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THE QUANTIFICATION OF AIR MOVEMENT PATTERNS IN A FOUR ZONE PASSIVE SOLAR HOUSE

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SUMMARY

The energy consumption and the indoor air quality in buildings can only be properly characterized if all the airflow rates are well known, both between the rooms and outdoors as well as among the different rooms themselves. In passive buildings those airflows are difficult to quantify due to the mutual dependence between the temperature differences and the air movement inside. So several procedures have been developed for the measurement of all those airflows, the most common being the tracer-gas technique. This paper describes how such technique was used for the measurement of all the pertinent airflow rates in a passive solar residence in Porto. Tests were carried out for different combination of the internal spaces, where three and four zones have been considered.

INTRODUCTION

The role of air movement patterns inside buildings upon their thermal behaviour and pollutant concentrations is a fundamental one. As a matter of fact, if an accurate thermal analysis of buildings is desired besides knowing its global air infiltration rate, it is necessary to know the rate at which air is exchanged amoung the various rooms, (1). Also, the indoor air quality to be achieved even in single zones depends on the air exchanges between them and outdoors, (2).

However, the measurement of all those airflow rates is not an easy task. They are dependent on pressure diferencials - created by the wind, stack effect and internal partions - established among the different zones of a building as well as across the building envelope, (3). Several numerical methods have been developed for the calculation of the air movement in buildings as function of the pressure diferentials, from the simplest ones - single cell models, (4) - to more complex ones - multi cell models, (5). Those models, powerfull for simulation, require on the other hand a very good knowledge of the building itself, with emphasis on envelope leakage characteristics, a reasonable computer effort and are not suitable for running them quickly for different buildings.

To overcome these difficulties, alternative methods have been developed, the most common one being the tracer-gas method, (6). This method can be implemented in different ways, with the most common being decay, (7), and steady-state concentration, (8), techniques. While this latter technique requires a more sophisticated control apparatus, the former has no such requirements but, on the other hand, the air volumes in each zone must be known, as show in the next section. These volumes, however, cannot be easily calculated due to the usual presence of furniture inside the rooms. A methodology that takes this problem in account has already been proposed. Utilizing just one tracer-gas, this methodology was validated under controlled laboratory conditions for a two-zone space, (9), as well as in a real building under natural climatic conditions, (10). In both situations, the airflow rates and zonal air volumes were evaluated with a good accuracy.

This work, based on the above methodology, characterizes the indoor air movement in a passive solar house in Porto, for different combination of internal spaces and under several operating modes (e.g. opened or closed room doors).

MATHEMATICAL MODEL

As previously discussed, the most common ways to implement tracer gas method in a n-zone building are the steady-state concentration and decay techniques. This latter technique, in turn, can be implemented with different procedures, according to equation (1):

$$n = x \cdot y \qquad (1)$$

Two limiting cases and one intermediate situation can be observed in equation (1):

Limiting cases:

- Use of one tracer (n=1) in n tests (y=n), (7).
- Use of n tracers (x=n) in one test (y=1), (11).

Intermediate case:

- Use of various tracers in a serie of different tests such that equation (1) is verified, (12).

No matter which procedure is to be utilized, it is necessary to build up a system of equations in order to obtain all the unknowns. These unknowns are the n(n+1) airflow rates, (13), and the n zonal airvolumes, for a total of n(n+2), (9).

The necessary equations can be derived from the generalized tracer-gas balance equation:

$$\sum_{\substack{j=1\\k=1}}^{n}\left\{V_j\left[c_j(x_2)-c_j(x_1)\right]-\sum_{i=1}^{n}\dot{V}_{ij}\int_{x_1}^{x_2}(c_i-c_j)\,d\tau+\dot{V}_{0j}\int_{x_1}^{x_2}c_j\,d\tau-\delta_{kj}\int_{\tau_0}^{\tau_1}\dot{q}_j\,d\tau\right\}=0 \qquad (2)$$

where:

$$\begin{cases} x_1=\delta_{kj}\tau_0+(1-\delta_{kj})\,\tau_1\\ x_2=\delta_{kj}\tau_1+(1-\delta_{kj})\tau_2\end{cases}$$

If one tracer is to be utilized, n equations (2) can be written, one per zone, for the tracer-gas injection period, plus n^2 equations for the decay period, one for each zone during each of n tracer-gas injections required by this methodology (equation 2, with m_j=2).

n additional air balance equations complete the required n(n+2) equation (one per zone):

$$\sum_{i=0}^{n}\dot{V}_{ji}=\sum_{i=0}^{n}\dot{V}_{ij} \qquad (3)$$

This methodology was used in the present work.

TEST FACILITY

The tests were carried out in a two-story passive solar house the C.T.O., (14), shown in Figs.1 and 2. The building, a three-bedroom single-family house, with 150 m^2, is wholly oriented to the south. There are only small windows on the north, east and west sides, to allow cross ventilation in summer. The main rooms face south and the service areas are on the north side, provinding a buffer zone around the main rooms.

The C.T.O. has an all-electric auxiliary heating system that can thermostatically control individual rooms to the desired temperature level, but it also has a fireplace in the center 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 in outdoor air for combustion when the fireplace is in operation, tests other than those reported in this paper, (15), have shown that the

Fig.1 - The C.T.O.

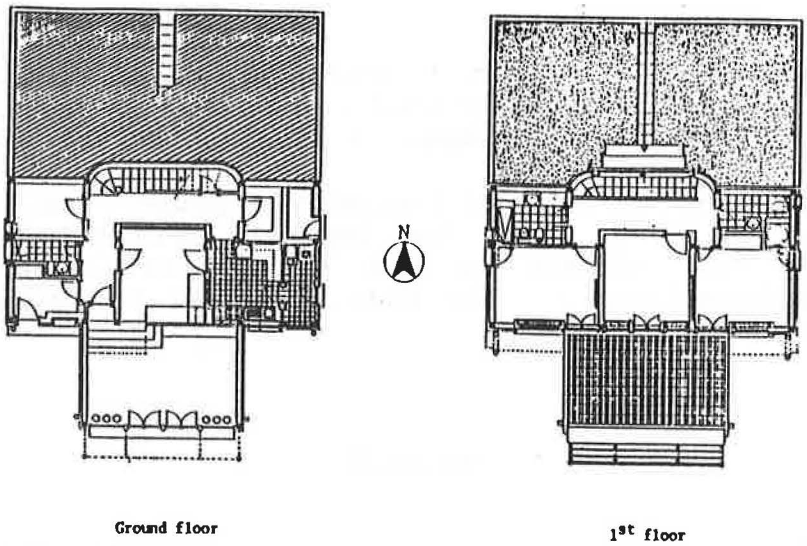


Fig.2 - C.T.O. Plans

influence of the fireplace upon air infiltration and indoor air movements is quite important. To avoid there effects, the fireplace was sealed. The attic, above the bedrooms, was also completely sealed from the rest of the building in order to minimize its already minor influence on the overall air patterns inside the CTO, (16). As such, in a first approach, 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 floors.

In order to verify if in fact a given floor of the CTO could be considered as a single zone a three zone situation was admitted: ground floor, one at the rooms of the upper floor and the remainder of the upper-floor. Tests were carried out so that the room considered as an individual zone was sucessively each one of the three in that floor, both with its door closed and open, while the doors to the other two rooms were keept open. Finally, a four zone test was performed to attempt to quantify the air exchanges between the rooms in the first floor.

TEST METHODOLOGY

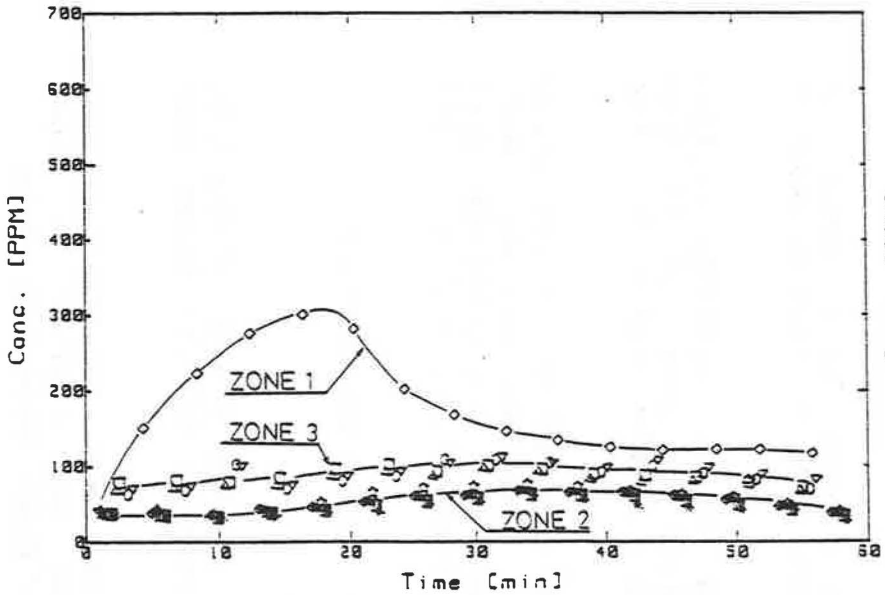
The tests were performed with CH_4 as a tracer gas. For each test, a fourteen minute low flow rate injection of CH_4 was released in one of the zones and the ensuying varying concentrations were measured in the remainder zones for a total of one hour. The procedure was repeated with the CH_4 sucessively injected in each of the other zones. Fig.3 shows the concentration of tracer gas in all the zones, in the three experiments of one of the three-zone tests that were carried out.

The concentrations were measured by a single calibrated infrared detector, which received air from all sampling points through a multiplexer programmed in an appropriate sequence.

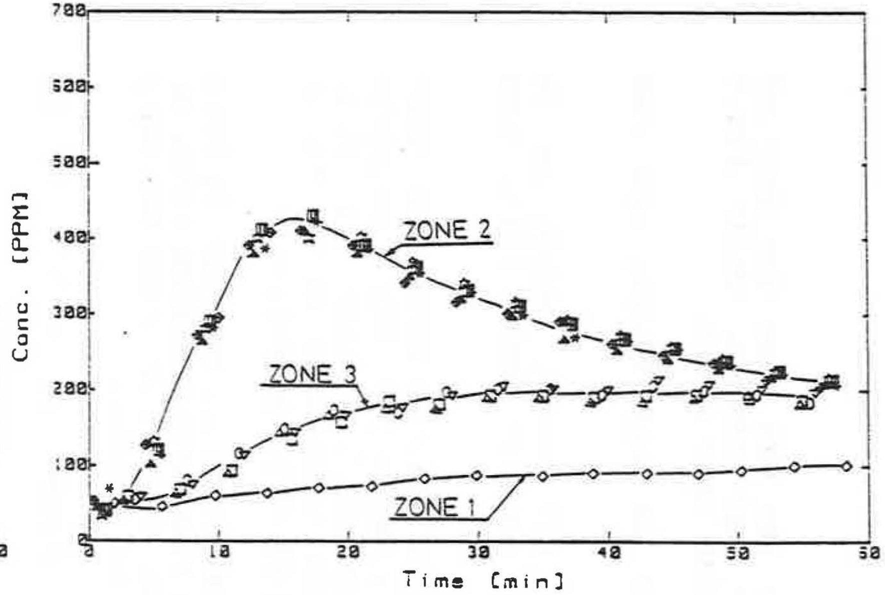
To enhance uniformity of indoor air properties, small fans were placed in each zone to improve mixing within them. Furthermore, the outlets of the tracer-gas injection lines were placed downstream of the fans in order to spread the gas more evenly.

RESULTS

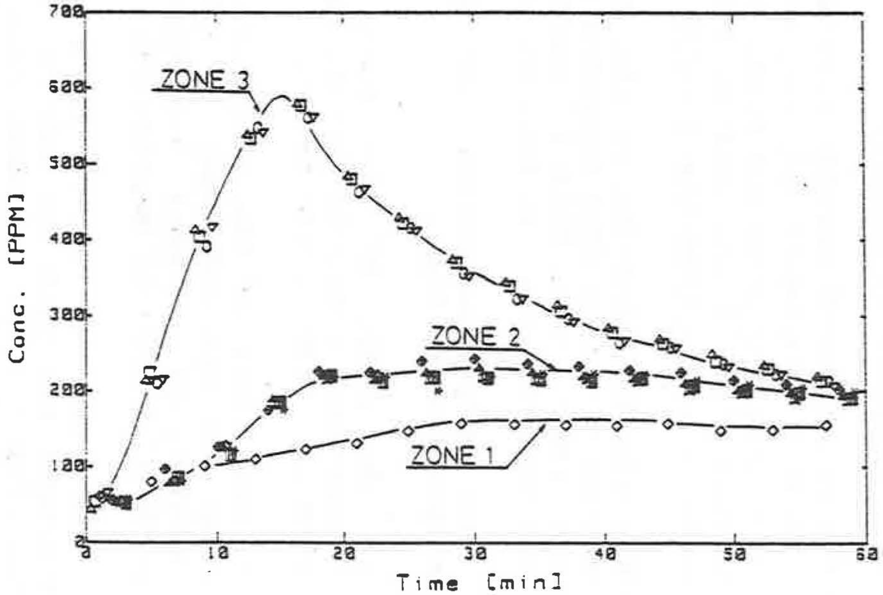
The tracer gas methodology described in the previous sections was first carried out for different combination of three zones inside the CTO: ground floor, one of the rooms of the first floor and the remainder part of this floor. The tests were carried out so that the room considered as zone was sucessively each one of the first floor. In the first group of tests the door of the room considered as zone was closed, while in the second group of tests that door was kept open. It was possible, then, to verify the effect of the opening or closing of doors in the indoor air movement of the CTO and, as a consequence, to check if each floor could be considered as a single one.



a) Pulse release in zone 1



b) Pulse release in Zone 2



c) Pulse release in zone 3

Fig.3 - Tracer-gas concentration profiles

Fig.4 shows the airflows inside the CTO when the door of the room considered as a zone was kept closed, while Fig.5 shows the established air patterns with open doors.

Regarding the results obtained in all tests, one can concluded that:

- There is a net upward flow in all tests, which is in agreement with results obtained in earlier work, (15), when the fireplace is sealed.

- The established average airflow rates between each room, when its door is closed, and the other zones - 2.5 m^3/h - is small when compared with the other average airflow rates - 81 m^3/h. Conversely, if the door of the room considered as a zone is open, these values are 23 m^3/h and 89 m^3/h respectively.

- The air infiltration of the central room is smaller in both groups of tests when compared with the corresponding value of the other rooms. This is reasonable since that room has only one exterior wall as well as only one window.

As main conclusions of both groups of tests, it is possible to say that:

- If the doors of the rooms are closed, they behave as independent zones of the house, with weak airflow conections with the rest of the house.

- If the doors of the rooms are open the air exchange between them and the remainder of the floor is large. It is thus possible to consider each story as a single zone without too much of a loss of generality.

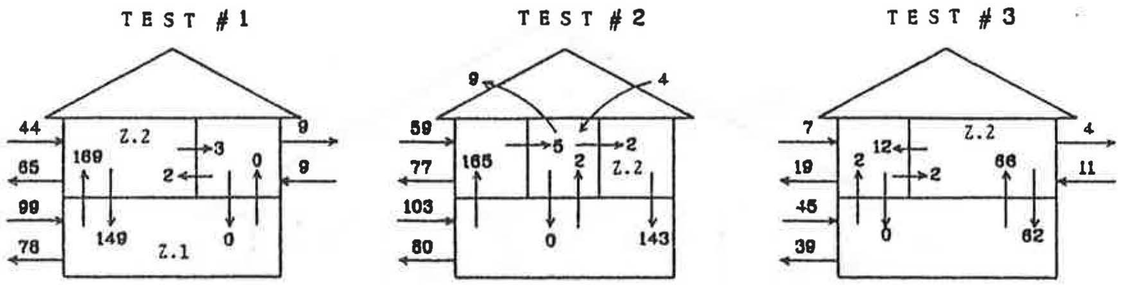
In order to verify if a given room of the first floor exchanges air with the others, a four zone test was performed: East room - Zone 1 -, West room - Zone 2 -, the remainder part of the first floor - Zone 3 - and ground floor - Zone 4. All internal doors were kept open.

The overall results of this test are shown in Fig.6.

It is possible to conclude that:

- There is a net upward flow between the two storys of the CTO, which is in agreement with the results of the three zone tests.

- The air exchanges between each of the rooms and the remainder zones (excluding the other room) are similar to those obtained earlier, when the internal doors were kept open.



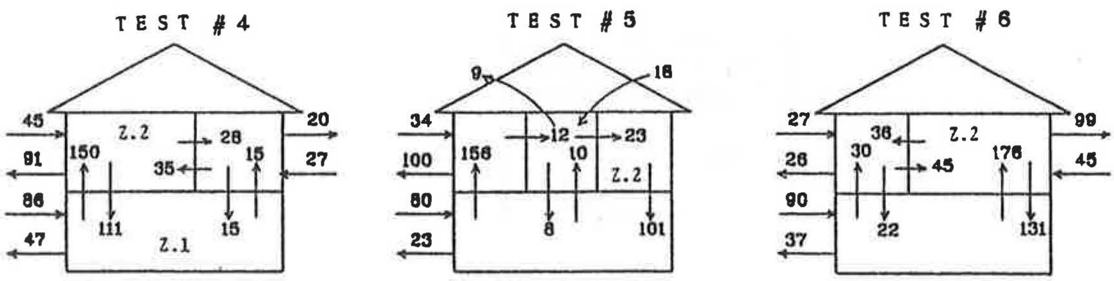
Test #	Climatic Conditions					
	Wind		Temperature [°C]			
	Dir [°]*	Int [Km/h]	Ext	Z.1	Z.2	Room
1	336	26,6	11,3	19,7	22,9	22,0
2	338	26,6	11,3	19,5	21,4	24,1
3	107	10,3	9,6	17,7	21,4	21,9

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

Zones	Volumes [m³]					
	Measured			Calculated in test #		
				1	2	3
1	181			176	174	173
Room	32	30	32	30	26	31
2	112	114	112	101	100	105

Test #	Infiltration [RPH]		
	Global	Multizone	Room
1	0,43	0,50	0,30
2	0,58	0,65	0,15
3	0,21	0,20	0,22

Fig.4 - Measured airflow rates in the C.T.O. (door of the room considred as zone closed).



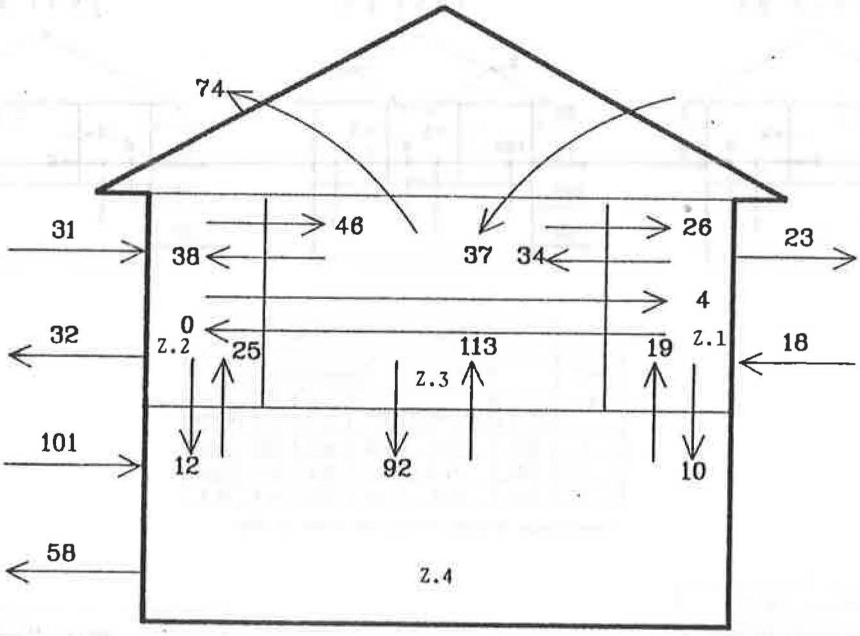
Test #	Climatic Conditions					
	Wind		Temperature [°C]			
	Dir [°]*	Int [Km/h]	Ext	Z.1	Z.2	Room
4	322	15,0	11,3	21,8	22,9	21,7
5	203	11,0	11,3	19,6	21,7	23,7
6	205	17,2	11,5	20,2	22,2	20,9

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

Zones	Volumes [m³]					
	Measured			Calculated in test #		
				4	5	6
1	181			176	176	174
Room	32	30	32	30	26	31
2	112	114	112	105	103	106

Test #	Infiltration [RPH]	
	Global	Multizone
4	0,52	0,51
5	0,41	0,43
6	0,50	0,52

Fig.5 - Measured airflow rates in the C.T.O. (door of the room considered as zone open).



	Climatic conditions						
	Wind		Temperature [°C]				
	Dir [°]*	Int [Km/h]	Ext	Z.1	Z.2	Z.3	Z.4
Before test	253	26,1	13,0	20,5	20,6	20,3	19,2
After test	231	18,0	12,7	20,1	20,4	20,2	19,0

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

	Infiltration [RPH]	
Zones	Global	Multizone
1	0,63	1,0
2		0,58
3		0,49
4		0,58

Fig.6 -Measured airflow rates in the C.T.O. in the four zone test.

- The air exchanges between the two rooms considered as zones are small when compared with the other ones. In fact, for this test, the airflow rate from the West room to the East room is 4 m^3/h, the opposite being 0 m^3/h.

So, we can say that there is no air exchange between the rooms of the first floor, i.e., each of the rooms only exchanges air with the corridor of the first floor and with the ground floor.

Therefore, the three tests in which the house was treated as having three zones were enough to quantify the air patterns in a five zone situation: the three rooms in the first floor, the remainder part of this story and the ground floor.

CONCLUSIONS

The tracer gas methodology used in this work has proven to be reliable for the measurement of indoor air movements in buildings under real conditions.

The test performed in the CTO showed that:

- When the internal doors are open, each floor of the CTO behaves approximately as an individual zone.

- If the doors are closed, the rooms with closed doors behave as additional zones with little interaction with the rest of the building.

- In the first floor, each room only exchanges air with the corridor and with the ground floor. There are no air exchanges between the rooms.

- An appropriate choice of the zones enables the characterization of a number of zones greather that the number of test theoreticaly necessary. In the CTO, three tests were enough to measured the airflow rate in a five zone situation.

These conclusions can be expected to be true in other similar buildings, if not quantitatively, at least qualitatively. Practical tracer-gas tests of multizone buildings can thus take this into consideration to simplify the measuring procedure required for each case.

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