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APPLICATION OF A PASSIVE TRACER GAS TECHNIQUE IN NATURALLY AND MECHANICALLY VENTILATED SCHOOL BUILDINGS.

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Application of a passive tracer gas technique in naturally and mechanically ventilated school buildings.

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SYNOPSIS

The homogeneous emission passive tracer gas technique is described. This technique relies on an even distribution of constant tracer gas emission rate within the object to be measured, so that the emission rate per volume unit is constant. The local steady state concentration of the tracer gas is directly proportional to the local mean age of air and the emission rate per volume unit.

The technique was applied in 10 school buildings, of which 4 were newly constructed naturally ventilated buildings, 2 were old naturally ventilated buildings, 2 were old mechanically ventilated buildings and 2 were newly constructed supply and exhaust ventilated buildings.

The result shows that the ventilation rates in naturally ventilated schools are relatively low compared to required standards. It demonstrates the importance of not only rely on the naturally induced ventilation rate, but also to use other means for improving the air quality during or between lessons, like window opening.

1. BACKGROUND

There is much concern about the air quality in school buildings in Sweden. One reason for this is the rapidly increase in the number of school children suffering from allergy and other hypersensitivity. Another reason is that the air quality often is quoted unsatisfactory by pupils and teachers. Many school buildings are therefore now retrofitted with new, more efficient ventilation systems. Another trend is to try "natural" ventilation principles even in newly constructed school buildings.

The most popular technique to estimate the air quality in schools, is to perform measurement of the carbon dioxide concentration during lessons. At present, regulations in Sweden, state that the carbon dioxide concentration in rooms, where the major part of contaminants emanates from people, must not exceed 1000 ppm on a regular basis. In a room, which is only ventilated with outside air, this means that the flow rate of supplied outside air must be 7-8 litres per second and person.

However, it is difficult to draw conclusions about the ventilation rate and the distribution of ventilation air in a school building only from measurement of carbon dioxide concentration. There are a number of reasons for that:

- Carbon dioxide concentration tend to be very fluctuating in time
- Concentration varies in space - measurement position is critical
- Steady state concentration is often not attained during a lesson
- Emission rate per person is uncertain and varying
- Window and door opening influences the dilution of carbon dioxide
- Equipment cost prevents simultaneous measurement in many rooms

In order to evaluate the ventilation rate and air distribution in school buildings as offered by the ventilation system and the building itself, measurements were carried out with a passive tracer gas technique during an extended time. Thus the result is not necessarily typically for periods of lessons, when the ventilation rate can be appreciably enhanced due to window opening and other circumstances.

2. THE LOCAL MEAN AGE OF AIR

A convenient choice of ventilation parameter to describe the air distribution patterns is to use the concept of "local mean age of air". Until recently it has been difficult to map the distribution of local mean ages of air in large enclosures and other large premises. The "homogeneous emission technique" is a relatively new tracer gas technique which allows a detailed mapping of local mean ages of air also in large premises.

The mean age of air has a close connection to "classical" ventilation quantities such as *Specific Ventilation Flow Rate*, often known as *"Air Change Rate"* (ACH) . The mean age of air leaving a building ($\bar{\tau}_n$) is equal to the inverted value of the *Specific Ventilation Flow Rate.*

3. MEASUREMENT TECHNIQUES

3.1 Conventional Techniques

The local mean age of air can only be measured using tracer gas. In the *decay* technique, all air in the ventilated system is to initially be marked to the same concentration (C(0)) with tracer gas. By following the dilution process $C(\tau)/C(0)$ as a function of time and integrating this function from $\tau=0$ to $\tau=\infty$ the average age of air at the measurement point is obtained.

There are several difficulties in the practical application of the decay technique in large buildings and buildings with many rooms. The most obvious one is that it is very difficult to achieve the necessary uniform initial concentration of tracer gas. Other difficulties are connected to sampling and analysing air from many positions in a large building

There is another important technique called the *step-up* technique, which however only can be used in mechanically ventilated buildings with a central air supply duct. In this case the tracer gas is injected at a constant rate in the supply duct and the local build-up curves of concentration are recorded. The technique is equivalent to the reverse of the decay technique and a necessary condition is that the final concentration is equal everywhere in the system. Any diluting air entering from e g infiltration will contribute to errors.

3.2 Homogeneous Emission Technique

Determination of the local mean age of air using the *homogeneous emission technique* relies on the fact that the local steady state concentration of a contaminant which is homogeneously emitted in a space is directly proportional to the local mean age of air. Homogeneous emission means that the source is continuously distributed in the space with equal emission rate per volume unit everywhere. This relationship has been shown by Sandberg (1984), and is also mentioned in the introduction to a NORDTEST (1988) method to measure the local mean age of air, but has not been utilised for development of any measurement technique until recently (Stymne *et al.* 1992, Stymne & Boman 1994, Walker *et al.* 1994, Stymne 1995).

A standardised method for measurement of local mean ages of air in large buildings and buildings with many rooms using the homogeneous emission technique has recently been proposed to NORDTEST (Stymne 1995).

3.2.1 Description of the homogeneous emission technique.

The basic principle of the homogeneous emission tracer gas technique is to inject tracer gas at a constant rate in all parts of a zone divided building, so that the tracer injection rate in each zone is proportional to the zone volumes. The local steady state concentration (C_p) will be equal to the tracer injection rate per volume (S/V) multiplied with the local mean age of air($\overline{\tau}_p$). Therefore the local mean age of air can be obtained from a measured local tracer concentration.

$$\tau_p = \frac{C_p}{S/V} \qquad (1)$$

The proposed NORDTEST-method (Stymne 1995) to measure local mean ages of air involves a technique to distribute inexpensive so called *passive tracer gas sources* in the building to be investigated, in order to approximate a homogeneous emission. In multi-room systems a natural choice of zones, is to consider a room of normal size as one zone, while larger rooms must be further sub-divided into several zones. In each zone a tracer gas source is positioned. In practice it is in most cases not possible to make all zones equally large due to varying room sizes. Therefore, the development of adjustable passive tracer gas sources was an important task of the technique. In the present investigation adjustable passive tracer gas sources of capillary type emitting $1\text{-}2 \cdot 10^{-5}$ g/h of a perfluorocarbon compound (PFT) were used.

The measurement of local concentrations can be performed either using pumped sampling or "passive" sampling. Both rely on adsorption of tracer gas on a charcoal sampling tube, for later analysis with gas chromatography at a specialised laboratory. In the present work passive sampling with diffusion tubes was performed.

The air sampling is performed only in those spaces, where it is interesting to know the ventilation, while tracer gas emission must be made in the whole ventilated system.

Validation of the homogeneous emission technique using adjustable passive tracer gas sources has been performed in a single family house (Stymne and Boman 1994).

One main advantage with the homogeneous emission technique, using passive tracer gas emission is that it can easily be applied also in large buildings at a moderate expense, where other techniques are inconvenient and expensive. The technique has recently been applied in 4 relatively large objects of 1200 m^3 -13500 m^3 (Stymne and Boman 1996).

4. DESCRIPTION OF THE SCHOOL BUILDINGS

10 different school buildings as indicated in the TABLE 1 below were investigated. The buildings are marked with Nn1-Nn4 for newly constructed naturally ventilated buildings, No1-No2 for older naturally ventilated schools, Mo1-Mo2 for older mechanically exhaust ventilated buildings and Mn1-Mn2 for newly constructed exhaust and supply ventilated buildings.

Most buildings are equipped with mechanical extract from the rest rooms.

TABLE 1. Some characteristics of the investigated school buildings.

Notation	year of construction /year of retrofit	ventilation system	possibility of forced ventilation *	total volume m^3	number of class/ group rooms	number of floor levels
Nn1	1993	naturally	m/c fan	850	4	1
Nn2	1992	naturally	m/c window	1300	6	1
Nn3	1993	naturally	a/c duct	2100	9	1
Nn4	1994	naturally	m/c window	2300	11	1
No1	~1910/1993	naturally	a/c fan	5000	18	3
No2	1925/1995	naturally	a/c fan	6000	32	4
Mo1	1932/1993	exhaust		1600	8	2
Mo2	1940/1993	exhaust		1700	19	3
Mn1	1995	exh./suppl.		350	6	1
Mn2	1995	exh./suppl.		1300	8	1

**m/c = manually control, a/c=automatic control (temp. or CO_2). Mechanically ventilated systems are run at a 24-hour basis during the experiment.*

5. DESIGN OF THE INVESTIGATION

In all school buildings the whole building space was investigated. In each building a "reference" volume corresponding to the smallest room of importance was decided on. Closets and other small spaces was not treated as separate zones but was normally included in the volume of a larger adjacent zone. The reference volumes varied between 15 m^3 and 120 m^3 in the different buildings. The number of reference volumes of each room decided the number and adjustment of tracer gas sources. Two reference volumes corresponds to one un-adjusted source. The number of tracer gas sources in a room varied from one to six. The total number of tracer gas sources in a building varied from 14 in the smallest school (334 m^3) to 94 in the largest school (6000 m^3). The homogeneous emission rate varied from 0.1μg/h,m^3 to 0.7 μg/h,m^3 in the different buildings.

The sources were normally mounted 2 cm from the walls at a height of 1.7 m above the floor. If there were several tracer gas sources (e. g. in large class rooms) they were evenly distributed in the room space.

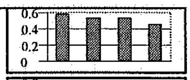
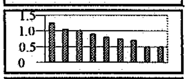
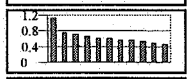
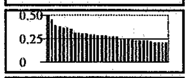
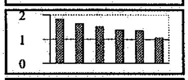
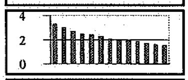
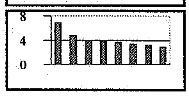
The average room temperature was recorded in all class rooms and in other spaces of importance. Passive samplers were distributed in the important occupational zones. Usually, two or more samplers were positioned in each class room - one always at a central position and sometimes at the teachers desk, at a pupils desk or close to an exhaust air device. The sampling tubes were continuously open during the measurement period, day and night and weekends.

In the naturally ventilated school buildings any possibilities to force ventilation during school hours (e. g. through window airing) could be used without restrictions during the measurement period. In the mechanically ventilated buildings, however, where the ventilation system normally are operated at a reduced level during "off-school" hours, the ventilation was continuously running (on a 24 hours basis) at day-time mode during the whole measurement period.

6. RESULTS

A summary of the results of measurements of the ventilation flow rates and the air distribution is given in TABLE 2.

TABLE 2. Results from the measurement

Notation	measurement time [h]	total ventilation rate [m^3/h]	total volume m^3	specific flow rate [ACH]	distribution of ACH
Nn1	672	428	850	0.50	
Nn2	1040	592	1300	0.47	
Nn3	575	1379	2100	0.66	
Nn4	670	1348	2300	0.58	
No1	761	3630	5000	0.73	
No2	190	1769	6000	0.29	
Mo1	1368	2025	1600	1.25	
Mo2	1367	3654	1700	2.13	
Mn1	334	938	350	2.75	
Mn2	360	4885	1300	3.86	

The primary result of the measurement yields the local mean age of air in the different locations. However, in TABLE 2 we have chosen to present the results as the inverted values of the local mean ages of air - here called "ACH", though the ACH-concept (Air Change Rate per Hour) is not as well defined for a local space as the mean age of air. Strictly, the inverse of the local mean age of air is equal to ACH, only in the exhaust air.

The column showing the specific flow rate refers values computed from the inverse of a volume-weighted average of local mean ages over the whole building space, while the column "distribution of ACH " only displays values obtained from a selection of class rooms and other important study-rooms.

7. DISCUSSION

7.1 Ventilation rate

The result shows that the ventilation rates in naturally ventilated schools are relatively low compared to required standards. It demonstrates the importance of not only to rely on the naturally induced ventilation rate, but also to use other means for improving the air quality during or between lessons, like window opening.

7.2 Air distribution

The result also shows that the measured air distribution is uneven in most of the schools. This result stresses the importance on not only to measure the total ventilation rate or an average of the air change rate in a building, but also to measure local ventilation parameters, like the local mean age of air.

The technique which is applied in this work - the homogeneous emission technique, has the advantage over most other constant emission techniques, in that it can yield a true picture of the air distribution. Using a well designed homogeneous emission technique, the differences in the steady state concentration of tracer gas at different locations are not caused by an uneven injection of tracer gas. Instead it reflects an uneven distribution of ventilation air. The reliability of the result is mainly depending on the success of achieving a homogeneous distribution of tracer gas emission rate in the whole building.

By the use of adjustable tracer gas sources and rather small subdivisions of room volumes the differences in the homogeneity of tracer gas emission rate was kept rather low, seldom exceeding 10%.

7.3 Measurement uncertainty

In addition to the uncertainty of measured local mean ages of air caused by incomplete homogeneity of tracer gas emission rate there are uncertainties due to *a)* variations in the emission rate of tracer gas sources (~5%), *b)* variations in uptake rate of samplers (~5%), and *c)* analysis uncertainty (~3%). By using several sources and samplers the uncertainty of the mean value decreases. A systematic error due to the difficulties of performing exact calibrations of uptake rate, emission rate and analysis can not be excluded, but is believed to be less than 5%. In the present case, an estimate of the total uncertainty of a local value is 15%, while the uncertainty of mean values of the whole building is estimated to be less than 10%.

7.4 Remarks on the effect of measurement time

The purpose of this investigation was to measure the ventilation performance of the buildings, during an extended time, in order to cancel out short term variations of the ventilation rate due to occupant habits, like window opening and other means of affecting the ventilation. The buildings were occupied approximately 20-25% of the measurement time. The measured average ventilation rate was therefore only marginally affected due to measures taken during the periods of occupation. The local mean age of air is computed from the average concentration of tracer gas during the measurement time. The instantaneous concentration is approximately inversely proportional to the ventilation rate. If we, for example, assume a ventilation rate of Q_n during non-occupation periods (75% of the time) and Q_o during occupation periods (25% of the time), the measured average concentration will be proportional to $(0.75/Q_n+0.25/Q_o)$. If we now assume that the ventilation rate is doubled during the occupation periods compared to the non-occupation periods, the average concentration will be proportional to $(0.75+0.125)/Qn = 0.875/Q_n$. Thus, the measured mean age of air will be only 12.5% smaller than that for the non-occupied periods, even if the occupants can double the ventilation rate.

Consequently, the measured ventilation performance is rather close to that, which the building and service system can yield, and only little affected by the occupants' behaviour.

In the mechanically ventilated buildings, the ventilation is normally drastically reduced at non-occupation time. However, for the purpose of continuous measurement over an extended period, such reduction was not performed during the measurement. Thus, also in this case, the measured ventilation performance is typical for what the building and service system can offer.

It would of course be desirable to be able to measure the ventilation for occupation and non-occupation periods separately. This would require samplers which can be opened and closed, thus making intermittent sampling, only during occupation or non-occupation periods. A development of devices which can perform such intermittent sampling automatically is under way.

8. CONCLUSIONS

The homogeneous emission passive tracer gas technique was easy to apply also in large school buildings. Despite the fact that the measurement time was nearly two months in a couple of cases, no destruction of the equipment was noticed and only a few samplers disappeared. An important reason is that the field equipment is simple, inexpensive and very discrete.

A detailed picture of the air distribution patterns could be obtained, showing that in most schools, the ventilation differs widely between different class rooms. This fact illustrates the importance of using a measurement technique, which like the homogeneous emission technique yields a reliable measurement of air distribution.

All measured naturally ventilated schools have a low average ventilation rate, comparable to that required in dwellings. It seems necessary to use various means of improving ventilation during occupation time in naturally ventilated school buildings in order to approach a reasonable air quality.

It should be observed that the ventilation rate with occupants present, may be quite different from the average values reported here. However, extended window airing during lessons is not very probably, due to the cold climate during the measurement periods.

9. ACKNOWLEDGEMENT

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