#5945

"Tracer Gas Technology for IAQ Measurements"

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Many studies of buildings with reported Sick Building Syndromes (SBS) have shown that the ventilation system is a main contributor to the problems. It is, therefore, of great importance to be able to quantitatively evaluate the performance of a HVAC system. In many systems it is difficult or impossible with existing techniques (Pitot tubes, air velocity sensors) to measure accurately the amount of outside air, air flows, and air exchange rate for a ventilation system. Often it is not possible to find a well developed velocity profile (straight duct), the outside air intake is not ducted at all, and you do not know if exhaust air is coming back through the air intake. By using a tracer gas technique these problems can be taken into account. At the same time it will be possible to measure air flow in ducts, air exchange rate, percentage of outside air, outside circuiting of exhaust air, amount of air inflitration and the overall efficiency of the system.

It is also important to be able to verify that the outside air is getting down to the occupants in the occupied zone. The tracer gas technique can also be used to evaluate the air distribution (air change efficiency) and the pollutant removal efficiency (ventilation effectiveness) of a system.

The present paper will set off the procedure for doing this type of measurement and show a couple of field measurements.

INTRODUCTION

Tracer gas measurements are used to evaluate air flow through a room or a building. The idea behind tracer gas measurements is to mark the air in a building with something easily identifiable, so that its movement can be traced. The type of tracers used in ventilation measurements are usually colorless, odorless, inert gases that are not normally present in the environment. The most used tracer gas is sulphur hexaflouride (SF_6).

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 more accurate, as it takes into account the large effect occupancy can have on a building's air exchange rate: for example the effect of opening and closing doors and windows. It is, after all, the air exchange 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 that is recirculated 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 were not taken into account in the planning stage of a building, and are not measured as part of regular building maintenance checks.

Tracer gas techniques provide the easiest, most accurate and, in some cases, only means of measuring several ventilation parameters critical to indoor air quality. The versatility of tracer gas methodology permits accurate airflow measurements to be performed in situations in which Pitot tubes, air veloicity meters or temperature sensors cannot be applied. These traditional measurement techniques are completely incapable of determining the extent of any external or internal re-entrainment of building exhaust into building supply or the amount of natural air inflitration. These two airflow parameters are important components of a building's fresh air supply characteristics and must be considered when determining compliance with ASHRAE's ventilation standard 62-89.

In this paper it will be described how tracer gas can be used to trace odors and pollutats, to measure air flows in the HVAC system and to measure the distribution of outside air in the occupied zone.

TRACING ODORS AND POLLUTANTS

The most simple way of using tracer gas is to trace how odors and pollutants are spreading in a building. The tracer gas is more or less used as a sophisticated smoke test. The tracer gas is released at a constant rate where the odor or pollutant source is located. Then the concentration is measured at different locations in the building to trace the flow and also, from the concentrations, calculate the amount of flow to the different parts of the building.

In a field measurement (Olesen, 1991) in a large office complex, the tracer gas was used to trace the odor from a food court into the offices. The complex, which covers an entire city block, contains several floors of offices surrounding a large atrium. At the base of the atrium is a food court with a number of small restaurants and vendors. A series of stairwells and elevator shafts rise through the office space where many individual air supply and return systems serve the antrium and the various offices, shops, and restaurants.

For a considerable time tenants had complained that odors from the food court were entering their offices. The building's managers assumed that the odors were drifting into and up the atrium, and then into the offices. As a result, they were considering an extremely expensive solution of building a new floor at the base of the atrium, to seal the food court off from the offices above.

To determine the actual air flow, the tracer gas was sampled in different areas of the building complex and SF_6 tracer gas released into the center of the food court.

As the measurements began, it became clear that levels of SF_6 were not substantially increasing in the atrium area. Indeed, the gas was hardly detectable in the upper reaches of the antrium throughout the experiment. By contrast, levels of the gas increased considerably at the rear of the food court, away from the atrium. The gas, and the food odors with it, was "pooling" in a wide passageway where there were two sets of doors.

The first set of doors led to the outside of the building; the second set of doors led directly into a stairwell reaching up to the top of the building.

One gas monitor was moved to sample the gas in the stairwell. The gas measured there was in high concentrations and was getting higher as time passed.

These mesurements showed that odors from the food court were being immediately sucked up the stairwell; however, they were only reaching some office corridors, seemingly at random. In fact, some floors were under positive pressure with respect to the stairwell and these resisted the influx of SF_6. Some, however, were under negative pressure, and it was these floors which were receiving high doses of SF_6 and, therefore, food odors.

AIR FLOW IN VENTILATION SYSTEMS

Before doing any extensive measurements of air flow, air change rate, age-of-air, etc. in the occupied zone, it is recommended to do an analysis of the air flows in and around the air handling unit (Olesen, 1991).

Test Procedure

A simplified drawing of a typical HVAC system is shown in Figure 1. The overall procedure required for this application involves dosing tracer gas at a constant rate at one point in the system and then monitoring the tracer gas concentration at the four positions shown in Figure 1.

(Figure 1)

The dosing point is located in the return duct coming from the zone. Dosing must be done at a point where good mixing of the tracer with the return air will occur. This should be before the duct branches, between the building exhaust and the mixing box. Good dosing points are located upstream of the return fan or before any bends in the dutwork, and as far upstream from the mixing branch as possible. If adequate mixing has been achieved, the tracer gas concentration will be the same in the recirculated and exhaust air streams.

Tracer gas concentrations are monitored in the return air duct both before and after the dosing point. These are positions 6 and 1 in Figure 1. Additionally, tracer gas measurements are made in the outdoor supply air (position 2) and in the supply to the zone (position 4).

Dosing is started at a constant rate until approximately steady-state concentrations are obtained at each sample point.

The results of the test are shown in Figure 2. Initially for 30 minutes the base-level concentration was sampled. At 19:22 hours, dosing started and continued uninterrupted for three hours. In this system, the supply air was actually branched out in a hot-air duct and a cold-air duct; but the tracer concentrations were the same before and after the ducts branched out.

(Figure 2)

Air Flow in the Return Duct

Air flow in a duct is calculated from:

$$V_r = G/(C_1 - C_6)\ m^3/s \qquad \text{(eq. 1)}$$

where:

V_r = air flow in duct m^3/s
G = dosing rate ml/s or mg/s
C_1 = concentration after dosing, ppm or mg/m^3
C_6 = concentration before dosing, ppm or mg/m^3

The application software used in the present test calculates the amount of tracer gas dosed.

A printout of the measured concentration and amount of dosed gas for position 1 is shown in Figure 3. The calculated dosing at near steady-state conditions (from 21:11:21 to 22:11:08) is 74700 mg in 3587 seconds. That is, the dosing rate G = 20.8 mg/s = 3.5 ml/s.

The average concentration over the same time period was:

C_1 (return after dosing) = 0.596 ppm (3.56 mg/m^3)
C_2 (outside) = 0.010 ppm (0.06 mg/m^3)*
C_4 (supply) = 0.464 ppm (2.97 mg/m^3)
C_6 (return zone) = 0.428 ppm (2.56 mg/m^3)
*(at detection limit)

The total flow rate in the return (V_r) is then:

$$V_r = 20.8\ mg/s/(3.56 - 2.56) mg/m^3 = 20.7\ m^3/s = 20700\ l/s$$

(Figure 3)

By knowing the amount of dosed tracer gas, which is 100% SF_6, and the resulting concentration, it is possible to calculate how much outside air is needed to dilute the tracer gas concentration to the obtained value. This is shown in Figure 3 as air change (Airch.) in m^3/s. The average over the steady-state period (21:11:21 to 22:11:08) is 5.8 m^3/s (5800 l/s). This corresponds to 28% (5.8/20.7 x 100%) of the total air flow in the return duct.

Outside Short Circuiting

The ratio of the concentration of tracer gas in the outdoor-air intake, C_2, to the concentration in the exhaust, C_1 (same as in the return duct) gives us the short circuit of exhaust air (V_{eo}) into the outdoor-air intake duct, $r_{so} = V_{eo}/V_s = C_2/C_1$. V_s = Supply air (Fig. 1).

The concentration in the outside air (C_1) is not significantly different from the detection limit (0.005 ppm) so no outside short circuiting is taking place ($V_{eo} = 0$).

Percentage of Outside Air

The ratio of the concentration of tracer gas in the supply air duct, C_4, to the concentration in the exhaust-air duct, C_1, gives us the total amount of return air back into the supply air, either in the mixing box (V_{rs}) or through outside short circuiting from the exhaust (V_{es}) into the outdoor air intake, $r_{rec} = (V_{rs} + V_{es})/V_s = C_4/C_1$.

The outdoor air (V_0) brought into a building by a ventilation system can be calculated from the air flow rate in the supply duct (V_s) and the percentage of the supply air that is outdoor air (not recirculated or short circuited extract air). The percent of outside air is:

$$V_0/V_s = (1 - r_{rec})100\% = (1 - C_4/C_1)100\% = (1 - 0.464/0.596)100 = 22\%$$

Percentage of Infiltration Air

The ratio of the concentration of tracer gas in the return duct from the zone, C_6, to the concentration in the supply air duct, C_4, gives the amount of supply air being extracted through the return.

The percent of infiltration air (V_i) in the return air is then:

$$V_i/V_r = (1 - C_6/C_4)100 = (1 - 0.428/0.464)100 = 8\%$$

Note that the percentage of outside air is in relation to the total air flow in the supply duct, while the percentage of infiltration is in relation to the total air flow in the return duct. The total air flow in the return duct was measured directly to be 20.7 m^3/s including 5.9 m^3/s (28%) outside air, of which 1.6 m^3/s (8%) is infiltration air.

The requirement for outside air in an office building is 10 l/s (20 cfm) per person. This means that in the building where the present test was made, the amount of outside air (5.9 m^3/s = 5900 l/s) is enough for 590 occupants.

Air Change Rate and Air Change Efficiency

From the step-up curve of the tracer gas concentration measured in the return (Figure 4) it is possible to calculate the air change rate for the zone as a whole and the overall efficiency of the air distribution. This is done by calculating the local age-of-air in the return and the zone average age-of-air. Both calculations are done based on the step-up curve in the return. The air change for the zone as a whole is equal to:

Air change rate, ach = 1/(age-of-air in return)

The overall air change efficiency is equal to:

Air change efficiency = (age-of-air, return)/(zone average age-of-air).

The local age-of-air in the return is calculated to be 2270s and the average age-of-air for the whole zone is 2480s.

Air change rate = 3600s/2270s • h^{-1} = 1.6h^{-1}

Air change efficiency = 2270s/2480s • 100 = 89%

This is close to perfect mixing, which is 100%.

(Figure 4)

AIR CHANGE EFFICIENCY AND VENTILATION EFFECTIVENESS

The listed outdoor air requirements or the air change rates listed in existing standards (ASHRAE 62-89) are based on a ventilation system with perfect mixing. This assumption does not always apply. In the future it will be necessary to take into account how efficiently the air is distributed in the occupied zone. If there are stagnant zones and short circuiting, the amount of fresh air must be increased. If, on the other hand, it is possible to establish a plug/piston flow, the amount of fresh air can be reduced. To properly assess ventilation in the critical breathing zone, one must determine:

- How quickly "old" contaminated air is replaced with "new" fresh air in the zone of occupation.
- How quickly generated contaminants are removed, and how effectively the contaminants are prevented from spreading to unwanted areas, like the occupied zone.

The air renewal and the contaminant removal processes are related but generally not identical. Consequently, these two processes have to be treated separately. The effectiveness of air renewal and contaminant removal are referred to as "air-exchange efficiency" and "ventilation effectiveness" respectively. Furthermore, it is necessary to differentiate between average and and local conditions.

Air-Change Efficiency

The definition of air-change efficiency is based on the "age" concept (Olesen 1990, 1991). The age-of-air in a room is a measure of the length of time it 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. Age-of-air can be considered as the local age-of-air, the room average age-of-air, and the occupied zone average age-of-air.

Local age-of-air is used if the ventilation of individual work stations, or the distribution of air in naturally ventilated buildings, is to be assessed. It is also used in mapping 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 ventilation can be assessed at individual work stations.

The average age of room 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.

The average of the occupied zone age-of-air is calculated as a mean value of the local age-of-air in different points in occupied zones. This value is more related to IAQ concerns as it represents the occupied zone and are not influenced by stagnant zones, etc. in the upper part of a room.

The efficiency with which ventilation systems exchange room air can be calculated by dividing the local mean age-of-air in the return by the room average age-of-air. In a system with perfect mixing these two values will be equal and the efficiency 1 (100%). In a perfect piston flow system the local mean age-of-air in the return is twice the room average age-of-air and the efficiency is 2 (200%).

For the indoor air quality it is, however, recommended to use the occupied zone average age-of-air instead of the room average age-of-air. This will probably also be recommended in a proposed ASHRAE test procedure (ASHRAE SPC 129P).

Ventilation Effectiveness

One main objective of ventilation is to remove pollutants generated in a space. The effectiveness of this removal is called the ventilation effectiveness. This is defined as the relation between the pollution concentration in the return air (C_e) and in the breathing zone (C_2). This can be measured using the tracer gas to simulate pollution sources. If the pollution sources are evenly distributed in the room (i.e. building materials, carpet, people) then the ventilation effectiveness will be similar to the air change efficiency.

Measuring Age-of-Air

Tracer gas techniques are also used to measure the age-of-air and evaluate the efficiency of ventilation systems. 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 age-of-air is simply the area under the concentration versus time. This method is preferred by many researchers because it avoids the difficulty of marking all infiltration air. The concentration decay method is also the only method usable in a naturally ventilated space. Another method is to use the step-up tracer gas method. The tracer gas is dosed in the supply or return air, and the increase of the gas concentration in the occupied zone and in the return, is measured. In this case the local age-of-air is the area between the concentration curve and the final concentration versus time.

If the point at which the concentration has been studied is in the return air duct, then the room average age-of-air can be calculated.

AIR DISTRIBUTION IN ROOMS

The air distribution pattern in a room depends on parameters such as types of outlets, position of outlets and return openings, velocity of supply air, and temperature difference between supply- and room air. Figure 5 (COST 613, Skaaret 1982, 1986) shows a generalized overview of the influence of positioning of supply and return openings together with the influence of the temperature difference between supply air and room air. The data is for Ventilation Effectiveness which characterizes how efficient the ventilation system/method is in removing pollutants. It is, however, assumed that the pollution sources are evenly distributed, which means that the numbers reflect the efficiency of the air distribution (air change efficiency). For an uneven distribution of pollution sources, the values in figure 5 may change significantly. It is seen that for cooling, i.e. the supply air is colder than the room air, the efficiency is for standard types of systems 90 to 100%. For displacement ventilation it may go up to 120 to 140%. If the supply air is warmer than the room air you may expect greater influence of the positioning of the supply and return grill. With a supply at the ceiling and return at the floor the air is completely mixed (efficiency 90-100%). For displacement ventilation and for systems with both supply and return grills at the ceiling, the efficiency may drop down to 20-40%. In general the figure shows that for cooling systems you can expect the air distribution to be close to complete mixing (air change efficiency around 100%) while for heating systems the air distribution depends very significantly on the positioning of the location of the terminal devices. It should be mentioned that the data in figure 5 does not take into account any effect of the characteristics of the air terminal devices or the flow rate of the supply air. Following actual examples of measurements in the field and laboratory will be presented.

(Figure 5)

Field Measurements in a Class Room

The first example is a continuation of the measurements in the ventilation system presented above. The air distribution was tested in one typical room. The supply grills were positioned in the ceiling and the return plenum was also in the ceiling. The test was done in the summer season, so the supply air temperature was lower than the room air temperature.

The tracer gas was dosed in the return and the buildup (step-up curve) was measured at different locations in the room, in the plenum, and in the return (Figure 6). The air handling unit was supplying more zones/rooms.

(Figure 6)

The results are shown in Figure 7. The buildup of the tracer gas in the different sampling points was very similar which indicates that the supply air was well mixed. Table 1 gives the results of the calculations of the age-of-air.

(Figure 7)
(Table 1)

In this zone of the building the age-of-air in the return was 1792 s compared to 2250 s in the return including all zones. This is equivalent to an air change rate of 2.0 h^{-1} for the present zone compared to 1.6 h^{-1} for the whole building. This means that some zones of the building must have an air change rate lower than 1.6 h^{-1}. The air change efficiency for the room may either be given with reference to the common return (age-of-air return/age-of-air occupied zone) or with reference to the nearest return grill in the ceiling (age-of-air plenum/age-of-air occupied zone). The occupied zone may either be represented with an average of all the sampling points or as a local efficiency for each location. In the present measurements there is no difference. The efficiency is 108% in all cases. This is higher than the average for the whole zone, 102%, and the average for the whole system 88%. The air change rate in the occupied zone may either be calculated as an average for all sampling locations or as individual values for each location. In the present test the conditions are very uniform, so the sampling location at breath level (2) will be used to represent the occupied zone. The air change can then be calculated as the reciprocal of the age-of-air (3600/age-of-air h^{-1}). This is for the present case 3600/1656 = 2.2 h^{-1}. The air change may also be calculated from the decay curves (figure 7). The slope of the decay curve in a log-plot gives directly the air change rate.

The class room has a volume equal to 159 m^3. With an air change rate of 2.2 h^{-1}, the ventilation system will provide 349 m^3/h or 97 l/s of outside air to the occupied zone. This is then sufficient for 9 persons in the room based on a requirement of 10 l/s (20 cfm) per person. To see if the ventilation rate was adequate, a measurement of the Carbon Dioxide (CO_2) level was also made at the same sampling points (figure 5). The results are shown in Figure 8. When the class room is occupied the level of CO_2 in the occupied zone sometimes exceeds 1000 ppm, which is normally recommended as the maximum value. It is recommended to increase the amount of outside air to this room. The number of occupants in a class was greater than 9.

(Figure 8)

Influence of Heat Load and Location of Supply/Return

Several laboratory and field measurements of air distribution have been done by Peter Olufsen (Olufsen 1991). All of these measurements used the decay method. The room air was filled and well mixed with tracer gas, and then the decay of the tracer gas concentration was measured at several levels in the room and also in the return. All measurements were made in the middle of the room. The local age-of-air was calculated from the decay curves. A local efficiency index was then calculated as the relation between the age-of-air in the return and the local age-of-air in at the different sampling locations. If this index is multiplied by 100, it is equal to the air change efficiency used in the previous example. A Global Efficiency Index (average for the whole room) was calculated as the relation between the age-of-air in the return and the average age-of-air for the whole room. Both values are calculated from the decay curve in the return (Olufsen, 1991). The results shown in Figure 9 are from measurements in a 28 m^3 laboratory test room with a ceiling height of 2.4 m. The measurements were made in the middle of the room, where the air change rate was 3 h^{-1}.

(Figure 9)

Curve A is a typical short circuit case occurring when preheated air (approximately 3°C above room temperature) is supplied through a ceiling diffuser and exhausted through an outlet in the wall just below the ceiling. The index assumes very low values in the lower part of the room because a stagnation zone, occuping the lower 60% of the room, develops. The global index is 0.6.

The flow field changes character when heat sources are placed on the floor without changing the arrangement of air supply and exhaust.

Curve B occurs at a heat load of 26 W/m² floor area. The heat sources used are designed as cylinders. Radiation and convection of heat from the cylinders correspond approximately to the conditions of a sedentary person in thermal neutrality. The heat load results in exhaust and room temperature higher than the supply air temperature which affects the flow field, but the most important reason that stagnation ceases is that convective flows around the heat sources create mixing in the room. The local index approaches 1 but increases slightly with the height above the floor. The global index is 1.0.

Curve C occurs when the exhaust is maintained but the air supply is moved to a slot at the floor over the full width of the room at the opposite side of the exhaust. The heat load remains unchanged at 26 W/m². The local index assumes values higher than 1 in the lowest part of the room where the supplied air first reaches, but higher up in the room, the index will be very close to 1. The careful supply of air below room temperature at floor level results in a slower mixing than when air is supplied through a ceiling diffuser. The flow pattern is characterized by a vertical displacement effect in the lowest part of the room and by mixing in the upper part. The global index is 1.1.

The three curves A, B, and C represent three main forms: short circuit, mixing, and vertical displacement, which occur when field measurements are performed in normally ventilated rooms. The corresponding air distribution patterns are shown schematically in Figure 10.

(Figure 10)

CONCLUSION

The method to quantify the air flows in a ventilation- or air conditioning system is based on the use of the tracer gas technique. Today most air flow measurements in ducts are done by Pitot tubes or air velocity sensors. The flow is calculated from an assumed air velocity profile. Often it is not possible to find a location in the system where a developed flow exists. Also, these measurements will not be able to measure if there is re-entrainment of exhaust air.

It is not enough to verify that the required amount of outside air is delivered through the supply. It must be verified that the outside air will reach the occupant. A good air distribution depends on several factors such as location and type of supply and return devices, supply air flow rate, difference between supply and room air temperature, and the level of the internal heat load. These are factors which must be taken into account at the design of the systems and in calculation of the necessary amount of outside air which will provide an acceptable indoor air quality in the occupied zone.

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Table 1. Age-of-Air and Air Change Efficiency calculations.

Location	Age-of-air	Zone Aver.	Air Change Efficiency		Air Change Rate
			Plenum	return	
	sec.	sec.	%	%	h^{-1}
1 Return	1792	1744		103	2.0
2 Breath Level	1656		108	108	2.2
3 Plenum	1791				2.0
4 Table	1666		108	108	2.2

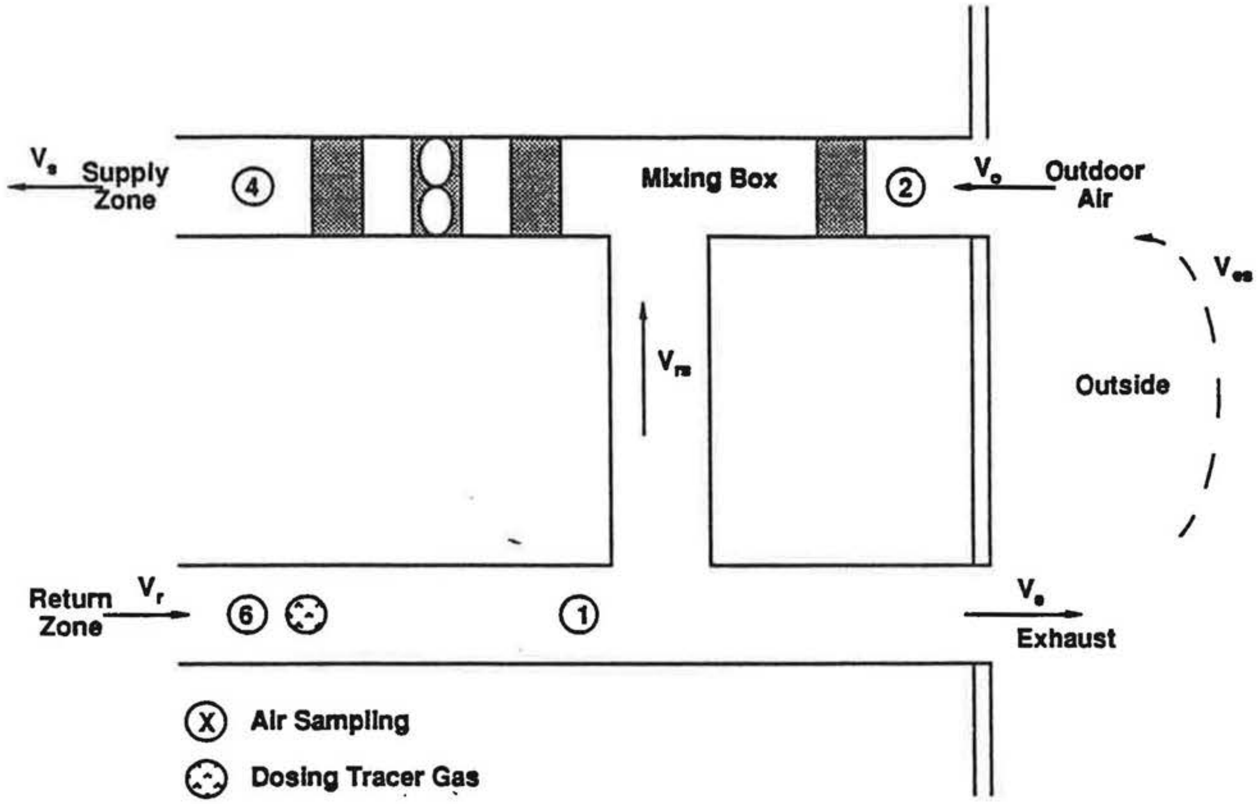


Figure 1. Dosing and sampling points for measuring air flow and age-of-air in a HVAC system.

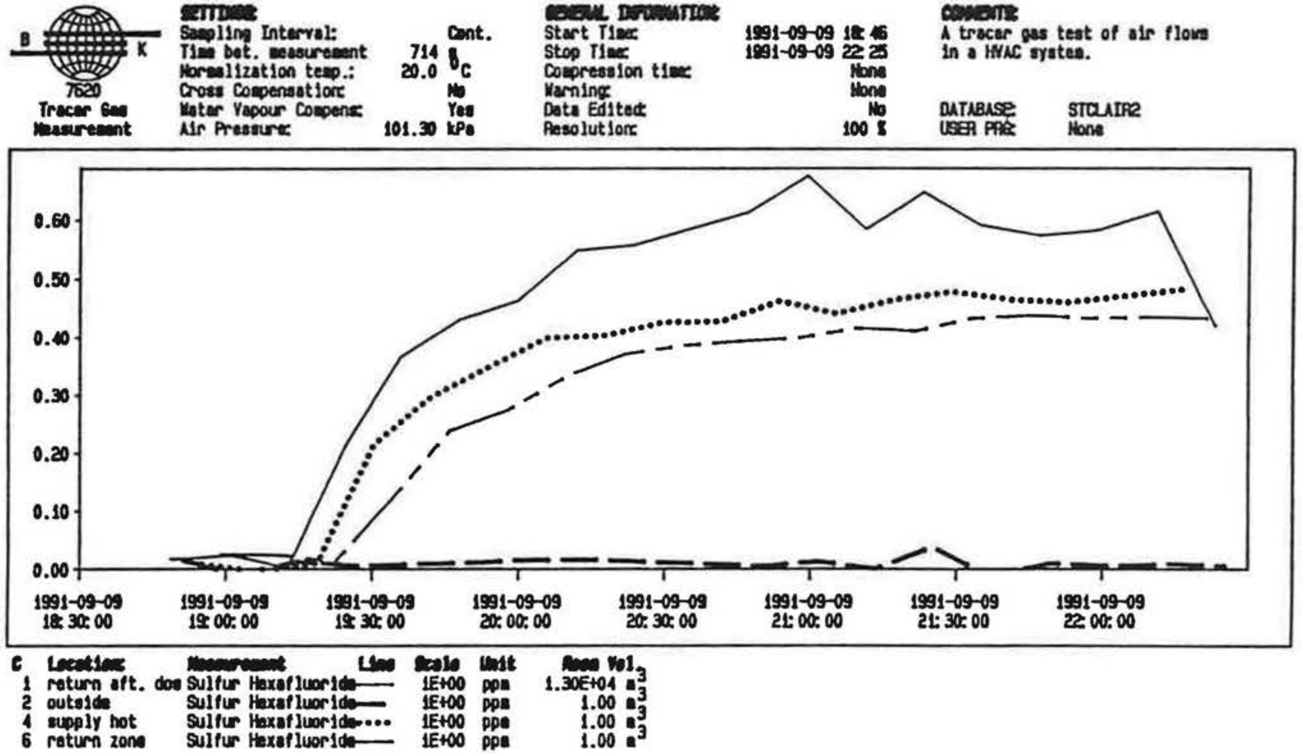


Fig. 2. Results of the tracer-gas test shown in Fig. 1.

Fig2

Fig3

B K 7620
Tracer Gas
Measurement

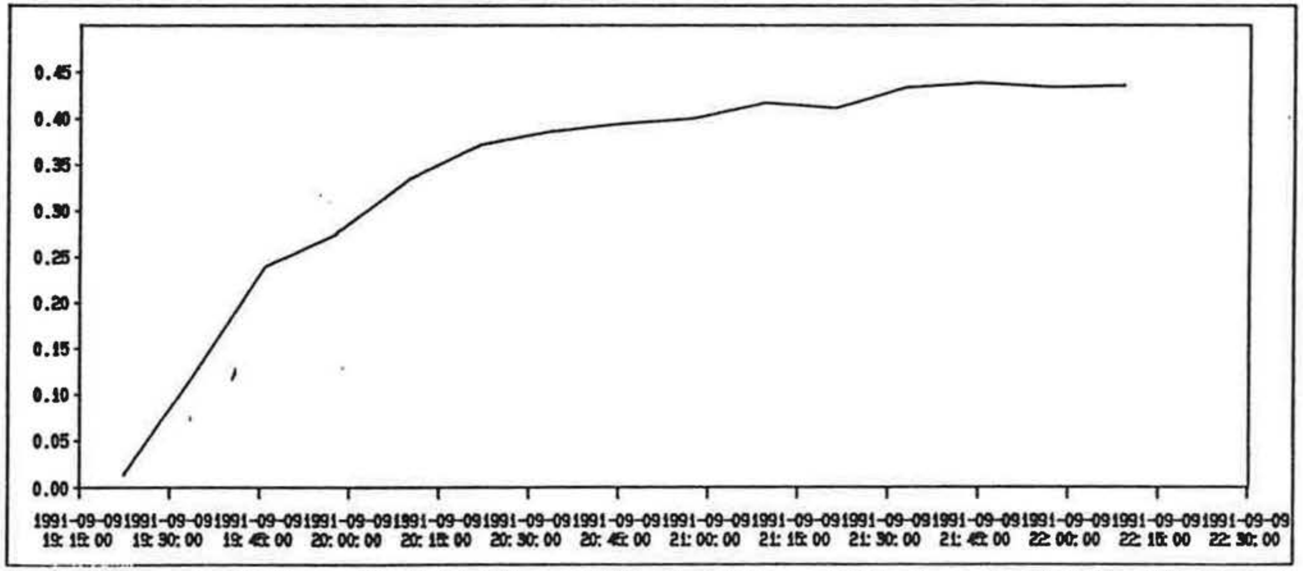
SETTINGS:		GENERAL INFORMATION:	
Sampling Interval:	Cont.	Start Time:	1991-09-09 20:35
Time bet. measurement	719 s	Stop Time:	1991-09-09 22:15
Normalization temp.:	20.0 °C	Compression time:	None
Cross Compensation:	No	Warning:	None
Water Vapour Compens:	Yes	Data Edited:	No
Air Pressure:	101.30 kPa		
DATABASE:	STCLAIR2	USER FOR:	None

return aft. dos		Sulfur Hexafluoride	Room Vol.	1.30E+04 m³	Warnings/Errors		
Channel 1		Result	Airch.	Dose.	7620	1302	1303-1
		[ppm]	[m³/s]	[mg]			
1991-09-09	20:36:17	5.86E-01	5.25	1.46E+04			
	20:47:18	6.15E-01	4.94	1.50E+04			
	20:59:18	6.75E-01	3.89	1.50E+04			
	21:11:21	5.84E-01	5.76	1.51E+04			
	21:23:06	5.48E-01	5.02	1.47E+04			
	21:34:44	5.91E-01	5.37	1.46E+04			
	21:46:46	5.73E-01	5.57	1.50E+04			
	21:58:53	5.83E-01	5.94	1.51E+04			
	22:11:08	6.15E-01	4.93	1.53E+04			

Fig. 3. Printout of the measured concentration and amount of dosed gas for channel 1.

B K 7620 Tracer Gas Measurement

SETTINGS:		GENERAL INFORMATION:		COMMENTS:
Sampling Interval:	Cont.	Start Time:	1991-09-09 19:15	Calculation of Local Mean-Age-of-Air in the return, Room Average Age-of-Air and Air Change Efficiency.
Time bet. measurement	715 s	Stop Time:	1991-09-09 22:15	
Normalization temp.:	20.0 °C	Compression time:	None	
Cross Compensation:	No	Warning:	None	
Water Vapour Compens:	Yes	Data Edited:	No	DATABASE: STCLAIR2
Air Pressure:	101.30 kPa	Resolution:	100 %	USER PRG: None



C	Location:	Measurement	Line	Scale	Unit	Room Vol.	L. mean age.	R. ave. age.	Air ex. effic.	Inf. val. curve.
6	return zone	Sulfur Hexafluoride	——	1E+00	ppm	1.00 m^3	2.21E+03 s	2.48E+03 s	44.54 %	4.45E-01 ppm

Fig. 4. Tracer-gas step-up curve in the return.

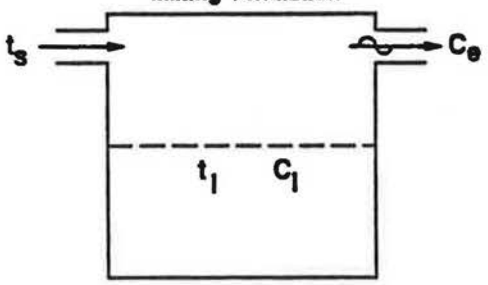
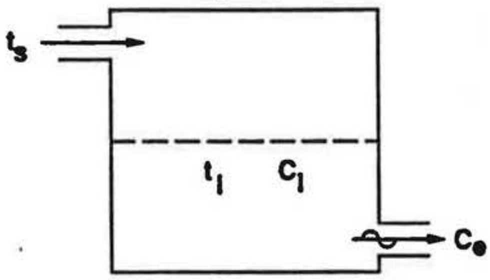
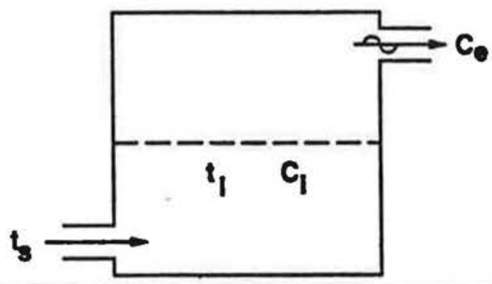
Ventilation Principle	Temperature difference between supply air and air in breating zone, $t_s - t_l$ °C	Ventilation Effectiveness C_e/C_l
Mixing Ventilation 	< 0 0 - 2 2 - 5 > 5	0.9 - 1.0 0.9 0.8 0.4 - 0.7
Mixing Ventilation 	< - 5 0 - .5 > 0	0.9 0.9 - 1.0 1.0
Displacement Ventilation 	> 2 0 - 2 < 0	0.2 - 0.7 0.7 - 0.9 1.2 - 1.4

Figure 5. Ventilation effectiveness in the breathing zone of spaces ventilated in different ways.

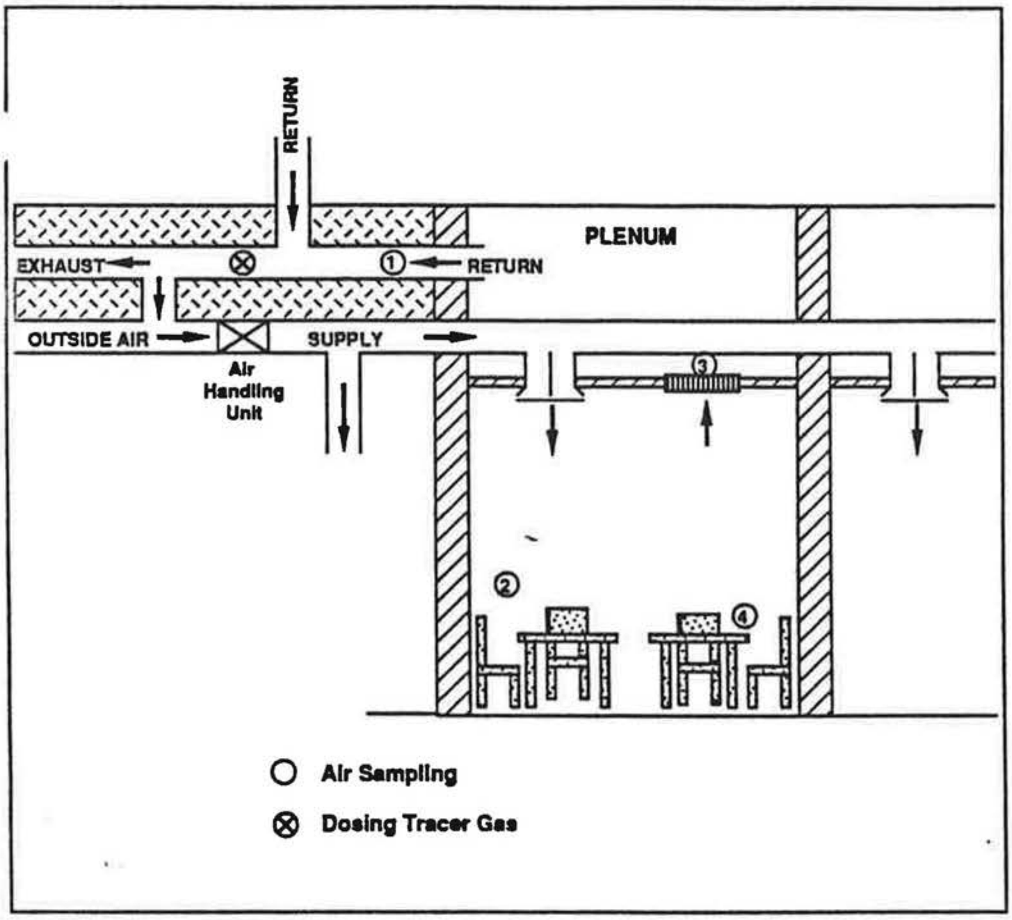


Figure 6. Dosing and sampling points for measuring age-of-air in a class room.

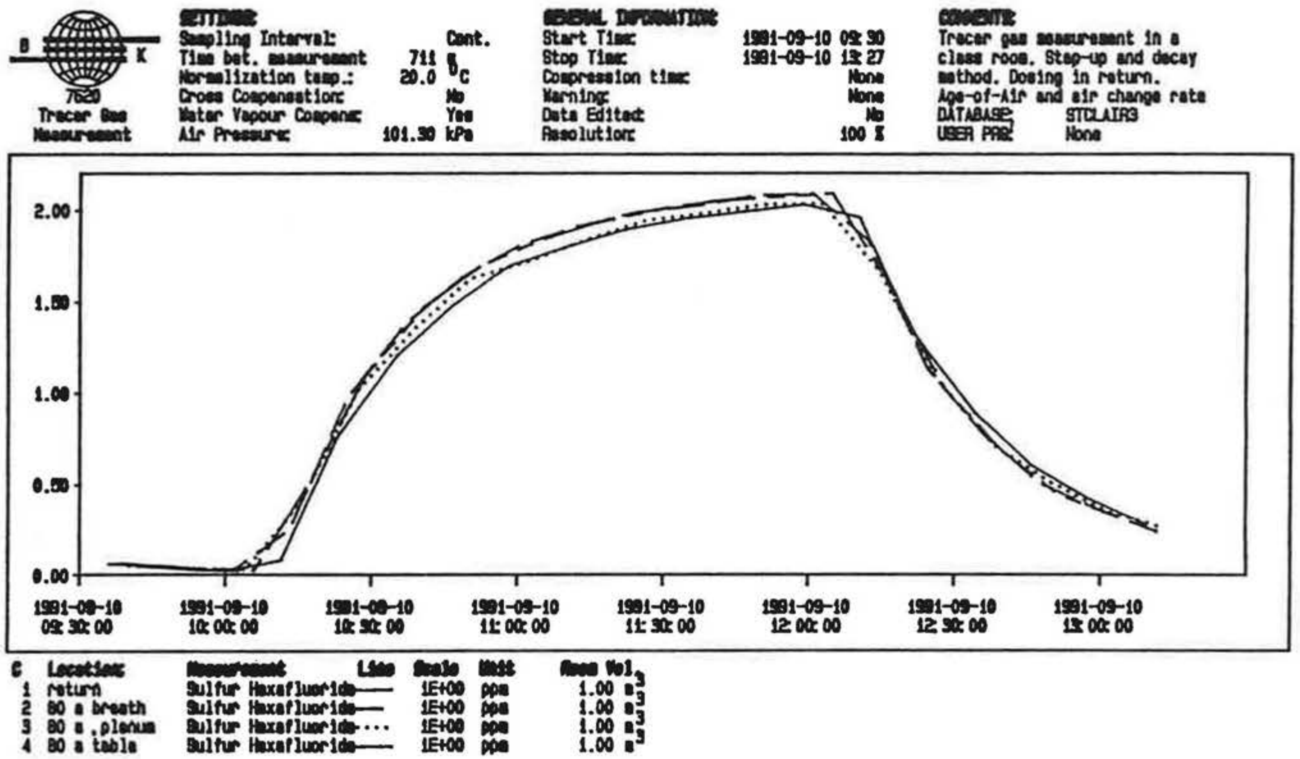


Figure 7. Tracer gas step-up and decay measurement in a class room.

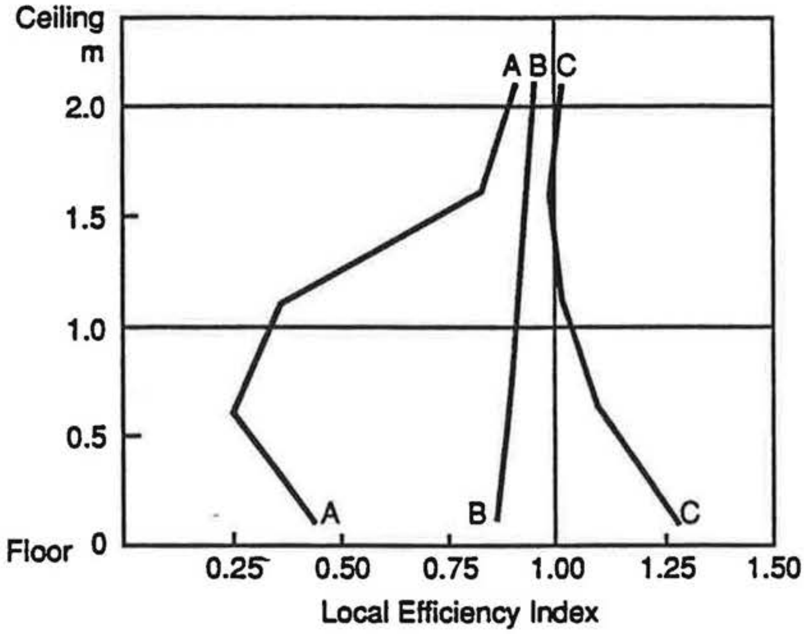


Figure 9. Vertical profiles of Local Efficiency Index in test room.
A: Short-circuit. B: Mixing. C: Displacement

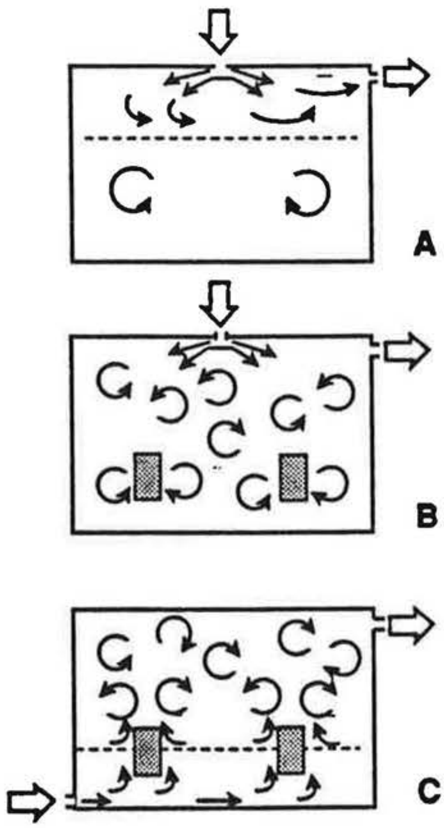


Figure 10. Principal flow patterns observed in test room.
A: Short-circuit. B: Mixing. C: Vertical Displacement