



INNOVA
AirTech Instruments

Ventilation Measurements

And Other Tracer-gas Applications



VENTILATION MEASUREMENTS AND OTHER TRACER-GAS APPLICATIONS

by
Innova AirTech Instruments

This booklet answers some basic questions about ventilation measurements and other tracer-gas applications. It explains some of the techniques and terminology used and gives some examples.

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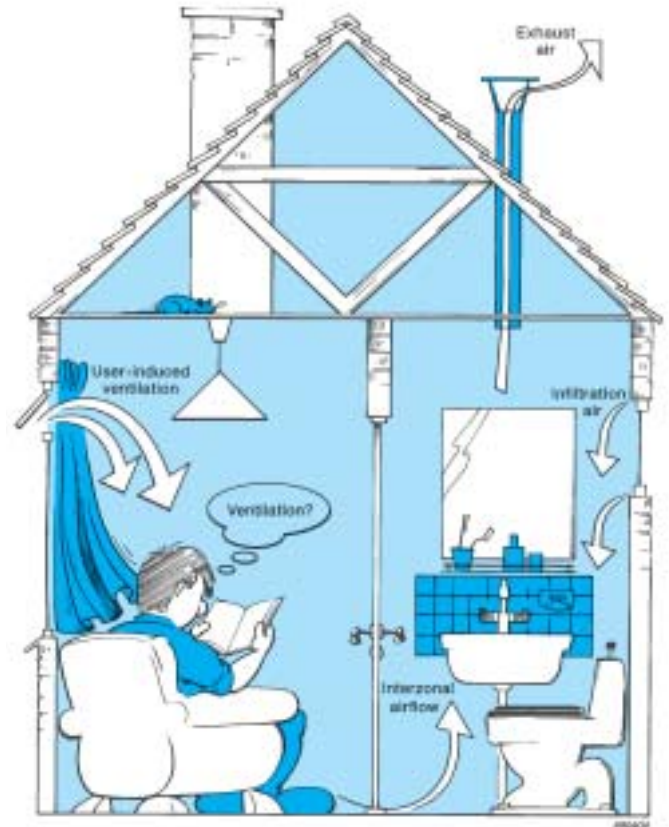
What Is Ventilation?

Most people have some idea of what ventilation is all about in general terms but are not quite so sure about its importance to us in our everyday lives, or of the terms used to describe the different types of ventilation that can occur. *Ventilation is the process of supplying and removing air by natural or mechanical means to and from any space.* This definition is rather broad and several terms are used to describe individual components of ventilation. Some of these components are illustrated in the drawing.

The term “natural ventilation” covers both the uncontrolled inward and outward air-leakage through cracks and interstices (i.e. infiltration and exfiltration) and the air entering and leaving the enclosure through openings provided intentionally such as open windows and doors, and vents. Infiltration and exfiltration are caused by the weather or other pressure-difference forces exerted on a building.

“Mechanical” or “forced” ventilation, on the other hand, is ventilation air provided by electric fans. These fans are often part of an air-conditioning system and may drive the supply airflow, the exhaust airflow, or both.

The principle of “hybrid ventilation” combining elements of natural and mechanical ventilation has recently been introduced and is receiving growing attention.

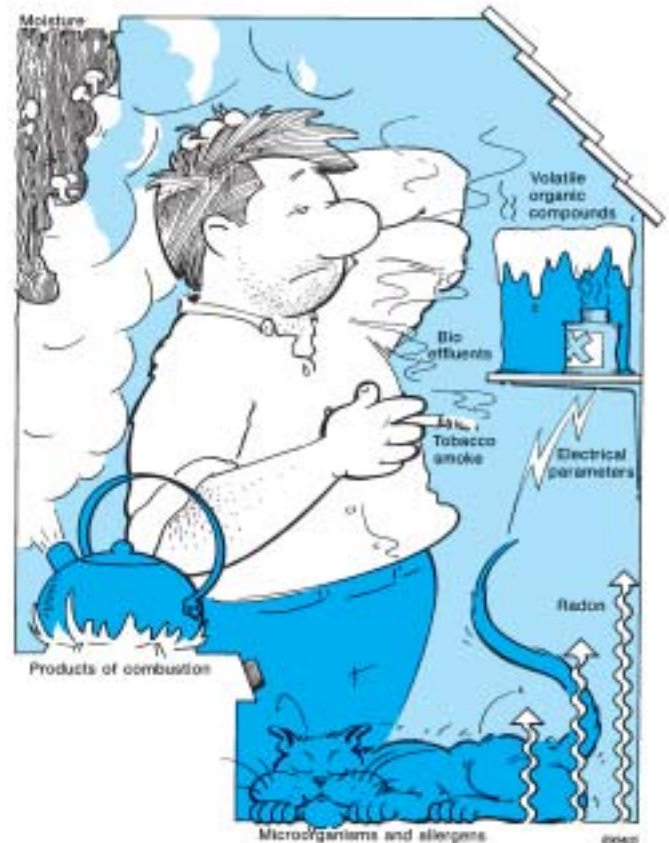


Why Do We Need Ventilation?

Over the past decades many new building techniques have been developed in an effort to reduce energy consumption. Unfortunately, this often resulted in buildings being so airtight that very little natural ventilation could occur and increased indoor air pollution resulted. Other factors which have increased indoor air pollution are the many new materials used in the construction and furnishing of buildings. Ventilation removes indoor air pollutants and thereby improves the quality of indoor air.

Indoor air pollutants may be in the form of tobacco smoke or fumes and dust from industrial processes. There are, however, many other important indoor air pollutants such as volatile organic compounds from various sources including glues, paints, and varnishes; products of combustion; moisture from washing and cooking; bioeffluents from people; and micro-organisms, allergens, and fibres.

Condensation of moisture and infiltration of radon are particularly worrying problems. Condensation of moisture on the inside surfaces of building structures causes mould and fungus growth and has rendered even almost-new buildings uninhabitable. Also, there are numerous studies indicating that damp buildings are associated with adverse health effects such as asthma and allergy. Radon, a radioactive gas present in many naturally occurring rocks and soils can represent a serious health risk to the inhabitants of houses built in areas with high ground concentrations and has, by some, come to be considered the most serious indoor air pollutant of all.



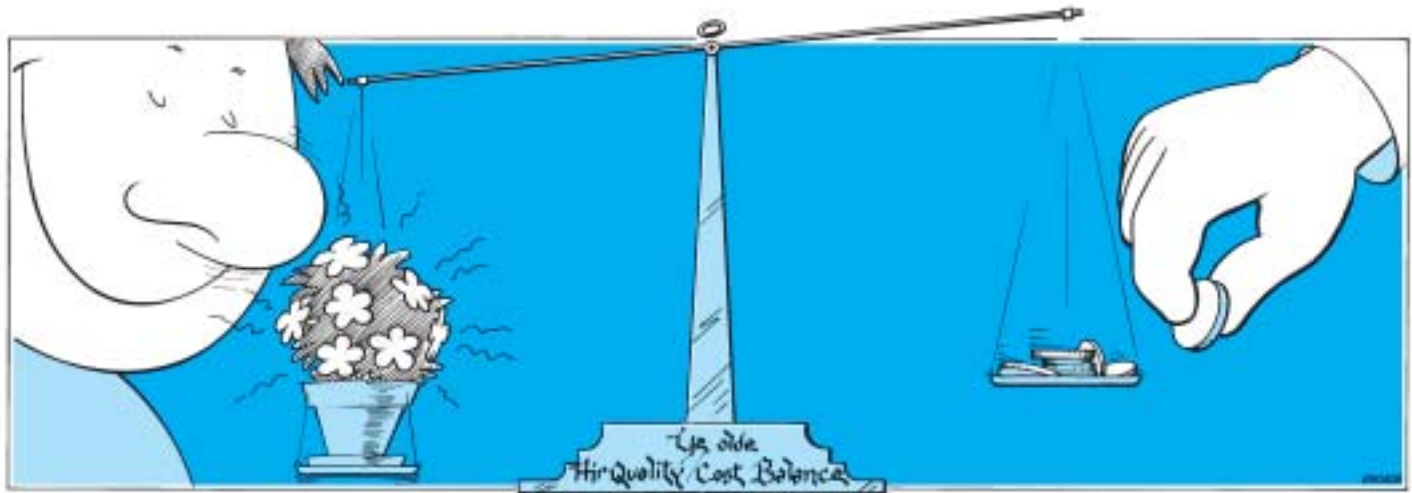
Why Analyse the Ventilation in Buildings?

Poor indoor air quality can have a negative effect on performance of e.g. office work. However, the reduced productivity of building occupants, and the increased maintenance costs for a building structure that can be caused by poor indoor air quality have to be balanced against the costs of improving ventilation and the global need for reducing the energy consumption and the environmental impact.

Ventilation systems can be costly to install, and to run once installed. It is therefore very important to be able to monitor a ventilation system to ensure that it is able to do the job it was commissioned to do and that it does it efficiently. It is also important to be able to check

a ventilation systems efficiency at regular intervals after installation.

When outdoor temperatures are considerably below the optimum indoor temperature, the heat lost from buildings due to air infiltration and ventilation can account for a considerable part of a buildings space-heating requirement. In the same way, when outdoor temperatures are high, or too much heat is generated within the building, cooling the supply air becomes a big drain on resources. By making measurements on ventilation systems we can both check to see that the people in a building are getting the required amount of outdoor air, and check that this air is distributed in an economical way.



How Is Ventilation Quantified?

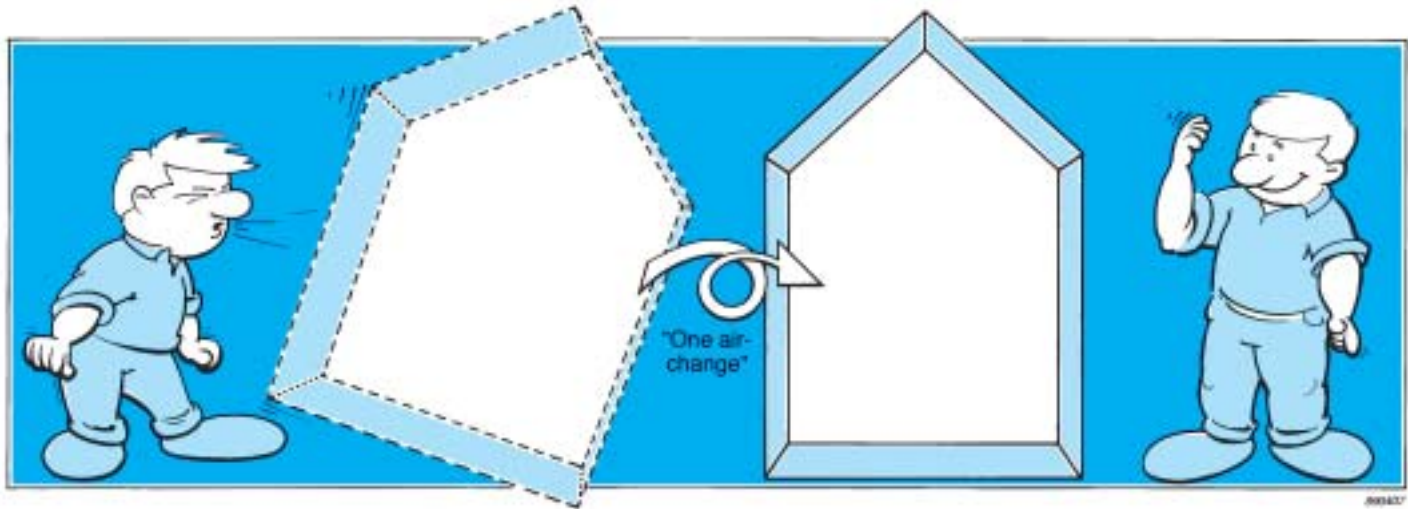
Ventilation standards normally quote either the outdoor air supply requirement (volume per time per person), or the outdoor air change-rate (h^{-1}), or both. The “efficiency of ventilation” is a fairly recent innovation and is growing in importance. This parameter is discussed in greater detail in the later sections concerning the measurement of the age-of-air.

The outdoor air change rate is defined as *the ratio of the volume of outdoor air entering an enclosure per unit of time (usually hour) to the effective* volume of the enclosure*. Note that air exchange rate always relates to a physical space, in contrast to some other measures (e.g. age-of-air), which may relate to a point in a space. The outdoor air exchange rate is a very useful term in the evaluation of ventilation,

since it takes into account the enormous variations in the volume of enclosures. The size of an office may, for example, vary from a small single office to a very large open plan office.

The outdoor-air supply-requirement defines the volume of outdoor-air each person in an enclosure should receive per unit of time. This requirement takes into account the fact that each person in an enclosure is a source of indoor air pollution, although seldom the dominant one. Some standards therefore list recommendations for both the outdoor air supply requirement and the outdoor air change rate.

* See Glossary



What Is Tracer-gas Monitoring?

The use of tracers in many types of research and especially in fault-finding activities is very widespread. Just a few examples that spring to mind include following the course of fluids in the human body, leak testing, and even the “ringing” of birds. In hydrological research it would not be unusual for a researcher to mark pebbles with brightly coloured paint or with a radioactive isotope in order to study the movement of sediment along a coastline or along a river bed. The basic idea is the same for ventilation measurements using tracer gas: the air in a building is marked with something easily identifiable so that its movement can be traced.

The types of tracers used in ventilation measurements are usually colourless, odourless, inert gases, not normally present in the environment. The idea behind tracer-gas analysis can be envisaged more easily if we imagine what happens when soap bubbles are blown in a room. The bubbles move around the room and through open doors, up stairways, and perhaps into other rooms in the building. Perhaps the most frequently used simple qualitative technique is smoke visualisation but many other methods can be used. Even smells can be used as tracers!



Why Use Tracer-gas Techniques?

Tracer-gas techniques are the only way of making many types of quantitative measurements of ventilation. These include infiltration and air exchange measurements, fume hood efficiencies, and spreading of pollutants. In other cases tracer-gas analysis methods are chosen in preference to other analysis methods because they are more convenient and more accurate. This is often the case when measuring airflow rates in ventilation ducts. Each of these subjects is discussed in later sections of this booklet.

A very important aspect of tracer-gas measurements is that they can be made in occupied buildings. This is not only much more convenient but is also much more accurate since it takes into account the large effect occupancy can have on a building's air

change rate – for example, the effect of opening and closing doors and windows. It is, after all, the air change rate of a building under normal working conditions that is important in most cases.

Results from properly conducted tracer-gas measurements on a ventilation system can provide information about the amount of outdoor air brought into each room; the efficiency of heat recovery units; the amount of extract air which is re-circulated into the supply air ducts; the outdoor short-circuit from exhaust to outdoor air intake, and distribution of supply air in rooms. Much wasted energy and many “sick” buildings result from the fact that these parameters have not been taken into account at the planning stage of a building and are not measured as part of regular building maintenance checks.



Air Change Rate Measurement Methods

The airflow through a room or a building is normally evaluated using one of three tracer-gas methods: the concentration-decay method, the constant-emission method, or the constant-concentration method. All three methods are based on a simple mass balance:

Change in amount of tracer in the room $V \frac{dC}{dt}$	=	amount of tracer introduced into the room $F(\tau) + q_v(\tau) \cdot C_{oa}$	-	amount of tracer that has left the room $q_v(\tau) \cdot C(\tau)$
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- V = volume of air in room, m³
- C = concentration of tracer-gas in room-air,
- τ = time, h
- F = rate of tracer-gas emitted into room,
- C_{oa} = concentration of tracer-gas in outside air,
- q_v = air-flow through room,

This can be written:

$$q_v(\tau) = \frac{F(\tau) - V \frac{dC}{dt}}{(C(\tau) - C_{oa})}$$

To find the air change rate, N, the airflow through the room is divided by the effective volume of the room. In the following few pages we will consider, in turn, the three main measurement methods for determining the airflow through a room or building. In each case we will assume that the outside air does not contain any of the chosen tracers.



The Concentration-decay Method

This is the most basic method of measuring air change rates and is used to obtain air exchange rates over short periods of time.

A small quantity of tracer-gas is thoroughly mixed into the room air. The source of gas is then removed and the decay in the concentration of tracer-gas in the room is measured over a period of time. To ensure that the tracer-gas concentration is the same at all points in a room at any particular time, one or more mixing fan is run throughout the measurement period. Provided that no tracer-gas is supplied to the room during the measurement period and the airflow through the room is constant, the concentration of tracer will decay exponentially: $C(\tau) = C_{\text{start}} \exp(-N\tau)$. By plotting the natural logarithm of gas concentrations against time a straight line is obtained and the gradient of the line is the air change rate in the room:

$$\text{Air - exchange rate, } N = \frac{\ln C(0) - \ln C(\tau_1)}{\tau_1} (h^{-1})$$

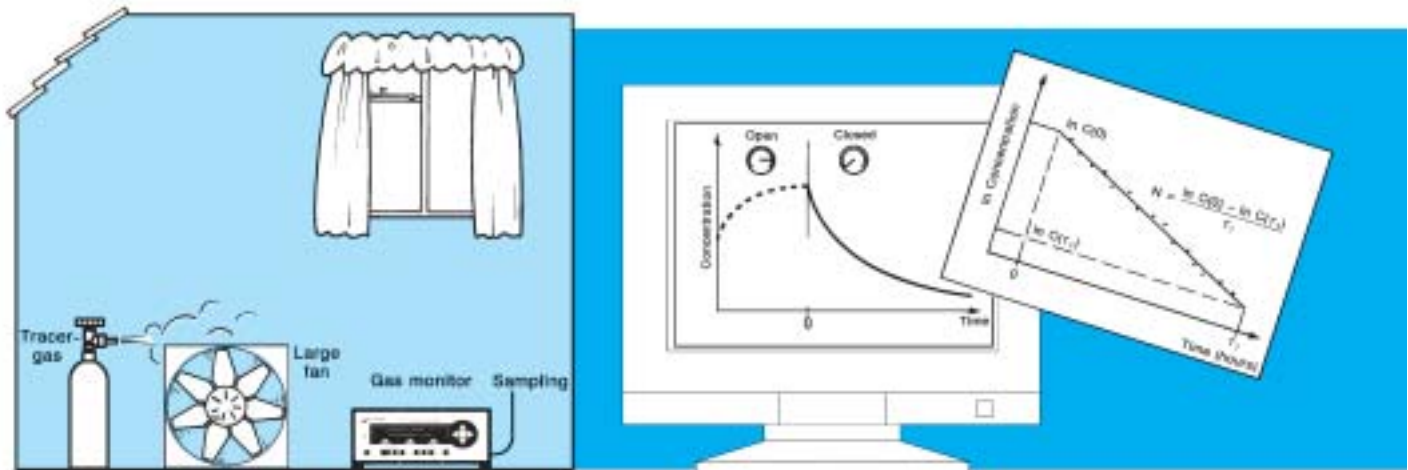
where $C(0)$ = concentration at time = 0

$C(\tau_1)$ = concentration at time = τ_1

τ_1 = total measurement period

If an approximately straight line is not obtained, then the room air cannot be considered well mixed and the results are thus not valid.

The only equipment needed for this measurement method is a gas monitor, a bottle of tracer-gas, and a mixing fan. This makes the method the least expensive and easy to perform.



The Constant-emission Method

This method is used for long-term, continuous air change rate measurements in single zones (discussed below), or for measurement of the airflow through ventilation ducts (discussed in a later section).

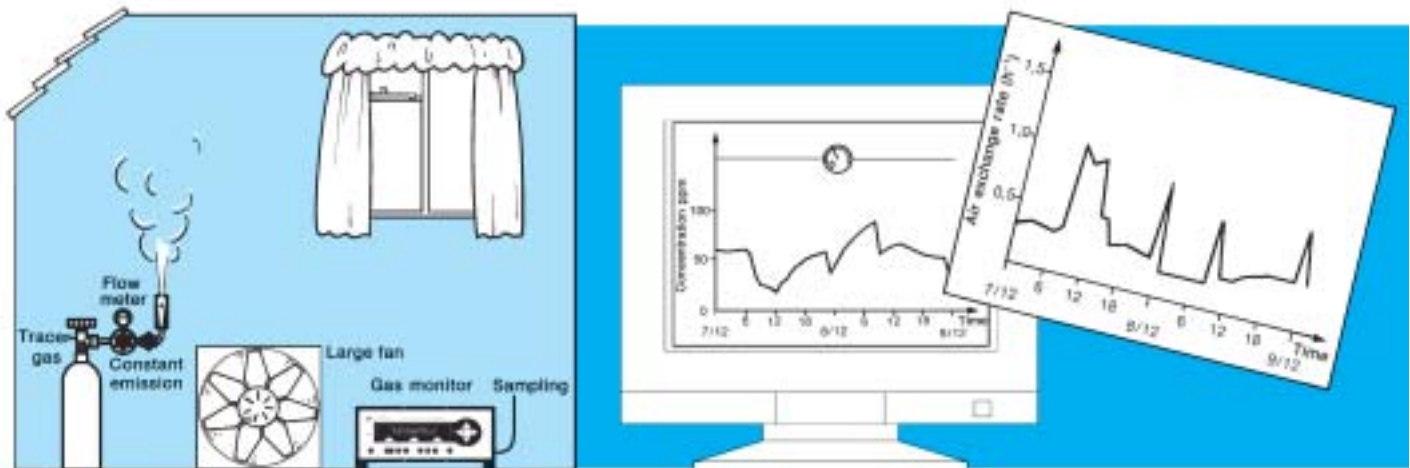
When using the constant-emission method, tracer-gas is emitted at a constant rate for the duration of the measurement period. Provided both the air change rate and the tracer-gas concentration in the zone are constant, the mass balance reduces to:

$$\text{Air change rate, } N = \frac{F}{V \cdot C} \text{ (h}^{-1}\text{)}$$

If either the air exchange rate or the tracer-gas emission vary during a measurement period, then the general mass balance has to be used

to obtain the air change rate. As with the concentration-decay method, the tracer concentration should be the same throughout the zone at any instant of time. The mixing needed to achieve this is done with fairly large mixing fans.

A flow meter is needed to measure the flow of tracer-gas emitted into the room. Since tracer-gas is emitted continuously into the zone throughout the measurement period, special attention should be paid to the cost and amount of tracer-gas used. Using a monitor that allows you to measure inexpensive tracer-gases and/or allows very low concentrations to be detected and measured can help to keep this cost down.



The Constant-concentration Method

This method is used for continuous air change rate measurements in one or more zones. It is particularly useful for conducting analyses in occupied buildings.

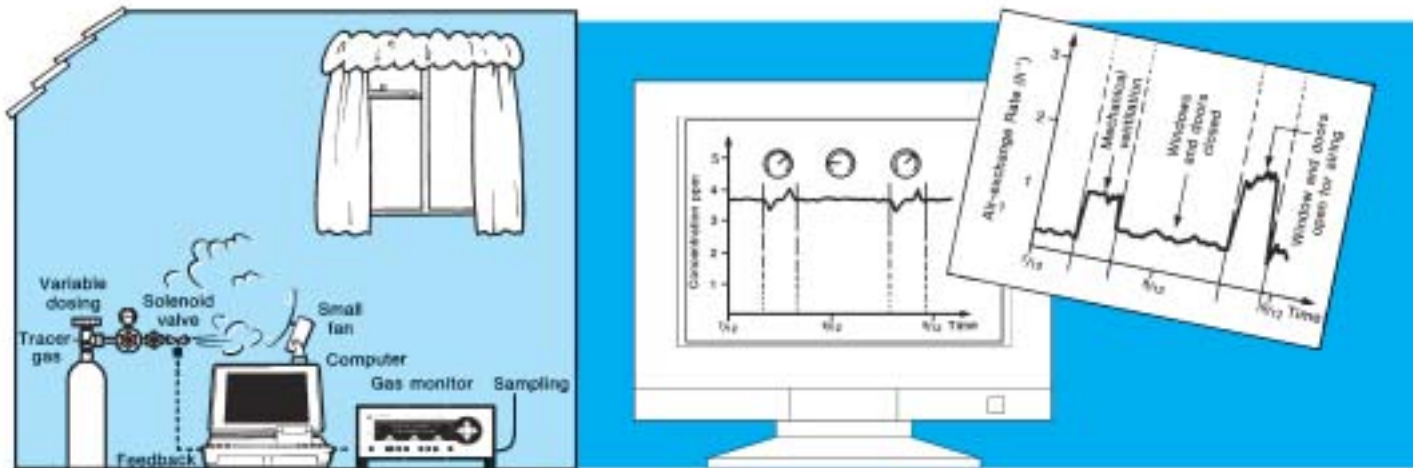
When using the constant-concentration measurement method, the concentration of tracer gas in a zone is measured by a gas monitor. This information is then sent to a computer that controls the amount of tracer-gas “dosed” into the zone in order to keep its concentration constant. A small fan is normally used to help mix the tracer with the room air. Provided that the concentration of tracer-gas in the zone is constant over time, the mass balance reduces to:

$$\text{Air change rate, } N(\tau) = \frac{F(\tau)}{V \cdot C} (\text{h}^{-1})$$

The air change rate is directly proportional to the tracer-gas emission rate required to keep the concentration constant.

This method offers two great advantages: not only can it be used to obtain an accurate long-term average air change rate in situations where the air change rate varies – for example, in occupied buildings; but it can also be used to document these variations in detail. As with the constant-emission method, tracer-gas costs may be an important consideration.

The constant-concentration method is also particularly well suited to the continuous determination of the infiltration of outside air into each individual room in a building.



Guarded Measurements

Guarded measurements are used to measure the air-exchange between one part of a building and: either another part of that building, or the outside air.

An example of a guarded air change measurement is illustrated in the diagram. The problem is to measure the outdoor air supply rate to the office shown in the upper part of the office building. This office is called the measured zone and the zones surrounding it are called guarded zones. Guarded measurements are done by dosing the measured zone and the guarding zones with a certain concentration of tracer gas (5 ppm, for example) and maintaining this concentration for the duration of the measurement period.

During the measurement period, all air exchanged between the guarded zone and measured zone will contain the specified concentration of tracer-gas and will therefore not cause any variation in the emission rate of tracer into the measured zone. Outdoor air entering the measured zone will, on the other hand, temporarily dilute the tracer-gas concentration there and result in some more tracer being emitted into the measured zone. The amount of tracer emitted into the office is directly proportional to the outdoor air change rate of that office.

The outdoor air change rate is calculated using the equation used for the constant concentration method shown on the previous page.



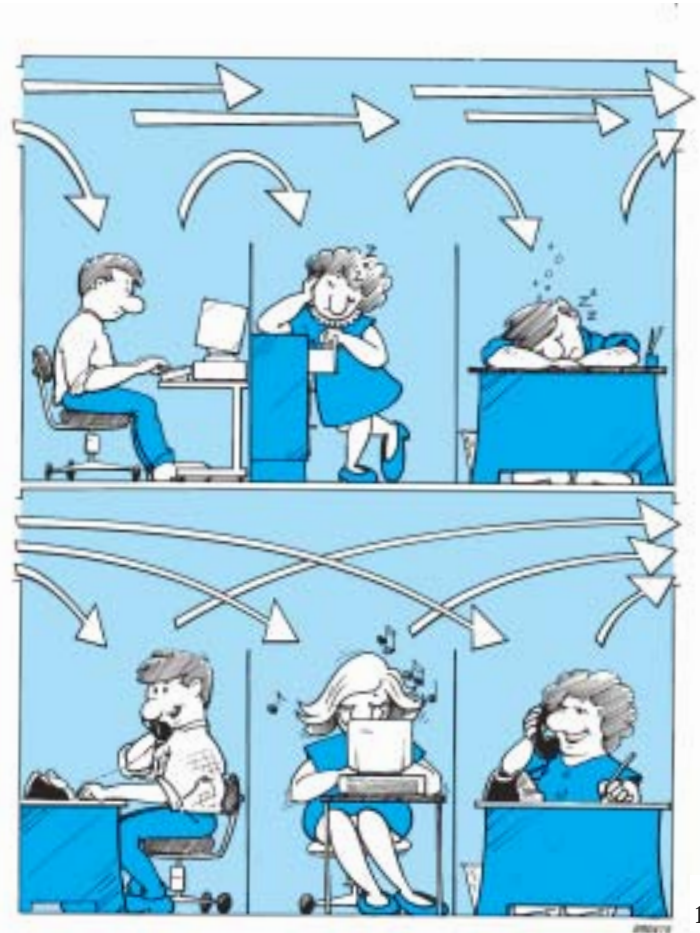
Airflow Characteristics in Rooms

Air change rate measurements provide information the amount of air supplied to a room or building but nothing about the airflow in the room or the distribution of the ventilation air entering the room. In other words, even though we find out if enough ventilation air is supplied to a room we do not know if this air is used efficiently; we do not even know whether this air ever reaches the people occupying the room.

A satisfactory distribution of ventilation-air in a room is essential if you want enough outdoor air and a low air pollution level at each individual work place in a room. It will often also make it easier to control the thermal environment at each workplace. It should be noted, however, that good distribution does not ensure a good environment but is an important step towards one.

An unsatisfactory airflow pattern may be due to the temperature of the supply air, temperature gradients within the room, type and positioning of supply and extract air-ducts, machines, furniture and other objects within a room.

Detailed information about the distribution of ventilation air in a room can be deduced from the measurement of the age distribution of the air in the room. The methods most commonly used to determine the age-of-air in a room are discussed in the following sections.



The Age-of-air

The age-of-air in a room is a measure of the time the air has been in the room. The “youngest” air is found where the outdoor air comes into the room, the “oldest” air may be found at any other point in the room. The age-of-air can be considered in two different ways: the local-mean age-of-air, and the room-average age-of-air.

Local-mean age-of-air is used if the ventilation of individual workstations is to be assessed. It is also used in the mapping of airflows through rooms. The big advantage of this method is that results apply to individual points within a room – areas of stagnant air can be located, and the ventilation air supply at head height at an individual’s workstation can, for example, be assessed.

Room-average age-of-air is a number that quantifies the performance of a ventilation system. This number takes into account both the amount of ventilation air supplied to the room and the efficiency with which it is distributed around the room.

Room-average age-of-air is measured in the extract air duct. This measurement is, however, not reliable in cases where a large proportion of air leaves the room by other means, for example, through random exfiltration.



Age-of-air And Air-exchange Efficiency

The lowest possible room-average age-of-air occurs when there is perfect piston flow* through that room. Piston flow is characterised by the fact that the oldest air is found at the extract air ducts.

If the air in the room is perfectly mixed then the room-average age-of-air will be double that of the case with piston flow. The age of air in the extract air duct is the same as that of all other points in the room.

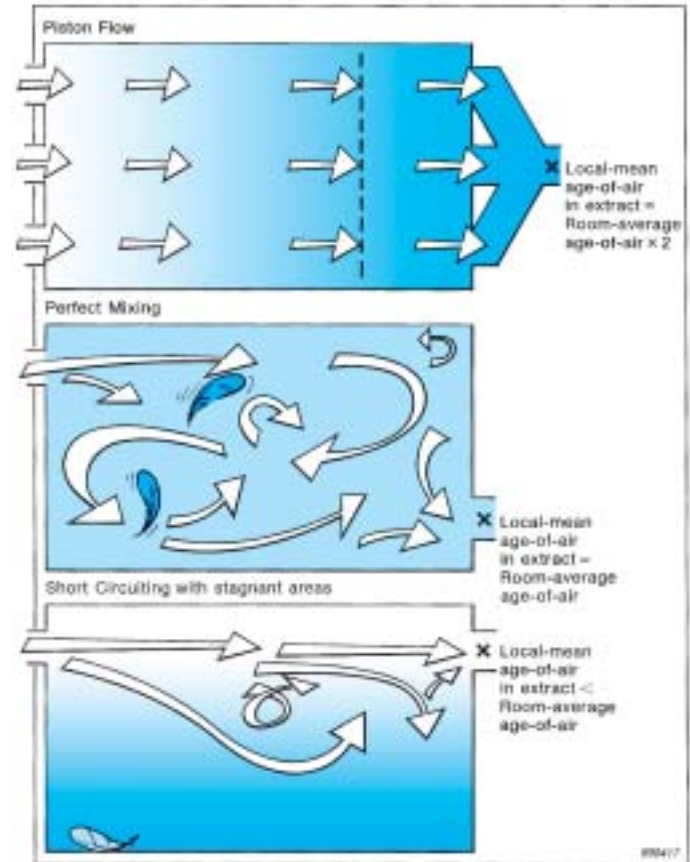
If there are areas of stagnant air in a room then the room-average age-of-air will be greater than the perfectly mixed case. Stagnant areas are characterised by the extract air being younger than the room-average age-of-air.

The efficiency with which the ventilation system exchanges the room air can be calculated by dividing the local-mean age-of-air in the extract by twice the room-average age-of-air.

The local-mean age-of-air in the extract is equal to the effective volume of the room divided by the airflow rate through it.

Several other terms are used to quantify the performance of ventilation systems. Among these is “ventilation efficiency”. Whereas air-exchange efficiency is a measure of how effectively the air present in a room is replaced by fresh air from the ventilation system, ventilation efficiency is a measure of how quickly a contaminant is removed from the room.

* See Glossary



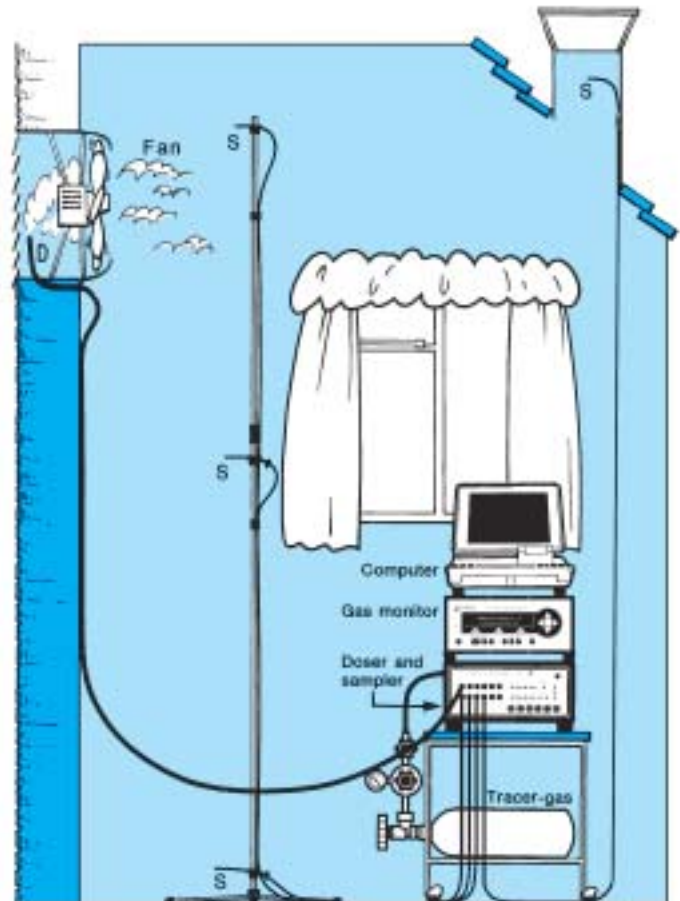
Age-of-air Measurement Methods

There are three tracer-gas methods for measuring the age of the air: pulsed injection; concentration-growth; and concentration-decay. The equation that allows age-of-air to be calculated can be found in Appendix A.

With the pulsed injection method, ventilation air entering the room is marked with pulses of tracer-gas (pt. D in figure) at definite times and the tracer-gas concentration in the extract duct and at points of interest in the room monitored (pts. S). The advantages of this method are that it is quick and comparatively little tracer-gas is used. The main disadvantage is that it is difficult to obtain rapid enough measurements of tracer-gas concentration in the room.

With the concentration-growth method, ventilation air is continuously marked with tracer-gas as it enters the room and the growth of tracer-gas concentration in the room is studied. This method is useful in cases where a uniform concentration of tracer-gas throughout the room is difficult to achieve – for example, in very large rooms such as assembly shops or aircraft hangars. A big disadvantage of the method is that only the distribution of supply-air provided by the ventilation system is measured.

Measurement with tracer-gas concentration-decay is the most popular age-of-air method. It is very similar to the air exchange rate concentration-decay method except that no room-air mixing takes place after the tracer has first been perfectly mixed into the room air. The concentration-decay method of measuring age-of-air is discussed in more detail in the next section.

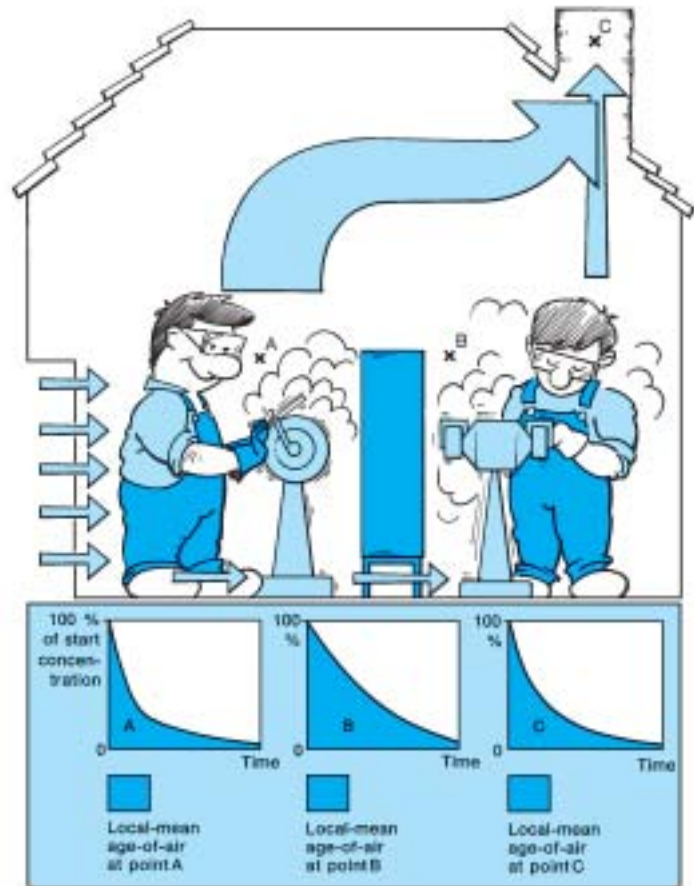


Age-of-air Measurement with Concentration-decay

With the tracer-gas concentration-decay method the air in the room is marked with tracer-gas and the decay of the gas concentration due to the infiltration of unmarked outdoor air into the room is studied. The local-mean age-of-air is simply the area under the concentration versus time curve. Many prefer this method because difficulties in marking all of the infiltration air are avoided. The concentration-decay method is also the only usable method where a space is naturally ventilated.

Typical plots of the tracer-gas concentration as a function of time are shown in the illustration. At the beginning there is a region with a non-exponential decay, but after a certain period of time, the gas concentration decays exponentially. In practice the measurements are stopped when the concentration begins to decay exponentially, since the residual area under the curve can be calculated with good accuracy using a simple equation (See Appendix A).

If the point at which the concentration change has been studied is in the extract air duct then the room-average age-of-air can be calculated. We can also calculate the air change rate for the room as a whole ($1/\text{local-mean age-of-air in extract}$) and see whether or not there are areas of stagnant air in the room. By measuring the local-mean age-of-air at different points in a room areas of stagnant air can be located (see pt. B in figure).

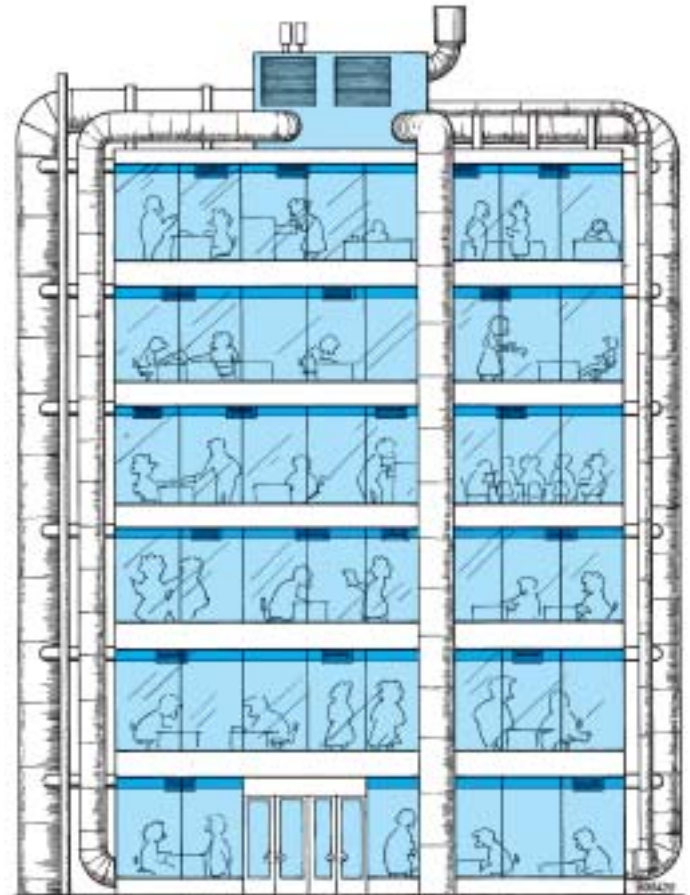


Measurements on Ventilation Systems

Airflow measurements are required during commissioning and maintenance of ventilation systems. One of the most important pieces of information in connection with mechanically ventilated offices and dwellings is the volume of outdoor air reaching each room. It is often impossible to measure the airflow in the outdoor air intake duct directly because this duct is often too short. However, there is an alternative method of making this measurement using tracer-gas (see the section “Short-circuit of ventilation air”).

In industry, the most important consideration is that the workers are not exposed to concentrations of toxic gases which may damage their health. Removal of toxic gases at source is the most effective way of reducing worker's exposure to them. In these cases it is often the effectivity (or “capture efficiency”) of point-source fume-hoods that is the main determinant of indoor air quality.

In the following sections determination of these ventilation system parameters using tracer-gas techniques will be considered.



Airflow Measurements in Ducts

Accurate airflow measurement in ducts with many bends is very difficult with Pitot* tubes but can be measured easily and accurately using a constant emission of tracer-gas technique. Unlike measurement techniques using Pitot tubes or air velocity probes the measurement of airflow in ducts with tracer gases is actually made easier with bends and turbulence in the ducts, as this increases mixing of tracer-gas with the air flowing in the duct. When making these kinds of measurements, however, it is important to ensure that the distance between dosing and sampling points is large enough to enable good mixing of the tracer-gas across the diameter of the duct.

In the case of a length of straight duct a distance between dosing and sampling point of 25 times the duct diameter is recommended. If there are one or two bends in the duct then more turbulence is created and a distance between dosing and sampling point of only 10 times the duct diameter is sufficient.

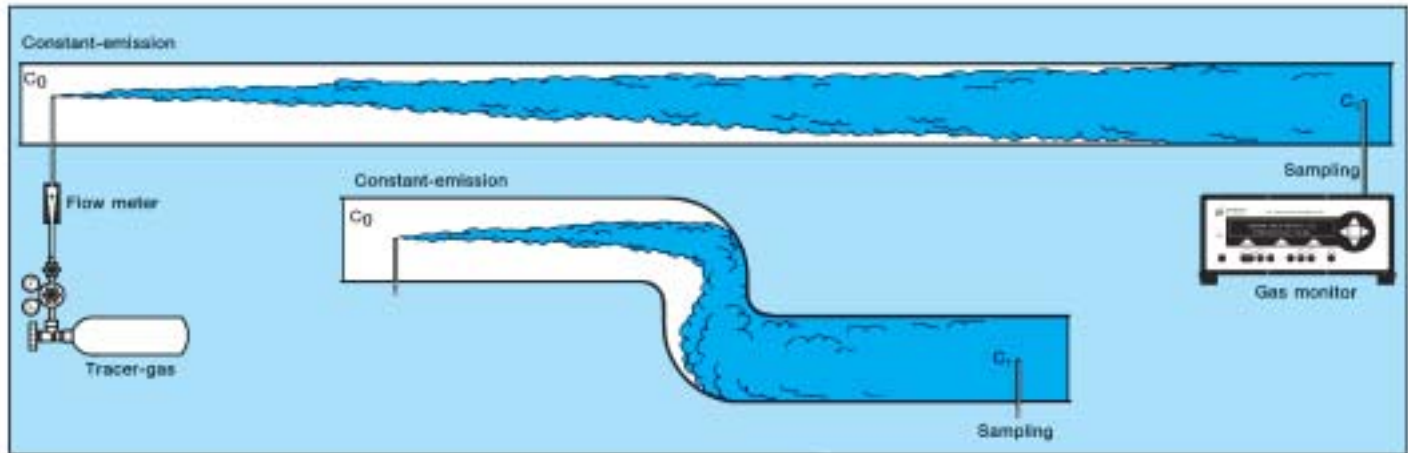
* See Glossary

These distances depend on many factors and can only provide a rough guide. When making the measurements the degree of mixing at the sampling point can easily be assessed by sampling at various points across the diameter of the duct. If there is large variation in the concentration of tracer-gas across the diameter, then the sampling point should be moved further down the duct.

Be aware of air entering or leaving the duct between the dosing and the measurement point. If air is entering the duct, the measurement determines the airflow rate at the measurement point, whereas the airflow rate at the dosing location is determined if air is leaving the duct.

$$q_v = \frac{\text{Dose [m}^3/\text{s]}}{C_1 - C_0 \text{ [m}^3/\text{m}^3]}}$$

where: C_1 = Concentration at sampling point
 C_0 = Background concentration in duct



Short-circuit Or Recirculation of Ventilation Air

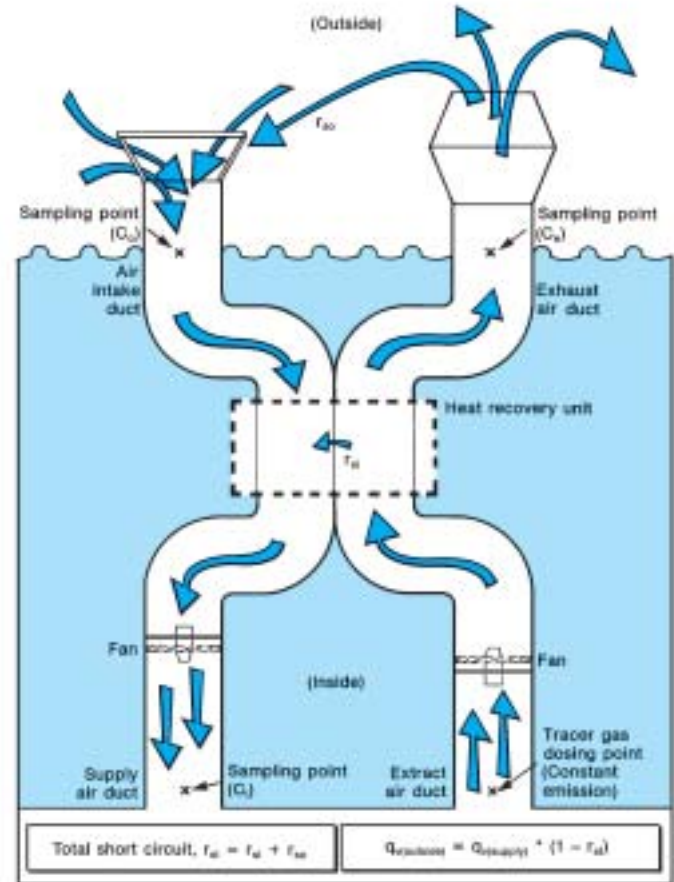
To calculate the percentage of extracted air recirculated into the supply air duct, tracer-gas is injected into the extract air duct upstream of the extract fan and the concentration of tracer-gas is measured downstream of the fan where the tracer is well mixed into the exhaust air – as well as in the air intake duct and in the supply air duct, downstream of the supply air fan.

The ratio of the concentration of tracer-gas in the outdoor air-intake, C_o , to the concentration in the exhaust, C_e , gives us the short-circuit of exhaust air into the outdoor air intake duct, r_{so} .

The ratio of the concentration of tracer-gas in the supply air duct, C_i , to the concentration in the exhaust air duct, C_e , gives us the total short-circuit of extracted air back into the supply-air. The total short-circuit for the ventilation system, r_{st} , is made up of both the outdoor short-circuit, r_{so} , and the short-circuit of air inside the system, r_{si} . Short-circuiting of extracted air inside the system may be intentional, or due to the unintentional leaking of air whilst passing through a heat-recovery unit. The leakage or extract-air diversion inside the system is simply the total short-circuit, r_{st} , minus the outdoor short-circuit, r_{so} . This value can be used in the optimisation of the percentage of extract-air recirculated in an economiser*.

The outdoor air brought into a building by a ventilation system can be calculated from the air flow-rate in the supply ducts, and the percent of the supply air that is outdoor air and not recirculated or short-circuited extract-air.

* See Glossary



Effectiveness of Fume-hoods

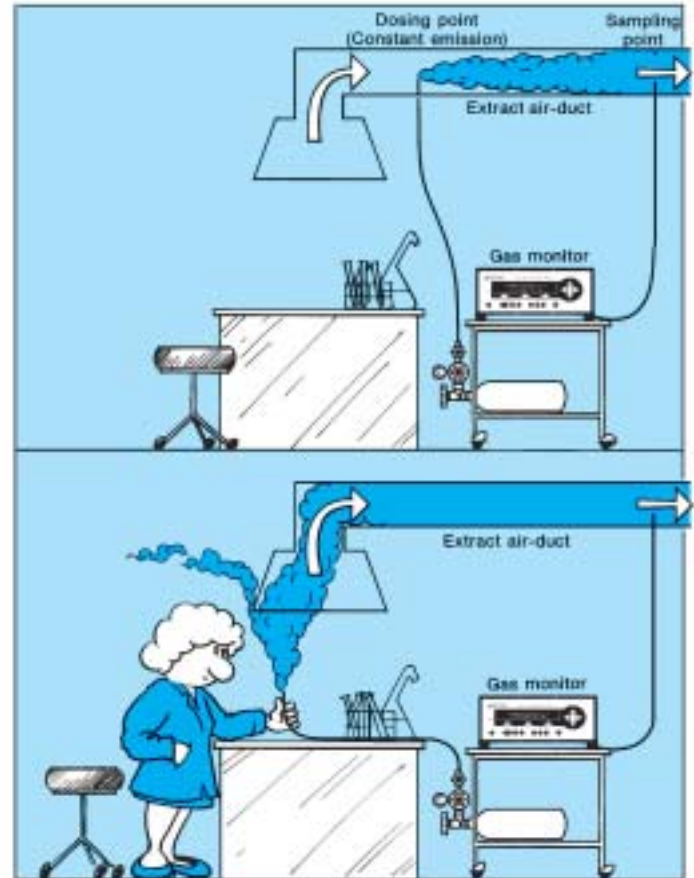
When working with noxious gases it is essential that the worker be well protected. Whether in a factory or in a laboratory this protection commonly consists of fume-hoods. The purpose of these hoods is to capture, extract and then dispose of enough noxious gas to ensure that occupants can work without risk to their health.

The performance of the extractor should be checked in situ since it will be affected by its position in relation to doors, air-conditioning systems, gangways, and other extractors. It is also important to take into account the effect the body of the person performing the measurement will have on the airflow.

The capture efficiency is a measure of the effectiveness of the extractor and this can be measured using tracer-gas techniques. A typical set-up is shown in the diagram.

Constant-emission of tracer-gas and concentration monitoring are carried out on the section of duct just downstream of the hood as in an ordinary duct airflow determination. The mean concentration measured during this part of the test represents a fume-hood capture-efficiency of 100%. The same volume flow rate of tracer-gas is then dosed at the position that, under normal working conditions, would be the source of noxious gas or pollutant. A simple ratio of the concentration of tracer measured in the duct during this second stage of the test to the concentration measured during the first stage represents the capture efficiency of the hood for that dosing point. When a detailed study is made, a map of capture efficiencies, for an area under or around the hood, can be drawn up.

As with all tracer-gas investigations the density of the tracer-gastracer gas should not be too different from the density of the gas being investigated. See Appendix B.

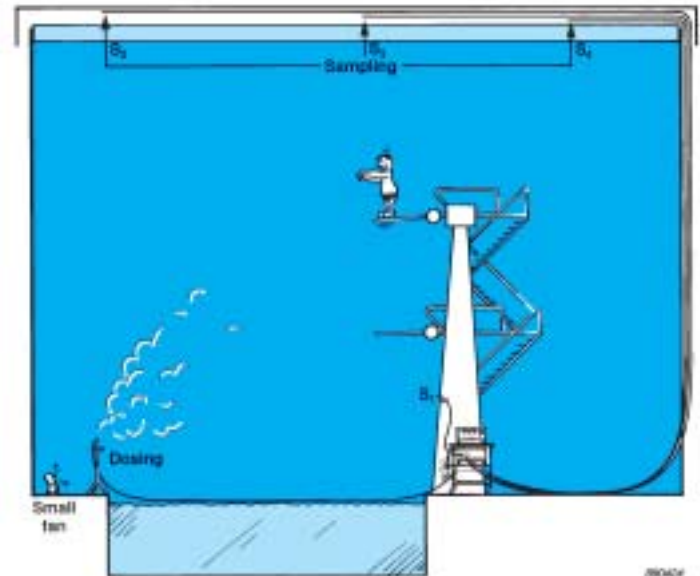
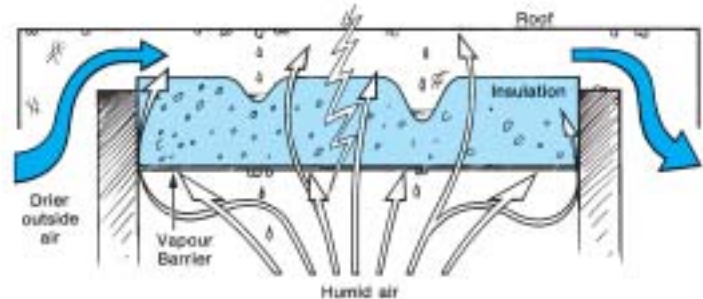


Measuring the Spread of Pollutants Using 1 Tracer-gas

Condensation of moisture onto a surface occurs when moist air comes into contact with a relatively cold surface. The problem of condensation is encountered in all sorts of buildings and is particularly common and damaging in roof spaces.

Condensation on the underside of the roof is often encountered in the roof space above swimming halls. When this happens, the condensed water often not only causes mouldy and rotting roof timbers, but also drips down onto the roof insulation (thus ruining it) and eventually, backs through the ceiling into the swimming hall.

Damp patches on the ceiling of the swimming hall are often the first noticeable signs of a problem. It is often difficult to find out the cause of the problem – is it due to condensation up in the roof-space or a leak in the roof? This is a typical situation in which tracer-gas pollution spreading techniques can be very useful. Tracer-gas is dosed to and kept at a constant concentration in the swimming hall, and a gas monitor measures the concentration of tracer-gas at one or more sampling points (S) in the swimming hall and in the roof-space over a period of time.

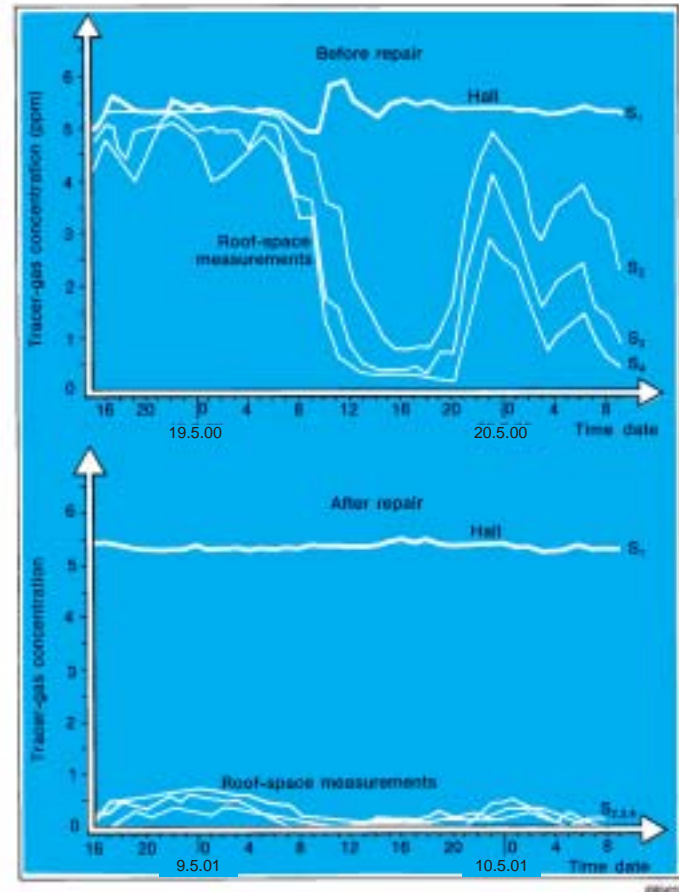


Measuring the Spread of Pollutants Using 1 Tracer-gas

In the example considered here a measurement period of 36 hours was considered suitable. From the measurement report we can see that the movement of moist air up through the swimming-hall ceiling is particularly serious and almost certainly the cause of the water dripping from the hall's ceiling. We can also see that more than 80% of the air entering the roof-space during the first night of measurements came from the hall. The large indoor-outdoor temperature difference at night is probably responsible for a strong rising air-current or "stack effect" inside the hall that is able to overcome the flow-inhibiting barriers of the ceiling.

The amount of leakage from the hall into the roof-space and the damage caused to the insulation was so serious in this case that the only real solution was to take down the ceiling and fit new insulation and a carefully-sealed vapourbarrier. In less serious cases, cheaper solutions to the problem may be possible such as increasing the outside air flow through the roof-space-thus lowering the humidity of air in the roof space to a level at which it would not condense.

As well as being a useful tool for the identification and analysis of problems, the tracer-gas techniques are very useful for checking that repairs have been successful.

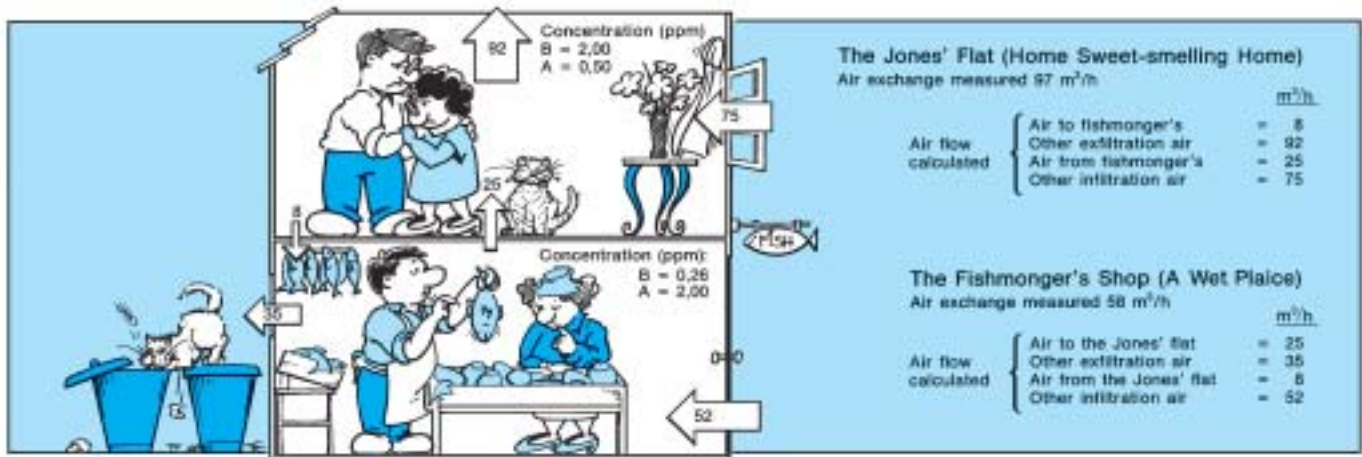


Measuring the Spread of Pollutants Using 2 Tracer-gases

Mr. and Mrs. Jones live above a fishmonger and are very happy that they do not have far to walk if they want fresh fish for their breakfast. When the shop first opened, however, they were worried by a strange smell that penetrated everything in their home, and by a pride of cats that followed them around when they walked outside. The local ventilation expert was called in to solve the problem and, after a quick inspection, she decided to use the two-tracer constant-concentration technique for a spread-of-pollutants investigation.

By dosing gas A to a constant-concentration in the fishmonger's, and gas B to a constant-concentration in the Jones' home, and recording the emission rates of the gases and the concentration of both gases in both zones very useful information was obtained.

If we regard the study as two ordinary constant-concentration air change rate measurements it is easy to see how the individual air change rates for the fishmonger's and the Jones' were obtained. Performing both measurements at the same time means that we can also calculate the airflow from the fishmonger's to the Jones' and/or vice versa. If the airflow or mixing between the two premises is significant, then we can use the results to help deduce the cause and, thereby, the best solution to the problem. The results of the initial investigation are shown in the drawing below.



Measuring the Spread of Pollutants Using 2 Tracer-gases

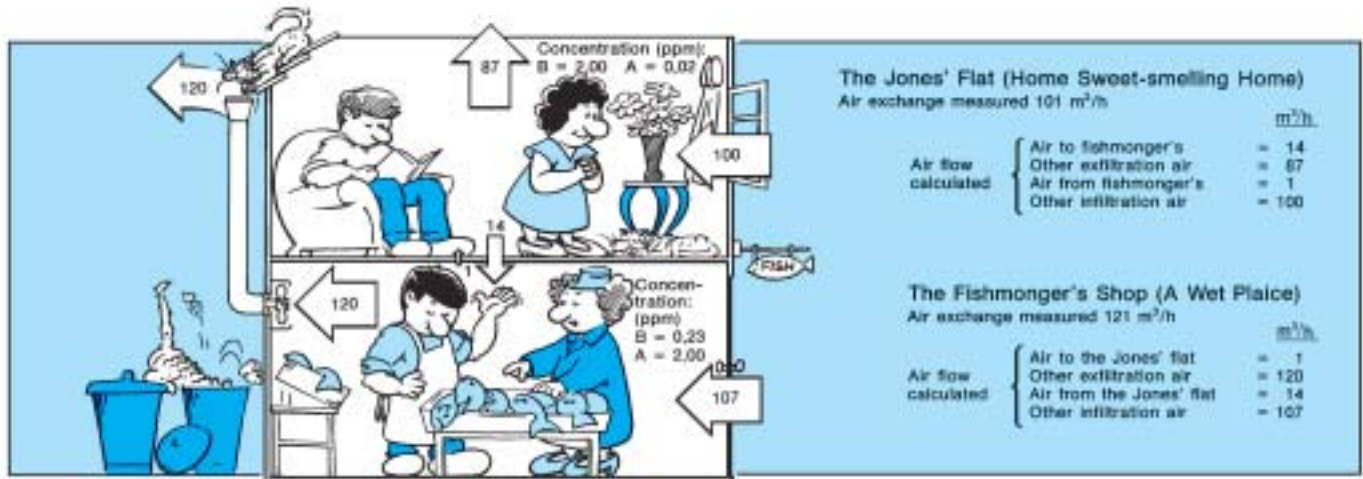
Pollution spreading between two zones is caused by either general mixing between the zones, or due to a pressure difference induced flow from one zone to the other. The solution to a pollution problem depends on the type and cause of pollution and the mode of spreading. If the problem is one of general mixing between zones and reducing the pollution at source is not a practical consideration, then the solution is to seal the two zones off from one another.

If, as was found to be the case in the fishmonger case study, the problem is one of a flow from one zone to another, then the best solution may be to alter the pressure differential between the two zones.

The original measurements also showed that ventilation of the fishmongers' was insufficient and the ventilation expert therefore concluded that the best way to solve the problem was for the fish

monger to install an air-extraction unit with a chimney. This solution should both have reduced the pollution at source and altered the pressure differential between the two spaces. Sometime after the extraction-unit had been installed the spread-of-pollutants study was repeated and, from the results obtained, appeared to be a great success.

This is not only a sunshine story about the Jones' family. Consider a high-rise building with complaints of diesel exhaust fumes on the top floors. Elevator shafts can in fact effectively move fumes from e.g. an underground parking area to any floor of a building. By dosing tracer-gas in the parking garage and measuring the concentration on the floor in question, the unwanted airflow can be documented.



What Makes a Good Tracer-gas?

To be suitable as a tracer, a gas should have a similar density to air, should not normally be present in indoor or outdoor air, and its concentration must be measurable to a good order of accuracy, even when highly diluted. Perhaps the most important considerations when choosing a suitable tracer-gas are, however, what it must not do!

For safety considerations, for example, the gas should be neither flammable nor explosive and, as measurements are often performed in occupied buildings, it should have no smell or any adverse health effects in the concentrations required for the tests. And finally, since tracer-gas analyses are based upon the mass-balance equation it is important to ensure that all the tracer leaving the enclosure does so by the process of ventilation. This means that the gas chosen must not be absorbed by walls or furnishings, and it must not react with building surfaces or the room air, nor decompose during the measurements.

No gas fulfils all the requirements given above, but several gases are used successfully as tracers. These include nitrous oxide, carbon dioxide, and sulphur hexafluoride. Appendix B gives a broad outline of the properties of some of the most commonly used tracer-gases.

Before starting tracer-gas analysis it is important to always check that the air in and around the building in which the analysis is to be performed contains none of the tracer-gas you intend to use, or any other gas that is likely to interfere with the measurement of the intended tracer-gas. If the air is found to contain either the intended tracer-gas or a likely interferant an alternative tracer-gas should be chosen.



Further Reading

A comprehensive database of relevant literature can be found at:
www.aivc.org

This is the official Homepage of the Air Infiltration and Ventilation Centre, inaugurated in 1979 by the International Energy Agency (IEA). The role of the centre is to provide technical support to those involved in the research and development of ventilation technology as well as to ensure the widest dissemination of information on related energy and air quality issues.

Of particular interest may be:

Claude-Alain Roulet and Luk Vandaele :Air Flow Patterns within Buildings Measurement Techniques, 1991, 284pp, Code TN 34. This handbook gives a comprehensive explanation of the theoretical and practical aspects of measuring important parameters for understanding air infiltration and ventilation within buildings. Discussed parameters include: airtightness of the building envelope and its component leakage paths; air exchange rates within a building and with the external environment; efficiency of the ventilation system; flow rates in the ventilation network. It has been designed so that material suited to differing levels of expertise is readily accessible.

Martin W Liddament :A Guide to Energy Efficient Ventilation.1996, Code GV. The purpose this guide to ventilation is to review ventilation in the context of achieving energy efficiency and good indoor air quality. Numerical descriptions have been kept to a minimum, while emphasis is placed on describing ventilation and the decision making involved in selecting and planning for ventilation. This guide is specifically aimed at the policy maker, architect, building services engineer, designer and building owners and occupiers who require a background knowledge to ventilation.

NORDTEST method Buildings - Ventilation air:
Local mean age Edition 2, approved 1988-09, 11 pages, NT VVS 019

NORDTEST method Buildings - Ventilating air:
Mean age of air, NT VVS 047, 1985

Appendix A: Age-of-air Measurement Equations

The table on the next page gives an overview of equations used for calculating age-of-air. An example of how the calculations are made in practice is shown below.

Using the tracer-gas concentration-decay method the room-average age-of-air, $\langle \bar{\tau} \rangle$, is given by:

$$\langle \bar{\tau} \rangle = \frac{\text{1st moment of measured area} + \text{1st moment of residual area}}{\text{Measured area} + \text{Residual area}}$$

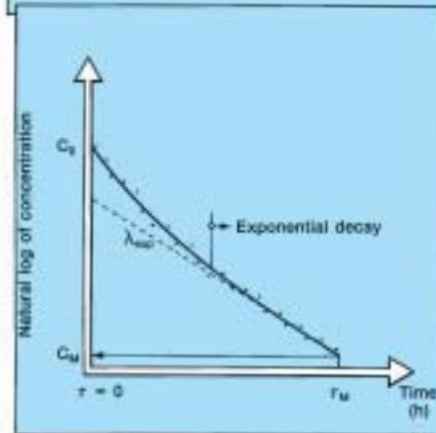
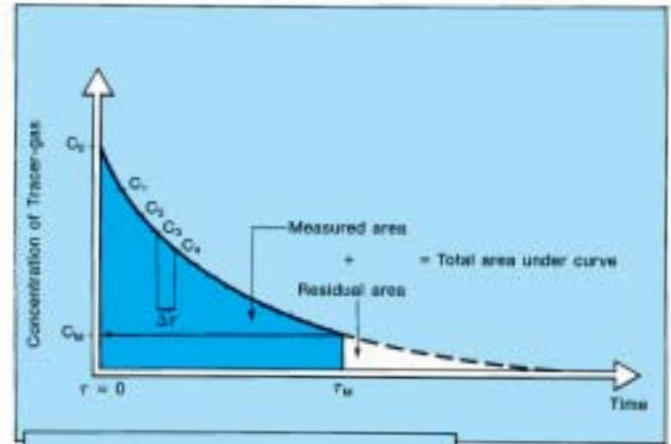
Measured area = $\frac{1}{2} (C_0 + C_M) \cdot \Delta\tau + \sum_{j=1}^{M-1} C_j \cdot \Delta\tau$

1st moment of measured area = $\frac{1}{6} C_0 \cdot \Delta\tau^2 + \frac{1}{2} C_M \cdot \Delta\tau \cdot \tau_M + \sum_{j=1}^{M-1} C_j \cdot \tau_j \cdot \Delta\tau$

Residual area = $\frac{C_M}{\lambda_{exp}}$

1st moment of residual area = $\frac{C_M}{\lambda_{exp}} \left(\tau_M + \frac{1}{\lambda_{exp}} \right)$

- where C_j = concentration measurement j
- C_M = final concentration measured
- M = number of measurements
- $\Delta\tau$ = sampling interval
- λ_{exp} = slope in the exponential decay region
- τ_j = time of measurement j
- τ_M = total measuring time, $\tau_M = M \cdot \Delta\tau$



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Appendix A: Age-of-air Measurement Equations (Cont'd)

Tracer-gas measurement method	Measurement Equation		
	Local mean air-of-air $\bar{\tau}_p$ (Arbitrary measurement point)	Room-average age $\langle \bar{\tau} \rangle$ (Measured in exhaust)	
Concentration decay method	$\frac{\int_0^{\infty} C(\tau) d\tau}{C(0)}$	$\frac{\int_0^{\infty} \tau C_{exh}(\tau) d\tau}{\int_0^{\infty} C_{exh}(\tau) d\tau}$	
Concentration growth method	$\int_0^{\infty} \left(1 - \frac{C(\tau)}{C(\infty)} \right) d\tau$	$\frac{\int_0^{\infty} \tau \left(1 - \frac{C_{exh}(\tau)}{C(\infty)} \right) d\tau}{\int_0^{\infty} \left(1 - \frac{C_{exh}(\tau)}{C(\infty)} \right) d\tau}$	
Pulsed injection	$\frac{\int_0^{\infty} \tau \cdot C(\tau) d\tau}{\int_0^{\infty} C(\tau) d\tau}$	$\frac{1}{2} \frac{\int_0^{\infty} \tau^2 C_{exh}(\tau) d\tau}{\int_0^{\infty} \tau C_{exh}(\tau) d\tau}$	
where	$C(0)$ = concentration at $\tau = 0$ $C(\infty)$ = concentration at $\tau = \infty$	$C_{exh}(\tau)$ = concentration in exhaust $C(\tau)$ = concentration at time τ	τ = time

Appendix B: Properties of a Selection of Tracer gases

Tracer	Formula	Density Compared to air	Max Concentration		Comments
			For Density ¹⁾ ppm	For Safety ²⁾ ppm	
Nitrous oxide	N ₂ O	1,53	640	25	Anaesthetic gas. Widely used as a tracer
Carbon dioxide	CO ₂	1,53	640	5000	High background concentration variation due to occupants. Readily available
Sulphur hexafluoride	SF ₆	5,11	83	1000	Detection can be affected by other halogenated compounds in air. Decomposes to toxic components at 550°C. Widely used as a tracer
Freon 134a	C ₂ H ₂ F ₄	3,86	116	1000	Detection can be affected by other halogenated compounds in air. Possible background levels. Used in multi-tracer work. Decompose to toxic components at high temperatures

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1) In terms of density the maximum concentration has been set at a level of tracer concentration above which the air/tracer mixture would differ by 0,03%. Such a density difference (equivalent to a temperature difference of ~0,1°C) is very unlikely to have a significant effect on the airflow or air change rate of a space.

2) These safety limits often vary with time and from country to country. You should always check what the local exposure limits are and stay within these limits when using any tracer gas within an occupied building.

NB:

Please note that the use of SF₆ may be restricted in some countries.

Appendix C: Reference Temperature And Pressure

Measurements of air quality parameters are made at different temperatures and pressures. In order to make a reliable comparison of results obtained at different places, then, the results must be expressed with respect to a reference temperature and pressure. It is also important to quote the temperature, pressure, and humidity at which the measurements took place.

At present no single set of reference values of temperature and pressure are available. The recommended values expected in the forthcoming ISO 8756 standard are 273 K and 103,3 kPa respectively.

Air exchange results made at temperature T_1 , and pressure P_1 , can be converted to reference conditions T_{ref} and P_{ref} using the following equation:

$$q_{v(ref)} = q_{v(t)} \times \frac{P_1}{P_{ref}} \times \frac{T_{ref}}{T_1}$$



Glossary

Air change rate

The ratio of the volume of air entering an enclosure per hour to the effective volume of the enclosure.

Air infiltration

The uncontrolled inward air-leakage through cracks and interstices. Infiltration is caused by the interaction between the building's leakage characteristics and external driving forces caused by the weather.

Capture efficiency

The percent of a pollutant gas an extraction device can extract directly from a specified point in a room.

Economiser

A device in a ventilation unit which recirculates air from the extract duct into the supply air duct.

Effective volume

The volume of air in a room excluding that unmixed air in, for example, built in cupboards, and including the volume of connected spaces with which the room air mixes freely.

Local mean age-of-air

The mean age of air- "molecules" passing an arbitrary point. The age of the molecule being defined as the time elapsed since it entered the room.

Room-average age-of-air

The mean age of all air present in the room. The age of the molecule being defined as the time elapsed since it entered the room.

Measured zone

The space or enclosure in which the measurements are made, normally a room.

Mechanical ventilation

Ventilation by means of one or more fans.

Natural ventilation

Ventilation using only purpose-provided ventilation openings and the natural forces of wind and temperature difference.

Piston flow

Piston flow or displacement ventilation is a method that pushes airventilation into a space over a large surface area so as to avoid high air velocities and turbulence. The overall effect is one of piston flow from the supply to the exhaust.

Pitot tube

A detector for transmitting the static and dynamic pressure of a moving fluid stream. The difference in the measured pressures is used to determine the velocity of the fluid.

Ventilation

The process of supplying and removing air by natural or mechanical means to and from any space.

Ventilator

Appliance or aperture for ventilating room, compartment, or mine, etc.





INNOVA

AirTech Instruments

Energivej 30
DK-2750 Ballerup, Denmark
Tel.: + 45 44 20 01 00
Fax: + 45 44 20 01 01
<http://www.innova.dk>
e-mail: innova@innova.dk

BR 0608-13 Capitol Copenhagen +45 45 80 08 31

