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A TRACER-GAS PROCEDURE FOR THE SIMULTANEOUS EVALUATION OF EFFECTIVE VOLUMES AND MULTIZONE AIRFLOWS

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1. Introduction

In order to properly quantify energy balances in buildings, it is necessary to know both the heat transferred by conduction and radiation and the convective heat transfer between the different zones which exist within the building. While the first two mechanisms of heat transport are well described by theory, even if difficult to quantify in real situations due the time-dependency of the boundary conditions in presence, the third mechanism, which is associated to the convective air currents, is more difficult to deal with because the variables required for the evaluation of temperatures and airflows cannot be characterized with enough detail.

One way to overcome this difficulty is to utilize tracer-gas techniques, which have been proven to be a reliable way to calculate all the internal airflows in a house, /1,2,3/. This technique can be implemented in different ways, but the most common are the steady-state concentration and the decay methods. In each of them, the tests can be carried out with different experimental procedures.

No matter which multizone tracer-gas method is used to extract the airflows from the tracer-gas experiments, the starting point for the subsequent calculations is a tracer-gas balance for each zone:

$$V_j \frac{dc_j}{d\tau} = \sum_{i=1}^{n} A_{ij} C_i - \left(\sum_{i=1}^{n} A_{ji} \right) C_j + \dot{m} \qquad 1 \leqslant j < n \qquad (1)$$

Where:

A_{ij} - flowrate from zone i to zone j

A_{ji} - flowrate from zone j to zone i

C_i - concentration in zone i

$\dot{m}$ - flowrate of tracer-gas release in zone j

n - number of zones of a building

V_j - effective volume of zone j

τ - time

If the tests are to be made by the steady-state concentration method, the left hand side of equation 1 is zero and it is not necessary to know the effective volumes of each of the zones. However, this method requires more elaborate control equipment in order to maintain the tracer-gas concentration constant in all zones for the duration of the measuring period.

In the decay method, the required equipment is simpler than in the steady-state method, but, conversely, the effective volumes of all zones must be known. In real buildings, however, there are furnishings which make it difficult if not impossible to measure the effective volumes of each zone. Then, it is usual procedure to make a rough estimate of the net volumes and use it for the calculations. This assumption, however, may be one of the most important sources of error in the estimation of the internal airflows. Indeed, it is possible to show that small variations in zonal air volumes can lead to important changes in the calculated airflows.

This paper describes a tracer-gas method which allows for the simultaneous evaluation of the effective volumes and all the pertinent airflows established between the different zones of a building. The method was implemented with a single tracer-gas /2/, demonstrating that it is not necessary to have sophisticated control equipment to measure indoor airflows with the tracer-gas technique.

Results are presented both for a single zone and for a two zone situation. The tests were carried out under controlled conditions in a laboratory.

2. Mathematical Procedure

In multizone spaces (n zones), there are (n + 1).n airflows to be evaluated, /4/. If the effective volumes are not known, and this is the case in almost all real situations, there are n additional unknowns for a total of (n + 2).n. Thus, it is necessary to establish as many equations to be able to extract all the volumes from the experiments.

As stated in the introduction, there are different experimental procedures to implement the tracer-gas decay method, namely:

1 - n different tracer-gases are introduced simultaneously, one in each zone of the building. The ensuing concentration evolutions of all tracers are then recorded in each room. With this procedure only one experiment is necessary, /5/.

2 - One tracer-gas is introduced into one zone and the concentration evolution is measured in all zones. The procedure is repeated introducing the tracer into each of the other n-1 zones in the building, one at a time. This procedure requires n experiments, /2/.

3 - y (y<n) tracer gases are released into an equal number of zones of a building, measuring the concentrations in all n zones. Once this test is completed, the same gases are introduced into a different group of zones, and the test is repeated, for a total of x tests, such that y.x=n, /6/.

It is possible to writte n x n tracer-gas mass conservation equations, equation 1, with any of these procedures. Because there is no mass injected during the decay, $\dot{m} = 0$ and, after rearranging the terms and integrating the equation, it is possible to obtain:

$$V_j\left[C_j(\tau_2)-C_j(\tau_1)\right]=\sum_{i=1}^{n} A_{ij}\int_{\tau_1}^{\tau_2}(C_i-C_j)\,d\tau-A_{oj}\int_{\tau_1}^{\tau_2}C_j\,d\tau \qquad (2)$$

Where: A_{oj} - flowrate of external air entering zone j.

n additional mass air balance equations complete the required number n (n + 1):

$$\sum_{i=0}^{n} A_{ij}=\sum_{i=0}^{n} A_{ji} \qquad 1 \leqslant j \leqslant n \qquad (3)$$

However, with the outlined procedure, the airflows can be calculated only by assuming that the zonal volumes V_j are known. If they are not known, then, in addition to the specified equations, an additional n are necessary if the V_j are also to be calculated. To obtain them, a tracer-gas balance must be established per zone during the injection of tracer-gas.

These equations also derive from equation 1, but now $\dot{m}$ is not zero:

$$V_j\left[C_j(\tau_1)-C_j(\tau_o)\right]=\sum_{i=1}^{n} A_{ij}\int_{\tau_o}^{\tau_1}(C_i-C_j)\,d\tau-A_{oj}\int_{\tau_o}^{\tau_1}C_j\,d\tau+\int_{\tau_o}^{\tau_1}\dot{m}\,d\tau \qquad 1\leqslant j\leqslant n \qquad (4)$$

Although Janssen et al, /7/, described a procedure to evaluate the effective volumes of buildings when they had a single zone, i.e., when the buildings could be considered as uniformly mixed, no other known methodology allows for the simultaneous calculation of volumes and airflows in a multizone building. The objective of this paper is to demonstrate the validity of the procedure which establishes a general methodology for this purpose.

3. Experimental Validation

3.1. Laboratory set-up.

The tests were conducted in a two room space, shown in Fig.1. Each room had a desk, a chair, two computer terminals and some electrical equipment. A central air-handling system supplied air to both compartments. Exhaust air from the compartments was drawn by a second fan. Total supply flowrates were measured by nozzles placed in the ducts.

The tests were performed with CO_2 as a tracer and were carried out in two ways:

- In the first, the objective was to calculate the supply air flowrate and the effective volume of room 1. The supply and exhaust air ducts to room 2 were shut off, the door between rooms was closed and the door connecting room 2 to the laboratory was kept completely open.
- In the second kind of tests, each of the rooms simulated one zone. The door connecting the rooms could be closed or opened in different positions and the door connecting room 2 to the laboratory was permanently closed.

The compartments had been designed not to reach an uniformly mixed state due to the lower than optimum ventilation efficiency of the forced air distribution system installed, /8/. Thus, uniform mixing had to be enhanced throughout the tests with small fans placed in each compartment. In all tests, the tracer was released in the supply air duct to each room, just before the diffusers.

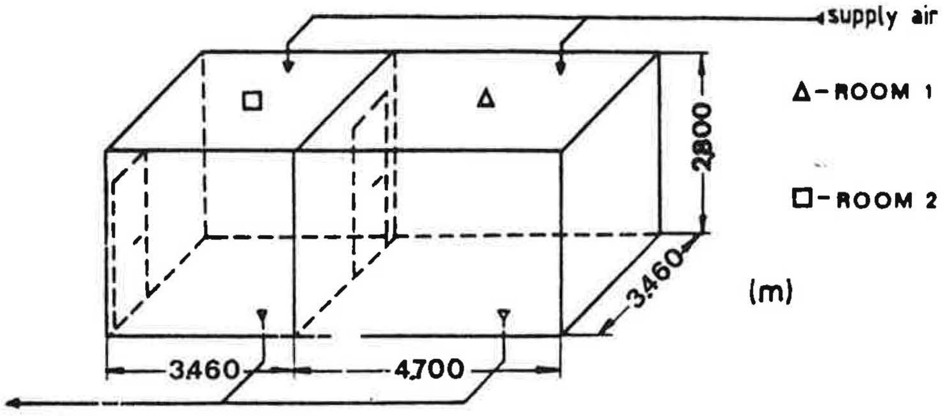

Fig. 1 - Schematic of the two-room space.

There were two sampling points within each compartment, 0.7 and 1.8 m above the centre of the floor. The concentrations of the supply and exhaust air for each compartment were also sampled. The concentrations were measured by a single calibrated infrared detector, which received air from all sampling points through a multiplexer propramned in an appropriate sequence, /2/.

Comparison of the data from the three sampling points characteristic of the compartment, the two inside the space plus the exhaust duct, also showed that there was a good mixing within each compartment, as only minute differences were measured (3.5% relative to the average value). Thus, the hypothesis of uniformly mixed zones in a nonuniformly mixed space was considered to be fullfiled. The value of the concentration of tracer-gas representing each compartment during the supply and decay tests was calculated as the average of the three concentrations.

The tests rooms were located inside a large laboratory such that no significant variation in the laboratory's CO_2 concentration was measured due to the exhaust and exfiltration from the rooms. The background CO_2 concentration in the laboratory was constant within ± 1% for the duration of the tests.

The tests were performed utilizing just one tracer-gas (procedure 2). Equations (2) and (4) were integrated in each case over the whole measuring period using Simpson's rule and the systems of simultaneous equations were solved numerically by Gauss elimination.

3.2. Results

As stated earlier, the tracer-gas methodology described in the previous sections was carried out for two kinds of tests - single zone (one compartment only) and two zones (both compartments used).

3.2.1. Single zone

A typical test of the single-zone situation is shown in Fig. 2, including the step-up and decay of CO_2 in compartment 1. Fig. 2 also shows the calculated and the measured airflow rates, and the physical and calculated effective volumes for that room.

Four different tracer-gas injection rates were used for each of four different supply airflows, for a total of sixteen tests. The results, listed in Table 1, show that the model is able to predict with good accuracy the effective volume of the compartment, with a standard error of only 2%. The average volume also looks quite reasonable because there was some furniture inside the room, which should account for the 1.2 m^3 difference between the calculated effective volume and the measured physical volume of the room.

TABLE I - Overall results for the single-zone tests

MEASURED AIRFLOW RATE(m^3/h)	CALCULATED VALUES					
		TEST 1	TEST 2	TEST 3	TEST 4	AVERAGE
58	CO_2 (l/min)	2.9	3.9	4.9	5.9	
	$\dot{V}$ (m^3/h)	54	55	51	50	52.5± 2(3.9%)
	V (m^3)	43	46	44	44	44.3±1(2.4%)
100	CO_2	2.9	3.9	4.9	5.9	
	$\dot{V}$	88 1)	91	93	86	89.5± 2.7(3%)
	V	44	44	46	45	44.8± 0.8(1.9%)
150	CO_2	4.9	5.9	5.9	5.9	
	$\dot{V}$	153	118	117	124	128.2±14.5(11.3%)
	V	44	44	45	44	44.2±0.4(0.98%)
190	CO_2	4.9	6.9	6.9	6.9	
	$\dot{V}$	154 2)	167	154	155	157.5±5.5(3.5%)
	V	43	45	44	43	43.8±0.8(1.9%)
Volume (total average)(m^3)						44.2±0.9(2%)
Measured volume(m^3)●						45.4

● Without accounting for furniture

1) $\dot{V}$ calculated by eqn. 5 = 91 m^3/h

2) " " " " = 169 m^3/h

There are differences between the measured and calculated airflows rates. However, the differences between the calculated and the measured supply airflow rates are actually smaller than the numbers indicate due to air leakage from the supply duct, which was impossible to quantify and to complety eliminate with the available facilities. That fact was checked in two of the situations listed in Table 1. For these 2 tests, the airflow rate was calculated from the concentration produced in the supply duct by the tracer-gas released, according to the equation (5):

$$\dot{V} = \dot{m}/c \tag{5}$$

The airflows calculated from equation (5), shown as a footnote in Table 1, are closer to those calculated by the numerical procedure, confirming that in fact air leakage occurs in the duct length between the measuring nozzle and the diffusers in the rooms (≃ 12 m). In all the other cases, the concentration of tracer-gas in the supply air was higher then the maximum measurable by the detector, and, therfore, the method could not be used for verification. However, the indication from these two tests seem to be quite conclusive.

Table I also shows that there is no influence of the tracer-gas flowrate upon the calculated values, volumes and air flowrates.

3.2.2. Two-zones

In all the 2 room studies, the total airflow supplied to both compartments was constant. Four tests were run: one with the door between rooms closed; another with that door completely open; and the remaining two with the door partially open, in two different intermediate positions. The tracer-gas flowrate was also held constant.

A sample-run of this procedure is shown in detail in Fig. 3, where plots a) and b) show the pulse and decay of CO_2 in both compartments during the release of the tracer-gas in compartments 1 and 2, respectively. Plot c) shows the measured and calculated air flowrates and effective volumes.

Fig. 4 shows the results of all four tests. It can be seen that the calculated effective volumes of both compartments are quite reasonable and, in all cases, the calculated total supply airflow is almost constant. Moreover, the relative magnitudes of all flowrates are in agreement with the airflow resistences between the rooms: as the door between both compartments is more and more open, the airflows between the two rooms also increases.

4. Conclusions

A simple experimental method for simultaneously calculating the effective volumes of rooms and the airflow rates between them and with outdoors has been shown to be feasible whenever steady-state conditions exist.

The method was implemented with a single tracer-gas and its validity was experimentally verified under laboratory conditions and shown to yield satisfactory results.

Further research is now needed to attempt the method's verification in real buildings, under conditions which may not be as steady as in the laboratory.

5. References

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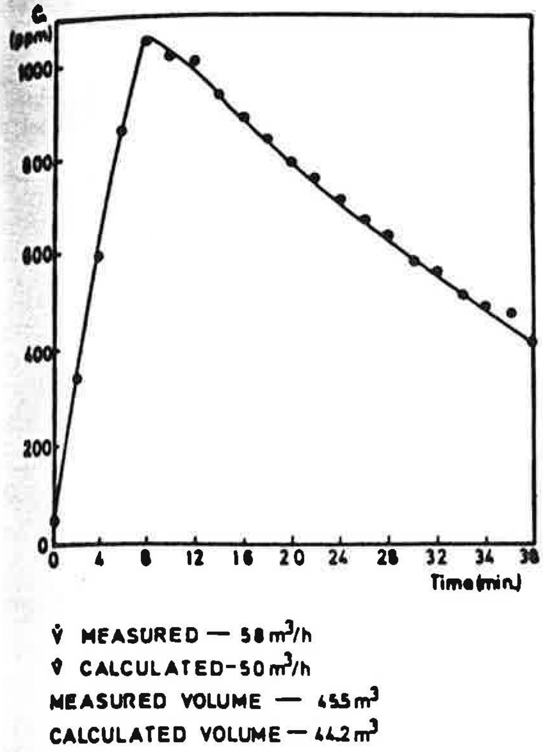

Fig. 2 - Tracer-gas concentration profile for the single zone experiment.

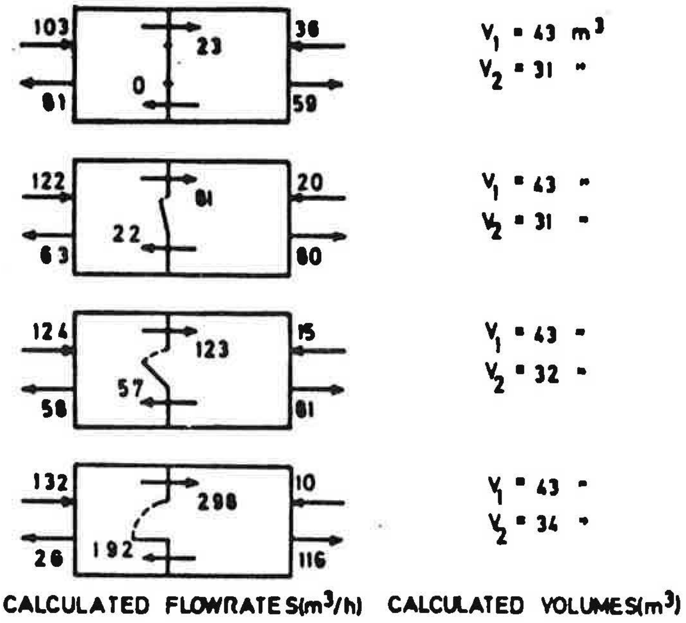

Fig. 4 - Overall results for the two zone tests

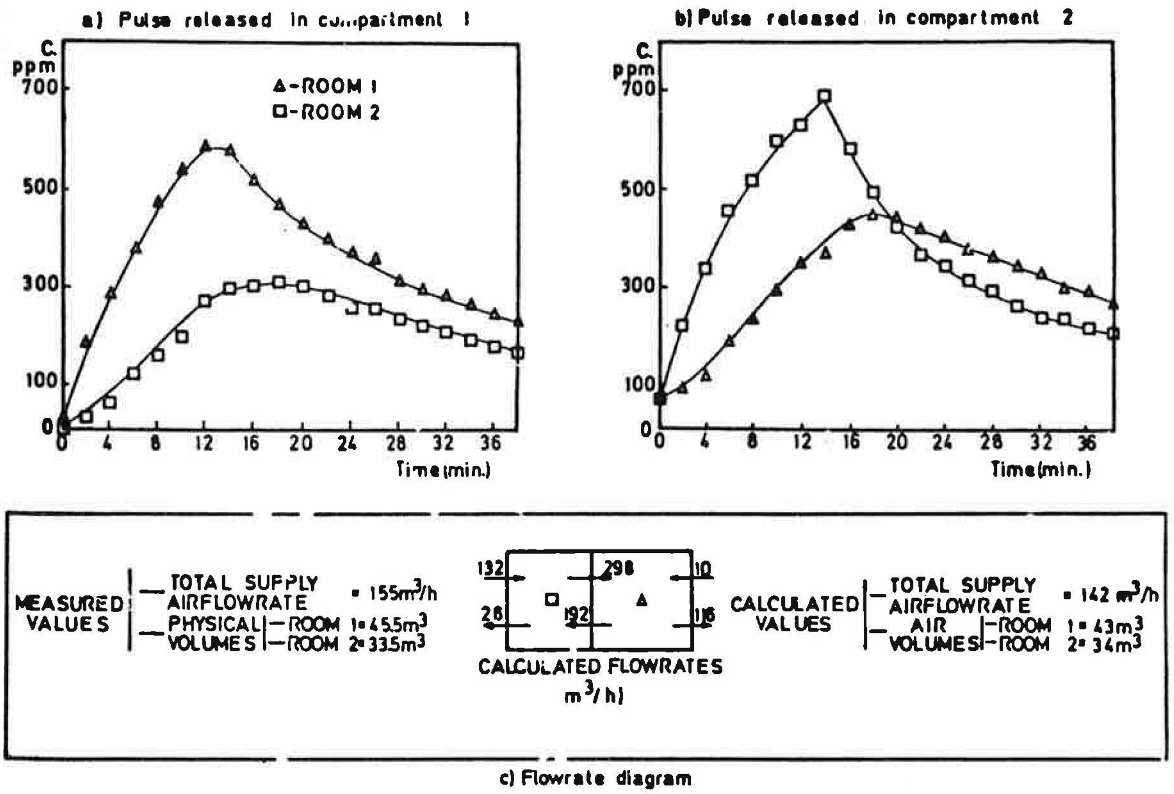

Fig. 3 - Experimental and calculated values and tracer-gas concentration profiles (two zones).