On Measuring Air Infiltration Rates Using Tracer Gases in Buildings with Presence Controlled Mechanical Ventilation Systems

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SUMMARY

The ventilation and air leakage of a school building was investigated. Information was collected from the parameters of the mechanical ventilation system and from measurements of the local mean age of air using the homogeneous emission method. While the average local mean ages of air can be accurately measured by passive integrative samplers, the estimation of the average room specific air change rate by taking the inverse of the measured average local mean age of air did not give correct results. The main problem is that integrative sampling represents a linear averaging process that is inappropriate to capture the average of nonlinearly related properties. This problem is accentuated when the ventilation rates for different periods differ a lot. A simple computational model was developed to discuss the system behavior. A partial solution to the measurement problem is to actively sample the different populations of air change rates separately.

PRACTICAL IMPLICATIONS

Integrative sampling represents an averaging process that accurately estimates averages for linearly related properties, but not for nonlinearly related properties. When ventilation rates vary a lot, tracer gas methods using passive integrative sampling accurately measures the average local mean age of air, but fails to estimate the average air change rate.

KEYWORDS

air infiltration, local mean age of air, room specific ventilation rate, ACH

1 INTRODUCTION

Measuring air infiltration rates in buildings using tracer gases is covered in standard procedures and in multi-zone buildings the homogenous emission method (HEM) is recommended for long term averages (ISO/DIS 16000-8, 2005). The advantage of HEM is that the concentration of tracer gas in any given position reflects the local mean age of the air at a given time. The air infiltration at a given time may be characterized by the room specific ventilation rate (ACH) that is inversely proportional to the local mean age of air. Integrative sampling of the local concentration gives the time averaged local mean age of air for the chosen time period. Sampling may be passive (where the tracer gas is collected onto an adsorbent by diffusive processes) or active (where a chosen air volume is pumped through an adsorbent). The latter is normally more suited for short term averages (minutes, hours), whereas the former is more suited for long term averages (days, weeks). The disadvantage of integrative sampling, as opposed to monitoring the concentration as a function of time, is that information on the time variation obviously is lost in the averaging process. For properties that are linearly related to the concentration, i.e. the local mean age of air, this is no problem since their time average is readily obtained from the time average of the local concentration.

For properties that are nonlinearly related, i.e. the room specific ventilation rate, the problem may be more severe.

We present experiences from a case study where we have used passive integrative sampling together with other sources of information to assess the local mean age of air and the room specific air change rate. The study object is a school building with four separate mechanical ventilation systems with heat recovery. In this paper we focus on the results from a selected classroom during one week of measurements.

2 MATERIALS/METHODS

The school building is situated in mid Sweden (see Fig.1). The building is equipped with mechanical ventilation systems that are of a recuperating type (Energy recovery ventilation system; ERV) using a rotating wheel. Ventilation in the various zones was controlled by damper positions on an on/off basis, but triggered in two ways depending on the function of the zone in question. In common zones, such as corridors or teacher offices, ventilation rates were determined by a chosen schedule. In classrooms, ventilation was activated by presence detectors and deactivated a half hour after the moment when no activity was detected in the zone. Air was supplied to the zones by means of displacement terminals and evacuated through terminals situated below the ceiling. Classroom doors were closed at all times except when pupils and personnel were passing through.

Figure 1: The studied school building

Figure 2: A passive sampler (left) and a tracer source (right)

The average local mean age of air was measured using the homogeneous emission tracer gas technique described in NORDTEST Standard VVS 118 (1997) and ISO 16000-8 (2005). The underlying multi-zone approximation of buildings is described in Etheridge and Sandberg (1996). A perfluorocarbon tracer (PFT) gas was used and the tracer gas sources (See Fig. 2) were adjusted to each zone to obtain a homogeneous rate of emission in the building. With the distribution of tracer sources used in this study, the PFT-levels in the building rarely rise above ppb-levels. Passive collection onto charcoal tubes (See Fig. 2) were used for long term averages (Dietz et al, 1986; Säteri, 1991; Stymne and Boman, 1994 and Stymne, 1995). Rotronic CL11 logging the CO_2 concentration, relative humidity and temperature every five minutes were used. At temperatures of 23 ±5 ˚C, the Rotronic CL11 has accuracies of ±30 ppm ±5% of the measured CO_2 value, less than 2.5% RH (between 10-90% RH), and ± 0.3 ˚C on temperature.

The measurements were performed from December 2014 to March 2015, but the main results presented here is for the week 16 February to 23 February. In the beginning of this week the outdoor temperature plummeted to -16 °C and then oscillated between +5 and -5 °C for the rest of the week. Earlier in this measurement campaign, the average local air leakage into the building was measured when all mechanical ventilation systems were turned off during

Christmas and New Year holidays 2014/2015 as described in more detail in Steen Englund et al. (2015).

3 RESULTS

The volume of the selected classroom (223) is 200 m^3. The logged damper position for the classroom during the measurement week, corresponding to the activity, is indicated in figure 3. The classroom temperature and the CO_2 concentration (indicating the load of human presence) are shown in figure 4.

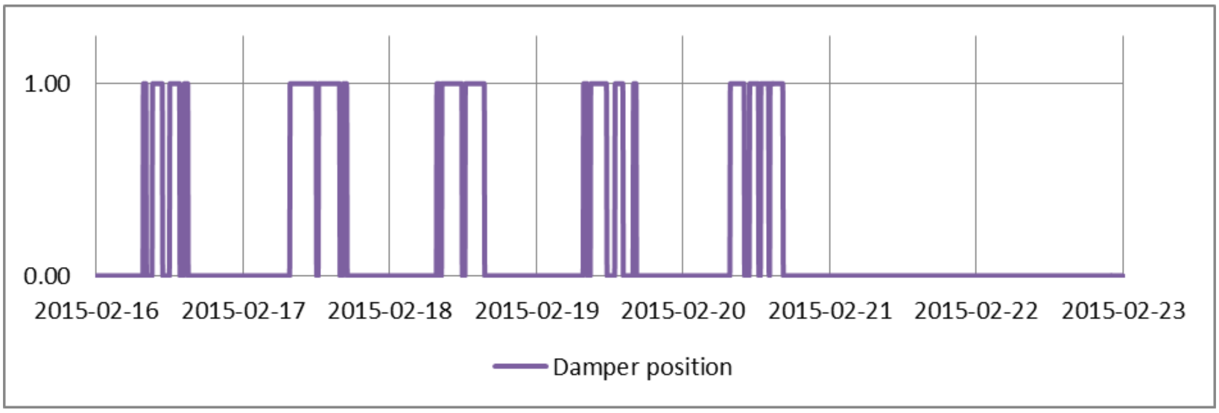

Figure 3: The position of supply air damper during working days Monday 16th to Sunday 23rd of February 2015. The value 0 indicates it is closed and 1 opened.

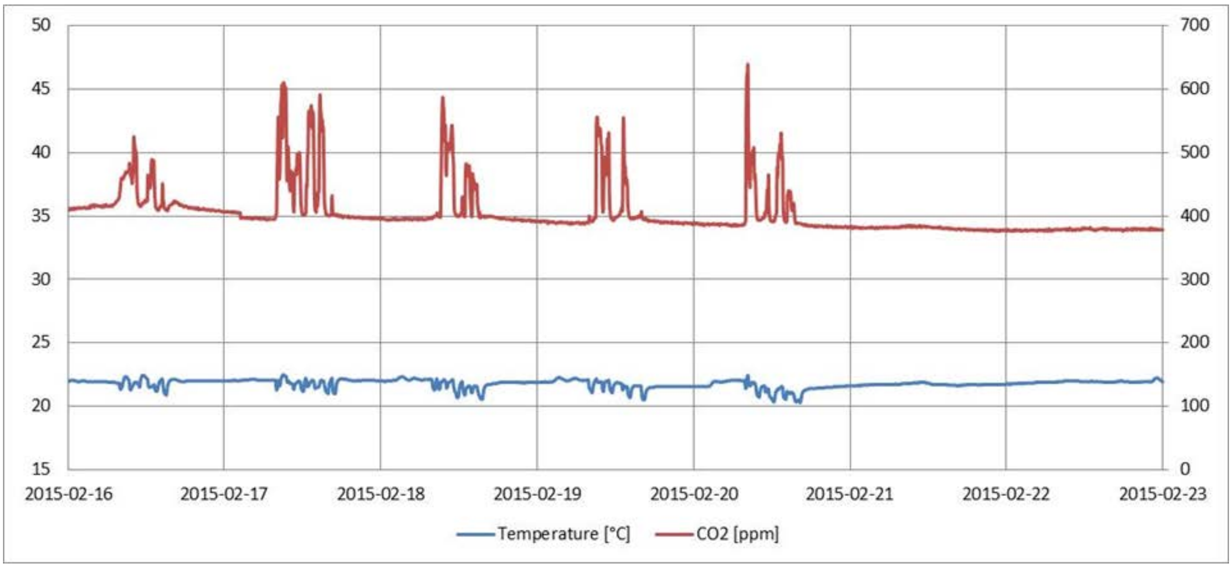

Figure 4: Temperature (left axis) and CO_2-concentration (right axis) are shown for classroom 223 during the period of Monday 16th to Sunday 23rd of February 2015.

The position of the air damper controls the air supply to the room. In essence, when it is closed, the air flow is determined by the air leakage. When opened, the air flow will correspond to the design air flow (including air leakage). The average leakage rate in the classrooms at low operation (damper closed) has been determined to an air change rate (ACH) of 0.08 h^{-1} (Steen Englund et al., 2015). The supply air to the classroom at high operation (damper open) was 300 liters/s corresponding to an ACH of 5.4 h^{-1}. (Note that the ventilation rates at low and high operation show a nearly hundredfold difference.) Using the logged damper positions in figure 3, the average air change rate during the week was evaluated to be 1.1 h^{-1}. The damper is open approximately 19.4% of the total time.

Since the inverse of mean age of air gives the air change rate, the air change rates at high and low operation would at *steady state* conditions give average ages of air corresponding to 12.5 h and 0.19 h respectively. A crude calculation, based on the damper position (open 19.4% of the time) and assuming no transient values, the mean age of air is estimated to be 10 h. This is almost double the value actually measured with a HEM passive sampler in the classroom during the period (5.8 ± 0.6 h). Furthermore, by thoughtlessly taking the inverse of the HEM value to obtain the average air change rate we get 0.17 [h^{-1}]. This is far from the expected value of 1.1 h^{-1} calculated above. Obviously, the calculated values do not agree and calls for a closer examination

To give the reader a picture of the system, a simple computational model was created to study the average age of air in a zone that is subjected to two ventilation rates as a function of time. The basis of the model is a mass flow balance of tracer gas in the considered zone with volume V [m^3], where the rate of change of the concentration C [kg/m^3] is dependent on the supplied and extracted air flow q [m^3/s] (here assumed to have identical values) and the tracer emission rate S [kg/s]. This is mathematically formulated as follows, where t [s] denotes time,

$$V\frac{dC}{dt} = S(t) + q(t)\cdot C_{supply} - q(t)\cdot C(t) \qquad \text{[kg/s]}. \tag{1}$$

The first two terms on the right hand side introduce tracer gas to the room, but for this case the concentration in the supply air is set to zero and the tracer emission rate is set to the constant value S. Upon discretizing time by using a small time-step Δt [s], Equation 1 can be reformulated to

$$C(t+\Delta t) - C(t) = \frac{\Delta t}{V}\left[S - q(t)\cdot C(t)\right] \qquad \text{[kg/m}^3\text{]}. \tag{2}$$

The air change rate n [h^{-1}] is defined as

$$n(t) = \frac{3600\cdot q(t)}{V} \qquad \text{[h}^{-1}\text{]}. \tag{3}$$

Rearrangement of Eq. 2 gives

$$\frac{V\cdot C(t+\Delta t)}{S} = \frac{V\cdot C(t)}{S} + \Delta t - \frac{n(t)\cdot \Delta t}{3600}\cdot\frac{V\cdot C(t)}{S} \qquad \text{[s]}. \tag{4}$$

Per definition, at steady state, the mean age of air τ [h] at the measurement point is

$$\tau(t) = \frac{C(t)\cdot V}{3600\cdot S} \qquad \text{[h]}. \tag{5}$$

The term $C\cdot V/S$ is readily identified in Eq. 4 and substitution, assuming complete mixing, gives

$$\tau(t+\Delta t)=\tau(t)\cdot\left[1-\frac{n(t)\cdot\Delta t}{3600}\right]+\frac{\Delta t}{3600} \qquad [\mathrm{h}]. \tag{6}$$

In Figure 5, a simulation of the mean age of air in a selected classroom (223) using Equation 6 is presented. The time step was 5 minutes and the damper's position from the period Monday 16th to Friday 21st of February 2015 (see Fig. 3) was used to describe $n(t)$ (damper closed implies an air change rate of 0.08 h^{-1} and open means an air change rate of 5.4 h^{-1}).

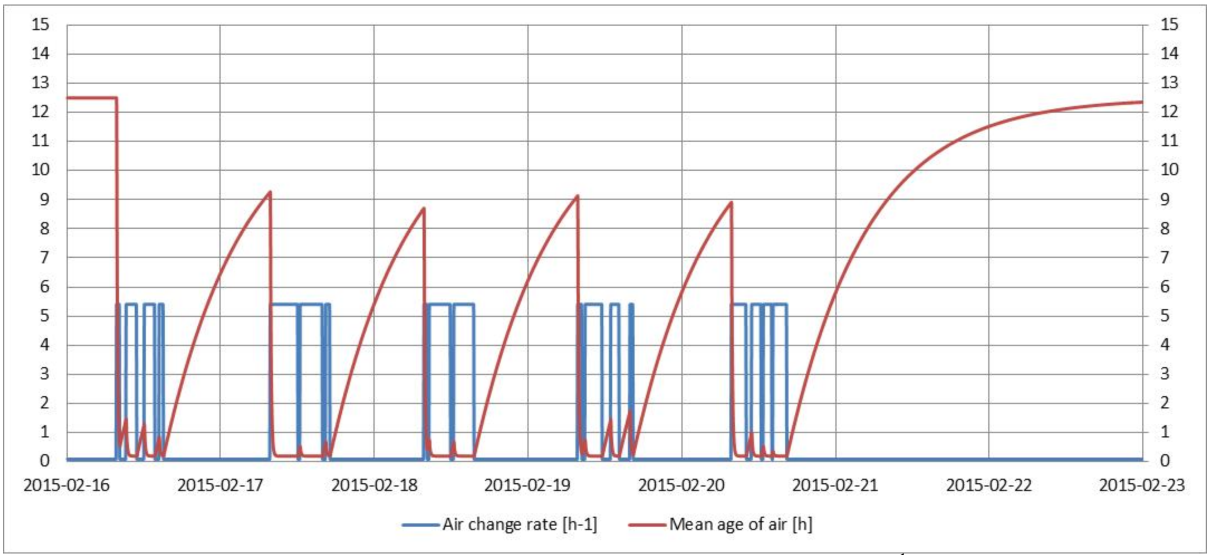

Figure 5: The diagram shows the air change rate (blue, left axis [h^{-1}]) based on the damper positions from Fig. 3 and using the average air leakage (0.08 h^{-1}) at low operation and 5.4 h^{-1} (see text) at high operation. The simulated mean age of the air (red, right axis [h]) using Eq. 6 is shown for the same room and period.

The time variation of the air change rate is shown in Fig. 5 and the average value for the period, calculated based on the damper positions (see Fig. 5), was 1.1 h^{-1} as shown above. The mean age of air varied logarithmically with time. After the weekend, the mean age of air was at a maximum (12.5 h) determined only by the leakage of the building. During the working week the mean age of air during the day was low and increased logarithmically towards (but not fully reaching) the maximum value. Integrating the mean age of air over time will correspond to a measurement by passive integrative sampling methods. For the period displayed in figure 5 the average mean age of air became 6.0 h, which is surprisingly close to the actual measurement by the HEM passive sampler (5.8 ± 0.6 h).

4 DISCUSSION

The HEM is based on the linear relation between the local tracer gas concentration and the local mean age of air. Since the amount of tracer gas collected by a passive sampler is linearly related to the local concentration, we expect that the total collected amount can be accurately transformed to represent a time average of the mean age of air. This is corroborated by the results reported from the simple simulation in Fig. 5. For the air change rate we are not as lucky, in this measurement, as shown by the discrepancies by the different estimates above. Firstly, it is important to realize that the relationship stating that the air change rate is the inverse of the average age of air is defined at steady state conditions. Secondly, the nonlinear relationship (inverse) poses fundamental problems when average values are used. This problem has been discussed previously (Stymne and Boman, 1997; Nazaroff, 2009). Using the mean age of air to estimate the air change rate becomes more problematic when the mean age of air fluctuates wildly. The main reason is that the total amount of tracer collected by the samplers show a strong information bias towards periods with high concentration of tracer, i.e. the average mean age of air is biased towards periods with little ventilation and older air. This is typically shown by our example (with two ventilation rates differing with a factor of 67) in figure 5, where the average mean age of air is close to half of the maximum. In the case of large differences between the ventilation rates, the information from the periods of high ventilation rates is in fact drowned by the dominance of the periods with low ventilation rates (Stymne and Boman, 1997). The average of the air change rate is instead, because of the inverse relationship, biased towards periods with high ventilation rates. This is the heart of the problem. On the other hand, in cases where the fluctuations of the mean age of air around an average are normally distributed the error using the inverse of the average mean age of air to estimate the average air change rate is usually within the standard error of the measurement (Stymne and Boman, 1997). In general, the same problem applies to all passive integrative sampling of concentrations that will be used in nonlinear relationships.

The overall purpose of our project is to assess the energy use in the building, using audit observations, drawings, energy bills and measurements of variables to be used as inputs to a building energy simulation calculation tool. After validation of the model, it would serve to study the impact of energy conservation measures and economic consequences. In this type of a building, the ventilation rate and air leakage usually plays an important role in energy use. Measurement results show that the average leakage ACH of the building corresponds to about 0.12 h^{-1} (Steen Englund et al., 2015). According to design values, full operation in the entire building involves an ACH of 2.36 h^{-1}, but only some 70% of the facilities are in use during a working day. Ventilation losses (after heat recovery of 70%) correspond to ACH 0.13 h^{-1} (that would not pass through the heat recovery exchanger). Air leakage adds on to ventilation heat losses with about 90%, i.e. induces the same quantity of heat losses as the ventilation system. It is estimated that losses from ventilation and air leakage together account for approximately 20% of the buildings thermal energy use, where the cost of heating infiltrating air is annually 5300 US$ (1.15 US$ /m²) or 4900 Euro (1.06 Euro/m²).

Considering the importance of ventilation and air leakage, the measurement problems discussed above had to be addressed. Determining the local air leakage in different zones of the building, with the ventilation turned off, could accurately be performed using passive samplers. During mixed operation only the averages for the local mean age of air were accurate to use in the comparison between different zones (Steen Englund et al., 2015). To assess the air change rates during mixed operation, we propose a partial solution where the day and night are sampled separately. Daytime operation, being an active time where the damper position usually is open, represents an estimation of the high air change rates. During the night the damper is nearly always closed and represents an estimation of the low air change rates. We have accomplished the separate sampling of the day and night using a home-built, programmable, low-flow pump and the detailed results of this study will be submitted elsewhere. While the problem of transients still remains, the two populations of air change rates are sampled more appropriately. Evidently, there is a logistic drawback since the required number of samplers is doubled for the proposed scheme.

5 CONCLUSIONS

When air change rates between different modes of operation of the ventilation system vary a lot, the average local mean ages of air can be accurately measured by passive samplers using the homogeneous emission method. Estimation of the average room specific air change rate by thoughtlessly taking the inverse of the measured average local mean age of air does not give correct results. A partial solution to the measurement problem is to actively sample the different populations of air change rates separately.

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