Building Ventilation: Theory and Measurement

David Etheridge
British Gas plc, Gas Research Centre, Loughborough, UK

Mats Sandberg
Royal Institute of Technology, Byggd Miljo, Gävle, Sweden

JOHN WILEY & SONS
Chichester • New York • Brisbane • Toronto • Singapore

of the differences between the recorded concentrations, C, and the predicted concentrations as given by the right-hand side of equation (12.4.44) (m is the number of samples)

$$\text{Sum}(A, B) = \sum_{k=1}^{m} (C(kT) - (AC((k-1)T) + B\dot{m}((k-1)T))^2$$

The solution is obtained by setting

$$\frac{\partial}{\partial A}\text{Sum}(A, B) = 0 \text{ and } \frac{\partial}{\partial B}\text{Sum}(A, B) = 0$$

When the coefficients A and B have been determined the flow rate and the volume can be obtained from (12.4.45) and (12.4.46) as

$$Q = \frac{1 - A}{B} \tag{12.4.47}$$

$$V = -Q\frac{T}{\ln A} \tag{12.4.48}$$

With no gas release one obtains an exponential decay and the coefficient A is determined. However, this means that only the ratio between the flow rate and the volume can be determined. This is inherent in the decay method which is an indirect method. If we set the volume equal to the geometrical volume of the room, the flow rate can be calculated as

$$Q = -V\frac{\ln A}{T} \tag{12.4.49}$$

Identification methods can give rise to unrealistic results such as negative flow rates and volumes that are greater than the geometric volume. Therefore side conditions must be imposed which constrain the estimates to be within a realistic domain.

12.5 OVERVIEW OF METHODS FOR MEASURING INTER-ZONAL AIR FLOW RATES

In a building consisting of N rooms or zones there is a total of $N(N + 1)$ flow rates. The same number of equations is required to determine these flow rates, as expressed in matrix form, equation (11.5.1). A sufficient number of equations is either obtained by using one tracer gas and repeating the measurement procedure as many times as there are unknown flow rates or by simultaneously using different tracer gases.

The number of unknown flow rates increases drastically with the number of zones. Even in a small house consisting of five rooms, there is a total of 30 flow rates and it is a laborious task to determine all these. As a consequence there is a practical limit to the number of flows that can be determined.

Normally inter-zonal flow rates are more difficult to determine than flow rates to and from outdoors. Inter-zonal flow rates are often buoyancy driven and are therefore vulnerable to changing indoor temperature. As a consequence flow reversal may occur during the measurement period. For example, the flow generated by radiators with an off-on control may reverse flows between rooms.

When determining inter-zonal flow rates the same injection strategies may be used as described earlier. Often system identification methods are used and an example of this application is Okuyama (1990) which uses one single tracer gas and one single analyser and injects periodic pulses of tracer gas; see Figure 12.6. In a validation test in a two-room house a maximum error of about 20% against the true flow rate was obtained. Okuyama attributed this error to the sequential sampling of the gas concentrations which results in a time lag between the concentration readings. Theory requires that the concentrations in all zones are recorded simultaneously. Owing to the time lag between the samples one has

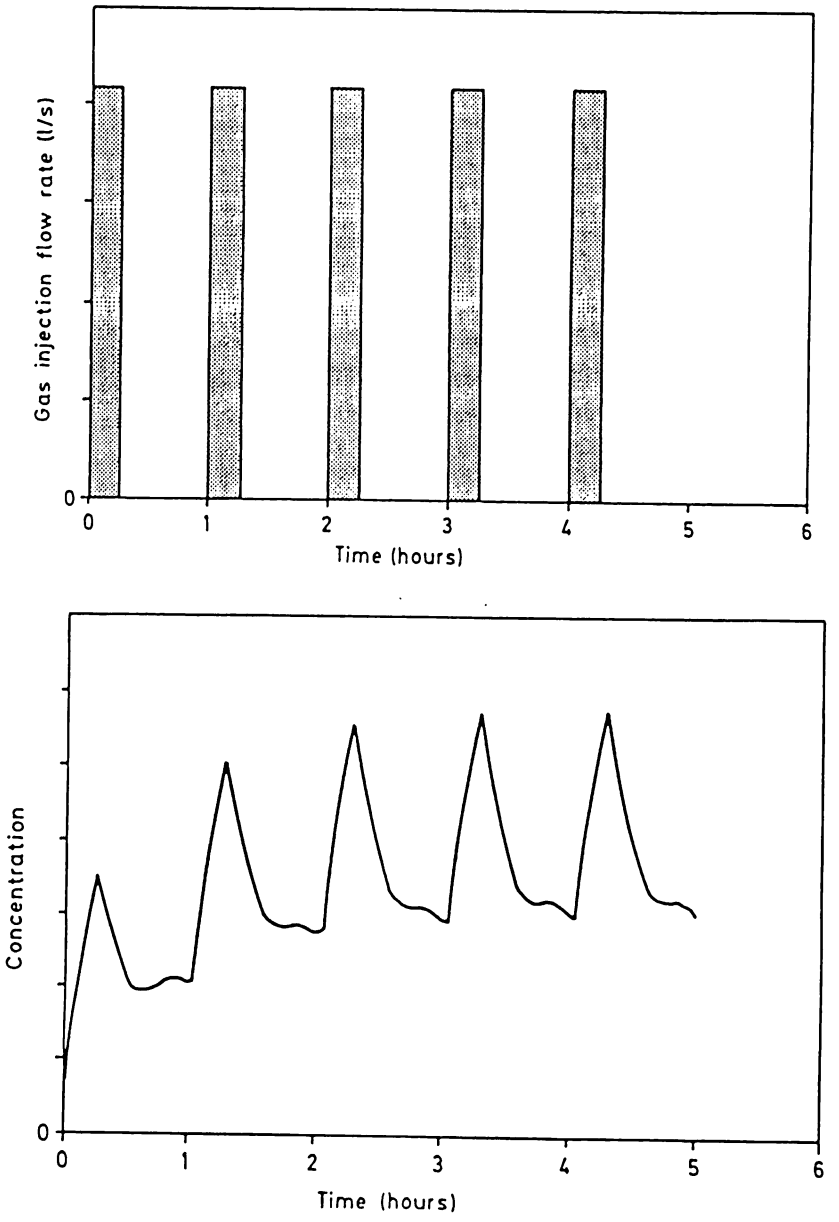

Figure 12.6 *Example of use of repeated release of gas (Okuyama 1990). Above: tracer gas injection history. Below: concentration response.*

only a concentration reading in one zone at the actual sampling time. The concentrations in the other zones are missing and the missing concentrations must be reconstructed. The simplest method is to use linear interpolation which Okuyama did. More sophisticated methods can be used, one possibility being Kalman filtering (see, for example, Brown (1983)). Kalman filtering is based on the assumption that the concentrations are generated by a random process. The missing concentrations are estimated from concentration readings up to the actual time. The method is recursive which means that not all past concentration readings are used each time the missing concentrations are estimated. Hedin (1994) has tested the use of a degenerated form of Kalman filtering which seems to work well.

12.6 COMPONENTS OF A TRACER GAS MEASUREMENT SYSTEM

This subsection partly draws on Roulet and Vandaele (1991) which contains a detailed description of various tracer gas techniques.

12.6.1 Main components

A tracer gas system has the following main components (see Figure 12.7):

- *tracer gas* in a container
- *injection system* allowing the injection of controlled quantities of *tracer* gas to the desired locations in the building

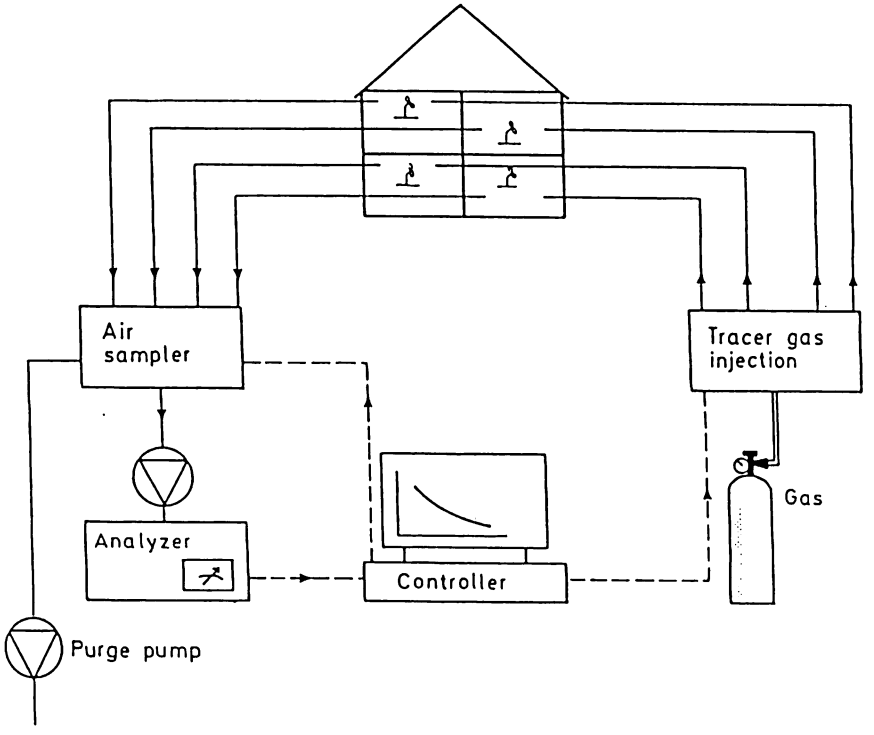

Figure 12.7 *Main components of an active tracer measurement system.*

— *artificial mixing system* for assuring perfect mixing of both tracer gas and air
— *sampling system*, for taking samples of *air* and bringing the sample to the analyser
— *gas analyser*, for measuring the concentration of the tracer in the air
— *control system* controlling the measuring function, e.g. manual change-over gear or a computer-driven interface.

Not all these main components are needed in all cases. Those that are needed depend on the method employed and conditions in the building being investigated. If one does not need immediate response of the gas concentration in the air sample then one can choose between analysis on site or taking samples back to the laboratory for subsequent analysis. A sampling network returning the air sample from each measuring point is needed for multi-point sampling.

12.6.2 Tracer gases

An ideal tracer gas should:

— not be a normal constituent of the environment to be investigated
— be easily measurable, preferably at low concentrations
— be non-toxic and non-allergenic to permit its use in occupied spaces
— be non-reactive and non-flammable
— be environmentally friendly
— be economical to use.

No single tracer gas fulfils all the requirements mentioned above. A wide variety of gases has been employed. Of all gases used as tracers, the characteristics of the most common ones are given in Table 12.2.

Nitrous oxide can be measured at the parts per million (ppm) level using the infrared technique. However, its potential toxicity has given rise to fairly low threshold limit values varying between 25 to 100 ppm in most countries.

Table 12.2

Gas	Molecular weight	Boiling point (°C)	Density (15°) (kg/m^3)	Analytical method (ppm)	Detection range (ppm)	Background concentration	Toxicity
Carbon dioxide	44	−56.6	1.98	IR	0.05–2000	Variable	Slight
Freon 12	121	−29.8	5.13	IR GC-ECD	0.05–2000 0.001–0.05		
Helium	4	−268.9	0.17	MS		5.24	
Nitrous oxide	44	−88.5	1.85	IR	0.05 – 2000	0.03	
Sulphur hexafluoride	146	−50.8	6.18	IR GC-ECD	0.05 – 2000 0.00002 – 0.5		
Perfluoro-n-hexane	338	57.0		GC-ECD	10^{-6}		

Carbon dioxide can also be measured at the ppm level but it has a background concentration of approximately 350 ppm. It is generated by people (see Section 7.9.7), and combustion of fuels. However, the influence of the production of carbon dioxide during a test can be compensated for, according to equation (12.4.10), and therefore does not necessarily impair its use as a tracer in an occupied room.

Halogenated gases such as sulphur hexafluoride, freons and perfluorocarbons can be analysed by gas chromatography equipped with an electron capture detector (ECD) which permits detection of concentrations below parts per billion (ppb). This minimises the volume of tracer gas needed to test a large system.

The perfluorocarbons are derivatives of parent hydrocarbons which contain only carbon and fluorine. According to Lovelock and Farber (1982) the perfluorocarbons are some of the very few tracers which do not readily attach to solid surfaces nor are they absorbed by water. (Unlike the other gases in Table 12.2.) Several perfluorocarbons are in liquid form at room air temperature. They can be dispersed either by flash-heating or by allowing them to diffuse from an impregnated fluoroelastomer source (Dietz *et al* 1985) or capillary source (see Figure 12.9).

Gases are usually stored in pressurised cylinders which are available in a number of sizes, the most common being 10, 20, 40 and 50 litres in volume.

12.6.3 Injection system

The injection system should transport the gas from the gas container and inject controlled quantities at desired locations in the building. Depending on the measurement method applied, this quantity of gas can be injected as:

- short *burst (pulse)* of gas in order to obtain an initial concentration (e.g. the decay method)
- *constant rate*
- *controlled rate* in order to obtain a constant concentration of the tracer in the building.

Several types of injection systems can be used. Where the gas is transported in tubes to the injection point, the injection system consists of the following components:

- pressure reduction valve at the cylinder
- tubes consisting of non-absorbent material
- injector that controls the amount of gas injected.

Constant mass flow Supply of a fixed mass flow can be arranged in several ways. One option is to use a stable pressure regulator system that keeps the pressure constant at a suitable level. This could be arranged by connecting a pressure governor to the line from a gas cylinder equipped with a pressure reduction valve. The pressure after the pressure reduction valve is recorded with a high-precision manometer and the flow rate is recorded with a rotameter. The desired flow rate is obtained by adjusting a needle valve. The flow rate obtained can be dependent on the length of the line, in which case calibration must be carried out with the whole line connected to the system. Pressure regulators normally control the gauge pressure, rather than absolute pressure, and in principle a correction to the mass flow should be made if the ambient pressure varies.

On the market there are proprietary mass flow controllers consisting of a hot wire (or hot film) which record the mass flow and a feedback loop which controls a needle valve. Calibration should be performed for each gas, since the response of the hot wire depends on the *gas used.*

Another type of a mass flow control is a *critical nozzle*; see Figure 12.8. In this case the gas is delivered through a nozzle that consists of a very small opening, usually a small hole in a membrane. At a sufficient high pressure drop the velocity in the small opening becomes equal to the local velocity of sound, c. Under these circumstances the nozzle is said to be choked, that is to say, however much the upstream pressure, p_u, is increased or the downstream pressure, p_d, is reduced, the mass flow will stay at its maximum value, ρAc.

Injection of a fixed amount of gas The simplest way to inject a given volume of gas is to fill a calibrated syringe.

Passive tracer gas sources Perfluorocarbon tracers (often called PFT) can be analysed in minute quantities. An easy way to inject small quantities is to let the tracer permeate through a suitable membrane (e.g. silicon rubber), or to diffuse through a capillary tube; see Figure 12.9. The sources consist of miniature containers with the tracer in liquid form and closed with a membrane or capillary tube. Owing to evaporation the volume between the liquid surface and the tap is filled with gaseous tracer. The partial pressure of the tracer gas is equal to the saturation pressure at the actual temperature. The flow rate of gas leaving the source is controlled by molecular diffusion.

Depending on the tracer used and on the thickness and area of the membrane (or length and diameter of the capillary tube), flow rates between 0.3×10^{-6} to 10×10^{-6} l/h can be achieved. Since the gas is stored as a liquid this means that the source may last for several years. For a capillary source the emission rate can be changed by changing the geometry of the capillary tube. Such a source is described by Stymne and Boman (1994).

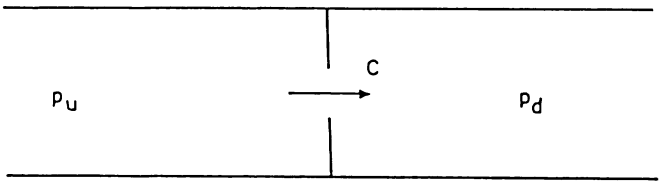

Figure 12.8 *Critical nozzle.*

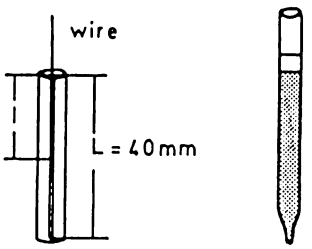

Figure 12.9 *Components in a passive system. Left: capillary source with adjustable emission rate. Right: Charcoal adsorption tube.*

The emission rate is adjusted by inserting a thin wire to different depths into the capillary; see Figure 12.9. Because the mass flow from the sources is controlled by diffusion the flow rate is dependent on the temperature. At room temperature, one degree temperature change will give rise to about 5% change in flow rate from the source. Hence it is important to record the daily average room air temperature or preferably to operate the sources at constant temperature. Similarly, the sources must not be placed close to heating or cooling surfaces.

Artificial mixing system Good mixing of the injected gas within the ventilated space is a prerequisite for determining the air flow rate. In order to achieve this artificial mixing is often necessary. The most widely used method is to use small *mixing fans* that enhance the internal circulation of air. The fan may be a small cooling fan used in electronic apparatus or a "table-top" fan (preferably oscillating). The gas is injected into the air stream generated by the fan.

This method works satisfactorily when relatively small amounts of gas are injected. The optimum number of mixing fans has been investigated by Sandberg and Blomqvist (1985). As a rule of thumb for an ordinary house they suggest the use of two fans in the largest room and one in each of the other rooms. Increasing the number of mixing fans does not always improve the mixing because an unfavourable flow pattern may be set up.

When pure gas is supplied in the air stream from the mixing fan the gas is rapidly diluted so the gas becomes a collection of discrete molecules and therefore any motion set up by the density difference between the gas and the air is prevented. Another possibility to avoid the problem with the density difference is to mix the gas with some other gas in order to obtain the same density as the air. However, even a very small density difference will give rise to a motion if the gas is injected as a concentrated gas. Therefore, it is still recommended to inject the gas into the air stream from the mixing fan.

The use of mixing fans changes the temperature gradient in the room (see Figure 13.4), and may somewhat change the air flow rate.

12.6.4 Sampling techniques

For ventilation tests using tracer gas techniques, the choice of a sampling method is dependent on:

- the tracer gas method
- the tracer gas employed
- the analytical instrumentation.

With the constant concentration technique there is no choice of sampling method. One must continuously sample and analyse the gas on site. This means that an expensive instrument is tied up to analyse the tracer gas at only one site. However, with the decay rate method or the equilibrium concentration method, one can choose to sample the gas on site and bring the samples back to the laboratory for subsequent analysis. In this way one can analyse samples collected from several sites simultaneously. There is a choice between:

- continuous (long-term integrated) sampling
- sequential time integrated samples
- several short-term or "grab" samples.

The mode of sampling can either be *active*, i.e. some sort of pump is used to draw the gas into the sample container or through an adsorbent tube, or *passive*. The latter relies on some natural, but uncontrolled, physical transportation process, e.g. air motion or diffusion, to fill the sample container.

Samples can be collected in a number of ways. One approach involves filling a soft bag or container which is subsequently connected directly to the measuring equipment. Alternatively, the tracer gas is trapped on suitable adsorbent material which is later treated to release the gas.

Bags or bottles Plastic bags are often used to collect gaseous samples. They may be of polyethene polyester (oven roasting bags), Mylar, or of more inert material such as Tedlar. To empty the bag it is first squeezed and then the sample is sucked into the container by a hand pump or a small battery-powered pump. Grot (1980) used a 10-litre five-layer air sample bag. Instead of a bag a plastic bottle may be used. Harrje *et al* (1982) used a 500-ml flexible polyethylene bottle with a 6-mm hole through the cap covered with a 2-mm thick natural rubber gasket. The sample is collected by removing the gasket and hand-squeezing the bottle ten times. Then the bottle is closed again and the gasket acts as a septum into which a hypodermic syringe can be inserted to draw a collected gas sample for analysis. One must be aware that in some bags (or bottles) the sample cannot be kept for a long time, because the gas may diffuse through the material or be adsorbed onto it.

Containers Samples may be collected in small metal cylinders with both ends openable. The sample is collected by opening both ends and "shaking" the container to fill it with new air and then both ends are closed. Tamura and Evans (1983) used evacuated glass tubes, silicone coated and stopped by 6.35-mm thick butyl rubber septa. The gas samples were taken from indoor air with a plastic syringe and transferred to the evacuated glass tubes. Twice the tube volume of gas was injected. There were no significant changes in concentration of samples after storage in the evacuated glass tubes for up to 21 days. A similar approach has earlier been used by Freedman *et al* (1975).

Solid adsorbent Examples of solid adsorbents for ventilation studies are charcoal and porous polymers. There are several commercial products. A charcoal adsorption tube is shown in Figure 12.10. To release the trapped gas for analysis the adsorbent is either washed with a suitable solvent or thermally desorbed by heating.

Sampling network For continuous monitoring of air samples at several points over a long period of time a sampling network is needed using tubes, valves for changing between sampling points and a control unit for the valves and pumps. Two pumps are needed, one (usually the analyser's pump) that sucks the air into the sampler and a "purging" pump which sucks from the tubes that are temporarily not connected to the analyser. This guarantees that "old" tracer gas is not included in the test.

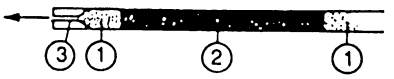

Figure 12.10 *Charcoal adsorption tube. 1, glass wool end plug; 2, charcoal granules 10–30 mesh; 3, 1 mm capillary (to hold filling).*

The tubing must be airtight and should not significantly adsorb or absorb the tracer gases. Suitable materials are nylon and polyethylene. Metallic tubes can also be used, but they are more difficult to install. Tubes which have previously contained pure tracers should not be used for sampling. Injection tubes should be marked and used exclusively for injection, e.g. use tubes of different colours for injection and sampling.

12.6.4.1 Methods of analysis of gases

The analysis of tracer gases is usually achieved by infrared spectroscopy, gas chromatography or mass spectrometry. The principle of infrared spectroscopy is based on the fact that many gases have characteristic IR absorption spectra, while gas chromatography is based on the fact that different gases migrate with different rates through a long column. In mass spectrometry molecules are sorted according to their mass to charge ratio by measuring their deflection in a magnetic field.

For any analyser the salient features to take into account are the following:

- *Sensitivity.* The more sensitive the analyser, the lower is the required working concentration. A sensitive analysing method is required when measurements are carried out in large spaces. Otherwise unreasonable amounts of gas are necessary. Furthermore from the point of view of health it is favourable to work with low concentrations.
- *Selectivity.* The analyser should not be sensitive to other gases usually present in air.
- *Speed (time constant).* The time needed for the analysis should be small in relation to the time constant of the variation. This is particularly important in active systems such as the constant concentration method where a rapid feedback is necessary in order to keep the concentration constant. Also if several points are to be sampled in sequence the time constant of the analyser may become critical. The analysis varies from milliseconds for mass spectrometers up to several minutes for gas chromatographs.
- *Infrared absorption spectrophotometry.* Infrared spectroscopy is a popular choice for analysing tracer gases. Its greatest advantage is the fast response time (about 10 seconds) achieved with this technique. An IR analyser can be a compact and rugged instrument suitable for field trials.

Infrared spectrometry is based on the fact that when light is passed through a gas, some of the frequencies are absorbed while the rest are transmitted without being absorbed; see Figure 12.11. Those frequencies which are absorbed correspond to the natural frequencies of the vibrational modes of the gas molecules or to a harmonic of those vibrations. The intensity of the light of the lamp, I_o, has a given distribution with respect to the wavelength. The fraction of the incident light at a certain frequency which is absorbed per path length in the medium is directly proportional to the concentration, C, of the absorbing compound.

$$\frac{d}{dx}(\log I) = -\varepsilon C$$

where I is the intensity of light.

Integration over the cell path length, L, yields

$$\log \frac{I_o}{I} = \varepsilon C L$$

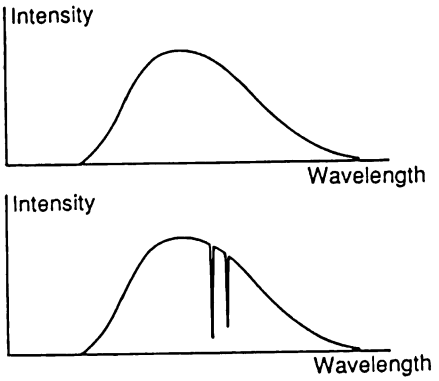

Figure 12.11 *Absorption of light in infrared spectrophotometry. Above: spectrum of radiation source. Below: spectrum after passing sample.*

where ε is the extinction coefficient, I_0 is the intensity of the light entering the cell and I_L is the intensity when leaving the cell.

The concentration is equal to

$$C = \frac{1}{\varepsilon} \log A$$

where $A = \log(I_0/I)$ is called *absorbancy* which is the quantity proportional to the concentration.

The basic components of an IR instrument are

- an IR light source
- some means of modulating the light (usually a rotating chopper)
- a chamber (cell) to contain the gas sample
- detector
- some method to process the signal.

Instruments designed for automated sampling incorporate additional components such as a pump and particle filters. To increase the sensitivity, mirrors are often inserted into the systems to increase the pathlength of the light through the sample.

Infrared absorption spectrometers may be either *dispersive* or *non-dispersive*. Dispersive spectrometers are tuned by the operator to a fine band of frequencies specific to the gas of interest. In non-dispersive devices the whole band of the infrared radiation is used.

When the dispersive technique is applied additional components are required to obtain a narrow bandwidth radiation. Optical filters are used for fixed wavelength radiation. For continuous tunability diffraction gratings or prisms are used.

The detector can be a microphone or a metal diaphragm (see below) that detects the pressure, or a meter that detects the change in velocity or flow rate caused by the pressure. The incident light is modulated by a chopper (rotating sector disk) in order to make it possible to identify the IR radiation emitted by the lamp from other sources of IR radiation. Therefore the detectors used detect fluctuating rather than steady changes in pressure or related quantities. In non-dispersive analysers the light from the infrared source is split along two paths; see Figure 12.12. One is a reference cell with clean air and the other contains the sample.

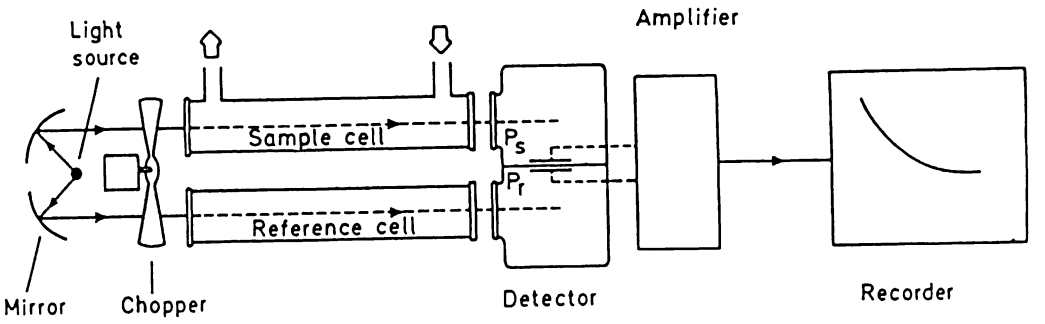

Figure 12.12 *Non-dispersive infrared gas analyser.*

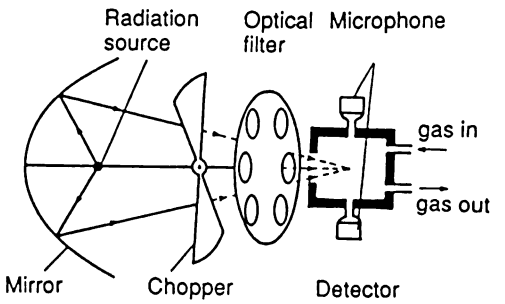

Figure 12.13 *Principle of the photoacoustic analyser.*

The detector consists of two sealed chambers filled with the same gas which is to be analysed in the air sample. As less radiation reaches the chamber on the sample cell side, the pressure there becomes less than in the chamber on the reference cell side. The amplitude of the chopper-modulated pressure differential is measured either directly by a thin metal diaphragm or indirectly by registering the flow rate of gas set up by the pressure differential.

Photoacoustic analyser This is also an infrared absorption spectrometer, but now the detector and the sample cell are combined into one unit. Again an infrared radiation beam is first chopped then optically filtered to leave only frequencies which are absorbed by the tracer of interest; see Figure 12.13. The beam enters a gas-tight chamber containing the air sample. The sample is heated and cooled in phase with the chopping frequency, thereby creating sound waves. The sound waves are detected by microphones (photoacoustic). The photoacoustic detector responds to the amount of light absorbed, $I_o - I$, in contrast to other instruments that record the amount of light, I, that is passed.

Gas chromatography This is a separation method where different substances can be separated from each other. Therefore the detector does not need to be selective to the substance of interest. The principle for separation is that the sample is injected into a separation column which is flushed with a carrier gas (often helium). Gases with high solubility in the stationary phase will migrate through the column with a lower velocity than gases with a low solubility. Depending on which stationary phase is used one can

distinguish between gas-solid chromatography (GSC) and gas-liquid chromatography (GLC). Figure 12.14 shows a basic gas chromatograph.

Samples are injected into a column (which contains the stationary phase) and is vaporised. Each component in the gas is detected when it reaches the end of the column, and the electrical signal thus generated from the detector is recorded as a function of time to give a chromatogram such as that in Figure 12.15. In this case the gas chromatograph was provided with two columns. At time t_1 the sample is directed to column 2 and the

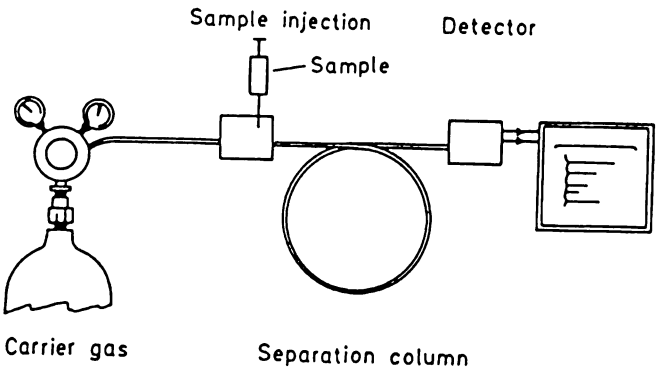

Figure 12.14 *Schematic diagram of a gas chromatograph.*

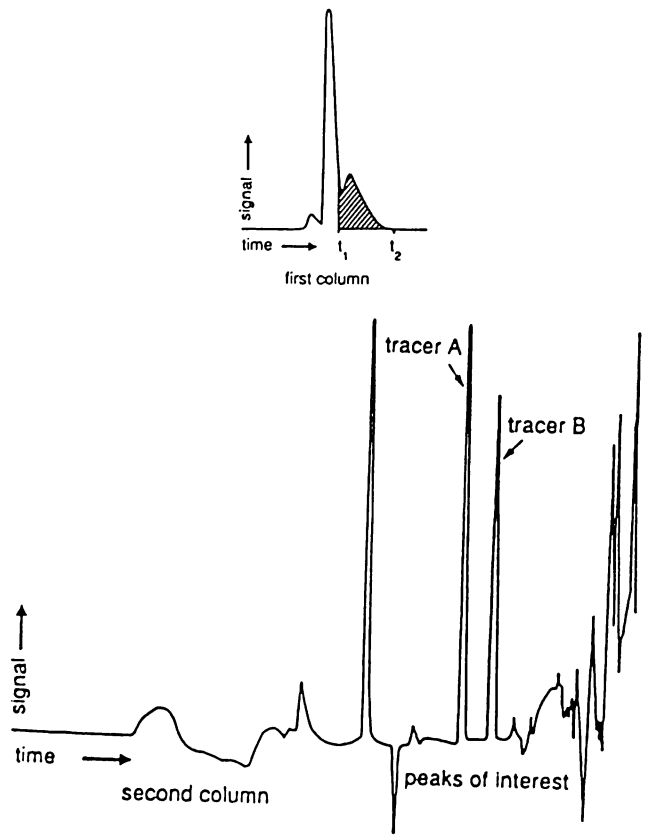

Figure 12.15 *Gas-chromatographic analysis of tracer gases.*

analysis of the shaded area was carried out between time t_1 and t_2. The height of the peak or the area under the peak is taken as a measure of concentration.

The detector responds to each component as it comes off the column. The important parameters of a detector include dynamic range, sensitivity, speed of response and linearity of response.

Mass spectrometry In a mass spectrometer molecular ions are sorted according to their mass to charge ratio by accelerating them through an electrical potential. Therefore the molecules are at first ionised.

High-resolution mass spectrometers are very expensive. However, there are cheaper instruments with lower resolution built for so-called residual gas analysis in vacuum systems. In these systems a so-called quadrupole filter consisting of four bars is used. Between the bars there is an oscillating electrical field. The filter is tuned to let through ions with a given mass to charge ratio. As the system works at very low pressure a vacuum pump is needed. These instruments are fast and several gases can be monitored continuously.

Chemical indicator tubes An electric pump or a hand-operated bellows pump (100 ml per stroke) is used to suck air through a glass tube packed with a solid absorbent treated with a selective reagent which gives a colour reaction with the gas in question. The more gas enters the tube, the further the coloured region extends down the packing. The number of strokes needed depends on which gas is to be analysed. For a given number of strokes (e.g. one or ten) the tubes have approximate calibration markings on them. These tubes allow a simple direct measurement of tracer gas concentration. They are available for the detection of many gases, among them CO_2. Detector tubes can only be used once and have to be discarded after each sample.

12.6.4.2 Location of injection and sampling points

In a multizone building one hardly ever obtains complete mixing within the whole building. There is always a difference between individual rooms and between upper and lower floors. Therefore the best strategy is to release gas in the rooms where the outdoor air enters and sample in the rooms where the air leaves the building. This strategy gives the maximum possibility for the gas to be diluted with all incoming air.

In a building ventilated with mechanical ventilation one can easily identify where the majority of air enters and leaves the house. In houses with no terminals or other purpose-provided openings it is more difficult to see where the air enters and leaves. Release of smoke may help to identify those points. If one cannot identify them the best strategy is to release tracer in each room and also to sample in each room.

12.7 PRACTICAL APPLICATION OF THE THREE MAIN METHODS

The practical application of the three main methods is illustrated by showing examples of their use in the same test house (see Figure 12.16) under identical conditions and with known flow rates. The house has five "rooms" and a total volume of 175.7 m^3. The measurements were conducted with an extract ventilation system in operation. The flow

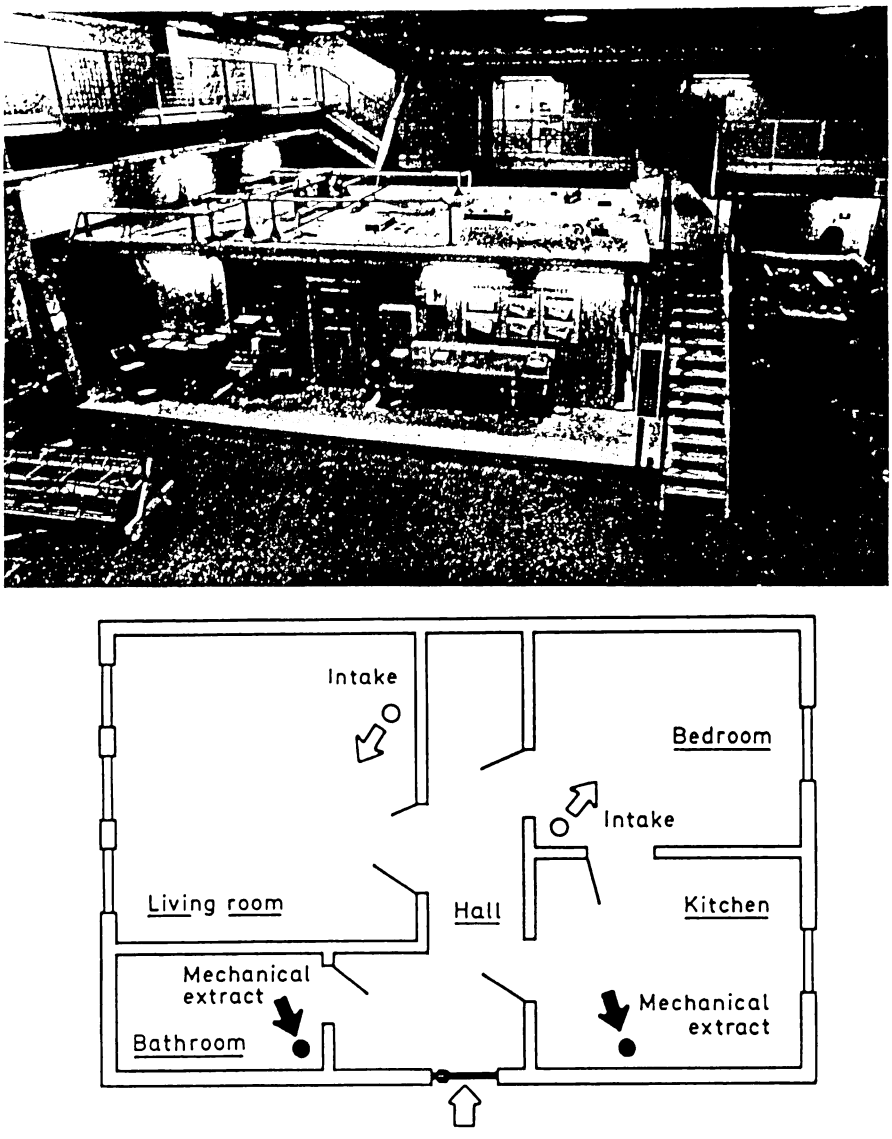

Figure 12.16 *Test house. From Sandberg and Blomquist (1985). Reproduced by kind permission of Elsevier Science Ltd., Kidlington OX5 1GB, UK.*

rates in the ducts were measured by orifice plates. The air was always extracted from the kitchen and the bathroom. N_2O was used as tracer gas and the analyser was of IR-type. The gas concentrations were recorded in each room, in each separate extract duct from the bathroom and the kitchen, and in the common main extract duct.

12.7.1 The decay method

Preparations for tests To be able to calculate the total flow rate with this method it is necessary to know the total ventilated volume and to establish complete mixing within the whole space. Therefore the internal doors should be opened and, if possible, all cupboard and storage room doors.

Measurement procedure The mixing fans are started and the tracer gas is released into the house by either walking from room to room and spreading it directly from the cylinder or via the tubes leading to each room. To facilitate the mixing of the gas it is advantageous to release the gas directly into the air stream created by the mixing fans. After approximately 10 minutes the gas is in most cases mixed within the ventilated volume and the recordings of the concentrations may begin. To obtain sufficient readings it is suitable to read the concentration at each measuring point at least once every 10 minutes. As a rule of thumb the total measuring time should be equal to the nominal time constant, if this can be assessed in advance, or at least one hour.

Example from the test house Based on the recorded concentrations the local mean age of air and the reciprocal, $1/\lambda_e$, of the slope of the logarithmic decay curve have been calculated and are presented in Table 12.3. Two cases are shown. The first with all doors closed and the other case with the bathroom door closed, as is normally the case during field trials. The total flow rate of outdoor air amounted to 95 m^3/h ($\tau_n = 1.85$ h) in the first case and to 93 m^3/h ($\tau_n = 1.89$ h) in the second case. The percentage deviation from the nominal time constant is given within parenthesis.

The recorded mean ages of air differ from room to room which shows that complete mixing was not obtained. However, the variation in the reciprocal of the slope is less, as predicted by the theory. By taking the average of the slope the predicted flow rate becomes in the first case $175.7/1.96 = 89$ m^3/h (relative error 6%) and in the second case it becomes $175.7/1.91 = 92$ m^3/h (relative error 1%). However, if the concentration is recorded in one room only and one assumes a "worst-case situation", i.e. one records the concentration in the room with the largest deviation from the true value, the accuracy becomes less. In the first case the flow rate predicted from recordings in the hall becomes 77 m^3/h (relative error 22%), while in the second case the maximum error is of the same order of magnitude as for the mean value, i.e. 1%.

Table 12.3 *The rate of decay method. Example of results obtained from the test house.*

Room	All doors open ($\tau_n = 1.85$ h)		Bathroom door closed	
	Reciprocal of the slope (h)	Mean age (h)	Reciprocal of the slope (h)	Mean age (h)
Living room	1.92 (+4%)	1.66 (−10%)	1.87 (−1%)	1.70 (−10%)
Hall	2.27 (+22%)	2.28 (+22%)	1.94 (+2%)	1.85 (−2%)
Bedroom	1.89 (+2%)	1.93 (+4%)	1.88 (0%)	1.94 (+2%)
Kitchen	1.92 (+4%)	2.15 (+16%)	1.89 (0%)	2.11 (+11%)
Bathroom	1.92 (+4%)	2.08 (+12%)	1.98 (+5%)	2.33 (+23%)
Average	1.96 (+6%)	1.95 (+6%)	1.88 (0%)	1.89 (0%)

12.7.2 The constant injection method

Additional equipment A reliable constant mass flow system is needed. This can be arranged in various ways. One alternative is to use a stable pressure regulator system that keeps the pressure constant at a suitable level. This can be arranged by connecting a pressure governer to the line from a gas cylinder equipped with a pressure reduction valve or by using a "choked" nozzle with a very small opening; see Figure 12.8.

Preparations for tests The preparations are the same as for the rate of decay method. The major points for inflow of outdoor air to the house should, if possible, be identified. If there are no air terminals one can release smoke to see where the air enters. The location of the point of tracer gas release is determined by where we expect the highest inflow of air to occur. The major points of outflow of air should also, if possible, be identified. Again release of smoke can be help to identify these points. Where there are well-defined extract points of air the concentration is recorded in those rooms where they are located. If there are no well-defined points of outflow of air, as can occur in natural ventilated buildings, the concentration is recorded in each room and the average concentration is calculated.

The constant injection technique relies on absolute calibration of the gas analyser. This can be achieved by means of bottled calibration gases. Since these can last for months or even years, it is highly advisable that an independent check on the calibration gas be made.

Measurement procedure The mixing fans and the release of gas are started. It is extremely important to achieve as good mixing as possible in the room where the gas is injected.

Example from the test house Release of gas was made into all rooms, one at a time. In Table 12.4 are presented the results (Sandberg and Stymne 1989) obtained with the mixing fans in operation and in Table 12.5 the results obtained with no artificial mixing. The predicted flow rate has been calculated as the ratio between the flow rate of gas injected and concentration recorded in the point in question (12.4.30). Total average refers to the flow rate calculated from the average concentration in the whole house, whereas in

Table 12.4 *The equilibrium method. Predicted flow rates (m^3/h). Mixing fans in operation.*

Source droom	Flow rate	Living-room	Hall	Bedroom	Kitchen	Bathroom	Extract	Total average	Average without source room
Living room	96	78 (−18%)	90 (+18%)	113 (−6%)	94 (−2%)	92 (−4%)	94 (−2%)	97 (+1%)	90 (−6%)
Hall	95	114 (+20%)	95 (0%)	127 (+33%)	98 (+3%)	95 (0%)	98 (+3%)	108 (+14%)	110 (+16%)
Bedroom	96	100 (+4%)	105 (+9%)	63 (−34%)	94 (−2%)	91 (−5%)	95 (−1%)	90 (−5%)	99 (+3%)
Kitchen	96	173 (+80%)	142 (+48%)	181 (+89%)	71 (−25%)	144 (+50%)	86 (−10%)	131 (+36%)	162 (+69%)
Bath-room	96	186 (+94%)	149 (+55%)	195 (+102%)	136 (+36%)	52 (−46%)	93 (−3%)	144 (+50%)	163 (+139%)

Table 12.5 *The equilibrium method. Predicted flow rates (m^3/h). No artificial mixing.*

Source room	Flow rate	Living-room	Hall	Bedroom	Kitchen	Bathroom	Extract	Total average	Average without source room
Living room	96	92 (−4%)	92 (−4%)	92 (−4%)	92 (−4%)	94 (−2%)	97 (+1%)	92 (−4%)	92 (−4%)
Hall	96	102 (+6%)	91 (−5%)	93 (−3%)	84 (−13%)	105 (+9%)	99 (+3%)	95 (−1%)	95 (−1%)
Bedroom	96	106 (+11%)	92 (−4%)	82 (−15%)	98 (+2%)	102 (+6%)	98 (+2%)	97 (+1%)	99 (+3%)
Kitchen	96	127 (+32%)	83 (−13%)	152 (+58%)	44 (−54%)	86 (0%)	95 (−1%)	87 (−9%)	112 (+16%)
Bath-room	95	159 (+67%)	140 (+47%)	182 (+91%)	149 (+57%)	77 (−19%)	90 (−5%)	141 (+48%)	155 (+63%)

the last column is given the flow rate predicted from the average concentration when the concentration in the source room is excluded. The percentage deviation of the predicted flow rate from the nominal flow rate is also presented.

From Tables 12.4 and 12.5 it can be seen that the best strategy is to inject gas where the outdoor air enters and to record the concentration where the greater fraction of air leaves the house. The gas must not be released in a room where the air leaves the house. In this case a fraction of the gas is lost without being diluted with the total air flow. The results above show that the error due to lost gas can be very large.

Where there are no well-defined extract and supply points of air the best strategy is release gas in the middle of the house and record the concentration in several rooms. The flow rate is calculated from the average concentration in the house.

12.7.3 The constant concentration method

Additional equipment Two sets of solenoid valves are needed. One set for the control of the sample lines, whilst the other is needed for the control of the injection of the tracer gas. The solenoid valves in turn are controlled by a computer or microprocessor. Software with a suitable control algorithm is needed to keep the concentration as close as possible to the desired target concentration. A PID controller will meet the requirements. The efficiency of different control algorithms has been explored by Sandberg and Blomqvist (1985). With a PID controller they obtained concentration fluctuations around the mean with a maximum standard deviation of about 3.2%. However, the maximum departure of the mean concentration from the target concentration (50 ppm) amounted to about 0.5%. This shows that the concentration fluctuations tend to cancel out when averaged. That one should expect this to occur has been pointed out by Etheridge and Stanway (1985). The amount of injected gas is calculated as the flow rate multiplied by the injection time. Therefore one must know the flow rate accurately in each individual injection line. As for the constant injection method one can use a constant mass flow system. The flow rate should be constant in each separate injection line. The number of injection lines connected to the gas cylinder will vary from time to time. A constant pressure regulator must be able to cope with this circumstance. This can be achieved by using a two-step precision pressure regulator on the cylinder followed by a pressure governor. The pressure after the

Table 12.6 *The constant concentration method. Predicted flow rates.*

Room	All doors open (m^3/h)	All doors closed (m^3/h)
Living room	33.2	41.8
Hall	34.6	6.3
Bedroom	34.1	44.3
Kitchen	0.0	5.2
Bathroom	0.0	0.2
Total	101.9	97.8
Nominal	98	95
Difference	+4%	+3%

governor is read with a precision manometer. The flow rate at a certain pressure in each separate injection line is calibrated with, for example, a bubble flow meter.

Preparations for test The constant concentration method relies on absolute calibration of the gas analyser and a known calibration gas must be used for calibration.

Example from the test house In Table 12.6 are given examples of recorded flow rates on two occasions, one with all internal doors open and one with all internal doors closed. It can be seen that the total flow rate is predicted with a high accuracy. Owing to the location of the supply opening the bulk of the air enters the living room and the bedroom. However, for the open-door case, it can be seen that quite a large inflow of outdoor air into the hall is predicted. What happens is that a part of the air that enters the living-room and the bedroom flows directly towards the hall. The inflow of air into the hall from the neighbouring room is predicted as a direct inflow of outdoor air into the hall. However, when all internal doors are closed the predicted inflows of air to different rooms are close to the correct ones.

12.8 SUMMARY

In this chapter methods for predicting the stationary flow rate of outdoor air to a house have been dealt with. The following three tracer gas methods have been discussed:

- the decay rate method
- the equilibrium concentration method
- the constant concentration method.

From the theoretical point of view all three methods require complete mixing and any departure from this will introduce an error. If complete mixing is not the natural state one tries to achieve this with artificial mixing. This can be done with small mixing fans. In an ordinary house one fan in the smaller rooms and two in the larger ones are sufficient.

Within a house there is normally an exchange of air in both directions between the rooms. Therefore the tracer gas concentration in one room is affected by the amount of inflow of outdoor air to other rooms. It follows therefore that with the use of the first two methods one can generally only predict the total flow rate of outdoor air entering a

house. However, by controlling the release of tracer gas to each individual room in such a way that the concentration is kept constant and the same in each room the effect of the exchange of air between the rooms is cancelled. Therefore the constant concentration method is the only method which in general predicts the distribution of the air entering the house. With the internal doors closed this method will very accurately predict this distribution. However, with the internal doors open it may sometimes happen that a fraction of the air that enters one room will be predicted as air entering a neighbouring room.

Apart from the constant concentration method (which requires both injection and sampling in each room) the best strategy is to release gas where the bulk of air is entering the house and to sample in the room where the bulk of air leaves the house.

The gas concentration can either be sampled on site or brought back to the laboratory. Release and sampling of traces gas can be done by either *active* or *passive* techniques. Active techniques are based on the use of pressurised systems for release of gas and pumped sampling, whereas in passive techniques the transport of gas is governed by molecular diffusion. Passive techniques are suitable for use in occupied buildings and for obtaining long-term averages.

There are two main techniques for analysing the gas concentrations:

- infrared spectroscopy (IR)
- gas chromatography (GC).

The main advantage of IR is the fast response (about 10 seconds) and an IR set-up is a quite compact and rugged instrument, suitable for field trials. With the IR-technique gas concentrations in the ppm range can be measured. One drawback is its lack of selectivity. It may respond to constituents other than the tracer gases, as for example water vapour.

Gas chromatography is a more sensitive but slower technique than the IR-technique. With GC, concentrations in the sub-ppb range can be detected. GC is more suitable for analysis in a laboratory environment than on site in a field trial. However, there are on the market instruments intended for use in field trials.

Other techniques for analysing gas concentrations have been described. One technique is mass spectroscopy and the use of detector tubes.

REFERENCES

Axley, J. and Persily, A. (1988) *Integral Mass Balances and Pulse Injection tracer Techniques*, Report NISTIR 88-3855. U.S. Department of Commerce. National Institute of Standards and Technology.

Brown, R. G. (1983) *Random Signal Analysis and Kalman Filtering*, John Wiley & Sons, New York.

Compagnon, R., Kohler, A., Roecker, C. and Roulet, C. A. (1988) Development of an efficient control algorithm for a multizone constant concentration tracer gas air infiltration measurement system. *Proceedings, 9th AIVC Conference, Ghent, Belgium*, Vol 2.

Dick, J. B. (1949) Experimental studies in natural ventilation of houses. *Institution of Heating and Ventilating Engineers*, **17**.

Dick, J. B. (1950) Measurement of ventilation using tracer gas. *Heating Piping and Air Conditioning*, **22**(5), 131-137.

Dietz, R. N., D'Ottavio, T. W. and Goodrich, R. W. (1985) Multizone infiltration measurements in homes and buildings using a passive perfluorocarbon tracer method. *ASHRAE Trans.*, **91**(2).

Dufton, A. F. and Marley, W. G. (1935) Measurement of rate of air change. *Institution of Heating and Ventilating Engineers*, **1**, 645.

Etheridge, D. W. and Stanway, R. J. (1985) Application of the constant concentration technique for ventilation measurement in large buildings. *Building Services, Engineering Research of Technology*, **6**(3), 129-133.

Freedman, R. W., Humphrey, W.G. and Craft, R. L. (1975) Use of vacutainers for collection of mine atmosphere samples. *Bureau of Mines Report of Investigations*, RJ 7999.

Grot, R. A. (1980) A Low cost method for measuring air infiltration rates in a large sample of dwellings. *ASTM special Technical Publications*, **79**, 50-59.

Harrje, D. T., Gadsby, K. and Linteris, G. (1982) Sampling for an exchange rates in a variety of buildings. *ASHRAE Trans.*, **82**(1).

Hedin, Björn (1994) Mätteknik med pårgas (in Swedish). Report TABK-94/1004 Installationsteknik, Lunds Tekniska Högskola, Swedon.

Hitchin, E. R. and Wilson, C. B. (1967) A review of experimental techniques for the investigation of natural ventilation in buildings. *Building Sci.*, **2**, 59-82.

Marley, W. G. (1936) The measurement of rate of air change. *Institution of Heating and Ventilating Engineers*, **2**, 499.

Okuyama, H. (1990) System identification theory of the thermal network model and an application for multi-chamber airflow measurement. *Building and Environment*, **25**(4), 349-363.

Olander, L. (1982) Luftomsättningsmätning med medelvärdesmätande instrument. *Undersökningsrapport* 1982:25, Arbetarskyddsstyrelsen, Sweden.

Pettenkofer, M. (1858) Luftwechsel in Wohngebäuden. Der J.G Cotta'schen Buchhandlung, Literarisch-Artistische Anstalt, Munich.

Roulet, C. A. and Vandaele, L. (1991) Air flow patterns within buildings measurement techniques. Technical Note AIVC 34.

Sandberg, M. and Blomqvist, C. (1985) A quantitative estimate of the accuracy of tracer gas methods for the determination of the ventilation flow rate in buildings. *Building and Environment*, **20**(3), 139-150.

Sandberg, M. and Stymne, H. (1989) The constant tracer flow technique. *Building and Environment*, **24**(3), 209-219.

Sandberg, M. and Sundberg, J. (1987) The use of detector tubes with carbon dioxide as a tracer gas. *Air Infiltration Review*, **8**(3), 6-7.

Sherman, M. H. (1990) Tracer gas techniques for measuring ventilation in a single zone. *Building and Environment*, **25**(4), 365-373.

Stymne, H. and Boman, C. A. (1994) Measurements of ventilation and air distribution, using the homogeneous emission technique — a validation. *Proceedings Healthy Buildings '94*, Budapest, Hungary.

Tamura, G. T. and Evans, R. G. (1983) Evaluation of evacuated glass tubes for sampling of SF6/air micture for air exchange measurement. *ASHRAE J.*, October, 40-43.

Tarantola, A. (1987) *Inverse Problem Theory*, Elsevier, Amsterdam.