I_W, and
I_{lrg} = the larger of the two components I_S and I_W.

Carbon dioxide concentrations were used as a proxy for a measure of indoor air quality. Data for the province of Quebec shows that most households have one or two occupants (the 2006 Canadian census shows that 31% of households have only one person, 34% 2 people, 16% 3 people and 13% 4 people, www.statcan.ca). From this data three occupancy schedules were developed:

1. Retired couple – this scenario represents the CO_2 generation of two people in the building at all times. This scenario is also representative of long-term VOC emissions that tend to a constant emission rate.

2. Working couple – this scenario represents the CO_2 generation of two people who both work and are present in the evening and overnight (5PM to 8AM), but out of the building during the day (8AM to 5PM).

3. Young family – this scenario represents a family of four where only one adult is at home during work/school hours (8AM to 5PM).

It is believed that these three profiles represent the majority of occupancy profiles found in Quebec City. The concentration of CO_2 was calculated using the whole house volume from the EnerGuide database, and a Eulerian formulation of the concentration equation:

$$V\,dC/dt = V\,I_{WS}\,[C_{out} - C] + G' \quad (8)$$

Where:
V = house volume $[m^3]$,
C = concentration of CO_2 $[mg/m^3]$,
t = time [hr],
I_{WS} = total air infiltration rate [ac/hr].
C_{out} = concentration in outdoor air $[mg/m^3]$, and
G′ = emission rate of CO_2 in the house [mg/hr].

The concentration equation was solved at six-minute intervals using the infiltration rate calculated hourly from the Shaw model and a CO_2 generation rate of 31.1 L/hr/person. The ambient CO_2 concentration was set to zero, therefore the results show the concentration above ambient.

Reference system

To compare the performance of infiltration alone in maintaining indoor air quality, the buildings were also simulated with a mechanical ventilation system. The rationale for this is that if the natural concentrations of CO_2 are less than those in the same building under mechanical ventilation then the mechanical system is not providing improved IAQ. The mechanical system was selected to provide 0.3 ac/hr of fresh air (CSA 1991).

SIMULATION

The above equations were implemented in a purpose written code. The code was validated against a separate version written in Excel. In total 2000 houses were simulated for each of the occupancy profiles for both mechanical only and infiltration only air supply with the Quebec City climate data from ESP-r [2007].

The EnerGuide For Houses database contained measured airtightness characteristics for almost 4000 houses, from which individual values for C and n were derived. That dataset did not contain values for the NPL, but did contain information describing the types of heating systems. Values for the neutral pressure ratio for each house were assigned based on their heating system type. Electrically heated houses were assigned NPL=0.6, mid-efficiency fuel-fired heating systems were assigned NPL=0.65, and conventional efficiency, fuel-fired heating systems NPL=0.7.

RESULTS

The results from the initial analysis are shown in Figures 1, 2 and 3. These figures show the CO_2 concentration above ambient within the modelled houses for the three occupancy profiles. Each figure shows the CO_2 data for infiltration only supply and for mechanical ventilation only for the 2000 houses (note that the points for mechanical ventilation are plotted at the same infiltration rate as the infiltration only supply points, for example see the points at approximately 2.5 ac/hr: these represent the same building and show the difference between the ventilation schemes).

In general there is an inverse relationship between CO_2 concentrations and average infiltration rates, and lower CO_2 concentrations for the equivalent mechanical ventilation at lower infiltration rates.

As can be seen for all cases at lower average infiltration rates, the average CO_2 level can be significantly higher than ambient (e.g. up to 3000 ppm higher in scenario 1, figure 1).

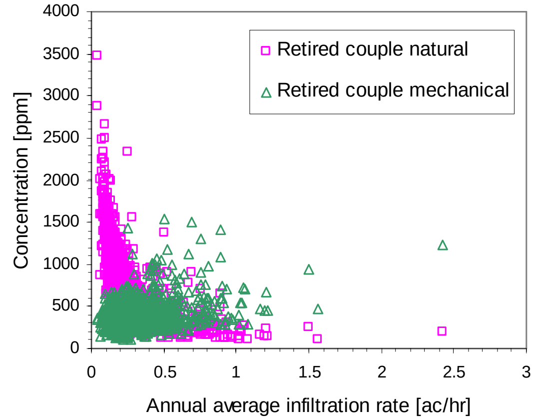

Figure 1: Annual average CO_2 concentration against average infiltration rate for occupancy scenario 1.

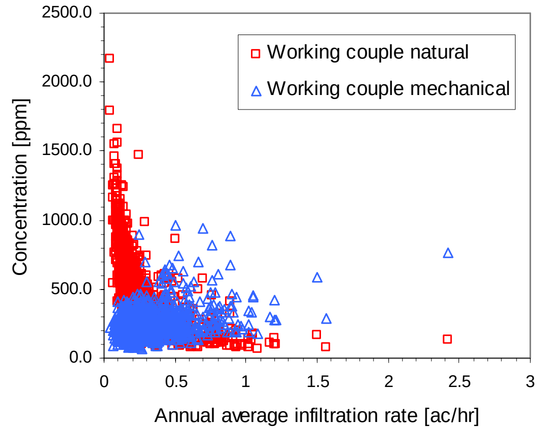

Figure 2: Annual average CO_2 concentration against average infiltration rate for occupancy scenario 2.

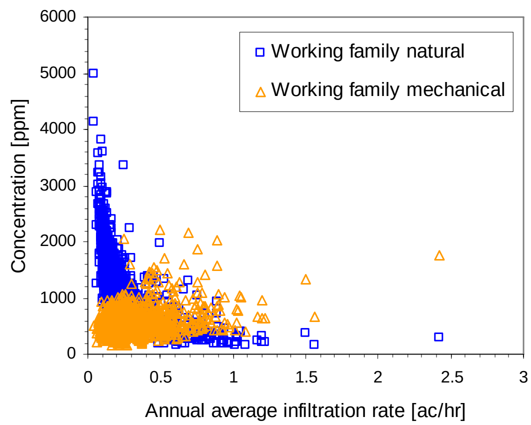

Figure 3: Annual average CO_2 concentration against average infiltration rate for occupancy scenario 3.

The results for mechanical ventilation show that for scenario 1 the annual average CO_2 concentrations can exceed ambient levels by more than 1500 ppm. This would indicate that even with mechanical ventilation the indoor air quality could be poor.

It appears from comparing the CO_2 concentrations resulting from infiltration to those resulting from constant mechanical ventilation, shown in Figures 1 thru 3, that the annual average infiltration rates greater than 0.3 ac/h typically provide annual average CO_2 concentrations equivalent to or better than those produced by mechanical ventilation at 0.3 ac/h.

Figure 4 shows the difference in annual average CO_2 concentration between mechanical and natural infiltration only. As can be seen in the more airtight buildings mechanical ventilation results in lower CO_2 concentrations compared to natural infiltration only (points below the x-axis). It can also be seen that the point where the x-axis is crossed is similar for all three scenarios.

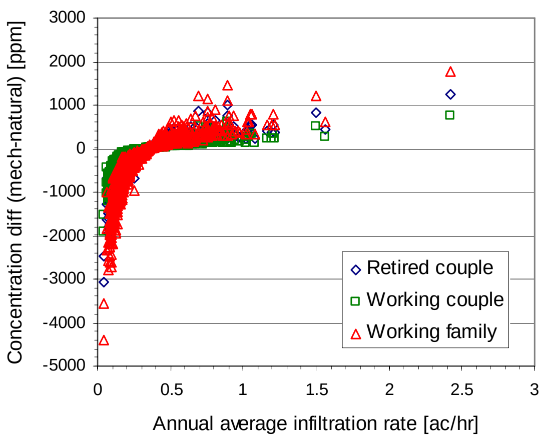

Figure 4: Difference between annual average CO_2 concentration between mechanical and infiltration schemes.

Figures 5 through 7 show the critical area where mechanical ventilation results in lower average CO_2 concentrations than infiltration alone for three mechanical ventilation rates: 0.25, 0.30 and 0.35 ac/hr.

As can be seen the cluster of points in all cases crosses the x-axis at an average infiltration rate higher than the mechanical rate. This indicates that to achieve a similar performance to mechanical ventilation a greater average natural infiltration rate is required.

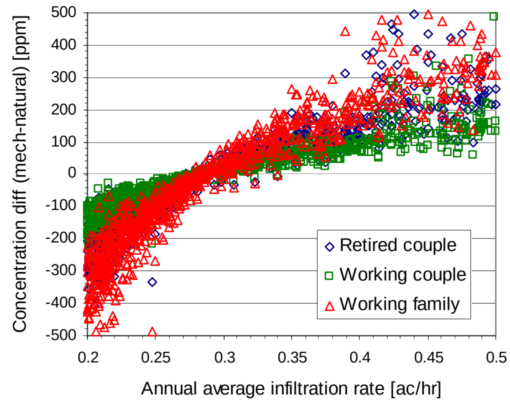

Figure 5: Concentration difference (with mechanical supply of 0.25 ac/hr) as a function of average infiltration rate.

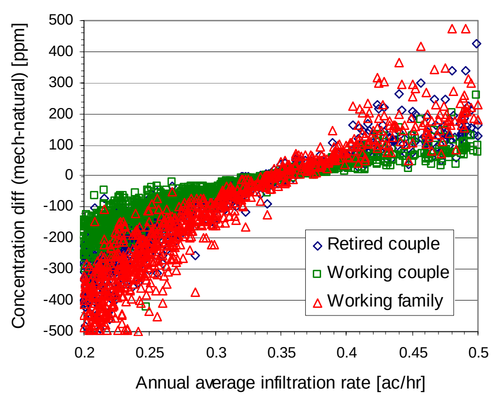

Figure 6: Concentration difference (with mechanical supply of 0.30 ac/hr) as a function of average infiltration rate (same data as figure 4).

Figure 7: Concentration difference (with mechanical supply of 0.35 ac/hr) as a function of average infiltration rate.

Also, as mentioned above, the points cross the axis at the same location for all three scenarios. This would suggest that the difference between mechanical ventilation and infiltration only are independent of contaminant generation rate or profile.

Figures 8 through 10 show the difference between the two ventilation schemes using the under supply metric (Macdonald and Reardon 2007). Under supply is defined as the volume of air that is not supplied to a space by natural means compared to the air volume supplied by a mechanical system, expressed as a percentage; no credit is given for times when the natural ventilation scheme provides a greater flow rate.

As can be seen in figures 8 through 10 there are conditions where a mechanical scheme provides lower average CO_2 concentrations than infiltration alone (points below the x-axis). However, there are also conditions when the opposite is the case, i.e., infiltration alone results in lower average CO_2 concentrations compared to mechanical ventilation (points above the x-axis). It would appear that the critical value of the under supply metric is in the region of 10%. This is slightly higher than suggested in Macdonald and Reardon (2007) where a critical value of 5-7% was identified.

This would indicate that to achieve an equivalent indoor air quality compared to a mechanical system the average infiltration rate would have to be greater than the prescribed mechanical rate. This would have an impact on the energy required to condition the air.

Infiltration energy load

The energy required to condition the fresh air was calculated assuming a constant internal temperature of 21^{o}C, constant specific heat capacity and density of air according to the ideal gas law.

For the simulated houses the infiltration load is displayed in table 1. As can be seen, there is a considerable energy saving if a mechanical system is used (not included is the energy required to operate the fan in the mechanical system, however manufacturer's data suggests that this would be in the region of 1500kWhr).

Table 1: Energy required to condition fresh air.

Supply rate [ac/hr]	0.25	0.30	0.35
Infiltration [kWhr]	57300	68500	79700
Mechanical [kWhr]	47400	56800	66300
Saving [%]	17	17	17

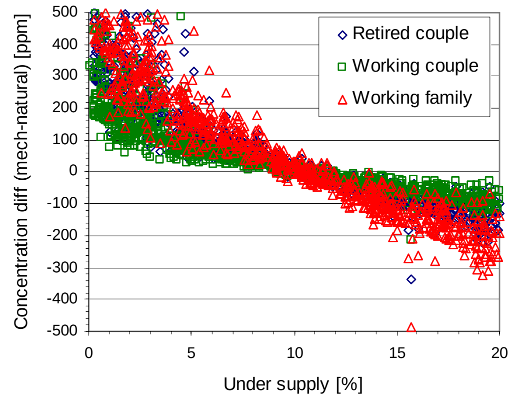

Figure 8: Difference between annual average CO_2 concentration between mechanical (0.25 ac/hr) and infiltration schemes.

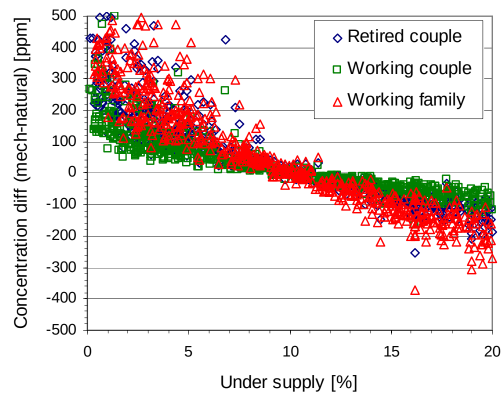

Figure 9: Difference between annual average CO_2 concentration between mechanical (0.30 ac/hr) and infiltration schemes.

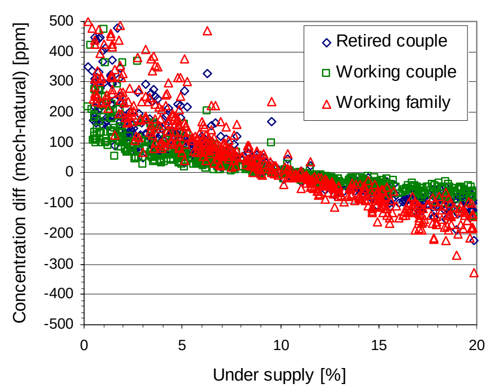

Figure 10: Difference between annual average CO_2 concentration between mechanical (0.35 ac/hr) and infiltration schemes.

DISCUSSION

This paper has shown that for a sub-set of Quebec City houses (those that were involved in EnerGuide surveys) to achieve equivalent indoor air quality via natural infiltration as compared with mechanical ventilation a slightly higher annual average infiltration rate is required.

Using the under supply metric the increase required was shown to be in the order of 10%. This result was independent of assumed mechanical supply rate and contaminant generation profile. The implicit assumption made for this analysis is that the selected mechanical flow rate would keep absolute levels of contaminants below levels which may cause concern. From the data presented in figures 1 through 3 it can be seen that average CO_2 concentrations are up to 2000 ppm greater than ambient concentrations. Therefore, it can be assumed that there will be times where the CO_2 concentrations are much higher.

The energy associated with conditioning fresh air was also calculated. This showed that there are savings to be made by using a mechanical system (due to a smaller volume of air being conditioned). However, for simplicity the calculation assumed that the internal temperature of the house was a constant 21^{o}C. For this reason it would be unwise to draw conclusions on energy use at present.

To analyse this issue further more detailed modelling is required. Assumptions will be required as to window opening and temperature profiles to be used. Both of these changes will affect the resulting infiltration rate (and thus under supply) as well as the energy required.

CONCLUSIONS

Although work remains to be done this study has shown that the trade off between mechanical ventilation and natural infiltration is independent of the contaminant generation profile (note that this is a difference rather than an absolute concentration). In addition the break even point occurs at an under supply of around 10%.

Future work will concentrate on generating profiles for building use including temperature settings and door/window opening. This will have an effect on both the under supply and the energy required to condition fresh air. It is hoped that a conclusion could then be made with regard to energy.

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