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ROOMVENT -87

Stockholm 10 - 12 June 1987

A MULTIPLE TRACER GAS TECHNIQUE FOR THE MEASUREMENT OF AIR MOVEMENTS IN INDUSTRIAL BUILDINGS

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ABSTRACT

This paper deals with a multiple tracer gas measurement system suitable for characterization of air flow patterns and ventilation effectiveness in large industrial premises and commercial structures. The highly automated system consists of a multipoint sampling unit, an IR-analyser and a microcomputer. Up to now, nitrous oxide, dichlorodifluoromethane and carbon dioxide have been used as tracers. The method was applied to study the distribution of the supplied air and the cleaned recirculated air in a finishing department of a steel foundry.

1. INTRODUCTION

The knowledge of airflow patterns is of vital importance for contaminant control in large work rooms. The distribution of airborne contaminants in work rooms depends on the characteristics of the contaminants themselves and the volumetric flow rates of clean air, but also on the flow field. The flow field in industrial premises is usually very complex involving e.g. supplied airflow, contaminant flow, infiltration flow and recirculation airflow. Turbulence is a typical feature of the airflows in industrial buildings. Therefore, a detailed description of air movements is extremely difficult or even impossible. The tracer gas method has proven to be a useful tool in exploring airflow behaviour and the performance of ventilation systems. Most investigators have used the single tracer gas technique. The multiple tracer gas technique has mainly been applied to air infiltration studies, in which the transfer of air between different rooms has been investigated. The application of the multiple tracer technique to chart the flow patterns in the same room has been rare.

Various tracer gas measurement strategies have been developed to determine airflow patterns in buildings /1/. Depending on the information desired a tracer gas is released into the supplied air or within the room. The most common modes of tracer inputs are step-down, step-up and pulse injections. There are several ways to analyze and interpret tracer gas responses. The infiltration rate or the air change rate, as it is usually called, can be determined from the slope of the decay curve during the exponential decrease when the mixing is complete. The analysis of the results may also be based on the relationship between steady state concentrations of supplied air at certain points within the room and exhaust air. In recent years the introduction of the age distribution theory has been shown to be successful in characterizing the ventilation effectiveness and the behaviour of airflows in rooms /2-4/. A useful approach to ventilation effectiveness in industrial premises is based on the determination of the local mean age of the supplied air or contaminated air.

The purpose of this paper is to describe a multiple tracer gas measurement system, which can be used to characterize airflow patterns and ventilation effectiveness in large industrial premises. The highly automated system consists of a multipoint sampling unit, an IR-analyser and a microcomputer. Up to eight sampling lines can be coupled into the sampling unit. The measurement system is rapid to install and relatively easy to use. Up to now we have used nitrous oxide, dichlorodifluoromethane and carbon dioxide as tracers. In principle the analyzer is capable of measuring as many as eleven wavelengths simultaneously. The method was applied to study the distribution of the supplied air as well as the cleaned and recirculated air in a finishing department of a steel foundry.

2. MEASUREMENT SYSTEM

The multiple tracer gas measurement system consists of an eight-channel selector, an infrared spectrophotometer and a micro-computer (Figure 1)

The channel selector consisting of the 3-way solenoid valves can operate in three modes: computer-controlled, stand alone, or manual. The measurements are usually carried out in a computer-controlled mode via the 7 bit GPIO which sends the number of channels in use and the current sampling channel. Up to eight sampling lines can be connected to the channel selector, which switches on each channel in succession, usually once every 30 sec to the gas analyzer. Therefore, the measurement cycle with e.g. eight sampling points takes four minutes. Two sampling pumps with air flow rates of 28 litre/min and 13 mm inner diameter sampling tubes are used. The first pump sucks air into the analyzer and the second, so-called pre-exhaust pump "washes out" the next sampling tube. The cuvette volume of the analyzer, 5.6 litre, sets the lower limit for the measurement cycle. The time constant of the analyzer is 12 sec. with a sampling rate of 28 litre/min. The measurement cycle can be shortened by increasing the sampling flow rate.

The selected sample is fed to the infrared analyzer (Miran 80 Foxboro Analytical) which can simultaneously measure the absorbances even at eleven wavelengths. For the present we have used three tracer gases: nitrous oxide (N_2O), dichlorodifluoromethane or freon 12 (CCl_2F_2) and carbon dioxide (CO_2). However, two tracer gases used simultanously have been either nitrous oxide and freon 12, or carbon dioxide and freon 12. The analytical conditions of the IR-analyzer are shown in Table 1. To eliminate the effect of variation in water vapour content or other interfering compounds, one additional wavelength is measured close to the analytical wavelength. This absorbance value is then used for the background correction. The necessary short-term stability was attained with this method.

From the infrared analyzer the absorbances are sent through the RS 232-interface to the computer (HP Model 216 S with 768 kB RAM). The absorbances are transformed to concentrations which are displayed in real time on the screen of the computer. Since the absorbance does not linearly depend on the concentration, a calibration curve composed of sequential linear parts was applied. At the end of the measurement the results are stored on a 3.5 inch microdiskette, and the concentration curves plotted with a plotter or a printer. The results may be analyzed immediately after the experiment or later in the laboratory.

The main features of the analyzing programme are the sections on data editing, calculation and picture editing. The data editing section contains the correction routines for a single data point and a baseline level. The picture editor enables the display of the concentrations in linear or logaritmic scales. The programme calculates several parameters describing ventilation effectiveness /5/.

In the case of the air change rate measurement the programme gives the slope of the concentration decay and the coefficient of correlation as a measure of fit. When the tracer gas test is stopped before the baseline concentration and the numerical integration to infinity is required the analytical extrapolation is applied beyond the measured concentrations. The programme fits an exponential tail to the experimental values.

In the case of pulse release, the programme calculates the parameters from the pulse response curve as if the ideal impulse had taken place at time t=0. This means that, supposing the injection time of a pulse is θ, the injection has been initiated at the time instant $-\theta/2$ and terminated at the time instant $+\theta/2$. The local mean age of the air or contaminant, τ, can be determined as the first normalised moment of the pulse response:

$$\tau = \frac{\int_0^\infty C(t)t\,dt}{\int_0^\infty C(t)dt} \qquad \text{Equation (1)}$$

In this papaer the term "local mean age" is used when the concentration measurements are performed at an arbitrary site in the room and the term "mean exit age" when the measurements are carried out in the exhaust duct. The total dosage, D_{tot}, or area under the pulse response curve is obtained in a usual way from equation 2:

$$D_{tot} = \int_0^\infty C(t)\,dt \qquad \text{Equation (2)}$$

The reliability of the system was tested in laboratory conditions by using nitrous oxide and freon 12 as the simultaneous tracer gases. The tests showed that the difference between mean exit ages measured at the same point with these gases was less than 10 percent.

3. MEASUREMENT PROCEDURE IN A WORKROOM

The double tracer gas tests were carried out in the cleaning department of a steel foundry (Figure 2 and 3). The tests focused on the spatial distribution of the supplied fresh air and the spatial spread of the filtered recirculation air.

The work operations in the cleaning room (Volume: 10.200 m^3) included mainly grinding of small castings, and welding to some extend. The castings were ground with portable hand grinding tools. For dust control grinding was performed in twenty cleaning booths fitted with the exhaust fans and the dust filter units. Dust contaminated air was sucked through the perforated back wall of the booth, filtered and blown upwards. The exhaust flow rate of the booth fan, serving two booths, was about 8 000 m^3/h. Two propellor fans E_1 and E_2 on the roof provided the general exhaust ventilation. The supply air duct was located above the row of ten cleaning booths dividing the room into two parts (Figure 2 and 3). The fresh outdoor air was symmetrically supplied through the duct grilles into both parts of the cleaning room. The nominal flow rate of the supply air fan was 16,000m^3/h. The outlets of the recirculation fans were located on the side of part I below the supply air duct. Therefore, the fresh air supply jets blown into part I, and the recirculation air flows from these ten booths partly interfered with each other.

The measurements were performed in the cleaning room by using two tracer gases simultaneously. The fresh supplied air was labelled with freon 12 and the recirculated air from the cleaning booths with N_2O. Each tracer gas was injected as a pulse during two minutes. The volume of freon 12 pulse was 130 litres and that of N_2O 100 litres. The release flow rates were controlled by the rotameters. The injection of the tracer gases was initiated at the same time as channel 1 was starting to sample. During these measurements four sampling lines were connected to the channel selector to achieve a reasonably short measurement cycle, i.e. 2 min. in this case. The short measurement cycle was important, because the concentration levels with the tracer gas volumes injected were rather low, about 10 ppm. The use of higher injection volumes was limited by the flow rate capacity of the rotameters available and the risk of ice generation in the tracer gas cylinders. In test 1 the sampling site of channel 1 was located just below roof fan E_1 and the other three were placed in the working zone. In tests 2 and 3 channel 1 and channel 3 were located below the roof fans and channels 2 and 4 in the working zone at booths 5 and 12, respectively. The concentrations of the tracer gases were monitored about half an hour after the release.

4. RESULTS

Equations 1 and 2 were used to calculate, from the tracer gas responses, the local mean ages at the sites in the working zone and the mean exit ages at both exhaust fans, as well as the corresponding total dosages. The results are presented in Table 2. Typical concentration curves are given in Figure 4 (test no 2 in Table 2).

The average total dust concentration was 0.85 mg/m^3 at the stationary sampling site in front of booth 5 and 0.50 mg/m^3 in front of booth 12. The dust concentration was measured during three days with the gravimetric method.

5. DISCUSSION

The results of test 1 indicate that both the fresh supplied air and the recirculated air were spread more efficiently towards roof fan E_1 than into the sampling sites in the working zone.

The mean exit age for the fresh air and the recirculated air was notably shorter than the values of the local ages measured in the working zone (booths 2, 5 and door opening). Also the total dosages observed at fan E_1 were clearly higher, actually two or three times higher, than those in the working zone. This was also verified by the repeated tests 2 and 3. The total dosages measured in the working zone near booths 2, 5 and the door opening were also smaller than those at the roof fans and at cleaning booth 12.

Tests 2 and 3 showed that the fresh air was more efficiently distributed to the working zone at cleaning booth 12, than to the other sampling sites, especially to the site in front of booth 5. This finding was also confirmed by the dust concentration measurements; the average total dust concentration at booth 12 was lower than at booth 5. It was assumed that the generation rate of dust was similar in both parts of the cleaning room, because the grinding activities were similar in both parts of the room. The recirculated air was spread approximately evenly towards the roof fans and into the working area at booth 12. On the other hand, the supplied air and the recirculated air spread more efficiently towards the roof exhaust fans than to cleaning booth 5. One can also see that the spreading of the recirculated air was stronger towards exhaust fan E_1 than towards exhaust fan E_2.

This unsymmetrical behaviour of the recirculated air was due to the supplied air jets blowing into part I of the cleaning room, and this interfered with the recirculation jets blowing upwards and then deflecting towards roof fan E_1. Because the outlets of the recirculation air fans were located only on the other side of the air supply duct, there was no interference in part II of the cleaning room. Owing to this interference between the two air flows the supplied air was not distributed very efficiently into the working zone in part I of the cleaning room.

To summarize, the double tracer tests showed that the fresh air was improperly distributed towards the upper part of the cleaning room under roof fan E_1. On the other hand, the fresh supplied air was efficiently introduced into the working area near cleaning booth 12. In the experiments carried out, the concentration levels of the tracer gases were rather low owing to the limited volumes of tracer gas injected. This is typical of tracer studies in large industrial buildings. Measurements in large rooms with high ventilation rates therefore set special demands on the sensitivity of the analyzer and the sampling system.

The multiple tracer gas technique described in this paper has been proven to be applicable in investigations of air flow patterns in large industrial premises. The technique enables the mapping of several airflows simultaneously. The multipoint measurement system is rapid to install and relatively easy to use. The automated data acquisition unit displays concentrations in real-time and calculates several parameters immediately after actual tests.

6. REFERENCES

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Table 1. Analytical conditions of Miran 80

Tracer gas	Analytical wavelength (µm)	Path length (m)	Calibrated measurement range (ppm)
Nitrous oxide (N_2O)	4.5	20.25	0 - 200
Dichlorodifluoromethane (CCl_2F_2)	9.3	20.25 0.75	0 - 200
Carbon dioxide (CO_2)	4.3	0.75	300 - 1 500

Table 2. Mean ages of inlet air and recirculation air in the cleaning department of a steel foundry

Test no	Measuring site	Freon 12 pulse into air supply (130 litre)		N_2O pulse into recirculated air (100 litre)	
		Mean age (min)	Total dose (ppm.min)	Mean age (min)	Total dose (ppm.min)
1.	Roof fan E_1	12.7	300	10.3	315
	Cleaning booth 5	20.5	160	14.9	140
	Cleaning booth 2	23.1	145	20.6	110
	Door opening	23.6	105	22.4	100
2.	Roof fan E_1	13.7	275	9.1	290
	Cleaning booth 5	18.2	145	16.0	135
	Roof fan E_2	11.6	310	13.2	210
	Cleaning booth 12	10.6	330	12.5	205
3.	Roof fan E_1	12.5	240	10.0	230
	Cleaning booth 5	16.2	100	15.4	85
	Roof fan E_2	10.4	270	12.6	175
	Cleaning booth 12	8.4	335	11.9	180

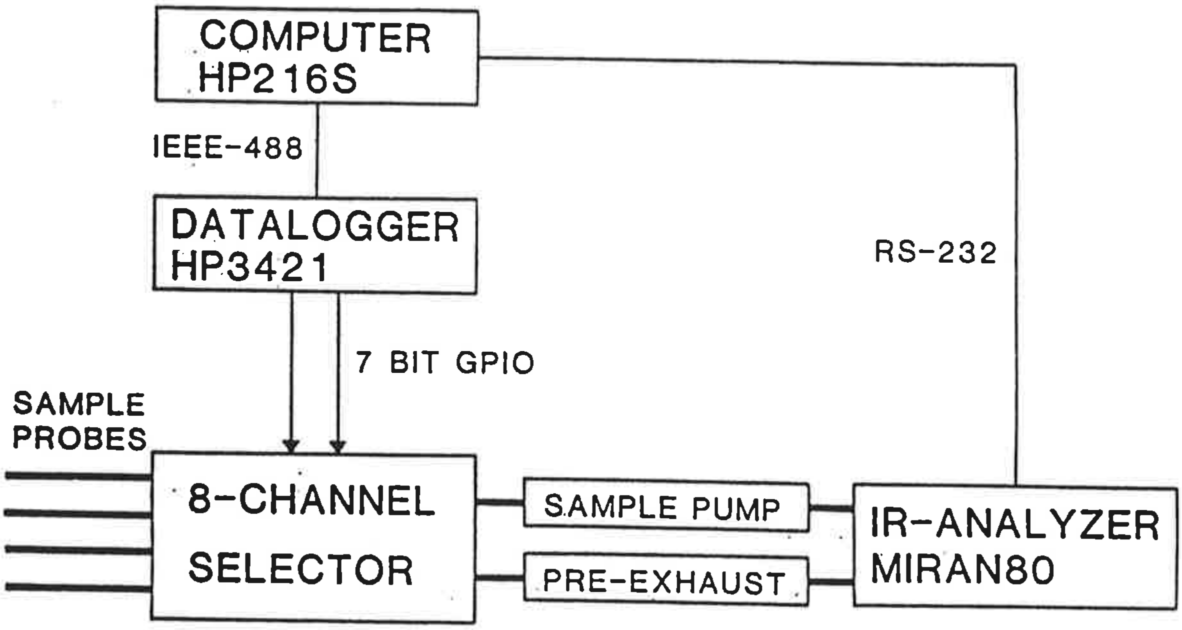

Figure 1. The tracer gas measurement system

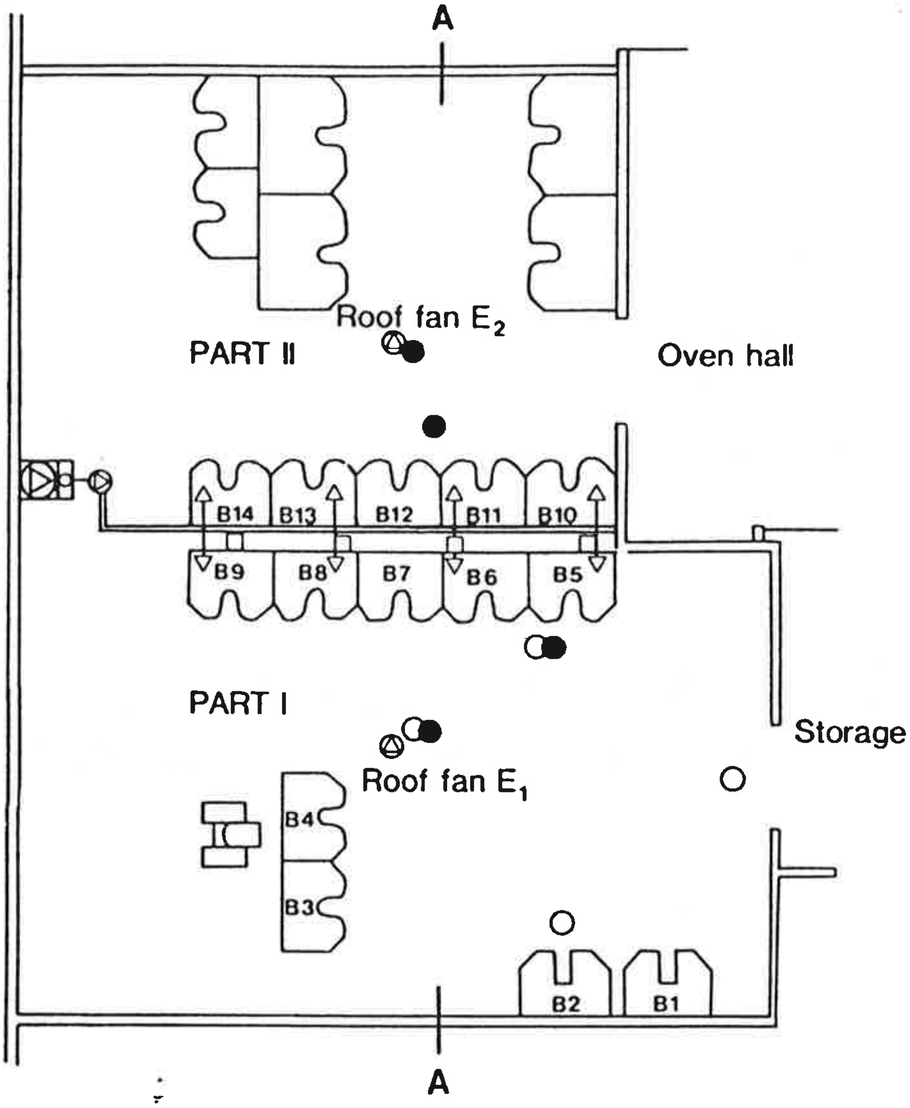

Figure 2. The lay-out of the cleaning room

○ locations of the sampling sites in test 1

● locations of the sampling sites in tests 2 and 3

—▷ inlet openings for fresh supply air (blown horizontally)

☐ blowing openings for filtered recirculation air (blown upwards)

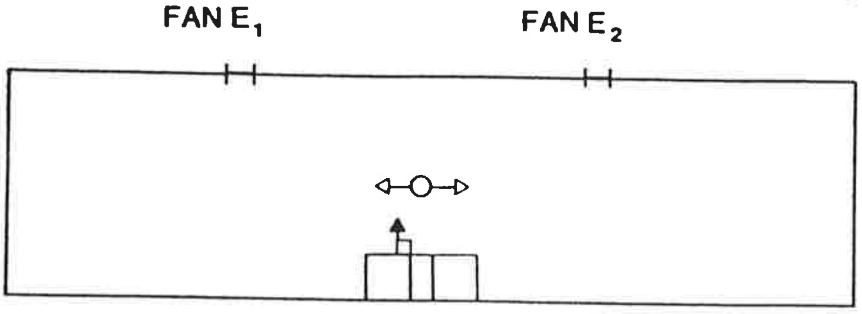

Fig 3. The cross-section (A-A) of the cleaning room

◁— fresh supply air

◀— recirculation air

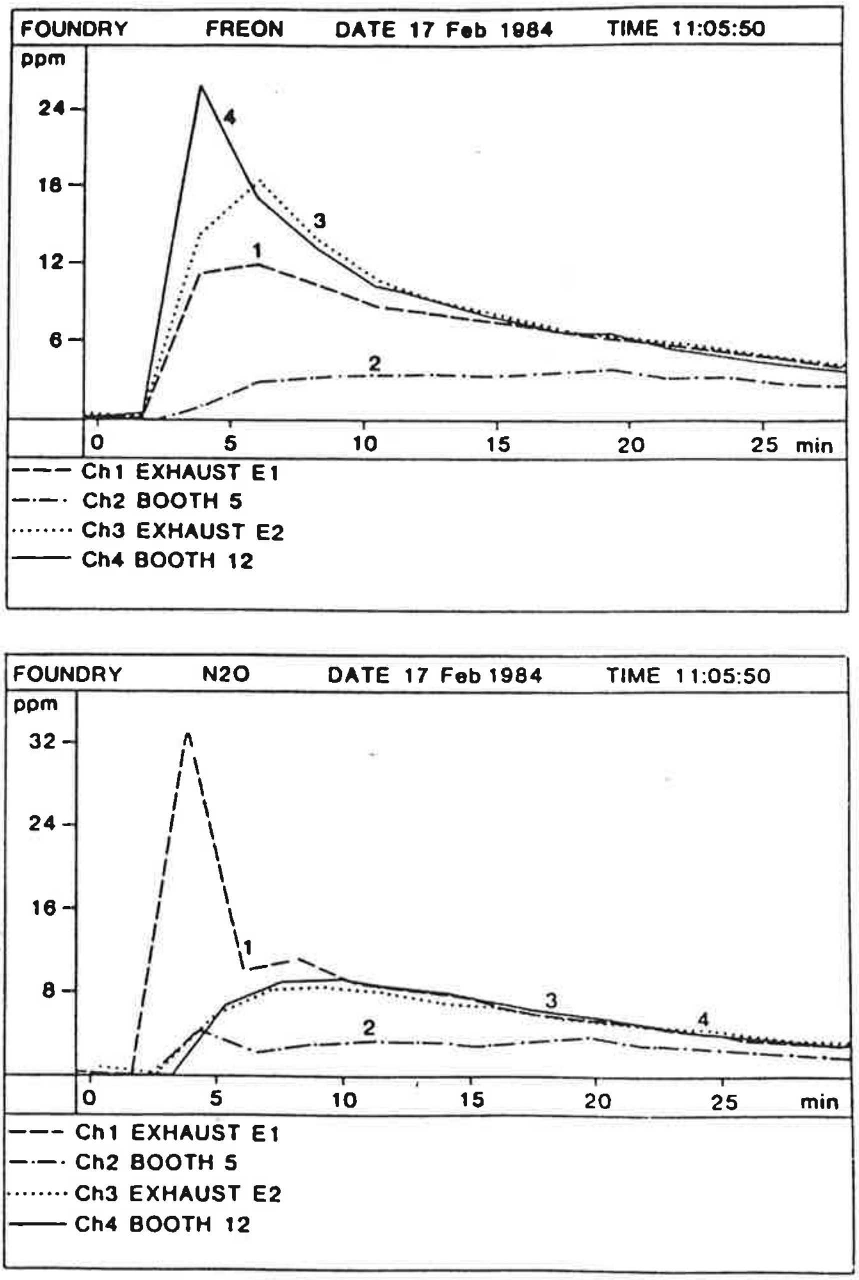

Figure 4. Typical concentration responses of tracer pulse input (test 2)