VENTILATION AND COOLING

18TH ANNUAL AIVC CONFERENCE, ATHENS, GREECE, 23-26 SEPTEMBER, 1997

Air distribution in an office building as measured with a passive tracer gas technique

by

Hans Stymne[1] and **CarlAxel Boman**[2]

only during occupation

Begrip: "average mean age of air"

[1]Royal Institute of Technology
Department of Built Environment
P. O. Box 88
S-801 02 Gävle, Sweden

[2]Pentiaq AB
P. O. Box 7
S-801 02 Gävle, Sweden

Synopsis

A passive tracer gas technique - the homogenous emission technique was utilised for measuring the air distribution in a part of an office building with displacement ventilation. Measurements were made during one winter period and one summer period. During the winter period the ventilation was run continuously, while on/off regulation was used during the summer period. The result from the winter measurement shows that the displacement effect was satisfactory but less pronounced close to the window-side of the office.

The paper discusses the effect of on/off ventilation strategy on the requirement of the measurement technique and the implications of such strategy on air quality. It is shown that the homogeneous emission tracer gas technique yields the true average mean age of air, also during transient conditions, but that special precautions must be taken when using intermittent sampling of the air.

1. Introduction

In most mechanically ventilated commercial buildings, the ventilation is varied depending on the occupancy. Usually ventilation is run in only two modes - on and off. During occupancy the ventilation is on, while it is off during nights and weekends. This type of operation has certain consequences on how to perform and interpret a ventilation measurement experiment and also affects the air quality during occupancy hours.

In the present paper, we present the result of ventilation measurements during two periods in the same office building. During the first measurement period, the ventilation was run continuously, while during the second period, ventilation was running only from 5 a.m. to 6 p.m. at weekdays.

In the first part of this paper, we discuss some general implication of varying flow rate on the measurement technique. In the second part we present the measurement and discuss the result in view of this general implications. Lastly, we discuss the effect of varying ventilation flow rate from an air quality and health aspect.

1.1 Measurement technique and varying flow rate.

The technique used in this work is a variant of a passive tracer gas technique called the *homogeneous emission technique*. This technique has been discussed in several recent papers (Stymne *et al.* 1992, Stymne 1994, Stymne and Boman 1994,1996). In essence, small passive tracer gas sources emitting a perfluorocarbon tracer (PFT) at a constant rate are distributed in a building in such a way that the emission is approximately homogeneous, which means that the emission rate per volume unit (S) is constant throughout the building space.

If the tracer emission is homogeneous, it has been shown (Sandberg and Sjöberg 1994, Stymne *et al.* 1994) that the local steady state concentration of tracer gas (C_p) will be directly proportional to the local mean age of air ($\bar{\tau}_p$), and that a measurement of local concentrations thus will yield estimates of the local mean ages of air and their distribution in space according to equation 1.

$$\bar{\tau}_p = \frac{C_p}{S} \quad (1)$$

One advantage of using the homogeneous emission technique is that the local mean age of air is a good air quality indicator. Many continuously emitting contaminant sources can be considered more or less homogeneously distributed in the building space and the local contaminant concentrations will therefore be proportional to the local mean age of air.

The measurement of the local tracer concentration is performed by use of passive diffusive samplers, distributed in the building. The passive samplers sample the air during an extended time and thus yield time integrated values of the concentrations.

A problem may arise when the ventilation rate and thus the mean age of air changes during the measurement period. The steady state assumed in eq. 1 will in such a case not be valid all the time.

However, the validity of eq. 1 is not limited to the steady state case. If there is a homogeneous emission of tracer, the instantaneous local concentration will always be proportional to the local mean age of air, even during transient conditions, for example such as appear when the ventilation rate or flow patterns change from one value to another. No formal proof of this statement will be made here, only a rather intuitive indication of the correctness of this statement, when the tracer emission is truly homogeneous (a similar picture was presented by Sandberg and Sjöberg (1983)).

The air around a point in space can be considered as composed of air entities equal in volume having spent different times in the building i. e. having different ages. The ensemble of air entities around the point have a certain distribution of ages, with a mean value corresponding to the local mean age of air. As the air entities find their way from the inlet to the point in question, they travel through regions each emitting a constant amount of tracer per time unit and volume unit. As the air entities having equal volume, they will carry with them an amount of tracer, which is proportional to the time they have spent indoors. Thus the volume around a point can also be considered as an ensemble of air entities having different tracer concentrations. As the concentration of each entity is proportional to its age, the mean concentration of air around the point must be proportional to the mean age of air at that point. This reasoning is independent of whether a steady state is reached or not. The only suggestion made is that the tracer emitted from the sources is carried away with the air passing the tracer source. This is a reasonable suggestion, because there exists no other carrier for the tracer than the air.

Thus, as the tracer concentration is proportional to the instantaneous local mean age of air in a homogeneous emission experiment, integration of the local concentration over time yields a measure of the average of the mean age over that time. This is an important conclusion because it means that one can perform an integrating sampling during times when people are present and get a fair estimate of the air quality, which the occupants are exposed for. If a measurement of the mean age of air instead is performed with tracer release only during the occupancy time, this could result in a misleading value, because very old air remaining from a low night ventilation rate remains a considerable time during daytime, increasing the average mean age of air well above the steady state value of daytime ventilation.

It is difficult to exactly calculate the transients of mean ages when a ventilation system changes between two flow rates in the general case of incomplete mixing. However, if the local mean ages do not differ very much from zone to zone, it is reasonable to make the approximation that after a step change in ventilation, the concentrations approach the eventual new steady state values (C_{2e}) exponentially with a time constant close to the new steady state mean age of air (τ_2) according to eq. 2.

$$C - C_{2e} = (C_1 - C_{2e})e^{-\frac{t}{\tau_2}} \qquad (2)$$

where C_1 is the concentration at the moment when the ventilation was changed (t=0) and C_{2e} is the eventual new steady state concentration.

Using this approximation it is possible to analytically calculate the time dependency of the tracer concentration. In figure 1 the computed time history under the assumption of a cyclic change between two different ventilation states are displayed.

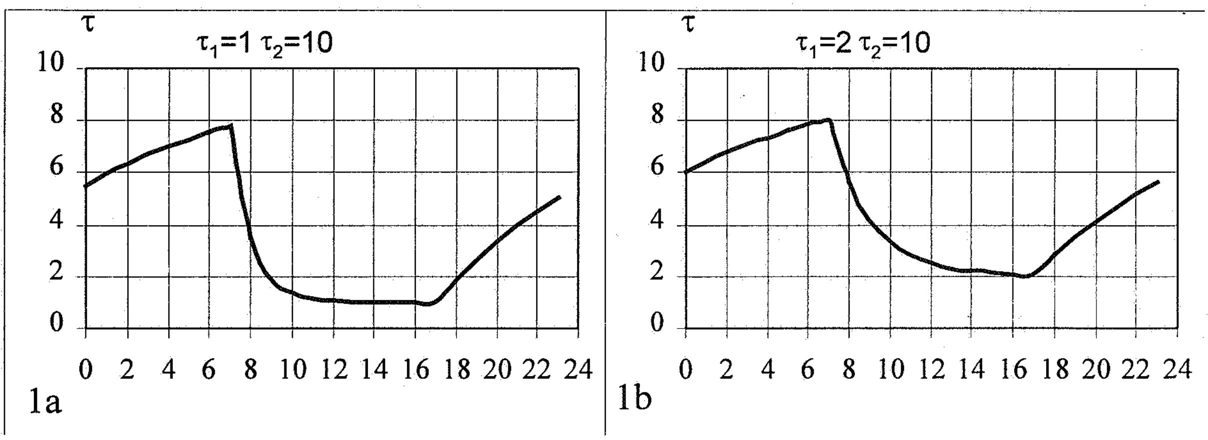

Figure 1. Display of the variation of the mean age of air, when the ventilation is cyclically changed between two modes, characterised of steady state mean ages of air τ_1 and τ_2 respectively. Mode 1 run between 7 a.m. and 17 p.m. and mode 2 during the rest of the day.

2. Description of the building and ventilation system

The investigated object is a part of an office building. The building was recently converted from an old naturally ventilated factory space into a modern office space with mechanical ventilation.

One part of the office building including 20 office modules (7 m^2 each) and 180 m^2 open area was investigated. The office modules consists of "boxes" along the walls of the space, leaving a corridor of approximately 3 m width between the two rows of office modules. The boxes, which are 2.10 m in height and open upwards have glazed walls with glass slide doors towards the corridor. The lower part of the glass walls are equipped with a steel mesh to allow air flow from the corridor into the boxes. The slide doors are normally left open by the occupants.

Ventilation air is admitted with under-temperature to the corridor with low velocity air supply devices. The return air is withdrawn at a few points close to the ceiling. It was suspected that the ventilation air may not easily penetrate to the office modules.

The ventilation is normally run only between 5 a.m. to 6 p.m. on weekdays. All other times the ventilation is off.

3. Experimental layout

3.1 Experiment 1

This experiment was performed during one week of cold winter conditions. During this experiment, the ventilation was run continuously at the same rate, day and night and weekend. This was made in order to be able to use integrating sampling during an extended period at approximately the same conditions which is valid during work hours.

Approximately 70 passive tracer gas sources were evenly distributed in the space to approximate a homogeneous emission. Approximately 50 samplers were distributed along the corridor and in some of the office modules at different heights in order to measure the local mean ages of air at different points. Samplers were also positioned close to air extract points.

3.2 Experiment 2

The second experiment was performed in the same object during summer conditions. The ventilation was run in its normal mode, which means that the ventilation is operating only on 13 hours each weekday.

The tracer gas sources were distributed in approximately the same patterns as in the first experiment. However, the number of sources were tripled to yield a higher emission rate in the space.

Approximately the same numbers and positions of passive samplers were also distributed in the space as in experiment 1. These samplers were left to sample the air continuously during 2 weeks i. e. also during hours with no mechanical ventilation.

However, a few additional diffusive samplers, which were electronically opened and closed were also positioned in the space. The latter samplers were meant to sample air only during 8 work hours during 5 days. As can be seen in the result and discussion sections of this paper, this part of the experiment was not entirely successful. However, the conclusions are valuable and worthwhile to report here.

4. Result

4.1 First experiment

In figure 2 the result from the first experiment is displayed in graphical form on a schematic plan of the office. The bars displayed in the plan, represent the local air change indices, i. e. the ratio between the mean age of the extract air and the local mean age of air. The lower lighter parts of the bars represent a unit air change index, that is the air change rate, which would have been expected if the ventilation had been of fully mixing type. The mean age of air at the extract point was determined to be 0.95 hours, which corresponds to an air change rate of 1.1 ACH.

As can be seen there is a pronounced displacement effect in the office. It is obvious that the displacement type of ventilation functions satisfactory. The computed total ventilation rate (1203 m^3/h) is close to the design value (1100 m^3/h).

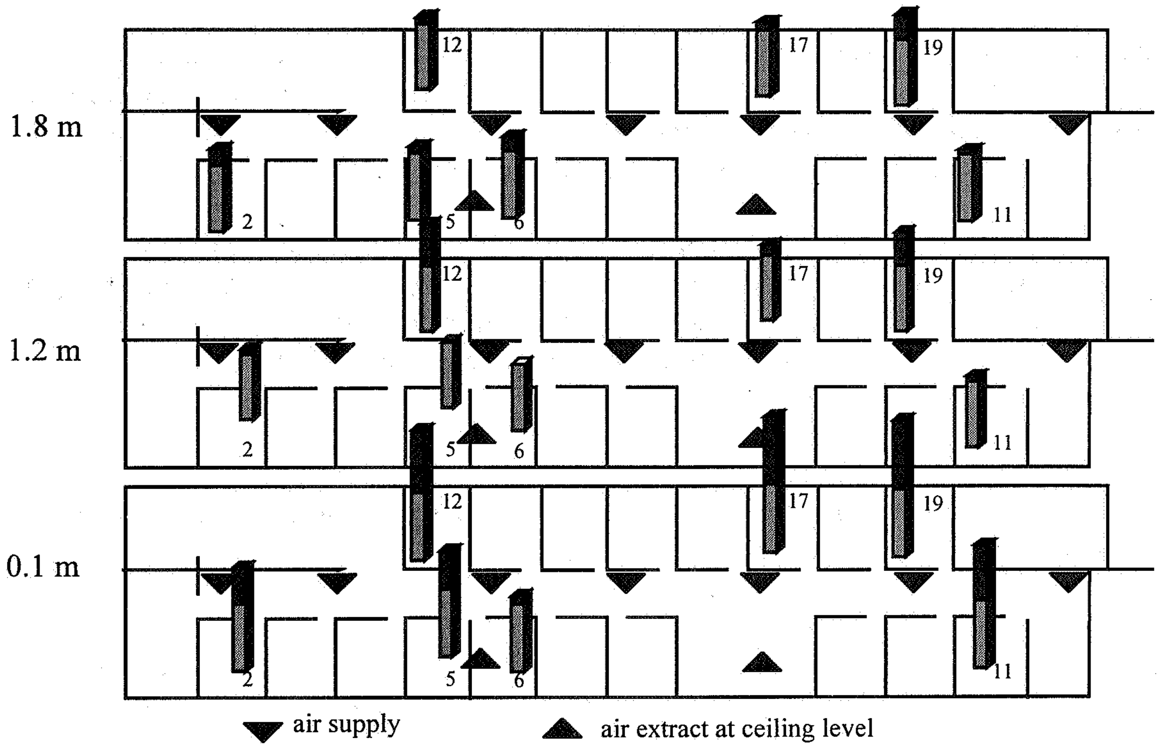

Figure 2. Plan of the office, showing the estimated local air change indices at different heights above the floor. The lower lighter part of the bars represents the air change rate corresponding to the air extract point, while the upper darker part of the bars represent the ventilation in excess of that which would be obtained with mixing ventilation.

4.2 Second experiment

4.2.1 *Continuos sampling.* During the second period, when the ventilation was run only between 5 a.m. to 6 p.m. on weekdays, integrating sampling during 14 days yielded local mean ages, which varied very little with the positions and height of sampling. Table 1 shows the computed mean ages of air. It is to be observed that the mean ages are computed from the total integrated sampling during the whole period and thus corresponds to an average of the mean age over that time. It is also to be noted that the computed mean age is significantly higher at the extract point than in the occupation zone. However, as there is no mechanical ventilation 61% of the total time the air at the extract point is not representative for air leaving the office.

Table 1. Estimated local mean ages [h] of air -averages over the whole period (337 hours).

	0.1 m	1.2 m	1.8 m	extract
rooms	4.5±0.4	4.8±0.3	4.8±0.4	5.7
corridor	4.7 ±0.3		5.0±0.3	

As can be seen from the small difference between different heights, there is no tendency of air stratification typical for displacement ventilation.

<u>4.2.2</u> *Programmed sampling*. Programmed sampling was also performed at a few points in the office. The microprocessor controlled closing device was programmed to open the sampling tube at 8 a.m. and close it at 4 p.m. during 5 workdays. The result from the programmed sampler showed an average mean age of 1.5 hours.

5. Discussion.

5.1 First experiment.

The result (figure 2) shows that there is a marked tendency of stratified flow, typical for displacement type of ventilation. However, the different rooms are not equally well ventilated. Rooms no. 12, 17 and 19 on one side of the corridor are considerably better ventilated at breathing height (1.2 m) than rooms on the other side of the corridor (rooms no. 2, 5, 6 and 11). The latter rooms show mean ages close to that which can be expected with mixing ventilation. A plausible explanation is that these latter rooms are located along the window wall, while the former rooms are arranged along an internal wall. The cold window surfaces will create a mixing convection on that side of the office.

The total air change rate (total volume divided with the mean age of air at the extract point) is 1.1 ACH, which is close to the design value, but must be considered to be rather low for an office.

5.2 Second experiment

<u>5.2.1</u> *Continuous sampling.* As discussed in the introductory section integrating sampling in a homogeneous emission tracer gas experiment will yield an average of the local mean age of air during the sampling time. In the present case the ventilation was operating at its design flow rate 13 hours each weekday (totally 130 hours) and was off rest of the time (207 hours). In figure 3 the computed variation of mean age of air during the exposure time is displayed, assuming 1 ACH during the operation hours and 0.1 ACH during the non-operation hours. A further assumption is the exponential approach towards steady state conditions as discussed in the introduction.

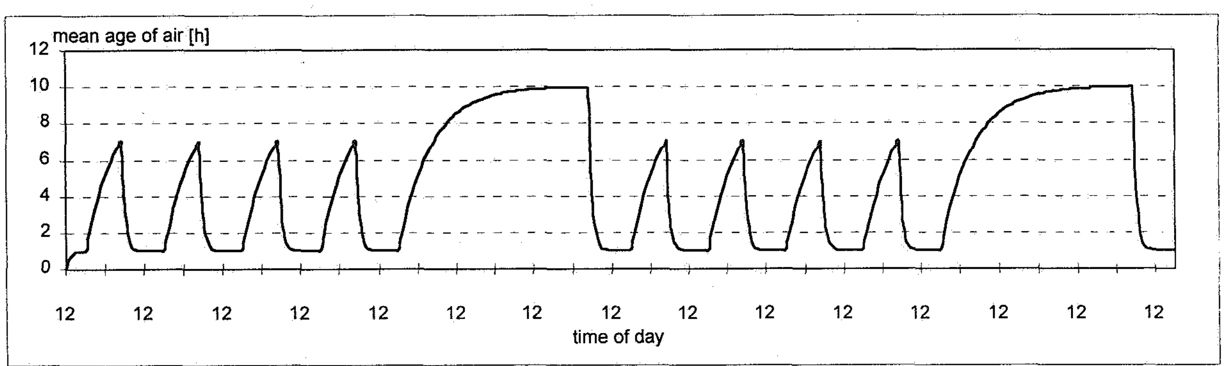

Figure 3. Computed time variation of the mean age of air assuming 1 ACH during operation (5 a.m. to 6 p.m. weekdays) and 0.1 ACH during off periods.

The average of the mean ages displayed in figure 3 is 4.7 hours, close to the value estimated from the integrating samplers in experiment 2. The value 1 ACH for the work hour ventilation rate was chosen from the result of experiment 1. However, the same result for the average mean age can be obtained for other combinations of on/off ACHs. Figure 4 displays the possible combinations of on/off ACHs yielding the same average

.

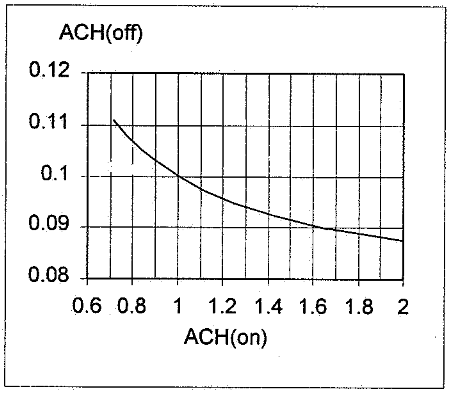

Figure 4. Relationship between ACHs with mechanically ventilation off and on respectively, in order to achieve an average mean age of air of 4.7 hours during a fortnight (13 hours on-mode each weekday).

It is noted from figure 4 that the result is very insensitive to variations in ACH(on), but very sensitive to variations in ACH(off). Whatever value for ACH(on) we choose in the interval 0.6 to 2 the ACH(on) must be around 0.1 in order to yield the measured integrated value. Thus we can conclude from this experiment that the air change rate during *operation-off* hours is approximately 0.1 [h^{-1}] corresponding to a steady state mean age of air of 10 [h]. However, we can not even guess the ventilation during *operation* hours from continuous integration data. It is necessary to have other supplementary information. Such supplementary data can for example be obtained from integrated sampling only during work-hours.

The aim of this experiment was also to test such sampling, the result of which is discussed under next heading.

<u>5.2.2</u> *<u>Programmed sampling</u>*. The device for the electronic open/close mechanism for the passive sampler was programmed to open the sampler tube from 8 a.m. to 4 p.m. during 5 workdays (totally 40 hours). The result showed an average age of air during this time of 1.5 hours.

Assuming the air change rates 0.1 [h^{-1}] and 1 [h^{-1}] for non-operation and operation hours respectively, we can calculate the theoretical average of the mean age of air during the opening time of the device. This amounts to 1.02 hours. Thus the result is not very encouraging. The discrepancy could of course be explained if the ventilation rate is lower during daytime, than we assumed (0.67 ACH instead of 1 ACH). However, such a low ventilation rate is not very likely. Instead, we suspect a leakage through the sampler sealing during the closed periods. The concentration is high during these periods, and time in closed conditions is long compared to that in opened conditions.

A simple calculation (figure 5) shows the effect which a small leakage may have on the computed mean age. The leakage is defined as the air sampling rate of a closed tube in relation to that of an open tube.

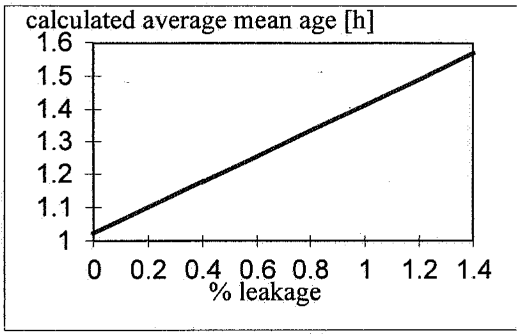

Figure 5. Effect of small leakage in the sealing of the sampler tube during closed conditions.

It is obvious that even small leaks during the closed condition of the programmed sampler tube have a deleterious effect on the result during the extreme conditions (high ACH(on)/ACH(off) ratio and short open compared to closed time) during this test. The erroneous result in the present test can be explained by a leakage of only 1.2%. Work is in progress to secure a 99.9 secure seal.

5.3 Air quality implications

As can be seen from figure 1, the local mean age of air, will only slowly attain the steady state value after a step change to a higher ventilation rate. The higher the ventilation rate, the quicker is the old air exchanged. Conditions according to figure 1a, will yield a 30 % extra contaminant dose for people present from 8 to 17, while the conditions according to figure 1b, yields a 90% extra dose during the same time, compared to the dose expected at constant ventilation rate.

6. Conclusions

The average local mean age during the occupation time in an office is suitable as an air quality indicator. It is concluded that the homogeneous emission tracer gas technique using passive tracer gas sources and integrating diffusive samplers is a convenient and satisfactory technique for measuring the average local mean ages and their distribution. However when the mechanical ventilation is intermittent or varied, special precautions must be taken when sampling only during occupancy hours. It is very important that the samplers are tightly sealed during non-sampling periods. This is especially true, when there is a large difference in ventilation rate, between sampling and non-sampling periods. Lower demand on tightness is required for example in naturally ventilated buildings, than in tight mechanically ventilated buildings with on/off regulation of ventilation.

On/off regulation of mechanical ventilation increases the mean age of air a considerable time after switching on ventilation in the morning. Examples are given, which may increase the integrated day-dose by 30-90% over that expected with constant ventilation rate.

It is shown that the displacement ventilation yields a satisfactory air stratification in part of the office, also during strong winter climate conditions. However, work stations close to the window wall, shows a mixed ventilation behaviour, probably due to air convection flows along the cold wall.

6. Acknowledgement

Financial support for this work was supplied from the National Swedish Building Research Council, which is gratefully acknowledged. The authors also wish to thank Mrs Anita Eliasson and Mr Jörgen Sundberg for laboratory and field assistance and prof. Mats Sandberg for valuable discussions.

7. References

Sandberg, M., Sjöberg M. 1983. The use of moments for assessing air quality in ventilated rooms. Building and Environment **18**, 181 [1983].

Stymne H, Sandberg M, Holmgren O. 1992. "Ventilation measurements in large premises". Roomvent '92. Proceedings of the Third International Conference on Air Distribution in Rooms, Aalborg, Denmark Vol. 2, p 33-47

Stymne H. 1994. "Method to determine local mean ages of air and air exchange efficiency in large buildings and buildings with many rooms". NT Technical Report 321 NORDTEST, Finland

Stymne H, Boman CA. 1994. "Measurement of ventilation and air distribution using the homogeneous emission technique - A validation". Healthy Buildings '94, Proceedings of the 3rd International Conference, Budapest, Hungary, Vol. 2, pp 539-544

Stymne H, Boman CA. 1996. "Application of a passive tracer gas technique in naturally and mechanically ventilated school buildings". Proceedings of the 17th AIVC-conference - Optimum ventilation and Air Control within Buildings Gothenburg, Sweden September 1966 Vol 1, pp 283-492

Stymne H, Boman CA. 1996. Determination of air distribution patterns in large premises - application examples of the homogeneous emission technique. Proceedings of ROOMVENT'96 - 5th International Conference on air distribution in Rooms Yokohama, Japan, July 1996 Vol 1, pp 485-492