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A Multiple Tracer Gas Technique for Measuring Air-flows in Houses

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ABSTRACT

A technique has been developed for measuring air-flows between internal spaces of houses using a portable gas chromatograph to monitor the concentrations of three tracer gases released in three distinct zones within the building envelope. Using the results of each measurement, which takes approximately two hours, the ventilation rate of each zone can be calculated along with the interconnecting air-flows. The paper presents the tracer decay equations involved, including their derivation and application. An account of the experimental method is included and the practical difficulties are mentioned. A programme of field work has commenced with the objective of investigating the magnitudes of air movement in a wide range of houses and conditions. The fourth section presents two of the early results which have been obtained by use of the multiple tracer gas technique.

RESUME

On a développé une technique pour mesurer les courants d'air entre les espaces internes des maisons, se servant d'une chromatographe à gaz portative à surveiller la concentration des trois gaz traceurs dans trois zones distinctes du bâtiment. Se servant des résultats de chaque mesurage, qui dure à peu près deux heures, on peut calculer le taux de ventilation de chaque zone et aussi les courants d'air communiquants. Cette étude offre les équations qui moutrent à l'égard de la réduction des gaz traceurs, leurs dérivations et leur usage. On a rapporté la méthode expérimentale et les difficultés pratiques. On a commencé un programme de travaux pratiques afin de rechercher les courants d'air dans des maisons, et des conditions, bien diverses. La quatrième partie rend des résultats préliminaires, que l'on a gagnés de l'emploi de la technique des gaz traceurs multiples.

INTRODUCTION

The manner in which air flows between internal zones of houses is important, not only because of its effect on the ventilation and heat loss of each zone, but also because of the condensation risk in colder zones, such as the roof-space and bedrooms, due to warm, moist air flowing into them from the kitchen and bathroom.

In 1950, Dick (1) measured single directional air-flows using a single tracer gas. His work was continued by Saunders (2) to measure air-flows into roofs from houses using nitrous oxide as the tracer gas. The present work is an extension of the technique used by Dick and Saunders to include two-directional air-flows, where recirculation of tracer gas occurs, and uses three tracer gases to permit the measurement of several air-flows simultaneously. The tracer gases and analysis equipment used are similar to those used by Foord and Lidwell (3) to estimate the rate of transfer of bacteria between rooms of a fully air-conditioned hospital. Their technique is, however, inappropriate to measuring air-flows in houses due to its lack of portability and reliance on continuous repeatable air-flows.

EQUIPMENT

A portable gas chromatograph is used to simultaneously measure the concentrations of three tracer gases in a sample of air. The three gases used at present are Freon 12 (dichlorodifluoromethane), Freon 114 (dichlorotetrafluoroethane) and BCF (bromochlorodifluoromethane). As shown in figure 1 below, separate polythene sampling tubes lead from each zone with gas taps to permit their selection one at a time. Each is terminated with a three-way sampling manifold to make allowance for stratification of tracer gas and non-isothermal air-flows. The internal diaphragm pump draws air through the manifold and tubing into the gas chromatograph, where the sample is split into its component gases by the column, and an electrical output proportional to the concentration of each is given by the electron capture detector. For a more detailed description see I'Anson, Irwin and Howarth(4). When a test is to be performed, the three tracer gases are released in the three spaces under consideration, where they are mixed for several minutes using oscillating desk fans. Sufficient samples are then taken from each zone for the curve shapes representing the variation with time of the concentration of each tracer gas in each zone to be defined. This normally

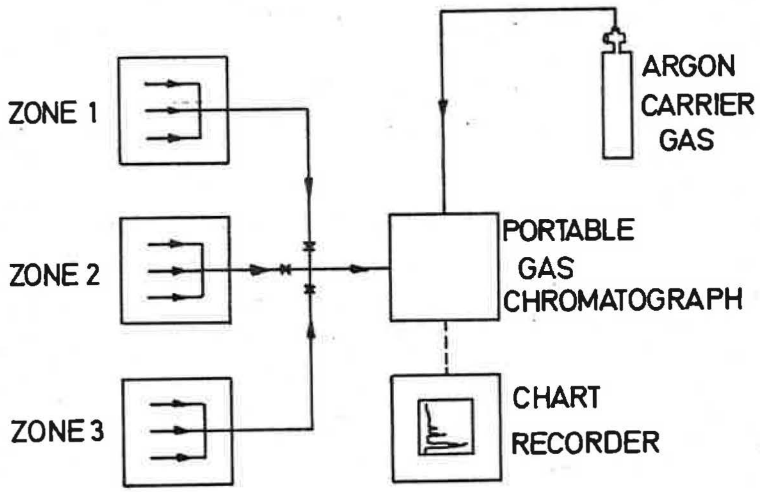

Figure 1. Layout of the experimental set-up.

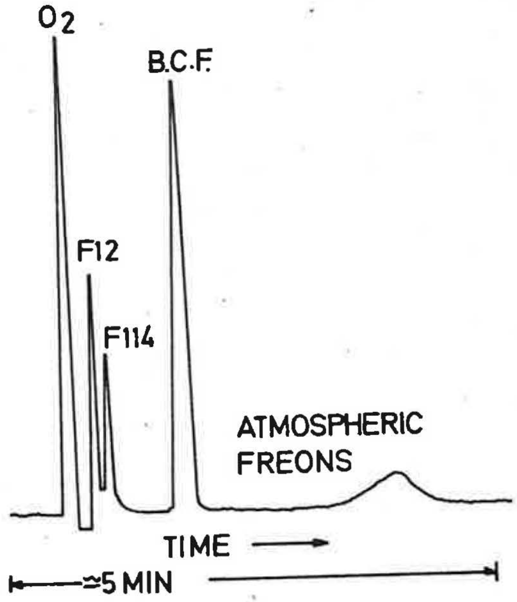

Figure 2. Chromatograph output as a chart recorder trace.

takes between two and three hours.

This experimental equipment is not perfect since samples may only be taken at five minute intervals since certain gases present in the atmosphere take longer to pass through the column than the tracer gases in use. However, there are many advantages over the alternative of using several, separate gas analysers, e.g. it is very portable, cheap, only small quantities of tracer gas are required. Improvements should be possible, in the future, by the use of column and detector heaters and, possibly, the use of entirely different, as yet untried, tracer gases with different column-detector combinations.

THEORY

The symbols used in this section are:

C   is concentration of tracer gas in ppm

Q   is the amount of air flowing out of a zone to the outside of the house in m^3s^{-1}

F   is the flowrate of air between two zones in m^3s^{-1}

t   is time in seconds

V   is the volume of a zone in m^3

N   is the ventilation rate of a zone in air changes per second (s^{-1}).

Non-zero number subscripts refer to a zone and letter subscripts refer to a particular tracer gas. The zero subscript indicates the value of the variable at t = 0. For example, C_{OA1} is the initial concentration of tracer gas A in zone 1 and F_{21} is the air-flow rate from zone 2 to zone 1.

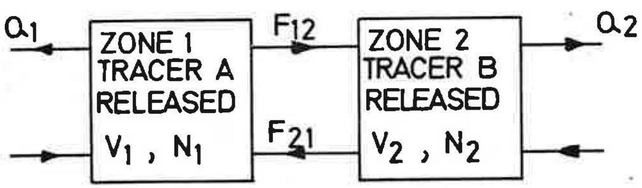

Figure 3.

By performing an air balance on the two zones illustrated in figure 3, two second order differential equations can be obtained:-

$$\frac{V_1V_2}{F_{12}}\frac{d^2C_{A2}}{dt^2} + \frac{V_1V_2}{F_{12}}(N_1 + N_2)\frac{dC_{A2}}{dt} + \left[\frac{N_1V_1N_2V_2}{F_{12}} - F_{21}\right]C_{A2} = 0 \qquad (1)$$

$$\frac{V_1V_2}{F_{21}}\frac{d^2C_{A1}}{dt^2} + \frac{V_1V_2}{F_{21}}(N_1 + N_2)\frac{dC_{A1}}{dt} + \left[\frac{N_1V_1N_2V_2}{F_{21}} - F_{12}\right]C_{A1} = 0 \qquad (2)$$

These can be solved (4) to give expressions for C_{A2} and C_{A1} by use of auxiliary equations in the normal way.

$$C_{A2} = \frac{\left[\frac{F_{12}C_{OA1}}{V_2} - (N_2 + Z)C_{OA2}\right]}{Y - Z}\exp Yt + \frac{\left[(Y + N_2)C_{OA2} - \frac{F_{12}C_{OA1}}{V_2}\right]}{Y - Z}\exp Zt \qquad (3)$$

$$\text{and } C_{A1} = \frac{\left[\frac{F_{21}C_{OA2}}{V_1} - (N_1 + Z)C_{OA1}\right]}{Y - Z}\exp Yt + \frac{\left[(Y + N_1)C_{OA1} - \frac{F_{21}C_{OA2}}{V_1}\right]}{Y - Z}\exp Zt \qquad (4)$$

$$\text{where } Y = \frac{-N_1 - N_2 + \sqrt{(N_1 + N_2)^2 - 4\left(N_1N_2 - \frac{F_{12}F_{21}}{V_1V_2}\right)}}{2}$$

$$\text{and } Z = \frac{-N_1 - N_2 - \sqrt{(N_1 + N_2)^2 - 4\left(N_1N_2 - \frac{F_{12}F_{21}}{V_1V_2}\right)}}{2}$$

The experimental points for C_{A1} and C_{A2} can now be fitted to equations (3) and (4) by a least squares curve fitting method which yields the values of F_{12}, F_{21}, N_1 and N_2.

Where there is a flow of air in one direction between two zones (say $F_{21} = 0$) then equations (3) and (4) can be simplified to:

$$C_{A2} = C_{OA2}\exp(-N_2t) + \frac{F_{12}C_{OA1}}{V_2(N_1 - N_2)}\left[\exp(-N_2t) - \exp(-N_1t)\right] \qquad (5)$$

$$C_{A1} = C_{OA1}\exp(-N_1t)$$

N_1 can immediately be found from equation (6) using the normal straight line graph of ℓnC_{A1} against t and measuring the gradient. If N_2 is also known, the only unknown left in equation (5) is F_{12} which can then be varied until the theoretical curve is seen to fit the experimental points. This is a technique which can be successfully performed manually, but a computer least squares fit can be used where more convenient as in the two-directional case. N_2 can most easily be obtained by simultaneously releasing a second gas B in room 2 giving:

$$C_{B2} = C_{OB2} \exp(-N_2 t) \tag{7}$$

A situation which cannot be dealt with using the two sets of equations above (equations (3) to (7)), is where there is a one-directional air-flow to a third zone from one of two zones involved in a two-directional flow. Clearly the ordinary one-directional equations do not apply since the decay in the source room is not of the form of equation (6) but is that given by equation (4). A separate integration must be performed to obtain this result. If the source room is room 1 and the receiving room is room 3:-

let $C_{A1} = A \exp Yt + B \exp Zt$

$$\text{where } A = \frac{\left[\frac{F_{21}C_{OA2}}{V_1} - (N_1 + Z)C_{OA1}\right]}{Y - Z}$$

$$\text{and } \quad B = \frac{\left[(Y + N_1)C_{OA1} - \frac{F_{21}C_{OA2}}{V_1}\right]}{Y - Z}$$

and C_{A3} is given by:-

$$\frac{dC_{A3}}{dt} + N_3 C_{A3} = \frac{F_{13}C_{A1}}{V_3} \tag{8}$$

which can be solved to give:-

$$C_{A3} = C_{OA3} \exp(-N_3 t) + \frac{F_{13}A}{V_3(Y+N_3)}\left[\exp Yt - \exp(-N_3 t)\right] + \frac{F_{13}B}{V_3(Z+N_3)}\left[\exp Zt - \exp(-N_3 t)\right] \tag{9}$$

A typical application is the measurement of the interconnecting air-flows between the upstairs, downstairs and roof of a house. The flow between upstairs and downstairs is two-directional and two estimates each for F_{12},

F_{21}, N_1 and N_2 can be found by releasing two tracers A and B and using two sets of equations of the forms of (3) and (4), one set for C_{A2} and C_{A1} and one set for C_{B1} and C_{B2}. By monitoring A and B in the roofspace two curves of the form of equation (9) can be drawn for C_{A3} and C_{B3}. Since A, B, Y and Z are known for both from the preceeding two-directional calculation, F_{13}, F_{23} and N_3 are the remaining unknowns in the two equations. N_3 can be found in the manner used in equation (7) for the simple one-directional case and F_{13} and F_{23} can then be varied until the theoretical curve is fitted as before.

RESULTS

Two results are presented here to give examples of commonly occurring air-flows which can be measured using the multiple tracer technique

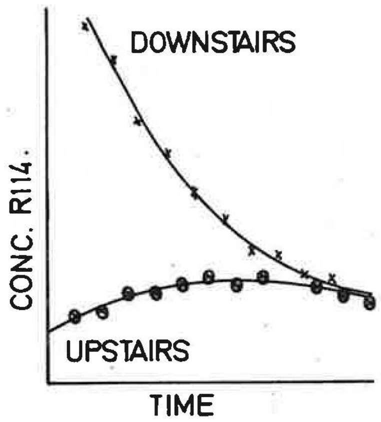

Figure 4. Concentration R114 verses time

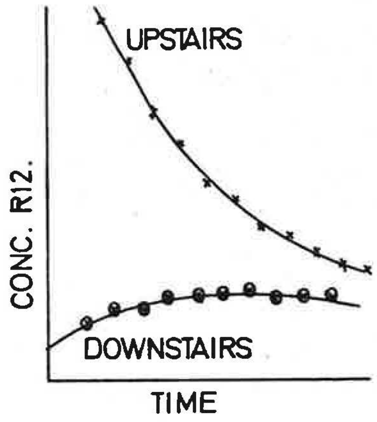

Figure 5. Concentration R12 verses time

Figures 4 and 5 show the two sets of two curves of the form of equations (3) and (4) obtained for a two-directional floor measurement between the upstairs and downstairs of a house. Freon 114 was released downstairs and Freon 12 was released upstairs. The points on the figures represent the experimental points and the continuous lines are the theoretical curves for:-

Downstairs ventilation rate	=	1.1 air changes per hour
Upstairs ventilation rate	=	0.8 air changes per hour
Air-flow from downstairs to upstairs	=	55 m^3 per hour
Air-flow from upstairs to downstairs	=	20 m^3 per hour

The volume of the ground floor was 110 m^3 and of the first floor 100 m^3.

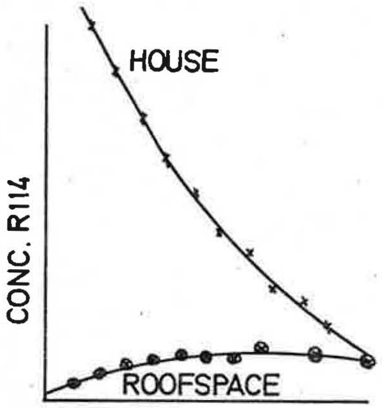

Figure 6. Concentration R114 verses time

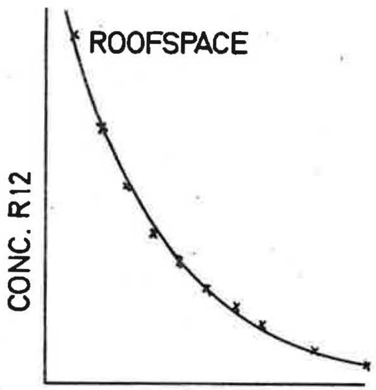

Figure 7 Concentration R12 verses time

Example 2 was a measurement of the air flowing from a house to its roof-space. Freon 114 was released uniformly in the house and Freon 12 in the roof. The three curve shapes in the figures 6 and 7 are those given by equations (5), (6) and (7). The theoretical curves shown are for:-

House ventilation rate	=	0.5 air changes per hour
Roof ventilation rate	=	4.3 air changes per hour
Air-flow from house to roof	=	28 m^3 per hour
Air-flow from roof to house	=	0 m^3 per hour

The volume of the house was 200 m^3 and of the roof 40 m^3. These results are to an accuracy of approximately 20% which is a reasonable figure (see ref (4)) since the weather dependent nature of these flows makes them very unrepeatable.

CONCLUSION

A technique has been described which enables many of the more interesting air-flows around houses to be quantified. A result takes between two and three hours to complete and, at present, has an accuracy of approximately 20%, which is not unreasonable since these air-flows are very sensitive to slight changes in windspeed, direction and temperature. Although for most of these results a manual calculation would be laborious, the use of a desk top microcomputer with a small range of programs makes calculation a simple matter.

The work will continue over the next year and will include investigation of the weather dependence of air-flows, condensation prediction for roof-spaces and bedrooms, investigation of energy losses due to oversizing of first floor radiatiors and heat losses in general due to air flowing through first floor ceilings.

ACKNOWLEDGEMENT

The authors are grateful to the Building Research Establishment and the Science Research Council whose financial support has made this work possible.

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Air infiltration problems in ventilation systems

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ABSTRACT

In this paper, the latest results of air infiltration research in Finland are presented. The aim of this research is to increase the knowledge of the influences of air infiltration on energy consumption, ventilation and indoor climate. The principles of a calculation model for predicting the interconnection between airtightness and air change rate are briefly described. Measurement methods are presented briefly, except a new method using existing fans in blocks of flats for pressurization. The airtightness of Finnish buildings has been recently improved. Attention is paid to construction details, some of which are presented. Finally, possibilities of draughtless and controlled fresh air intake through the building envelope are discussed.

RESUME

Le présent document comporte les derniers résultats obtenus en Finlande dans le domaine de la recherche d'infiltration d'air. Cette recherche vise à augmenter la connaissance des effets qu'exerce l'infiltration d'air sur la consommation d'énergie, sur la ventilation et sur l'air ambiant. Les principes de calcul pour déterminer la corrélation entre l'imperméabilité à l'air et le taux de renouvellement d'air sont brièvement présentés. Les méthodes de mesurage sont présentées en peu de mots, sauf une nouvelle méthode basée sur l'utilisation des ventilateurs déjà existantes dans les immeubles en vue de la pressurisation. L'imperméabilité à l'air des bâtiments a été récemment améliorée en Finlande. Une attention particulière a été portée sur les détails de construction dont certains se trouvent présentés. Enfin, la possibilité d'assurer une introduction d'air frais contrôlée et sans courants d'air nuisibles, se produisant par l'enveloppe du bâtiment, est présentée.