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MEASUREMENT OF AIR INFILTRATION, NATURAL VENTILATION AND DUCTS AIRFOWS WITH TRACER GAS TECHNIQUE: CASE STUDIES

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ABSTRACT

In buildings without mechanical ventilation, the fresh air needed by the occupants is only supplied by air infiltration or natural ventilation. Its quantification by analytical methods is difficult, and so experimental methods are most useful, namely the tracer gas technique. In this work, several case studies are presented, where one may see the potential of this technique to detect small differences in building air tightness, due to different envelope elements, namely the type of window frames and location of blinds' boxes. The applicability of this technique to other spaces rather than buildings can also be analysed. When dealing with mechanical ventilation, it is difficult to measure with precision the duct air flow rate, due to the necessary minimum duct length to obtain a good mixing of the tracer gas with the air, when conventional probes are used. Research was carried out with the development of new probes in order to overcome this situation, and results are also shown. With accurate measurements of air flow rates, it is possible to reduce CO_2 emissions due to air heating or cooling in buildings.

Keywords: tracer gas technique, airflow rates, buildings, air ducts, measurements.

INTRODUCTION

With successive energy crises in the last century and with the growing awareness of finite energy resources, western countries tried to make buildings envelopes as tight as possible, regarding the income of outside air, reducing in that way the energy consumed to heat or cool this new air. In buildings without mechanical ventilation, the fresh air needed by the occupants is supplied by air infiltration or natural ventilation.

One of the ways to save energy in buildings consists in reducing air infiltration, which, in several countries/buildings, is the only way to promote air renovation. However, this air renovation cannot go below certain limits, as the occupants would be exposed to internal pollutant concentrations above the acceptable limits (Woods, Maldonado and Reynolds, 1981). The maintenance of a clean indoor air in buildings depends on the capacity to eliminate the internal pollutants generated indoors. These pollutants are either due to the permanent release of VOC's by internal materials, or to the physiological processes of occupants. So, one way to increase the indoor air quality is to increase the indoor air flow, within certain limits, based either on air infiltration or natural ventilation. The quantification of these air movements by analytical methods is rather difficult, and so experimental methods are most useful, namely the tracer gas technique.

In this work, a review of this technique was carried out and several case studies are shown. As will be seen, details in building construction that can promote different air exchanges can be accurately identified with the tracer gas technique. The applicability of this technique to different envelopes, rather than buildings, will also be presented.

In buildings with mechanical ventilation it is difficult to measure with precision the duct air flow rates with the tracer gas technique, due to the necessary minimum duct length to get a good mixing of the tracer gas with the air, when conventional probes are used. So, a new injection and sampling probe was developed to overcome this problem, which enables the measurement of duct air flow rates in complex duct networks. The new probes and the results obtained are shown in this work.

Once air flow rates are measured, measures can be taken in order to reduce the energy spent for heating or cooling incoming air and, as consequence, to reduce CO_2 emissions.

TRACER GAS METHOD FOR MEASUREMENT OF AIRFLOW RATES IN SPACE

In any closed space there are always air exchanges between the outside and inside air, because it is almost impossible to make them air tight, as can be seen schematically in Fig.1.

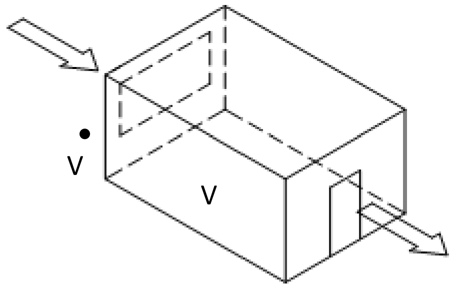


Fig.1 Scheme of the air exchange in a closed space.

As said, it is important to know the air flow rate through the envelope of the space due to energy issues and indoor air quality. However, when it is necessary to compare different spaces regarding global air leakage (or air tightness), it is more important to know how many times per hour the inside air is replaced (changed) by new one coming from outside - air exchange rate - I (air changes per hour). By definition:

$$I = \frac{\dot{V}}{V} \tag{1}$$

For example, if I = 1 ach this means that all the inside air of the space is replaced by outside one in one hour; if I = 0.5 ach the air is replaced by new one in each two hours, and so on. In these examples, it is assumed that the air exchange rate is a hypothetical plug (piston) flow.

In order to experimentally calculate the value of I, the best method is the tracer gas technique, as in the above equation the air flow rate is the only unknown. This technique consists in the introduction of a certain quantity of a known gas in the space where the air exchange rate (infiltration, natural or mechanical air ventilation) is to be measured – the tracer gas – and measuring the tracer concentration along time with an appropriate gas analyser. Once the tracer concentration evolution with time is known, it is possible to evaluate the air flow rates through the envelope of the space, after an appropriate mathematical analysis (Hitchin and Wilson, 1987). For that, it is supposed that the space under study behaves as a single zone, i.e., with an inside uniform tracer gas concentration. The tracer gas balance of the space results in the following equation:

$$q.dt - (c - c_{atm}).I.V.dt = \left(\frac{dc}{dt}\right).dt.V \tag{2}$$

As in the beginning of the tests the initial tracer concentration can be written as $c = c_{atm} + c_0$ (c0 the initial concentration in the space), the last equation becomes:

$$c = c_{atm} + \frac{q}{I.V}.\left(1 - e^{-I.t}\right) + c_0.e^{-I.t} \tag{3}$$

The tests can be implemented by several methods, namely the constant concentration, the constant tracer emission and the decay methods.

Due to its simplicity, this last method is the most common in single zones. It consists in supplying tracer gas to the space under study, from one pressurized bottle to the tracer dozer through a very sensitive low pressure regulator, until some initial and uniform concentration is reached, c0, after which the tracer supply is cut off. Then the tracer gas concentration decays, due to air exchanges of outside air with the inside one, and samples of the internal air are acquired by a gas analyser where the concentration is recorded. As the density of the tracer gas can be different from the indoor air one, it stratification of the gas may occur and then it will be impossible to obtain a uniform concentration within the space. To eliminate this problem, it is usual to place small fans inside the space to disperse the gas across the interior space. As the tests are carried out by the tracer decay method (q = 0), the solution represented by equation 3 results in the following equation:

$$I = \frac{1}{t}.\ln\left(\frac{c_0}{c}\right) \tag{4}$$

As can be seen through the above equation, only two measurements of the tracer concentration (c0 and c for a certain time interval) would be enough to calculate I for the space. However, in this situation, the error in the evaluation of I can be large as the measured value of c at a certain time (t) can differ from its value at another time instant, Fig. 2. So, it is usual to measure several values of the tracer concentration at regular time intervals. These values plotted in a graph ln(c) versus time lie around a straight line, in which the absolute value of the slope is equal to the air exchange rate of the space. In order to check the accuracy of the method, a test was carried out in two different houses. The results obtained in both houses are plotted in the same figure for an easy comparison between them. As can be seen, the measured air infiltration rate was I = 0.95 ach in house #2 (larger slope) and I = 0.77 ach in house #1 (lower slope). The visualization of that kind of graphs also enables to verify if the air infiltration rate during the test is steady (only a straight line) or unsteady (two or more slopes).

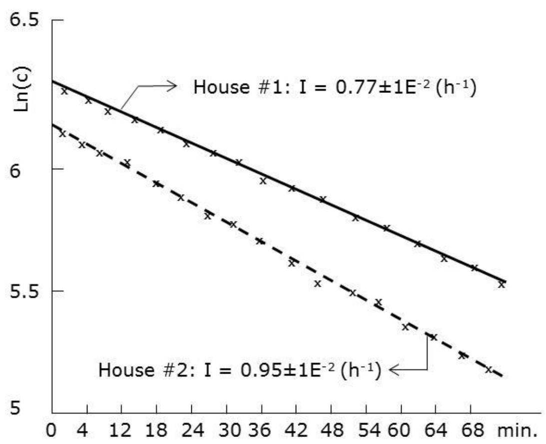


Fig.2 Tests carried out in two different houses.

As can be expected and seen in the same figure, the air infiltration rate was I = 0.95 ach when the fireplace is open and was I = 0.77 ach when the fireplace was closed. The visualization of that kind of graphs also enables to verify if the air infiltration rate during the test is steady (only a straight line) or unsteady (two or more slopes).

CASE STUDY 1 – MULTI-FAMILY APARTMENT BUILDINGS

The results obtained in Oporto city for buildings with less than twenty years are shown in Table 1, (Afonso, 1988). In each apartment about six tests where done with almost constant weather conditions – wind and temperature difference between inside and outside. So the obtained values are representative of each apartment for the prevailing conditions.

Table 1 I of typical housing in OPorto city.

Housing	Multi-family apartment buildings			Social apartments
	Windows frames		Average	
	Wood	Aluminum		
I (ach)	0.58	0.43	0.55	1.14

As can be seen from the above table the average air infiltration rate of multi-family apartment buildings is 0.55, which is in the range of normative values. However due to a leaker wooden frame windows comparing to the aluminium ones, the air infiltration rate of the first ones are about 34.9% large then the second ones. The social apartments, of worst quality, have an air infiltration rate of 1.14, i.e. 107% larger than the average value of the normal multi-family apartment buildings. This means that much more energy must be used to warm up (in winter time) or cool down (in summer time) the outside air in order to achieve the same indoor comfort temperatures.

CASE STUDY 2 – DETACHED HOUSES

The same kind of tests where done in another city in Portugal, Vila Real, in the countryside (NE), the results being shown in Table 2 (Azevedo, 1989). Two different types of houses where tested: in the city itself and in the rural areas close by and again with two different windows frames, wooden and aluminium and with two different box blinds, one inside and others outside the house itself. In each house several tests where done with almost constant weather conditions – wind and temperature difference between inside and outside. So the obtained values are representative of each house for the prevailing conditions.

Table 2 I of typical housing in Vila Real city.

	Windows frames							
	Aluminum (run type)				Wooden (opening type)			
	Internal box blinds		External box blinds		Internal box blinds		External box blinds	
	Urban	Rural	Urban	Rural	Urban	Rural	Urban	Rural
I	0.72	0.64	0.49	0.44	0.86	0.76	0.65	0.56

In average it is possible to say that air exchange rate of these houses are similar to the measured in Oporto city. But the main conclusions to withdraw are:

- houses with aluminium frames have a lower air infiltration rate when compared with the ones with wooden frames – 0.60 ach against 0.75 ach in urban houses and 0.54 ach against 0.66 ach in rural houses; the cause may be due to the weather that warp the wooden frames;

- the location of the box blinds in the windows also reflects significantly in the air infiltration of the houses. There is an increase of about 24% in the air exchange rate when the boxes are located inside the houses. This is due to the fact that the air has a free path from outside to inside of the house.

CASE STUDY 3 – OFFICES

In order to verify the applicability of the tracer gas method also for natural ventilation, tests were carried out in the Department of Mechanical Engineering of Faculty of Engineering of OPorto University (FEUP) in a typical four-story building.

The offices have only one window and one door connected to an internal corridor. Tests were done always with the door closed (normal situation) and the window closed (air infiltration) or semi opened (natural ventilation), (Afonso et all, 2004). Typically there is only one person per office.

The tracer gas method was implemented by the decay technique and the obtained air exchange rate and the 95% confidence interval of each office and for several tests were carried out. The data on measured air exchange rate are aggregated values from several measurements on several different days of the year. The weather conditions changed significantly from test to test in each office as they were carried out in the four seasons of one full year. Unfortunately there is not a unique set of values recommended for this kind of buildings in the different countries. Each one has its own regulations, (Tip). So, in these tests, the measured air exchanges rates were compared with the ones recommended by ASHRAE for this kind of offices, 7 l/s and 19 l/s per person of fresh air for offices without and with smokers, respectively.

The main results of the mentioned comparison are shown in Fig.3 and 4.

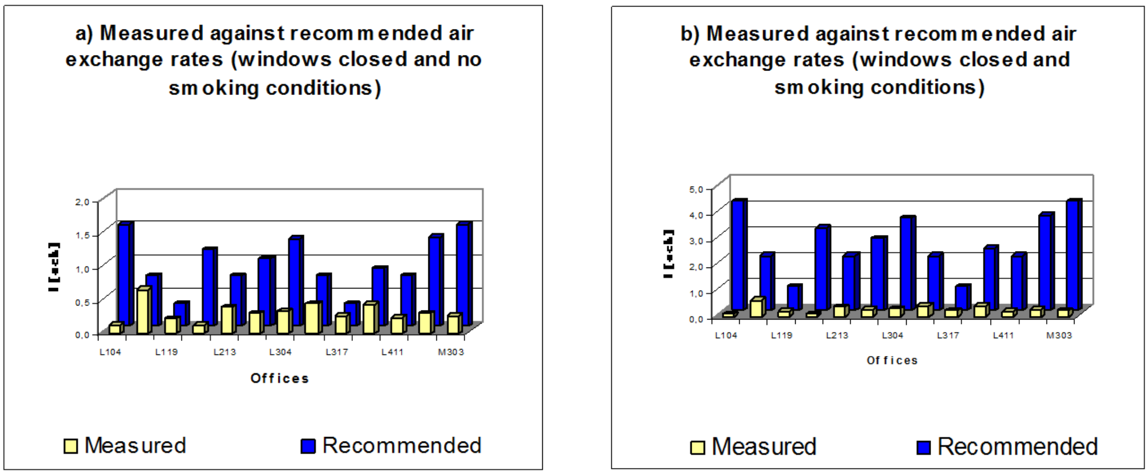
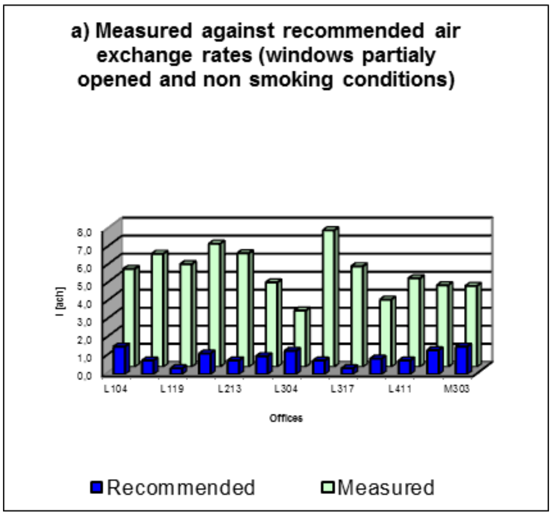


Fig.3 Comparison between the measured and recommended air exchange rate for the offices with the windows closed and for a) non-smoking and b) smoking conditions.



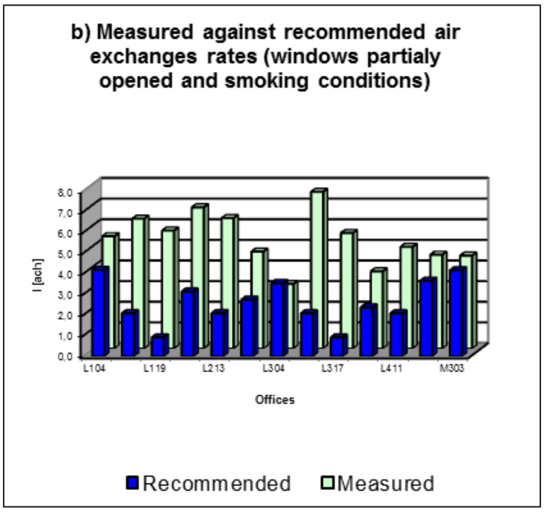


Fig.4 Comparison between the measured and recommended air exchange rate for the offices with the windows partially opened for a) non smoking and b) smoking conditions.

By the obtained results, the main conclusions to withdraw are:

- when the windows are closed, the air exchange rate of the offices is far below the recommended ones even for no smoking conditions;

- however, if the windows are partially opened (10%), the natural ventilation is enough even if there are smoking people inside.

Another conclusion can be withdraw from the global tests: in spite of being a relatively new building, their offices are not offering the occupants standard comfort and hygiene conditions. They are exclusively dependent on the air infiltration when the windows are closed, which is clearly demonstrated to be insufficient. As windows cannot be kept open due to the noise of the highway, this implies a most probable deficient indoor air quality that can lead to the sick building syndrome. This requires that measures must be taken regarding the ventilation either by increasing the air infiltration or installing mechanical ventilation.

CASE STUDY 4 – MEASUREMENT OF AIR MOVEMENTS IN MULTIZONE SPACES

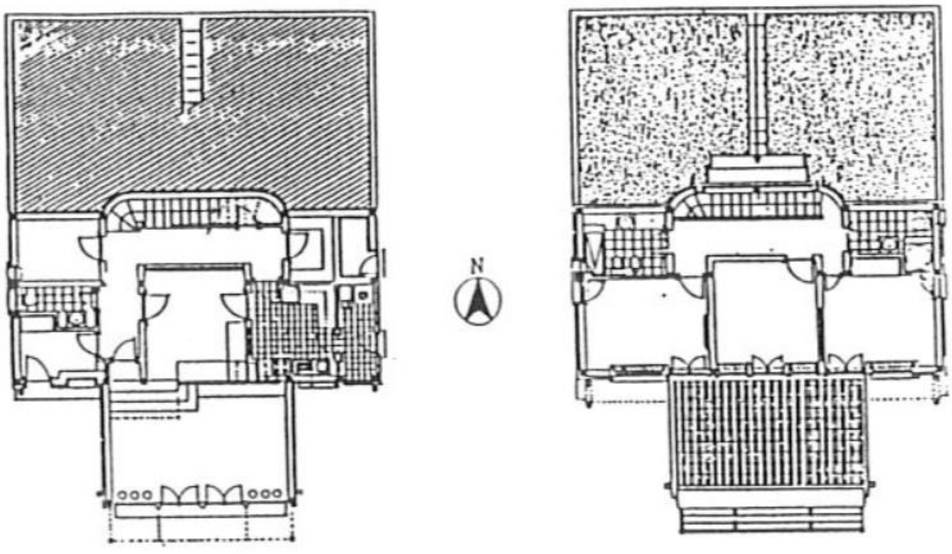
So far, only spaces that behave as a single zone, i.e., where there were no internal air movements and with a uniform concentration inside all the space were considered.

However there are spaces, for example buildings, where that does not happens, for example two or multi-storey buildings, where there are different zones, for example, ground floor and first floor at different temperatures which cause convective air currents that combine with outdoor air infiltration for complex circulation patterns.

Direct measurement of these air patterns is almost impossible because of the very low prevalent air velocities (Hitchin and Wilson 1967). Indirect forms of measurement are thus required, and again the tracer-gas technique is the most feasible one. It can also be implemented with the decay method.

In order to study these air patterns, tests were carried out in a two-story passive solar house, the CTO, (Project Monitor, 1987), shown in Figs 5 and 6 and was considered behaving as a two zone building, ground and first floor. The building, a three-bedroom single-family house with 150 m2, is wholly oriented to the south.

Fig.5 The CTO.



a) Ground floor b) 1st floor

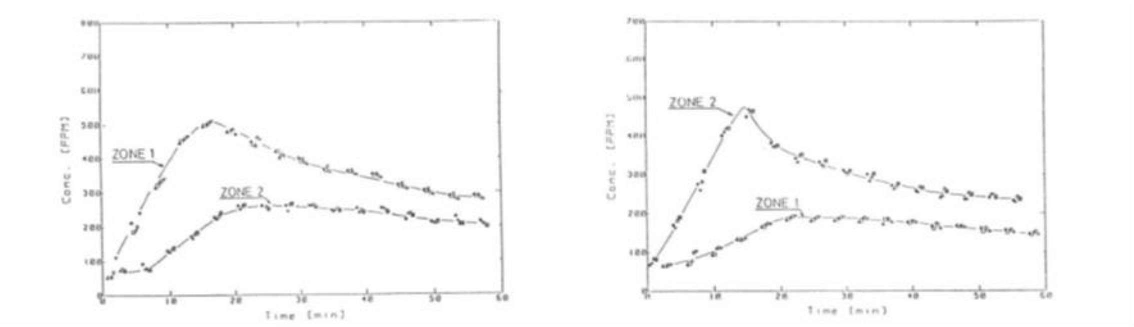
Fig. 6 C.T.O. Plans.

The CTO has a fireplace in the centre of the living-room in the lower-floor. Although great care was put during construction to ensure the tightness of the chimney and the duct that brings outdoor air for combustion when the fireplace is in operation, the results described in a 1ater section show that the influence of the fireplace upon air infiltration and indoor air movements is quite important. The attic above the bedrooms was completely sealed from the rest of the building to minimize its influence upon air infiltration and indoor air movements. As such, the house could be considered as a two-zone space, as long as all the internal doors were kept open all the time, each zone corresponding to each of the two floors.

Tests other than those reported in this paper, (Afonso, 1989), have shown that, when a door is closed, the respective room behaves as a separate zone with 1itt1e interaction with the rest of the house.

The tests were performed with CH4 as the tracer-gas. For each test, a pulse of CH4 was released in one of the zones and the ensuing varying concentrations were measured in both zones. The procedure was repeated with the CH4 pulse released in the other zone. Fig. 7 shows the concentration of tracer gas in both zones, in the two experiments of one of the tests carried out.

A total of 15 individual tests were performed. The sample length was 40 mm (±0.5 mm) with slightly varying width according with their technical specifications (≈10 mm). The mechanical tests were performed at slow displacement rate (5 mm/s) and at room temperature (≈25º C). The mechanical testing was carried out on a testing setup purposely built for low load soft tissue testing (Martins, 2006). According with a previous study (Dietz, 2003), temperature doesn't influence the results significantly. From the tensile test two stiffness parameters were extracted E_I and E_{II}. E_I used load-displacement data in the range of 0-500 g, the estimated physiologic load range (Dietz, 2003). For the calculation of E_{II} the load range was 500-2000 g.



a) Pulse release in zone 1 b) Pulse release in zone 2

Fig. 7 Tracer gas concentration profiles.

To enhance uniformity of indoor air properties, small fans were placed in each zone to improve mixing within then. Furthermore, the outlets of the tracer-gas injection lines were placed downstream of the fans in order to spread the gas more evenly.

Indoor air movements inside the CTO range of course with the prevailing outdoor weather, i .e, wind speed, wind direction and air temperature which strongly affect air infiltration. A thorough analysis of air infiltration in the CTO (Afonso, 1988), carried has shown that the air infiltration could be correlated with wind speed, wind direction and stack effect according to the equation

$$I = 0.512 + 6.184E\text{-}3\ \Delta T + 0.014V^2_{south} + 0.008E\text{-}3V^2$$

where:

ΔT - temperature difference

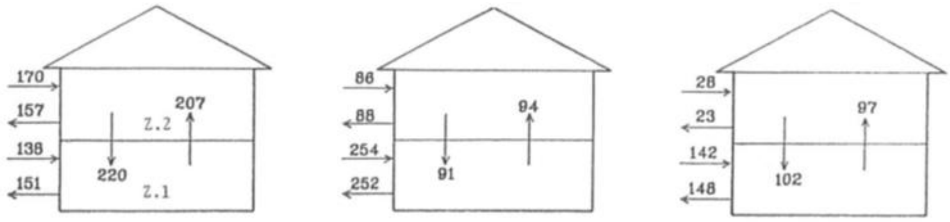
V_{south} - wind component acting on the south façade

V - wind component acting on the other façades

The average air infiltration for the mean seasonal climatic conditions is 0.75 RPH.

These tests showed that the south wind plays a fundamental role in the air infiltration as can be seen in the above equation, the regression coefficient for the south wind component has a significantly higher value when compared with the remainder weather coefficients, namely other wind directions and stack effect. Physically, this is related to the large glazed area of the south façade, and small wind variations in that direction have significant effects upon the subsequent air infiltration.

In order to verify the influence of outdoor weather conditions upon the indoor air movements in the CTO several tests were carried out following the methodology described. Fig.8 shows the airflows inside the CTO under widely varying outdoor weather conditions, with winds blowing from several directions.



Test #	Climatic Conditions				
	Wind		Temperature[°C]		
	Dir [°]*	Int [Km/h]	Ext	Z.1	Z.2
1	188	26,6	15,6	20,7	21,6
2	316	28,5	13,8	22,0	22,4
3	254	12,8	14,4	20,4	21,4

*Azimute Angle: 0°=North; 90°=East; 180°=South; 270°=West

Test #	Infiltration [RPH]	
	Global	Multizone
1	1,0	0,98
2	1,0	1,0
3	0,62	0,54

Fig. 8 Measured airflow rates in the CTO (opened fireplace).

The main conclusions obtained from these results are the following:

- Each floor of this two-story residence exchanges air both with outdoors and with the other floor, through the staircase. There is a downward flow of cooled air along the north wa11 of the building and an upward flow of warmer air through the main shaft of the staircase.

- There is a net downward flow under most circumstances, which is related with the induced stack effect of the fireplace chimney.

As can be seen, the changes in indoor air movement with outdoor weather are more pronounced in magnitude, as the overall directions of the airflows remain relatively constant.

In order to verify the influence of the fireplace upon air infiltration in the CTO, the fireplace was completely sealed from the rest of the house, which therefore behaved as if the fireplace did not exist. Tracer-gas tests were then performed following the same methodology used in the tests just described.

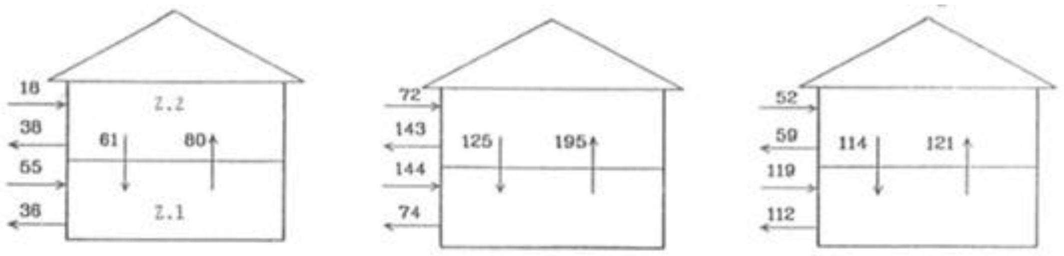
In this new situation, the air infiltration is related with wind speed, wind direction and stack effect according the following equation:

$$I = 0.294 + 0.014\Delta T + 0.019V^2_{south} + 0.008E\text{-}3V^2$$

The average air infiltration for the mean seasonal climatic conditions is I = 0.47 RPH.

Once again, the south wind plays a fundamental role upon air infiltration, but there is a clear decrease of the magnitude of air infiltration - almost 50% -when compared with the usual running mode, i.e., with the fireplace not sealed.

Several two zone tracer-gas tests were also carried out when the fireplace was sealed, as shown in Fig.9.



Test #	Climatic conditions: Wind Dir [°]*	Wind Int [Km/h]	Temperature [°C] Ext	Z.1	Z.2
4	108	9,6	13,8	21,0	21,9
5	90	29,2	9,3	18,9	21,4
6	256	18,2	14,7	21,7	22,2

*Azimute Angle: 0°=North; 90°=East; 180°=South; 270°=West

Test #	Infiltration [RPH] Global	Multizone
4	0,22	0,23
5	0,72	0,70
6	0,54	0,56

Fig.9 Measured airflow rates in the CTO (fireplace sealed).

The main conclusions obtained from these tests are the following:

- the net airflow rate between the two stories of the CTO is now from the ground floor towards the first floor, i.e., it is the opposite of the direction identified in the previous case. This is related to the absence of the stack effect induced by the fireplace chimney. This can be seen schematically in Fig.10.

- the net airflow rate between the two stories of the CTO is now from the ground floor towards the first floor, i.e., it is the opposite of the direction identified in the previous case. This is related to the absence of the stack effect induced by the fireplace chimney. This can be seen schematically in Fig.23.

- there is a decrease in the g1oba1 air infiltration of the CTO when compared with the situation of open fireplace. This is in agreement with the single-zone whole-house obtained earlier (above equation).

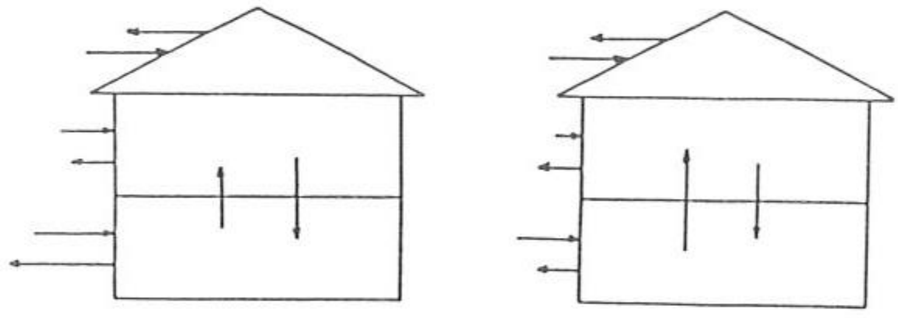


Fig.10 General scheme of the airflows in the CTO with open and closed fireplace.

CASE STUDY 5 - MEASUREMENT OF MECHANICAL VENTILATION

One of the most feasible ways to measure duct airflows is by tracer gas techniques, especially for complex situations when the duct lengths are short as well as their access, which makes extremely difficult or impossible other methods to be implemented. One problem associated with the implementation of tracer gas technique when the ducts lengths are short is due to the impossibility of achieving complete mixing of the tracer with airflow and its sampling, Fig. 11.

Important research work have been done by (Riffat, 1990, 1993) with the aim of application of tracer gas measurement in ducts, using 8mm tubular injection probe with a row of 3mm holes. Results were presented until a minimum distance between the tracer injection and sampling of $X/D_h = 7$. In countries like Sweden the method of duct airflow calculation by tracer gases is wide spread (Dantec, 2001) and has been implemented with simple multi tube tracer injection, for distances between de injection and sampling point great than $X/D_h = 10$.

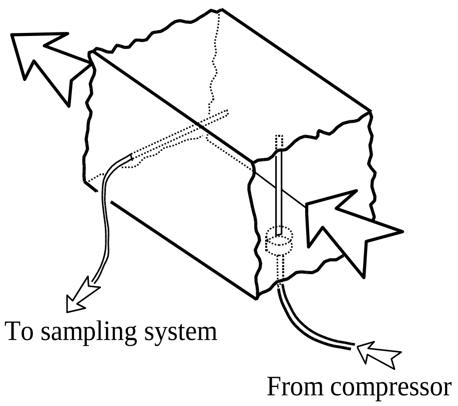


Fig. 11 Relative position of the probes in ducts.

So to say in almost all work carried out in duct airflow measurements by tracer gas technique the plans of injection and sampling are located far way (ISO Standards, 1977; Grieve, 1989). However in situations of real application, the distances between those plans can be very close. Therefore it is of great importance the development of new techniques studying the dispersion of tracer gas for short distances, even though values of $X/D_h = 1$. For that it was developed new injection and sampling probes (Silva, 2002) in order to solve the major difficulty for a tracer gas injection devices for duct airflow measurements: the capacity of gas dispersion in extremely short distances.

The present solution consists of a 300mm nominal length probe, Fig. 12, with an array of 200-micron diameter micro sonic jets feed by four distribution chambers. The probe diameter is 12.5mm. Four miniaturized hydraulic equilibrated circuits, with only one common inlet, feed these chambers. This number four comes from analyses of the geometry of all the circuit. This configuration minimizes velocities gradients, and consequently minimizes pressures gradients. The array of sonic jets (15 in each chamber) is then feed by near equal pressures. The injection orifices are all equal in diameter, made by high precision technique, and operating in sonic regime. So, the tracer gas flow obtained with this arrangement is almost equal for all the jets of the array and the tracer gas injection along the body of the probe is well balanced.

Fig. 12 Tracer gas injection device prototype.

The sampling device works exactly the same principle but in vacuum. The array of sampling points along the device collects the sample, carrying out in this way a very effective integration of the tracer gas concentration. Additionally the injection probe has the possibility of scanning angular movement. In this system the adjustment of the scanning angle has a maximum regulation of 45º for each one of the sides (left/right). In this probe it was adopted a system with a regulated alternative movement. The cope for this feature is an improvement in the tracer gas dispersion for low duct air velocities.

The test facility used to test the probes consists basically in a specially calibrated wind tunnel allowing different air flow rates of interest. The injection probe is in a counter flow to the airflow. Some results are shown in Fig. 13 that represents the comparison between the measured airflows using the new tracer gas device and the reference ones measured with a Pitot tube. As can be seen the results are promising mainly due to the very short distance between the tracer injection and sampling.

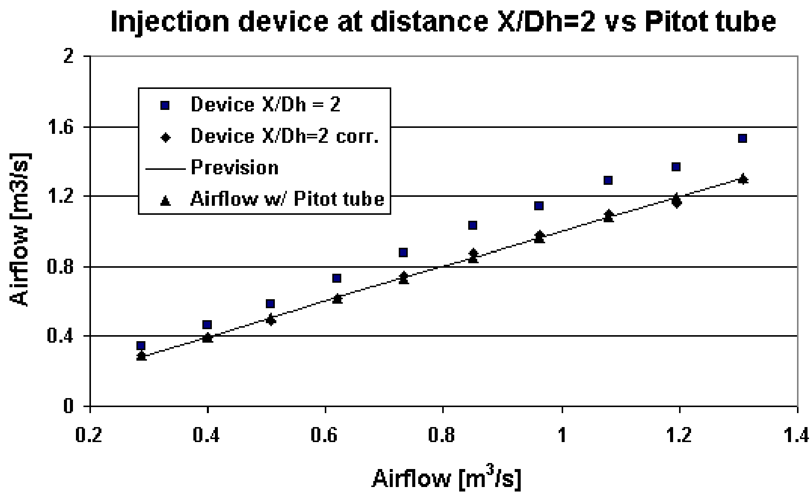


Fig. 13 Device at distance X/Dh=2.

It is clear from figure 26 that for the very short distances, for example of X/Dh = 2, a bypass effect is present. To overcome this effect, due to an incomplete tracer gas dilution, a simplified method of correction was proposed for these distances. Correction relations were established, using as a basis the reference Pitot tube measurements. The expression proposed for calculating the corrected values after the measured air flow rate values, has the following generic form:

For distances X/Dh greater than 2 there is no need of correlations, (Silva, 2004).

CONCLUSIONS

In this work a method to measure the airflow rates of several spaces were presented, the tracer gas method. The way it should be implemented in different dwellings as well as the necessary equations to calculate the airflows trough the space was shown. Conclusions to be withdrawn from the tests were also exemplified for different kind of buildings and offices either with only air infiltration either with natural ventilation.

Tests were also carry out with the same technology in a two store building where all the airflows patterns between were precisely calculated.

The development of a new device for the injection of tracer gas in mechanical ventilation ducts was also discussed with the objective of practical application in the field of HVAC airflow measurements, a device for practical field deployable measurement of airflow rates for short distances. Work had already been done with this device with good results regarding the mixing of the tracer gas with the main air stream.

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