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A Single Tracer-gas Method to Characterize Multi-room Air Exchanges

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SUMMARY

Quantification of whole-building infiltration rates is not enough to properly characterize indoor air quality and energy consumption in a building. It is also necessary to know the air exchanges between each room and outdoors, and among the different rooms themselves.

A method to accomplish this objective using a single tracer gas was developed and experimentally verified under laboratory conditions. The method proved to be feasible and able of predicting airflows to within 10%.

The advantages and disadvantages of this method, compared with multiple tracer-gas procedures to solve the same problems, are examined. Potential applications and perspectives for further developments are finally discussed.

INTRODUCTION

One of the major difficulties which arises when attempting to model indoor air quality and energy flows in buildings is the need to quantify air exchanges within the building and with outdoors.

Air quality has long been an issue of concern. Outdoor air quality has been in the public eye for a long time due to the increasing pollution levels which resulted from the strong industrial development of the last decades. As a consequence, there has been concerted action at the national and international levels towards reduction of emissions to control pollution at more acceptable levels.

Conversely, indoor air pollution has received much less attention, in spite of the much longer time during which the occupants are exposed to an indoor environment in their lifetime. Moreover, numerous studies have shown much stronger contamination indoors than outdoors. Indoor air quality has been under study for some time, and the air exchange rate in a particular space has been recognized as one of the major parameters which influence it. In most cases, the larger the amount of outdoor air brought into a space, the better the indoor air quality.

However, the increasing cost of energy, and the ensuing efforts for energy conservation, have resulted in a tendency to reduced air exchange rates, both by infiltration and natural or mechanical ventilation. These lower rates imply worse indoor air quality, and recent ventilation standards have attempted to reach a compromise between energy consumption and air quality. To quantify the energy consumption adequately, the air exchange rates also need to be quantified.

Tracer-gas methods have been the most widely used means of evaluating air exchange rates. Inexpensive techniques have been developed which do not introduce any change in airflow patterns during the measuring period.

The objectives of tracer-gas tests have evolved considerably over the years. Initially, as proposed by Marley [1], the house was considered fully mixed, behaving as a single-zone space. It was soon realized, however, that tracer-gas tests could also be used for non-mixed spaces [2]. This latter approach has led to more recent studies which introduced the concepts of ventilation effectiveness in both naturally and mechanically

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ventilated spaces [3 - 5]. Another more recent development concerns the attempt to quantify the airflows which occur among the various rooms in houses, which are thus treated as multi-zone spaces [6, 7]. This should be the preferred method for studies on indoor air quality, while single-zone methods should be limited to applications which deal exclusively with quantification of infiltration loads for energy consumption evaluation [8].

This paper describes a method for measuring the airflows which are established between the various zones of buildings and between those zones and outdoors, using a single tracer gas.

ESTIMATION OF AIR FLOWS IN BUILDINGS

As previously discussed, it is important to quantify the air exchanges across the building envelope and among the different spaces within the building. When a building can be considered as a single uniformly mixed zone, it is sufficient to determine the air flow across the building envelope. The tracer-gas decay method has been thoroughly studied and accepted as suitable for this purpose [8].

Unfortunately, the single-zone building is an exception. Then, it may also be necessary to know the airflow rates among the different contiguous rooms. In recent years, tracer-gas methods have also been used to attempt to quantify these internal airflows. However, the particular methodologies have been more complex than those used for the single zone building [4, 9 - 11].

The mathematics and the difficulties involved in the application of tracer-gas methods to a non-mixed multi-room building were earlier described by Sinden [12]. Considering that a steady state exists, that the concentration of tracer gas in the outdoor air is zero, and that a building can be treated as consisting of n uniformly mixed zones (Fig. 1), the following balances can be written:

- Tracer-gas mass balance for zone j:

$$V_j \, \mathrm{d}C_j/\mathrm{d}t = \sum_{i=1}^{n} Q_{ij}C_i - \sum_{i=0}^{n} Q_{ji}\, C_j \qquad (1)$$

$$1 \leqslant j \leqslant n$$

where:

V_j = effective volume of zone j

C_j = concentration in zone j

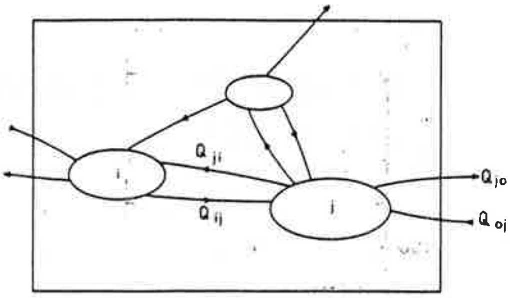

Fig. 1. Multi-zone model.

C_i = concentration in zone i

Q_{ij} = flow rate from zone i to zone j

Q_{ji} = flow rate from zone j to zone i

t = time.

After rearranging the terms and integrating, eqn. (1) leads to

$$V_j[C_j(t_2) - C_j(t_1)]$$

$$= \int_{t_1}^{t_2} \sum_{\substack{i=1\\ i\neq j}}^{n} Q_{ij}(C_i - C_j)\, \mathrm{d}t - Q_{0j}\int_{t_1}^{t_2} C_j \, \mathrm{d}t \qquad (2)$$

where Q_{0j} = flow rate of external air entering zone j.

- Air mass balance for zone j (assuming properties calculated using the same temperature):

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

The number of unknown flow rates involved in these equations is $n(n+1)$, as each of the $(n+1)$ zones, including outdoors, exchanges air with the other n zones*. Thus, to solve for all the flow rates, an equal number of equations is needed.

Sinden suggested that eqn. (2) could be integrated for n different intervals from the concentration decay curves for each zone. Thus, n^2 equations could be obtained which, together with n conservation-of-mass equations, eqn. (2), would yield the necessary number of equations to solve for all the unknowns.

This method requires only one single experiment, in which the decays in each of the rooms are simultaneously measured. This simplicity, unfortunately, does introduce some major drawbacks: as the n different

*$Q_{jj} = 0$

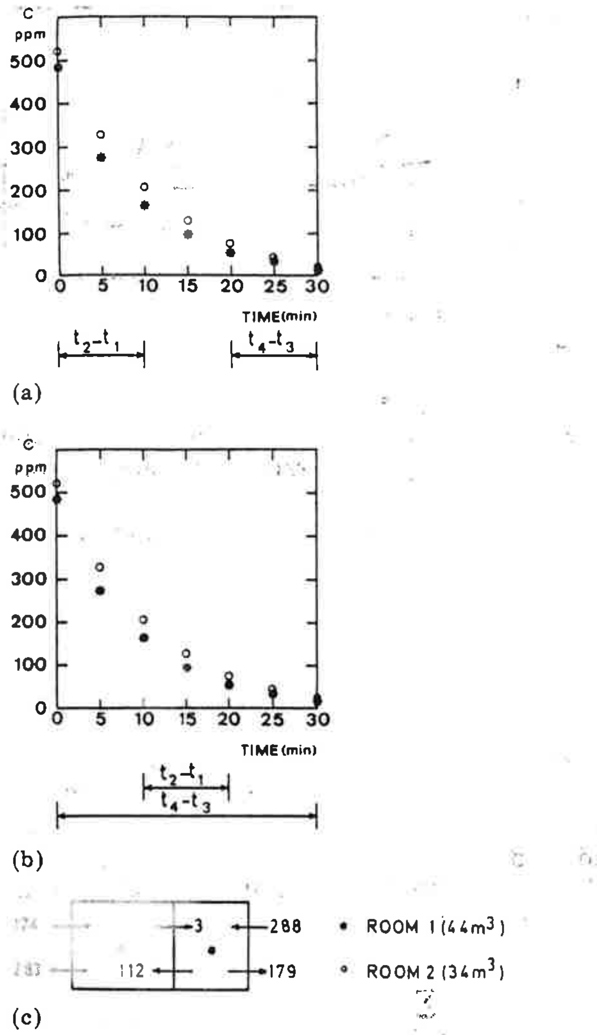

Fig. 2. Example of the influence of interval selection for integration of eqn. (2). (a) tracer gas decay in short time intervals — case (a). (b) tracer gas decay in one long time interval — case (b). (c) real flow rates (m^3/h).

intervals to integrate eqn. (2) can be arbitrarily chosen, different systems of equations can be obtained which also result in distinct values for the flow rates. This is, of course, unacceptable. This fact can be easily verified with the example shown in Fig. 2 which represents the decay of tracer-gas concentrations in each of two rooms of a particular building. Both decays resulted from the same experiment, i.e., they were obtained simultaneously. The same curves are shown in both Figs. 2(a) and 2(b), but each of these plots shows a different selection of intervals for integration of eqn. (2). The two selected forms of integration would yield the flow rates listed in Table 1. Not only are the flow

TABLE 1

Calculated and exact flow rates for example in Fig. 2

Case (a) (m^3/h)	Case (b) (m^3/h)	Exact solution (m^3/h)
$Q_{01} = 271.9$	$Q_{01} = 307.3$	$Q_{01} = 288$
$Q_{21} = -94.5$	$Q_{21} = 90.2$	$Q_{21} = 3$
$Q_{02} = 157.6$	$Q_{02} = 178.8$	$Q_{02} = 174$
$Q_{12} = 218.1$	$Q_{12} = 86.4$	$Q_{12} = 112$
$Q_{10} = -40.7$	$Q_{10} = 311.1$	$Q_{10} = 179$
$Q_{20} = 470.2$	$Q_{20} = 175.0$	$Q_{20} = 283$

rates distinct for both cases, but some are even negative, an obvious impossibility given the formulation of the problem.

A comparison between the real and the calculated values shows that the results from case (a) are much further from the correct values than those from case (b). The reason for this difference lies on the length of the integration periods that were selected, short in case (a) and long in case (b). In the latter case, one interval was even selected as the whole measuring period. Thus, to obtain better results, it is convenient to use long integrating intervals because experimental error is minimized and more pertinent information is included for analysis. Ideally, then, this would imply that each of the integrating intervals should be the whole measuring period. Of course, were such an approach selected, the equations would be equivalent to each other and no solution could be obtained.

To overcome this difficulty, there are two possible ways in which to conduct the experiments and obtain the correct solution:

(1) 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. For each zone, n different equations can then be obtained by integrating eqn. (2) for the whole measuring period, as it was found necessary by the previous discussion.

(2) 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. As in method (1), n independent equations (one for each tracer) can be ob-

tained for each zone by integrating eqn. (2) for the whole measuring period.

In both methods, it is assumed that measurements are taken until all concentrations are negligible and that n air mass-balance equations, eqn. (3), are also obtained to complete the correct number of equations needed to solve for an equal number of unknowns.

Each method has its advantages:

- Method (1) needs only one tracer gas, i.e., one gas analyser only. Equipment cost is therefore lower than for method (2), which requires either n analysers or one flexible analyser capable of detecting all tracer gases used in the experiment, or some combination of these two alternatives.
- Method (2) requires smaller experimental time to be performed, as only one simultaneous measuring period is required contrary to the n distinct periods necessary to complete method (1).

The time required to conduct method (1) makes it more appropriate to study steady-state or quasi-steady-state situations. Otherwise, as conditions change, the flow rates might change enough during the measuring period that the calculated flow rates may be meaningless. On the other hand, even if small changes occur in a quasi-steady-state situation, the mean flow rates obtained are more representative of the actual air exchanges than instantaneous values.

If a situation is highly unsteady, neither method will be applicable because the flow rates might change significantly from the beginning to the end of even the single measuring period necessary for method (2).

Some experimental work has already been reported on variations of method (2). Dietz [6, 9] has carried out measurements with four tracer gases using the constant concentration method, in which the concentrations of each tracer were kept constant through an elaborately controlled gas-releasing equipment in each of the zones. Roulet and Scartezzini [13] also used the constant concentration method to evaluate the global air change rates in all the compartments of a house in two situations, i.e. with all windows closed or with some of them opened.

The following sections describe how method (1) was used to determine the main flow rates in a 2-compartment laboratory under steady-state conditions.

EXPERIMENTAL SET-UP

The tests were conducted in a two-room space with the configuration shown in Fig. 3. The dimensions of the two compartments were $4.5 \times 3.4 \times 2.8$ m^3 and $3.4 \times 3.4 \times 2.8$ m^3.

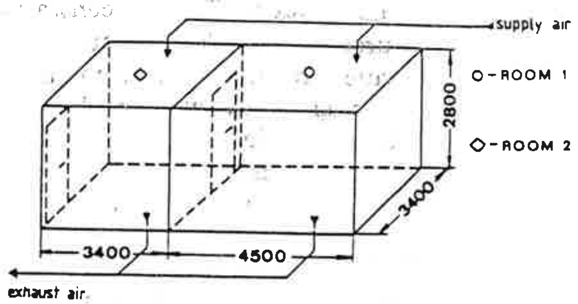

Fig. 3. Schematics of the two-room space.

There was no furniture inside the two compartments. Thus, the effective volumes of both spaces were equal to those defined by the net interior dimensions previously cited. A central air-handling system supplied air to both compartments. Exhaust air from the compartments was drawn by a second fan. Total supply and exhaust flow rates were measured by nozzles placed in the ducts.

The tests were performed with N_2O as a tracer. For each test, a pulse of N_2O was released in one of the compartments and the ensuing varying concentrations were measured in both compartments. The procedure was then repeated with the N_2O pulse released in the other compartment.

When a pulse was released, the N_2O concentration in both compartments was negligible. As, following the pulse release of tracer gas, the compartments would not immediately reach a uniformly mixed state due to the lower-than-optimum ventilation efficiency of the forced-air distribution system installed [14], uniform mixing was enhanced throughout the tests with small fans placed in each compartment.

There were four sampling points for each compartment: one in the supply duct; two inside the space, 0.7 m and 1.8 m above the centre of the floor; and another in the ex-

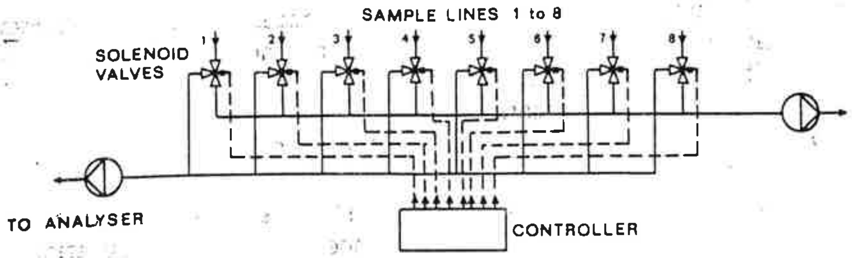

Fig. 4. Multiplexer.

haust duct. The concentrations were measured by a single calibrated infrared dectector, which received air from all sampling points through a multiplexer, Fig. 4, programmed in an appropriate sequence.

Comparison of the data from the three sampling points placed in each compartment also showed that there was a good mixing within each compartment, as only minute differences were measured (4.5% relative to the medium value). Thus, the hypothesis of uniformly mixed zones in a non-uniformly mixed space was considered to be fulfilled. The value of the concentration of tracer gas representing each compartment during the decay tests was calculated as the average of the three concentrations measured within the compartment.

The test rooms were located inside a large laboratory such that no measurable concentration of N_2O resulted from the exhaust and exfiltration from the two rooms.

Equation (2) was integrated in each case over the whole measuring period using Simpson's rule and the system of simultaneous equations was solved numerically by Gauss elimination.

RESULTS

The tracer-gas methodology described in the previous sections was carried out for different combinations of airflow rates to both compartments. The flows measured in the nozzles placed in the supply ducts were compared with those calculated from the tracer-gas concentrations which resulted from each of the two pulses released into the compartments. The flow rates were also analysed against the pressure differences that were measured between each compartment and outdoors.

Two sample-runs of this procedure are shown in detail in Figs. 5 and 6. Plots (a) and (b) show the decay of N_2O in both compartments following the pulse releases in compartments 1 and 2, respectively. Superposed on the experimental data points are the theoretical concentration decays which would occur if the flow rates were exactly as calculated by this method, and listed in diagram (c). A good agreement can be observed between the experimental and calculated concentrations, as well as between the experimental and the measured airflow rates.

The relative magnitudes of the flow rates are also in agreement with the measured pressure differences between the compartments and outdoors. In the case shown in Fig. 5, the pressure difference between compartments 1 and 2 is positive (0.5 Pa). Thus the flow rate from compartment 1 to compartment 2 should be larger than in the opposite direction, which is indeed the case. The flow rate Q_{21} is not zero as the positive pressure difference might indicate. Indeed, turbulence and air circulation patterns cause a cross-over of air in both directions, although always with an excess going towards the compartment with lower pressure. Fig. 6 shows a totally similar pattern. This is true with the door between the two compartments opened or closed.

As both compartments have a slight positive pressure difference relative to the atmosphere, exfiltration is also expected to occur. This is also confirmed by airflow measurements, which indicate an excess of 340 m^3/h and 40 m^3/h in Figs. 5 and 6, respectively, for the supply air over the exhausted air.

The differences between the calculated and the measured total air supply rates may have actually been smaller due to air leakage from the supply duct. A smoke test proved the occurrence of the leakage which was, however,

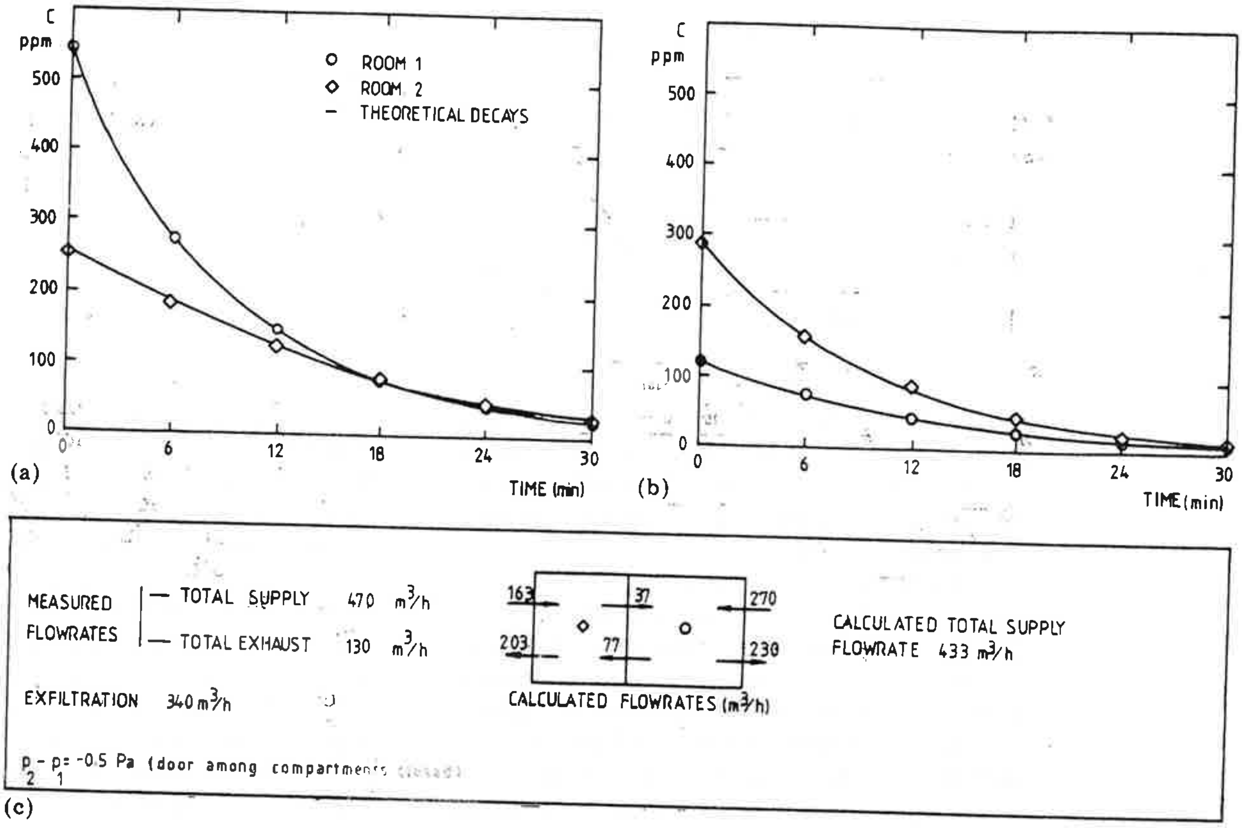

Fig. 5. Experimental and calculated flow rates and tracer-gas concentration profiles. (a) pulse released in compartment 1. (b) pulse released in compartment 2. (c) flow- rate diagram.

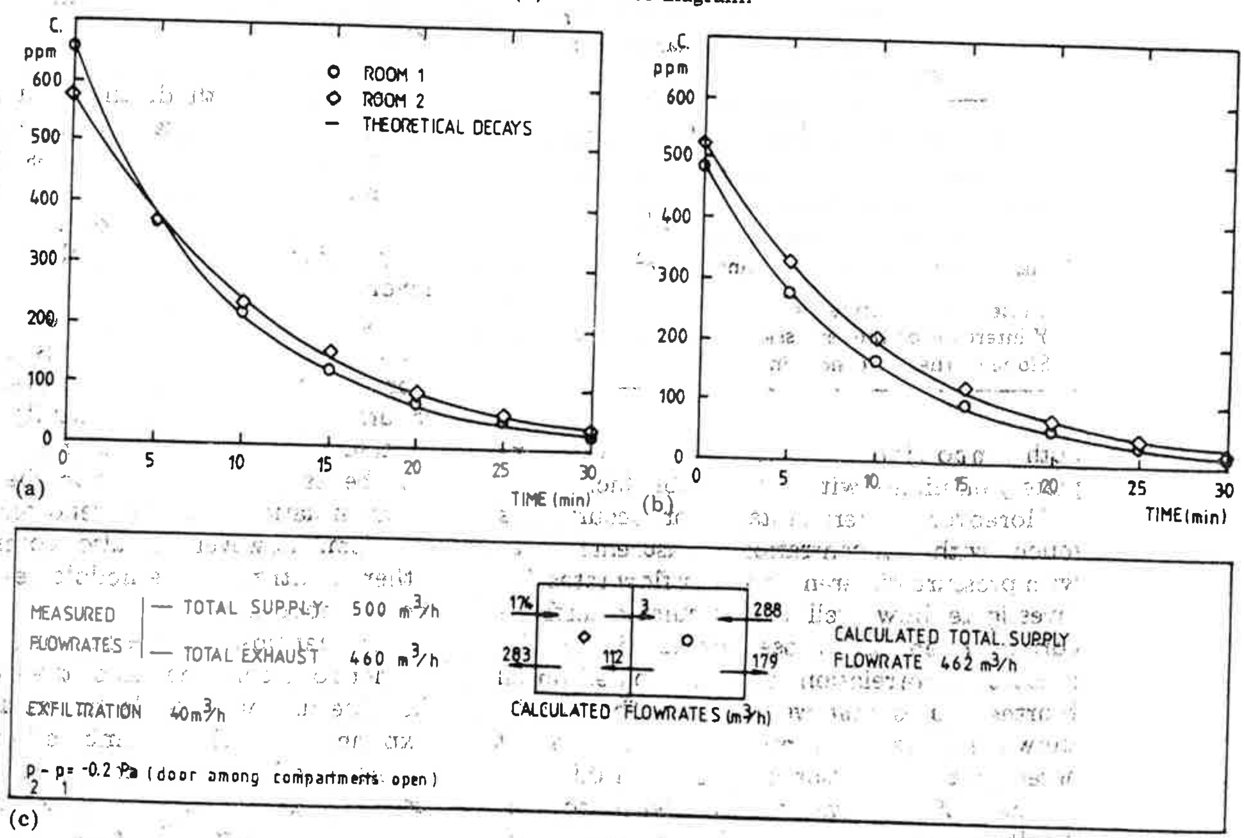

Fig. 6. Experimental and calculated flow rates and tracer-gas concentration profiles. (a) pulse released in compartment 1. (b) pulse released in compartment 2. (c) flow-rate diagram.

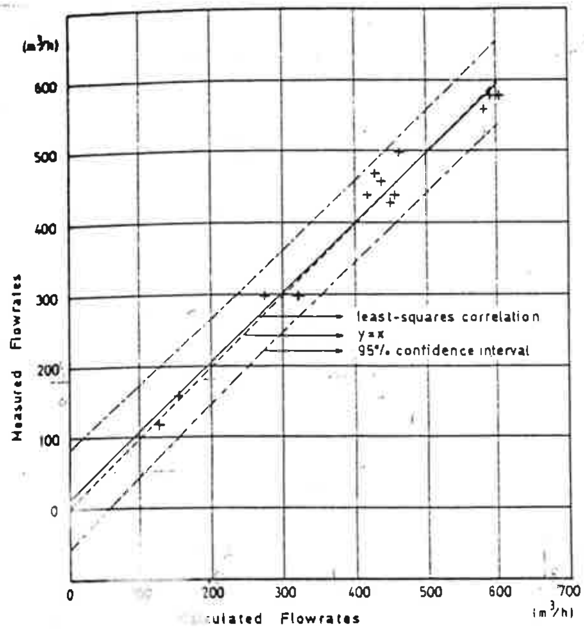

Fig. 7. Comparison of calculated and measured flow rates.

TABLE 2

Anovar table for correlation in Fig. 7

Source of variation	Sums of squares	Degrees of freedom	Mean square	Variance ratio F
Regression	271147	1	271147	420
Error	7738	12	645	
Total	278885	13		

$F^{(1,12)}_{(0.95)} = 4.75$

Unbiased coefficient of determination: $\hat{r}^2 = 0.969$

95% interval of confidence:

Y intercept of the regression line: $\alpha = 10.6 \pm 45.5$

Slope of the regression line: $\beta = 0.973 \pm 1.06$

both impossible to quantify and to completely eliminate with the available facilities.

Moreover, experimental error occurred as much with concentration measurements as with pressure differences and airflow rates. To investigate how well the calculated airflows corresponded to those measured by the nozzles, a correlation was made based on all fourteen cases that were tested. The results, shown in Fig. 7, demonstrate an excellent agreement (correlation coefficient of 0.99).

The 95% interval of confidence for the results is also shown. The corresponding analysis of variance (anovar), shown in Table 2, indicates that there is no statistically significant difference between the correlated equation and $y = x$ (shown as a dashed line in Fig. 7). Thus, within an acceptable uncertainty, the calculated and measured flow rates are identical.

CONCLUSIONS

A simple experimental method to calculate airflow rates between rooms in a building and with outdoors has been shown to be feasible whenever steady-state conditions exist. These conditions are characteristic of most spaces with a constant air-volume mechanical system and in most other spaces under relatively constant exterior weather conditions.

The method requires a single tracer gas, making it a less onerous alternative to multi-gas methods, which in turn have the advantage of being completed in a shorter period of time.

The validity of the method was experimentally verified under laboratory conditions and shown to yield quite satisfactory results, certainly within the usual accuracy possible when measuring airflow rates in open spaces.

Although the tests were conducted by the tracer decay method, they could be done also by the steady-state concentration method, utilizing just one tracer gas. In this case the implementation of the method is similar to that required by the decay method with only minor changes in the mathematics involved.

Further research is now needed to attempt its verification in real buildings, under conditions which may not be as steady as in a laboratory. Another difficulty will also pertain to the definition of zones, which may not be as well defined as in the 2-compartment situation that was reported here. This problem, however, is also common to all other multi-zone methodologies that have been proposed so far.

Another possible line of work is the development of a combination of the two methods, i.e., the use of multiple tracers and multiple experiments. This combination may be interesting in cases with a large number of zones: e.g., a 12-zone building could be solved using three different tracers and four experiments. In this case, three simultaneous pulses of different tracers could be released in three different zones of the house, repeating the procedure four times until one pulse is released within each zone. While a single tracer would require very long experimental periods, multiple tracers with a single experiment might require very expensive equipment. Moreover, such a large number of tracer gases might just not be available for a particular application. Thus, some optimum mix of multiple tracers and multiple experiments might lead to reduced costs for testing a building.

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