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INTERZONAL AIRFLOW MEASUREMENT - A TOOL TO SOLVE POLLUTION PROBLEMS.

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ABSTRACT

Knowledge of air movement within a building is often a condition for solving problems with the spread of pollution. The internal airflow paterns are mostly very complex and a survey of the airflow normally demands that measurements are carried out.

Measuring equipment for defining air movement within buildings almost always uses the tracer gas technique. We have used two tracer gases and have kept a constant concentration of these in the polluted and the clean zones respectively. Thus enabling us to get a time history of the airflow between the two zones. Concurrently, with measurements of the airflow between clean and polluted zones, we have measured the concentration of pollution components.

The article describes both the results from testing the measurement method in an uninhabited test-house and the results from field measurements in a house and in a large factory building. From the results, the accuracy of the measurement method and the relationship between the calculated and actually measured pollution concentrations are discussed.

1. INTRODUCTION

Problems with the spread of pollution in buildings and problems in calculating the concentration of the pollution source are often so complex that simple measurement methods and common sense are not sufficient to achieve the correct results. Such problems require more advanced measurement techniques.

The tracer gas measurement methods are among the most effective and flexible tools available when you want to trace air movements. If you make use of several tracer gases you will come a long way in understanding the often very complex air movements in buildings. In our investigations we have used a measurement equipment capable of keeping a constant concentration of tracer gas in up to 12 rooms and handling 2 different tracer gases at the same time. With this equipment you will also be able to register the pollution concentrations and temperatures in the rooms.

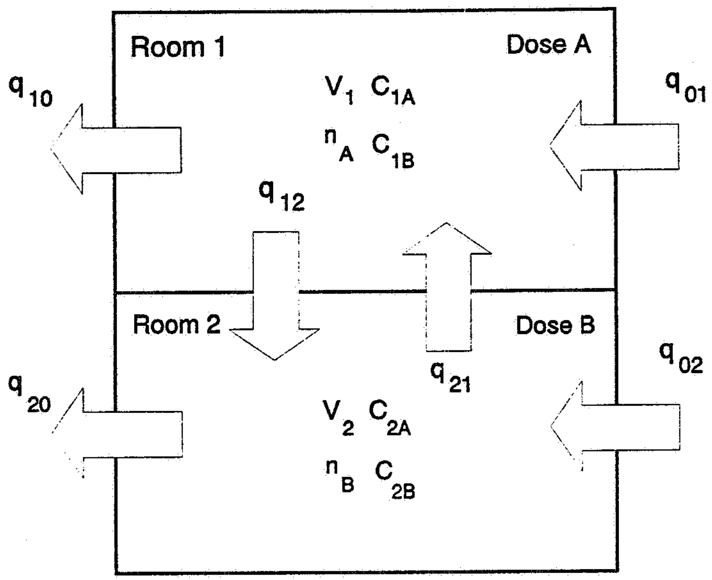
The measurement equipment will calculate the outdoor air-exchange and make current print-outs, whereas the calculation of interzonal airflow must be done manually. In the following chapter the equations being used for calculating the interzonal airflow are explained. We are dealing with 2 different sets of equations, each related to the 2 main types of measurements. When performing the type of measurement we call split-measurement we keep a constant concentration of tracer gas A in one area of the building and a constant concentration of tracer gas B in the rest of the building. When performing the type of measurement we call supplement-measurement the concentration of tracer gas A is kept constant all over the building and in addition to this a constant concentration of tracer gas B is kept in a limited area of the house.

We have carried out three measurements, two of which are reported in the present text. One measurement in a factory hall is not included, as we have not been able to demonstrate any interzonal airflow between the polluted and the clean area of the building.

2. Calculation of Interzonal Airflow.

In figure 1 the flows which can be calculated by the split-measurement method are shown. The unknown values are the 6 flows marked with arrows, and the known values are the measured air-exchanges, concentrations and volumes. During the measurement the concentration of tracer gas A is kept constant in room 1, and the concentration of tracer gas B in room 2. Tracer gas A is not dosed in room 2, and tracer gas B is not dosed in room 1.

In figure 1 the 6 equations which are used for calculating the unknown airflow are stated. The 6 equations derive from stating a mass balance for tracer gas A, tracer gas B and the airflow for each room. The equation system is easily solved, especially if there is stationary flow and you wait until all tracer gas concentrations are stable.



$$n_A \times V_1 = q_{01} + q_{21} \times (1 - C_{2A}/C_{1A})$$

$$n_B \times V_2 = q_{02} + q_{12} \times (1 - C_{1B}/C_{2B})$$

$$V_1 \times dC_{1B}/dt = q_{21} \times (C_{2B} - C_{1B}) - q_{01} \times C_{1B}$$

$$V_2 \times dC_{2A}/dt = q_{12} \times (C_{1A} - C_{2A}) - q_{02} \times C_{2A}$$

$$q_{10} = q_{01} + q_{21} - q_{12}$$

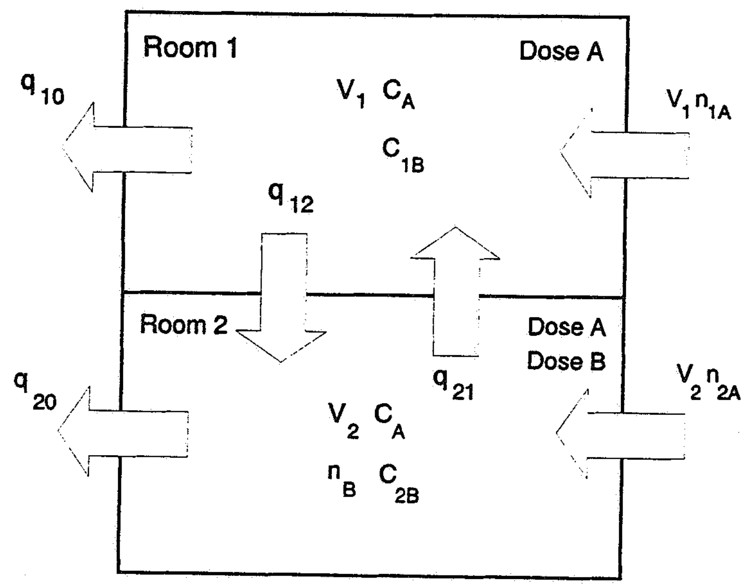
$$q_{20} = q_{02} + q_{12} - q_{21}$$

n =	measured air-exchange
V =	room volume
C =	concentration of tracer gas
q =	airflow
dC/dt =	change in tracer gas concentration with respect to time.

Figure 1: Equations for calculation of interzonal airflow by split-measurements.

When using the supplement-measurement method we only have to calculate 4 unknown flows, as the flow of outdoor air into the two rooms is measured direct. In figure 2 the 4 unknown flows are marked with arrows out of and between the rooms. The known values are the measured air-exchanges, concentrations and volumes. During measurement a constant concentration of tracer gas A is kept in room 1 and 2, and a constant concentration of tracer gas B in room 2. Tracer gas B is not dosed in room 1.

In figure 2 the 4 equations used for calculation of the unknown airflow are stated. The 4 equations derive from stating a mass balance for tracer gas B and for the airflow for each room.



$$(n_B - n_{2A}) \times V_2 = q_{12} \times (1 - C_{1B}/C_{2B})$$

$$V_1 \times dC_{1B}/dt = q_{21} \times (C_{2B} - C_{1B}) - V_1 \times n_{1A} \times C_{1B}$$

$$q_{10} = V_1 \times n_{1A} + q_{21} - q_{12}$$

$$q_{20} = V_2 \times n_{2A} + q_{12} - q_{21}$$

Figure 2: Equations for calculation of interzonal airflow by supplement-measurements.

3. Measurement in Test-House.

As a control of the equipment a measurement was performed in a test-house at the Thermal Insulation Laboratory. It is a two-storied house with the size of a normal Danish one-family house. The measurements were carried out on the ground floor which consists of two almost equal-sized rooms of 135 m^3 and 142 m^3 respectively.

At first the leakage of the house was determined by the constant concentration measurement method. Tracer gas SF6 was used and the target for the tracer gas concentration was 1 ppm. The measurement was running during 12 hours and the following results were achieved:

Basic air-exchange rate = 0.01 1/h
Mean value SF6 concentration = 1.01 ppm
Spread in concentration = 0.02 ppm

The basic air-exchange is much lower than normally for Danish houses. However, in the test-house all joints was sealed very carefully. The outdoor climate during measurement of the basic air-exchange was:

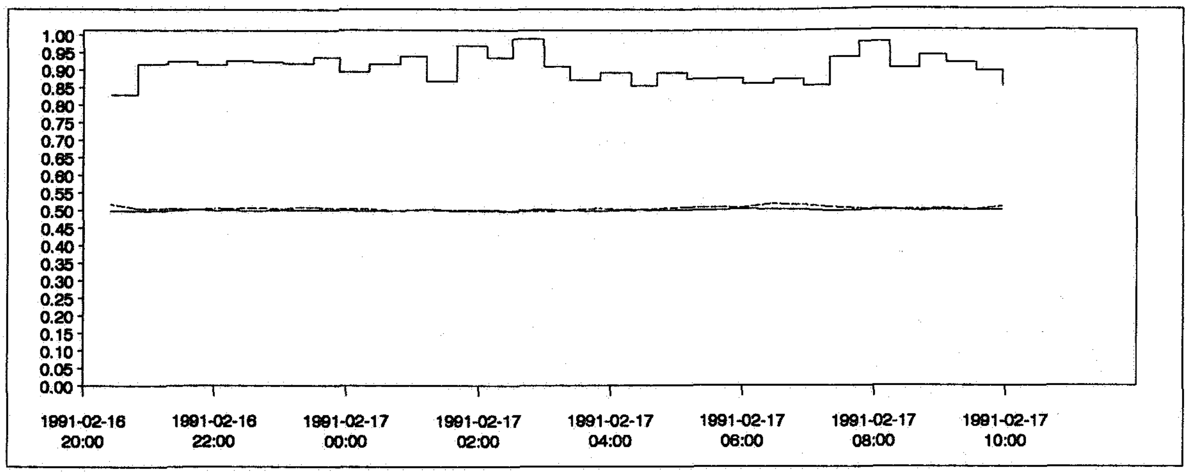
Mean wind velocity = 6 m/s
Temperature = -3,0 ^{o}C

Then 3 ventilation plants were installed in the test-house, two of which were used to ventilate the two rooms with outdoor air and one to create an airflow between the two rooms. A plate orifice was installed in 3 of the ducts, enabling us to measure the exhaust airflow from each room and the flow from room 1 to room 2.

Four measurements were performed in the test-house with 4 different flow between room 1 and 2. They were all split-measurements and a concentration of the tracer gas Flourcarbon-22 was kept at 10 ppm in room 1 (vestrum), and a concentration of the tracer gas SF6 was kept at 1.0 ppm, in room 2 (oestrum). All measurements were running until all tracer gas concentrations were stable. In figure 3 an example of measured tracer gas concentrations and air-exchanges in the two rooms during a period of 12 hours is shown.

7620
Tracer Gas
Measurement

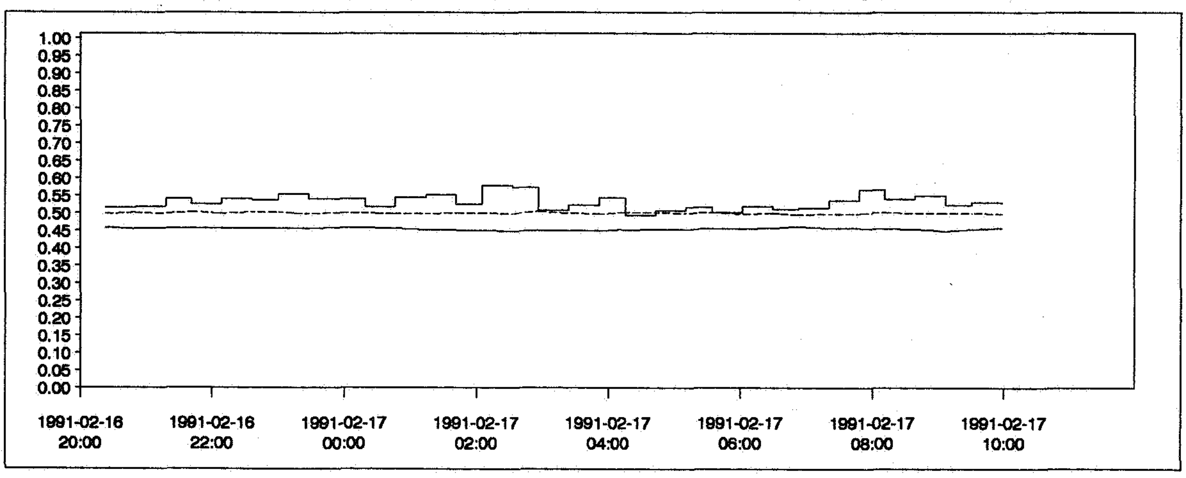
SETTINGS:			GENERAL INFORMATION:		COMMENTS:
Sampling Interval:	Cont.		Start Time:	1991-02-16 20:00	Luftskiftet i oest- og vest-rummet.
Time bet. measurement	1570	s	Stop Time:	1991-02-17 10:00	Infiltration ca. 30 m3/h.
Normalization temp.:	20.0	°C	Compression time:	None	
Cross Compensation:	No		Warning:	None	
Water Vapour Compens:	Yes		Data Edited:	No	DATABASE: EXPHUS3
Air Pressure:	101.30	kPa	Resolution:	11 %	USER PRG: None



C	Location:	Measurement	Line	Scale	Unit	Room Vol.	Mean val.	Sprd. of c. p.
1	Vestrum	Flourocarbon 22	——	2E+01	ppm	135.00 m³	9.99 ppm	2.97E-02 ppm
1	Vestrum	Sulphur Hexaflouride	- - -	5E-01	ppm	135.00 m³	2.52E-01 ppm	2.55E-03 ppm
1	Vestrum	Air-change	step	1E+02	m³/h	135.00 m³	90.57 m3/h	3.79 m3/h

7620
Tracer Gas
Measurement

SETTINGS:			GENERAL INFORMATION:		COMMENTS:
Sampling Interval:	Cont.		Start Time:	1991-02-16 20:00	Luftskiftet i oest- og vest-rummet.
Time bet. measurement	1578	s	Stop Time:	1991-02-17 10:00	Infiltration ca. 30 m3/h.
Normalization temp.:	20.0	°C	Compression time:	None	
Cross Compensation:	No		Warning:	None	
Water Vapour Compens:	Yes		Data Edited:	No	DATABASE: EXPHUS3
Air Pressure:	101.30	kPa	Resolution:	11 %	USER PRG: None



C	Location:	Measurement	Line	Scale	Unit	Room Vol.	Mean val.	Sprd. of c. p.
7	Oestrum	Flourocarbon 22	——	5E+00	ppm	142.00 m³	2.27 ppm	1.54E-02 ppm
7	Oestrum	Sulphur Hexaflouride	- - -	2E+00	ppm	142.00 m³	9.99E-01 ppm	3.06E-03 ppm
7	Oestrum	Air-change	step	2E+02	m³/h	142.00 m³	106.38 m3/h	3.99 m3/h

Figure 3: Tracer gas concentrations and air-exchange rate in test-house during test No. 3. Room 1 is location "Vestrum" and room 2 is location "Oestrum". The plotted values are half-hour mean values.

From the figure you can see that the tracer gas concentrations are very stable during the entire measurement, but the air-exchange rates vary. E.g. from 3.00 to 7.00 a.m. the air-exchange is lower than the average air-exchange which is equal for both rooms. We cannot explain any direct source to these variations. They are probably caused by variable outdoor climate, or changes in the ventilation fans' flow caused by variation in the mains voltage.

Table 1 shows a summary of the measurement results from the test-house. At the measurement method "Tracer gas corr." corrections are made for the set-off on concentrations measured from one channel to the other. E.g. if you measure on a very high concentration of tracer gas on one channel and afterwards on clean air on the next channel, the gas monitor will read out a few percentage of the last measured high concentration. This phenomenon we call the memory effect. How big the memory effect is, depends on the ability of the specific gas to stick to the surfaces in the sampling system. As for the tracer gas SF6 it is app. 3% and for Flourocarbon-22 it is 4-5%.

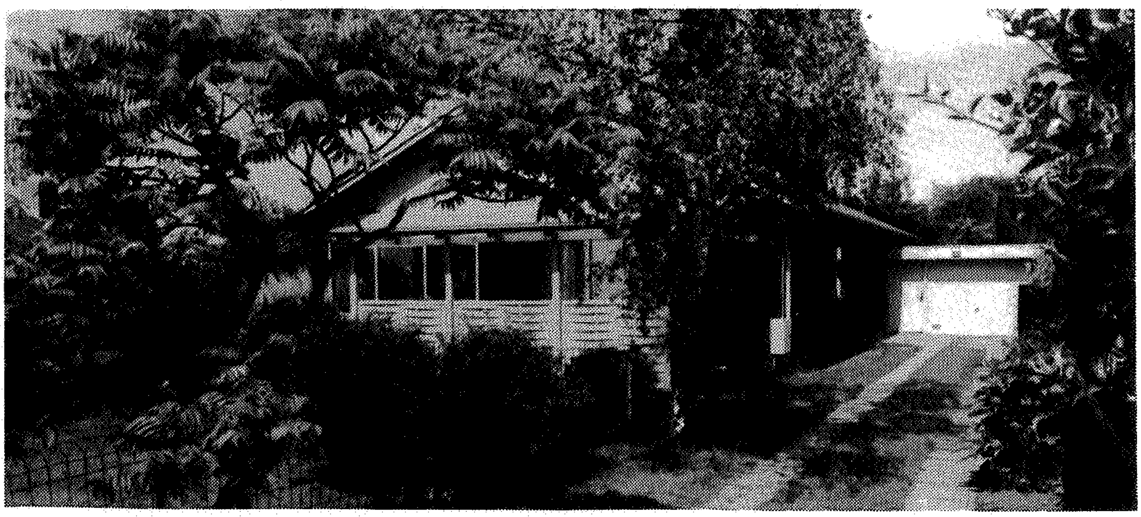
Test No.	Measurement Method.	Flow m^3/h			
		q_{10}	q_{20}	q_{12}	q_{21}
	Tracer gas	75	89	4	2
1	Tracer gas corr.	77	89	0	0
	Pitot Tube	73	81	0	
	Tracer gas	67	82	17	16
2	Tracer gas corr.	69	81	12	15
	Pitot Tube	72	75	11	
	Tracer gas	70	88	26	24
3	Tracer gas corr.	74	84	19	23
	Pitot Tube	71	81	23	
	Tracer gas	68	87	32	31
4	Tracer gas corr.	76	81	25	31
	Pitot Tube	70	80	30	

Table 1: Flow measured with Pitot tube and tracer gas in m^3/h and 4 different interzonal airflows. In fig. 1 you can see which flows are shown and how they are calculated. At the measurement method "Tracer gas corr." corrections for the memory effect in the measurement system have been made.

From the table you will find a mean difference of 4 m^3/h in the measurements on tracer gas and Pitot tube. The Pitot Tube measurements should result in somewhat lower values than the tracer gas measurements, as they do not compensate for airflow caused by leak in the construction.

4. Measurement in a one-family house.

Measurements were carried out in a typically Danish one-family house, see photo below. It is a one-storey house inhabited by 2 adults and 1 child. In figure 4 you will see a plan of the house.



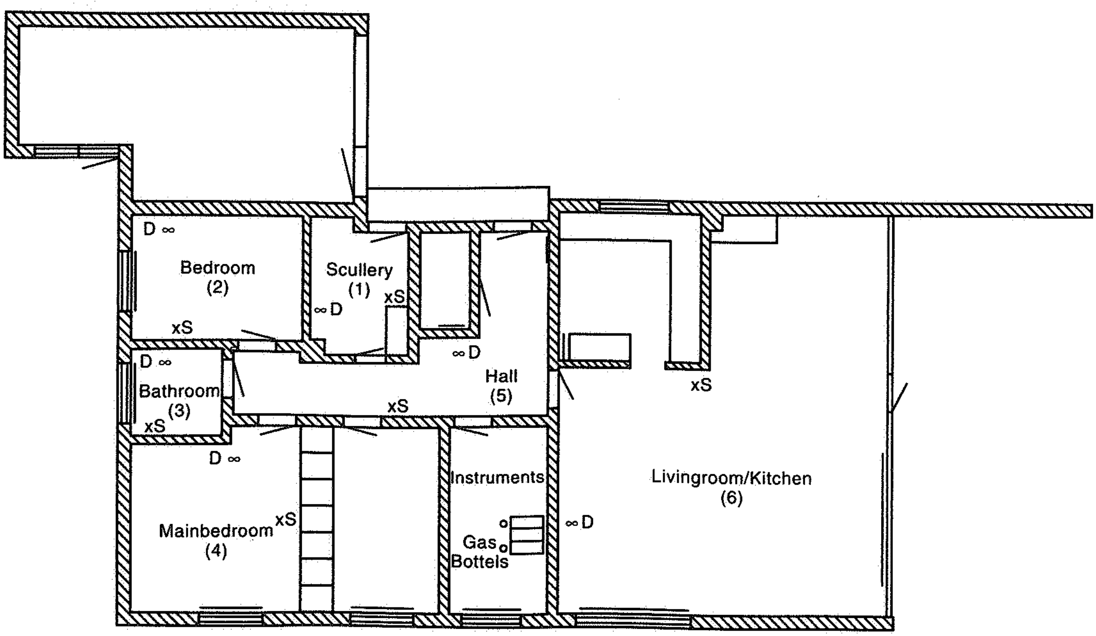
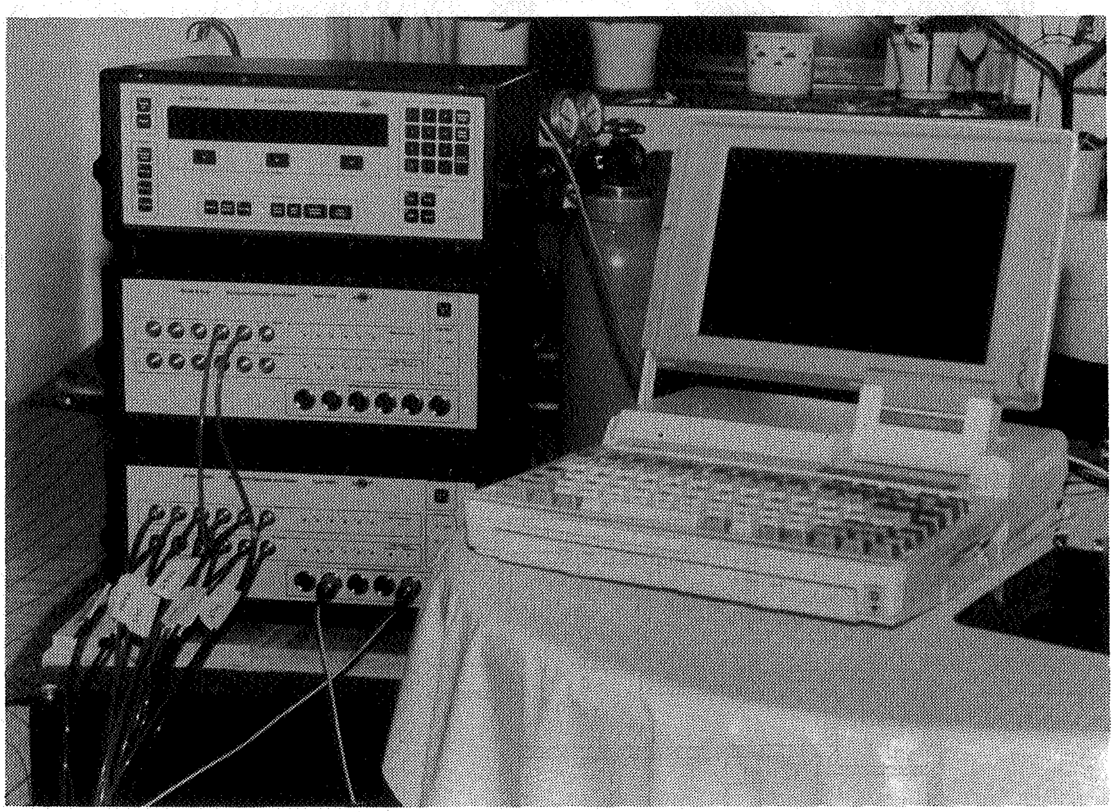


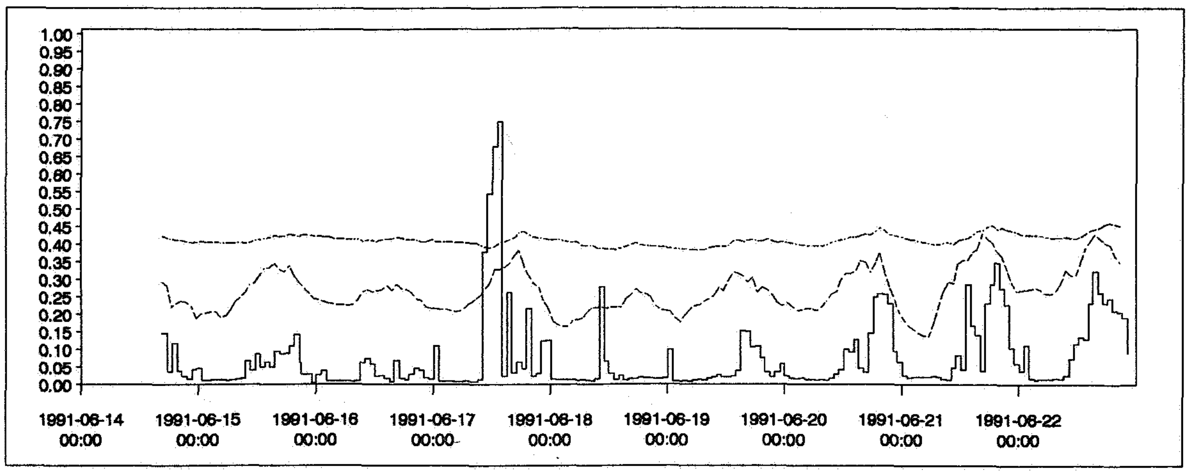
Figure 4: Plan of house with room numbers, dosing points and sampling points entered. During measurements the doors between the hall and the two rooms next to the living room were open.

The measurements were carried out as supplement-measurements. The tracer gas SF6 was used to measure the flow of outdoor air into each separate room, and the tracer gas R-22 was used to measure the total airexchange in one individual room, - as well the outdoor air entering direct from outdoor as the outdoor air entering from adjoining rooms. At this measurement especially the airflow to Main bedroom and Livingroom-Kitchen was examined. In addition to the measurement of airflow, the concentrations of carbon dioxide in the rooms and the temperatures in- and out-door were registered.

Below is shown a photo of the measurement equipment set-up in one of the guestrooms in the house. All tube connections to the equipment were placed so that the family was able to live as always in the house, and we asked the family to act as they used to with regard to airing and opening and closing of internal doors.



In figure 5 you will see the total air-exchange as function of time. Especially the most variable air-exchange is significant, and this is typically for a naturally ventilated house (ref. 1 and 2), with a very low air-exchange during night and some peaks during the day caused by airing.



C	Location:	Measurement	Line	Scale	Unit	Room Vol.	Min.Val.	Max.val.	Mean val. of c.p.
W	Weighted mean	Air-change		1E+01	h-1	278.10 m^3	3.05E-02 h-1	7.48 h-1	7.38E-01 h-1
5	Hall	Temperature	-------	5E+01	^0C	72.00 m^3	19.15 C	22.95 C	20.56 C
2	Bedroom	Temperature	----	5E+01	^0C	23.00 m^3	6.85 C	21.45 C	13.27 C

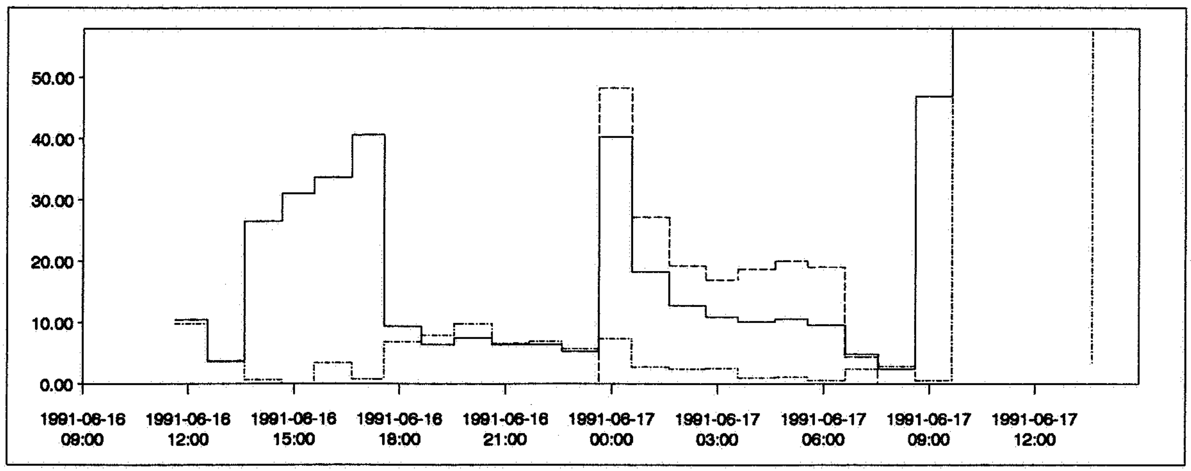
Figure 5: The air-exchange in the house and in- and out-door temperatures as function of time.

In the upper plot of figure 6 "C 4" states the measured airflow of outdoor air into the main bedroom, and "C 10" states the total measured air-exchange in the same room. The equations in figure 2 have been used to calculate the flow from the hall into the main bedroom during the period from 11 p.m. to 8 a.m. The flow calculated is shown in the upper plot.

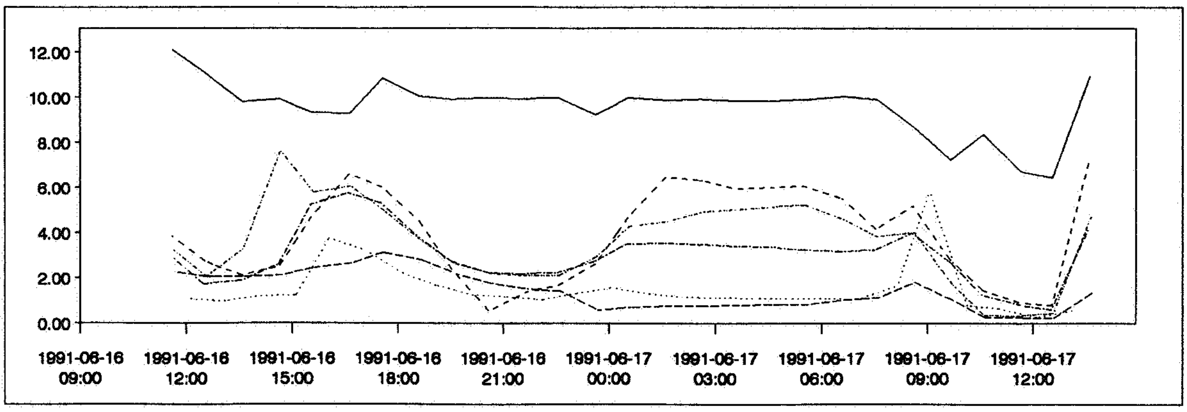
On the second plot you can see how the air from the bedroom is circulated to the rest of the house, and e.g. a low air-exchange between the main bedroom and the livingroom/kitchen is seen.

If you compare the three graphs in the figure you will see that the door between the main bedroom and the hall has been left open from 1 p.m. to 5 p.m., then it has been closed until 11 p.m., and then again it has been partly open during the night.

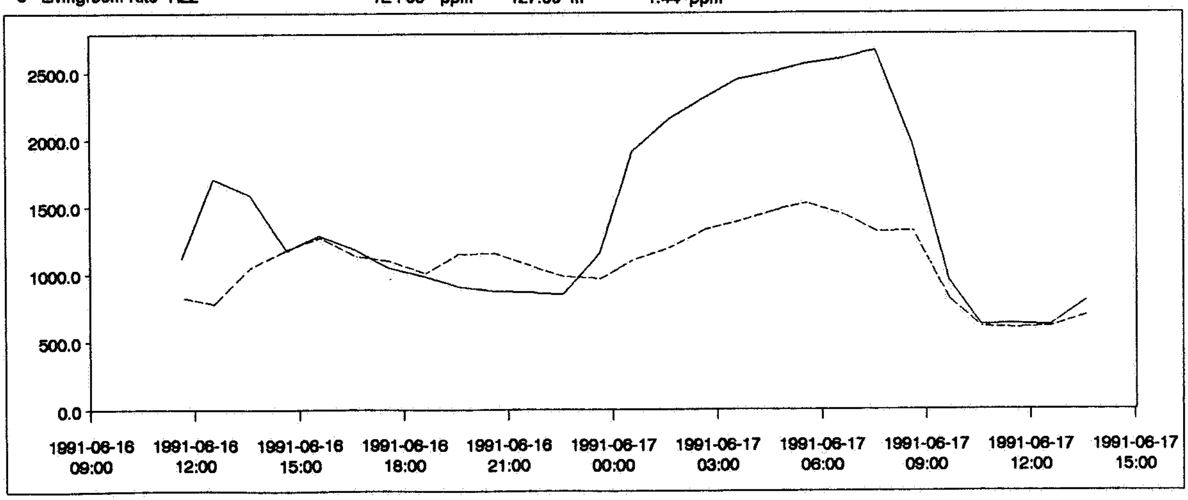
At some occasions it could be very useful to combine measurement of air-exchanges with measurement of pollution concentrations, as this will give you the possibility to determine the source strength of a pollutant in a certain room. In this example we will calculate the produced volume of carbon dioxide during the night in the main bedroom.



C	Location:	Measurement	Line	Scale	Unit	Room Vol.
4	Main bedroom	Air-change		1E+00	m^3/h	34.00 m^3
10	Main bedroom	Air-change		1E+00	m^3/h	34.00 m^3
1	User index 1	Calculated		1E+00	m3/h	



C	Location:	Measurement	Line	Scale	Unit	Room Vol.	Mean val. of c.p.
1	Scullery	R22		1E+00	ppm	14.00 m^3	1.52 ppm
2	Bedroom	R22		1E+00	ppm	23.00 m^3	3.04 ppm
3	Bathroom	R22		1E+00	ppm	8.10 m^3	3.90 ppm
4	Main bedroom	R22		1E+00	ppm	34.00 m^3	9.59 ppm
5	Hall	R22		1E+00	ppm	72.00 m^3	3.63 ppm
6	Livingroom-Kitc	R22		1E+00	ppm	127.00 m^3	1.44 ppm



C	Location:	Measurement	Line	Scale	Unit	Room Vol.	Max.val.	Mean val. of c.p.
4	Main bedroom	Carbon Dioxide		1E+00	ppm	34.00 m^3	2.66E+03 ppm	1.46E+03 ppm
5	Hall	Carbon Dioxide		1E+00	ppm	72.00 m^3	1.53E+03 ppm	1.08E+03 ppm

Figure 6: Airflow into main bedroom, tracer gas concentrations in the house and carbon dioxide concentrations in the bedroom and the hall.

The equation used to calculate the source strength of a pollutant in the room is:

$$F_{1P} = V_1 \times dC_{1P}/dt + q_{01}(C_{1P}-400) + q_{21} \times (C_{1P}-C_{2P})$$

F_{1P} is the source strength of pollution in room 1.

V_1 is the volume of the room.

dC_{1P}/dt is change in pollution concentration with respect to time.

q_{01} is flow into room 1 from outdoor.

q_{21} is flow into room 1 from adjoining room.

C_{1P} is pollution concentration in room.

C_{2P} is pollution concentration in adjoining room.

A somewhat easier way to calculate the carbon dioxide production is to use the following simplified equation:

$$F_{1P} = V_1 \times n_B \times (C_{1P} - 400)$$

n_B is the total measured air-exchange in the room (the graph C 10).

However, this equation has its limitations, especially because it assumes that the carbon dioxide concentrations and the R-22 tracer gas are equally spread all over the house. Especially at the beginning of the night this is not true. The result of the calculations using these two equations can be seen in figure 7. Calculation of the production using the first-mentioned equation is shown as "User index 2", and calculation using the second equation is shown as "User index 3".

From figure 7 it appears that the calculated production is varying during the night from 25 l/h to 30 l/h. The expected production from 2 adults is 38 l/h in the first hour of the night and 26 l/h the rest of the night (ref. 3).

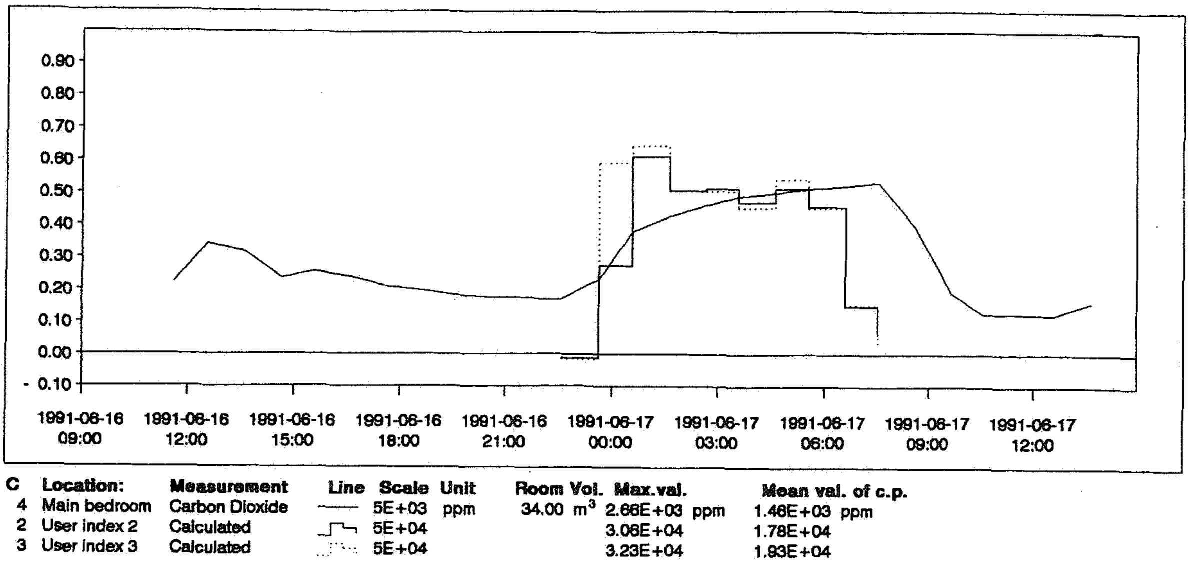


Figure 7: Carbondioxide concentration in main bedroom and the calculated production in the main bedroom. "User index 2" and "User index 3" show production of Carbondioxide in ml/h. "User index 3" shows calculation using the simplified equation.

In figures 8 and 9 the data are shown for a 24-hours period with a constant concentration of the tracer gas R-22 in the livingroom/kitchen. As in figure 6 you will also here see the low air-exchange between livingroom/ kitchen and the rest of the house. Only twice during the day you find the door between the two rooms open for a longer period.

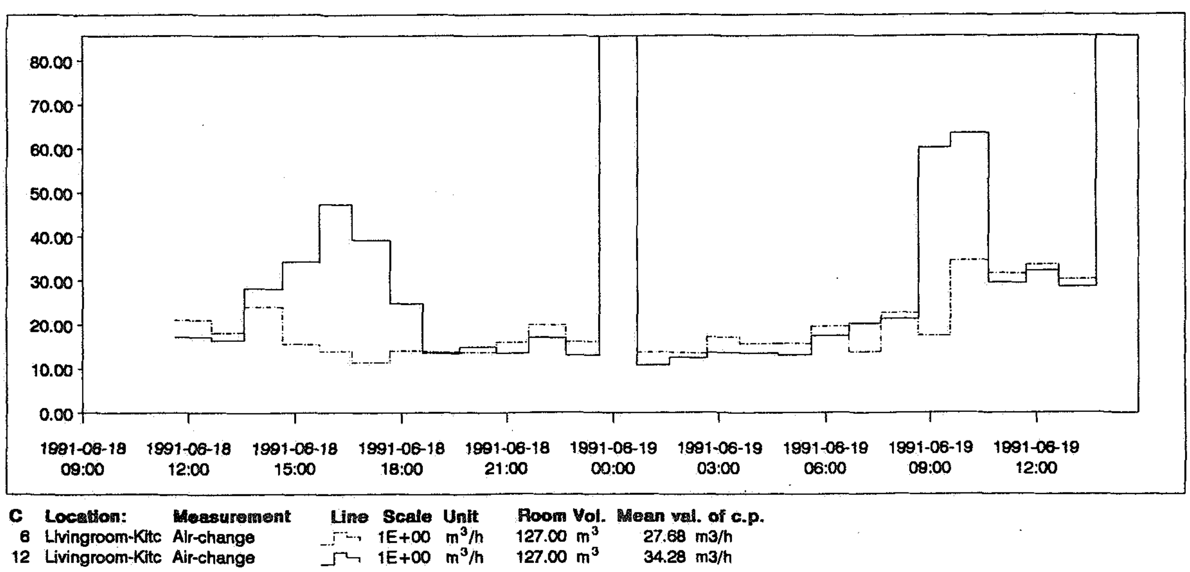
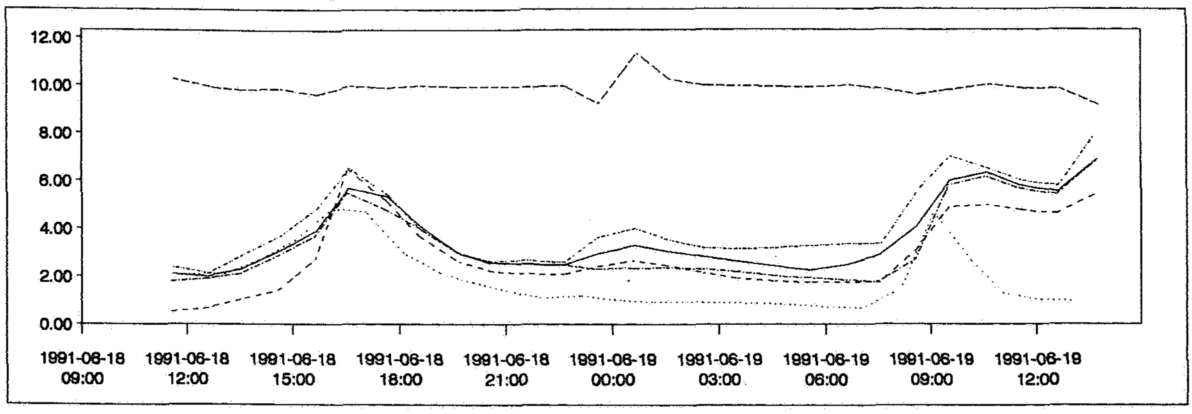


Figure 8: Airflow into the livingroom/kitchen.



C	Location:	Measurement	Line	Scale	Unit	Room Vol.	Mean val. of c.p.
1	Scullery	R22	....	1E+00	ppm	14.00 m^3	1.90 ppm
2	Bedroom	R22	-.-.-.-	1E+00	ppm	23.00 m^3	3.29 ppm
3	Bathroom	R22	- - - -	1E+00	ppm	8.10 m^3	2.86 ppm
4	Main bedroom	R22	———	1E+00	ppm	34.00 m^3	3.65 ppm
5	Hall	R22	..-..-..	1E+00	ppm	72.00 m^3	4.15 ppm
6	Livingroom-Kitc	R22	----	1E+00	ppm	127.00 m^3	9.91 ppm

Figure 9: Tracer gas concentrations in the house.

5. Conclusion.

The most exiting results from the performed measurements are the capability of the measurement method to determine the source strength of a pollutant placed in a certain room. The possible applications for this type of measurements are many, a.o. determination of the strength of a humidity source in houses or to calculate production rate of pollution in the industry.

The measurements carried out also prove that the measurement method gives reliable results of interzonal airflow, although we have not adduced any real proof of the accuracy of the measurement method. In order to evaluate the accuracy of the measurement method we have to compare this with a more precise reference than the test-house. Therefore, we are not able to decide whether it is a good idea to correct the measured tracer gas concentrations before they are used to calculate the interzonal airflow.

When calculating the production of carbon dioxide in the main bedroom the accuracy was surprisingly high, in fact much better than could be expected, as the calculated strength of the source deviated less than 10% from the expected values.

6. References.

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2. Bjørn Kvisgaard and P.F. Collet, "The User's Influence on Air Change", pp67-76 in "Air Change Rate and Airtightness in Buildings" by M.H. Shermann, STP 1067, ASTM, March 1990.

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4. Bjørn Kvisgaard, P.F. Collet "Constant Concentration Measurement with 2 Tracers", Paper 10 of Proceedings of the 9th AIVC Conference, vol. 1, 1988.