AN INVESTIGATION
USING THE TRACER GAS METHOD
FOR THE MEASUREMENT OF VENTILATION RATE IN ROOMS,
AND AIR FLOW RATE IN DUCTS.

A dissertation
submitted as part of the requirements for
the Degree of
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by

P. J. Weatherall B. Sc.

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Introduction.

General Introduction.

Both the measurement of ventilation rate in rooms and air flow rate in ducts are very difficult to measure accurately in any industrial situation, but each is required for the design and functioning of any heating and ventilation or air conditioned installation. The use of the tracer gas has been the most popular method of measuring the natural ventilation into a space since "Roscoe" in 1857, illustrated the diffusion of air from a closed room by liberating carbon dioxide and then measuring the rate at which its concentration diminished. In recent years nitrous oxide has been preferred to carbon dioxide as a tracer gas, especially with the development of smaller, more accurate infra red gas analysers to measure the concentration level within a space.

The possibility of using the tracer gas technique to measure air flow in ducts has been investigated to compare the results with the conventional traversing technique. This method of measuring air flow has been used for many years in other fields such as measuring air flow in coal mines and liquid flow rate using tracer substances.

Infiltration and Natural Ventilation.

Infiltration is the fortuitous leakage of air through a building due to imperfections in the structure and principally due to :-

a) Wind pressure, particularly on tall buildings

b) Stack effect

c) The temperature differential across the building

d) Building construction, particularly window type and external doors

e) The entry of the occupants of the building

f) External shape and dimensions of the building.

Natural ventilation is the air flow resulting from design provision such as openable windows and ventilators which can normally be controlled by the occupants.

As both of these air flows mainly depend on the exterior climate of the building, their air interchange can only be estimated assuming a range of meteorlogical conditions. Therefore, measuring such quantities can only be correct for the outside conditions existing at the time of the test. Although both infiltration and natural ventilation are very difficult to accurately estimate, they have to be known, not only to calculate the heating or cooling requirements, but also in the determination of the quality of the air within the building when such factors as relative humidity, carbon dioxide level, and contaminant concentration are significant criteria.

Depending on the working environment, the infiltration rate may be relied on as an adequate flow of fresh air, although neither infiltration nor natural ventilation can provide a guaranteed rate of air interchange under all conditions. In this age of fuel economy, infiltration should be reduced to a minimum to cut down on fuel costs especially during the heating season when, due to adverse weather conditions, infiltration will probably be at its highest. The quantity of fresh air required depends on the following factors :-

a) Provision of a continuous supply of oxygen for breathing. About 0.2 l/s is sufficient to sustain life.

b) Removal of the products of respiration and occupation. Only I.0 l/s per person of fresh air is required to prevent the carbon dioxide produced by respiration from increasing the carbon dioxide concentration in the space beyond the threshold limit value.

However the dilution of odours by outdoor air supply is much more significant and depends on the occupants and their occupations in the work space.

c) Removal of artificial contaminants produced within the ventilated space by process work, such as water vapour created by cooking.

d) Provision of sufficient oxygen to support combustion, particularly in industrial situations.

The rate of supply of fresh air necessary to meet the four above listed requirements depends on the diversity and density of occupation in the space.

From table B 2.I in the I.H.V.E. Guide (2), the statutory minimum volume of air space per person in factories and offices is II.5m^3 and the corresponding minimum outdoor air supply is 4.72 l/s per person. Although however, one would not wish to design to the absolute statutory minimum requirements as there are many psychological and physiological aspects which have not been mentioned.These include points such as human comfort which can be greatly improved upon by "air freshness" which requires much greater ventilation than the above minimum. However, if the rate of infiltration can be reduced to a known minimum and the remaining fresh air requirement introduced mechanicelly, a more comfortable environment can be created.

Natural ventilation can be used during the summer to reduce the heat load of the building, if air conditioning is not installed. So,"a summertime temperature" can be produced within the building,if the quantity of air flow into the space is known,so as to evaluate the internal conditions.

This gives an indication of how important infiltration and natural ventilation are in the designing of building services for an enclosure ~~and~~ although it is very difficult to measure these quantities accurately, because of the large number of variables, most of which are uncontrollable, an investigation has been made to measure these quantities using the tracer gas technique. Indeed, it is very difficult to see what alternative method could rival it for ease of producing readings in the field.

Synopsis of Section Content.

The objective of this piece of research was to examine as many techniques as possible of using the tracer gas method. Owing to the limited time permitted, this resulted in some areas not being as fully investigated as one would have liked.

The project has been divided into the following sections:-

I. A summary of the more commonly used concentration measuring techniques and of some other methods that have been used or suggested.

2. As nitrous oxide was used in all the experimental work its diffusion properties were considered in some depth and comparisons made with other gas systems to see what influence it might have on the results.

3. Several methods of liberating tracer gas into the room were examined and the results compared with the air flow rate into the space, measured by the pitot-static tube.

4. The "rate of decay " method of liberating tracer gas into a room was subsequently used to measure the ventilation rate in a number of rooms and the results compared with the simple infiltration estimation technique, and empirical values from the I.H.V.E. Guide (A4)

5. In view of the many sources of error in conventional methods of air flow measurements, the tracer gas method was used to measure different air flow rates in a piece of ductwork and the results compared with the pitot-static tube readings.

6. A short account of the conclusions reached from the whole project with a mention of further research required.

7. A brief description of the apparatus used in the experimental work and in particular some details of the functioning of the infra-red gas analyser.

I. A Short review of Tracer Gas Techniques.

I.I Introduction

Various tracer gases have been used to measure ventilation rates in rooms and a brief description of the different gases with their associated instrumentation is included in this section. All the experimental work for this piece of research was performed using nitrous oxide as the tracer gas with an infra-red gas analyser measuring the concentration.

The earlier work conducted at B.R.S. in 1927 (3) describes how the ventilation rate of a room was determined by measuring the increase in CO_2 resulting from the burning of three standard candles, for three hours. The carbon dioxide concentration was estimated by absorption in barium hydroxide and titration of the excess with oxalic acid.

Steam or increased moisture content of the air was later used as a measure of ventilation rate, but this was found to be unsatisfactory due to absorption of water vapour by the walls, furniture etc.

Besides the preliminary experiments, most of the earlier work was performed by using either helium or hydrogen as the tracer, and measuring the concentration with a katharometer. This was the basis of J.B. Dicks research work (4), which was presented in a paper of 1950. In this he describes a method of measuring ventilation rate in a house with a number of these instruments.

Since those earlier days, many methods have been used for measuring the ventilation rates in rooms from chemical analysis and infra-red absorption to radio-active tracers, besides many more. In all the techniques accuracy and convenience of use of the measuring instruments are important and automatic analysis giving immediate estimations are an advantage with short experimental times. The most common measurement devices are described below.

Concentration measuring Techniques.
I.2

a)Katharometer.

The katharometer measures changes in the thermal conductivity of the air-tracer gas mixture. The instrument is essentially a Wheatstone bridge circuit whose arms are platinum filaments as shown in Fig I.I

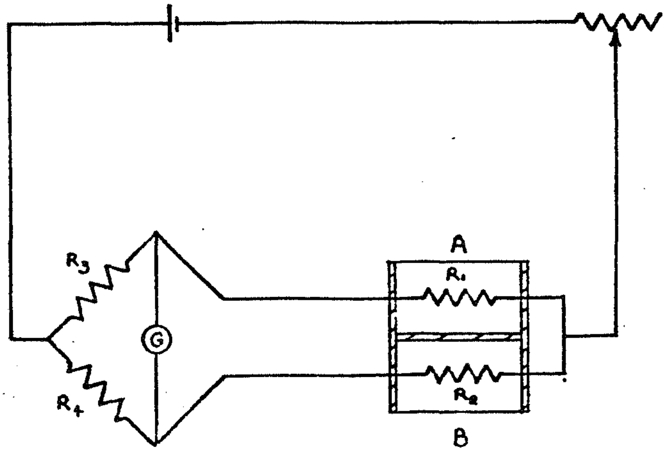


Fig I.I The Katharometer

A and B are separate cells, one filled with a reference gas and the other one open to the sample being examined. Both cells are in a solid copper block to ensure a constant temperature. A current through the bridge raises the filament temperature by about 15°C, the exact temperature and therefore the resistance depending on the heat loss rate in the cell. Air through cell B from the room unbalances the bridge which results in a deflection of the galvonometer and this can be calibrated to be a measure of the tracer gas concentration.

The calibration of the katherometer is normally linear over a wide range of concentrations, depending on the tracer gas used. Hydrogen is a popular tracer gas with this instrument as its thermal conductivity is seven times that of air. Other gases suitable for use as tracers include helium and carbon dioxide which, although they produce less of an effect with the katharometer than hydrogen for a given percentage of gas in air, have the advantage of safety in occupied spaces.

As all changes of air composition will affect the thermal conductivity of the mixture, gases and vapours which are present , but whose concentration may vary, such as carbon dioxide and water vapour must be removed from the samples. This is achieved normally by drawing the gas into the instrument through one or more absorption chambers.

Several disadvantages with this instrument are, the high concentrations of tracer gas needed for detection, even with hydrogen an initial concentration of 0.2 to 0.3% is required; drift of the zero which has to be checked frequently; and the instrument is affected by temperature changes although this can be minimized.

b)Chemical Analysis.

Various organic vapours have been used as tracers, mixed with room air and the concentration measured either calorimetrically or by PH changes. Visual colours and matching of them is perhaps rather inconvenient, but photoelectric methods are more sensitive and reproducible. "Lidwells" apparatus for measuring transfer indices using acetone (C_3H_6O) and pH changes, was quite simple but the reliability of the estimates was poor.

"Noronha's" paper (5) on a proposed method of measuring the rate of air change in factories using ammonia in small quantities as a tracer also measured its rate of decay by a calorimetric method. Concentrated ammonia solution was sprayed into experimental rooms and contaminated air was sampled through dilute sulphuric acid with a small quantity of Nesslers Reagent. This gave a yellow appearance, depending on the quantity of ammonia absorbed.

By comparing the samples with a standard concentration the quantity of ammonia could be found. Both acetone and ammonia are unpleasant and in an occupied room the latter is toxic with a maximum top limit of 10^{-2}% by volume whilst the minimum concentration of ammonia detectable is approximately 10^{-4}% by volume.This results in only a small working range.

In an earlier research paper by "Lidwell and Lovelock" (6) another method is described in which the same principle is applied. A highly volatile chemical tertiary butyl hypochlorite is evaporated into the air of the room. This is allowed to disperse. A drop of another solution O-tolidine and benzoic acid in petroleum ether and chloroform is placed on a filter paper. The O- tolidine reacts with the butyl hypochlorite in the air to give a blue colour on the paper, and the rate of development of this colour is proportional to the concentration of butyl hypochlorite in the air. From this the air change rate can be deduced.

c)<u>Infra-red Absorption.</u>

Measurement of the absorption of infra-red radiation enables the quantity of many gases in a complex gas mixture to be measured. Carbon monoxide, carbon dioxide, sulphur dioxide , methane and other hydrocarbons and vapours of water; acetone, ethyl, alcohol, benzene and others may be measured in this way. Oxygen, hydrogen, nitrogen, chlorine, argon and helium do not absorb infra-red radiation and are therefore ignored by the instrument. The infra red analyser calibrated for nitrous oxide and used in this piece of research work is described in more detail in section 7.

Although many gases can be used with the infra-red gas analyser, in recent years most of the research to measure ventilation rate in rooms has been performed using nitrous oxide as the tracer gas. One of its main advantages is the small concentration which the detector can respond to (one part of nitrous oxide in a million parts of volume by air) This method has been used for measuring the rate of ventilation of large rooms and other places where the katharometer could not be used owing to the large amounts of tracers required.

d)<u>Radio-active tracers</u>

The increased availability of radio-active gases in recent years has provided several new easily detected tracers suitable for mixing with air. Of the radio-active gases available, krypton (^{85}Kr) is the most popular since adequate sensitivity can be obtained without exceeding the maximum permissible radiation dose.

Measurements of any of the three ejected products of radio-active decay, normally α, β and γ particles may be made with Geiger counters or scintillation detectors.

Several corrections have to be made to the readings which are peculiar to the use of radio-active tracers, such as, a detector will respond to background radiation when no radio-active gas is present. The radio-active decay of the tracer will cause an error in the apparent ventilation rate which can be corrected for and will hasten the reduction of the activity to the threshold for the instrument. Argon -4I is rather poor in this respect as it has a half-life of only IIO minutes. Krypton -85 is much more stable, having a half life of 9.4 years. "Evans and Webb" (7) who have recently examined (I97I) the use of radio-active tracers in measurements of ventilation have shown that the accuracy can be better than ±3%

e) <u>Other Measurement Methods</u>

There are some other tracer mentods which have been used or suggested, but most of them have serious disadvantages. "Dufton and Marley (I934)" (8) investigated the practicability of measuring the rate of disappearance of water vapour using a hygrometer ,which had been liberated into the room. It was found that in a ordinary room many hours elapsed before the walls and furniture came into equilibrium with a changed humidity. In addition to hygrometers and wet and dry bulb thermometers, several other techniques have been used to determine water vapour content.

These include wet and dry bulb resistance thermometers, wet and dry bulb thermocouples, infra-red absorption, ion-exchange transducers and humidity sensitive capacitors and resistors, and electrolytic methods.

I.3

Comparison of different methods

From "Hitchin and Wilson's" (9) comprehensive review of the different types of tracer gas methods,in which they conclude that helium,with a katharometer as the measuring device, is the most favourable gas. In the absence of a high temperature, nitrous oxide, measured by infra-red analysis offers a wider range of usable concentration, but hydrogen, measured with a katharometer has much the lowest cost and a range of concentration similar to that of helium.

Radio-active gases were considered as unsuitable owing to the maximum concentration of gas allowed in a room which would render most measurements unreliable.

2. Simplified diffusion theory of Gases.

2.I Introduction.

Diffusion is the process by which matter is transported from one part of a system to another as a result of random molecular motions. As such it should not be confused with convection, as the former can still occur in a static system of uniform temperature.

The diffusion of nitrous oxide into the air has been considered in some detail due to the low diffusion coefficient, compared with a system such as helium into the air. The significance of this property and that nitrous oxide is denser than air, was considered ordinarily to be the greatest contributing factor to the high percentage errors which occured at the low air change rates. Assuming that, the rate of diffusion of the gas into air may have a considerable influence on the results.

The transfer of heat by conduction is also due to the random molecular motions. This was first recognized by "Fick" who put diffusion on a quantitive basis by adopting the mathematical equations of heat conduction derived some years earlier by "Fourier"

Much of the theory of diffusion is therefore based on that of heat conduction and many of the solutions to the heat-flow equations can be applied to the diffusion problems.

2.2 Diffusion Theory

"Ficks" first law of diffusion is based on the hypothesis that the rate of transfer of diffusing substance through unit area of a section, is proportional to the concentration gradient measured normal to the section.

$$F = - D \frac{\partial C}{\partial x} \qquad (2.I)$$

where F - rate of transfer per unit area of section

C - the concentration of the diffusing substance

x - space co-ordinate measured normal to the section

D - diffusion coefficient $(m^2 \ s^{-I})$

The negative sign arises as diffusion occurs in the direction opposite to that of increasing concentration.

This above expression is generally true only for an isotropic medium, whose structure and diffusion properties in the vicinity of any point are the same, relative to all directions. Due to this symmetry, the flow of diffusing substance at any point along the normal to the surface of concentration through the point.

"Ficks" second law of diffusion is an isotropic medium derived from the above equation.

Consider an element of volume in the form of a rectangular parallelpiped whose sides are parallel to the axes of co-ordinates and are of lengths 2dx, 2dy and 2dz.

Let the centre of the volume be at P (x, y, z) where concentration of diffusing substance is C.

Let ABCD and A'B'C'D' be the faces perpendicular to the axis of x as shown in Fig 2.I. Then the rate at which the diffusing substance enters the element through the face ABCD in the plane x-dx is :-

$$4\ dy\ dz\ \left(Fx - \frac{\partial Fx}{\partial x}\,dx\right)$$

Where Fx - rate of transfer through unit area of the corresponding plane through P.

Similarly the rate of loss of the diffusing substance through the face A'B'C'D' is :-

$$4\ dy\ dz\ \left(Fx + \frac{\partial Fx}{\partial x}\ dx\right)$$

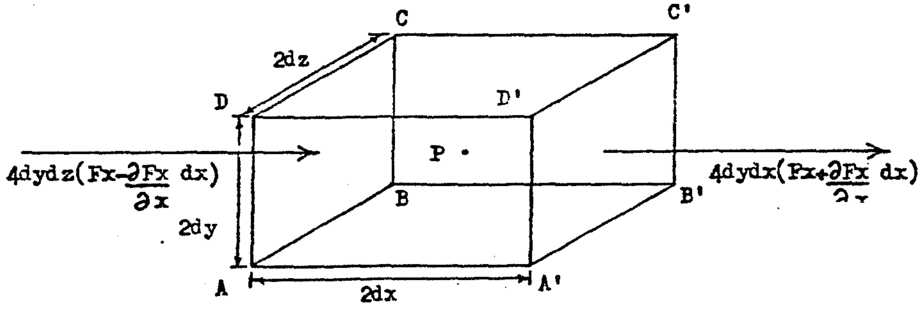


Fig 2.I Element of volume

The rate of increase of the diffusing substance in the element from these two faces is equal to :-

$$4\ dy\ dz\ (Fz - \frac{\partial Fx}{\partial x} dx) - 4dy\ dz\ (Fz + \frac{\partial Fx}{\partial x} dx)$$

$$= -8\ dy\ dz\ dx \frac{\partial Fx}{\partial x}$$

Similarly from the other faces the rate of increase of diffusing substance in the element is :-

$$-8\ dx\ dy\ dz \frac{\partial Fy}{\partial y} \text{ and } -8\ dx\ dy\ dz \frac{\partial Fz}{\partial z}$$

But the rate at which the amount of diffusing subsatnce in the element increases is also given by :-

$$8\ dx\ dy\ dz \frac{\partial C}{\partial t}$$

Therefore :-

$$\frac{\partial C}{\partial t} = - \left(\frac{\partial Fx}{\partial x} + \frac{\partial Fy}{\partial y} + \frac{\partial Fz}{\partial z} \right)$$

From equation(2.I)

$$Fx = -Dx \frac{\partial C}{\partial x} \quad ; \quad Fy = -Dy \frac{\partial C}{\partial y} \quad ; \quad Fz = -Dz \frac{\partial C}{\partial z}$$

Therefore :- $\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} (Dx \frac{\partial C}{\partial x}) + \frac{\partial}{\partial y} (Dy \frac{\partial C}{\partial y}) + \frac{\partial}{\partial z} (Dz \frac{\partial C}{\partial z})$

If the diffusion coefficients are constant, $D = Dx = Dy = Dz$

Therefore $\frac{\partial C}{\partial t} = D \left(\frac{\partial^2 C}{\partial x^2} - \frac{\partial^2 C}{\partial y^2} - \frac{\partial^2 C}{\partial z^2} \right)$ (2.2)

Equation 2.2 applies for diffusion in three dimensions that if there is a gradient of concentration along each axis in an isotropic medium of constant diffusion coefficient.

2.3 Calculating diffusion Coefficient.

D_{12} is a binary diffusion coefficient of two gases from "Fick's" basic equations for diffusion. It can be found experimentally and from exact theory to depend only weakly on the concentration ratio of the gases. The exact theory by "Chapman and Enskog" is complicated, but the simpler "Maxwell" equation gives values which compare well with experimental data. "Maxwell's" equation for calculating the diffusion coefficient is :-

$$D_{12} = \frac{\sqrt{\bar{C}_1^2 + \bar{C}_2^2}}{3\pi v S_{12}^2} \qquad (2.3)$$

where $\bar{C}$ = mean molecular velocity of each gas

$$\left\{ = \frac{(3RT/m)^{1/2}}{1.086} \right\}$$

R = Universal Gas Constant - 8314.3 J/k mol K

T = Absolute Temperature (^{o}K)

m = Molecular Weight

v = total number of molecules per unit volume

(= 9.8364×10^{22} T / K molecules per m^3 at one atmosphere at temperature T)

S_{12} - the mean molecular collision diameter

(= $1/2\sigma_1 + 1/2\sigma_2$) where σ are the collision diameters calculated for the viscosities of pure gas.

From data in tables 2.I and 2.2 the following diffusion coefficients are calculated using "Maxwells" Equation (2.3)

Mixture	D_{I2} at 25°C (m^2s^{-I})
Helium - Air	$5.55 \times IO^{-5}$
Nitrous Oxide - Air	$I.23 \times IO^{-5}$
Water Vapour - Air	$I.54 \times IO^{-5}$

2.4 Instantaneous Point Source.

The diffusing substance (nitrous oxide) deposited within a certain restricted region such as a balloon at time (t = o) and left to diffuse throughout the surrounding air. As the balloon source is of negligible volume compared with that of the room, it was thought appropriate to consider the balloon as a point source in an infinite volume, for simplicity.

The solution for an instantaneous point source in an infinite volume is obtained by recognizing that :-

$$C = \frac{A}{t^{3/2}} \exp\left(- (x^2 + y^2 + z^2) / 4Dt \right) \qquad (2.4)$$

is a solution of equation 2.2

where A is an arbitrary constant.

GAS	MOLECULAR WEIGHT	$I/2\sigma$ (nm)	$\bar{c}$ (ms^{-I}) 25°C
Air	28.96	0.I87	467
Nitrogen	28.02	0.I89	474
Helium	4.00	0.I09	I26I
Nitrous Oxide	44.02	0.233	378
Water Vapour	I8.02	0.233	590

Table 2.I

Mean molecular collision diameter - ε_{I2}

$$\varepsilon_{I2} = I/2\sigma_I + I/2\sigma_2$$

Gas Mixture	ε_{I2} (nm)
Helium - Air	0.296
Nitrous Oxide - Air	0.420
Water Vapour - Air	0.420

Table 2.2

By differentiating equation (2.4) with respect to time and let $B = \dfrac{-(x^2 + y^2 + z^2)}{4Dt}$

$$\frac{\partial c}{\partial t} = A\exp B \left\{ \frac{t^{-7/2}(x^2 + y^2 + z^2) - 6Dt^{-5/2}}{4D} \right\} \qquad (2.5)$$

Differentiating equation (2.4) with respect to x

$$\frac{\partial c}{\partial x} = \frac{-A\, t^{-5/2}\, x}{2D} \exp B$$

and $$\frac{\partial^2 c}{\partial x^2} = A \exp B \left(\frac{t^{-7/2}\, x^2 - 2Dt^{-5/2}}{4D^2} \right) \qquad (2.6)$$

Similarly for $\dfrac{\partial^2 c}{\partial y^2}$ and $\dfrac{\partial^2 c}{\partial z^2}$ substituting appropriate variables of y and z.

By substituting equation (2.5) into (2.6) with appropriate variables of x,y,z. It can be shown that :-

$$\frac{\partial c}{\partial t} = D \left\{ \frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} + \frac{\partial^2 c}{\partial z^2} \right\}$$

equation (2.2)

When the arbitrary constant A (ref. equation 2.4) is expressed in terms of M, the total amount of substance diffusing , by performing the integration,

$$M = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} c\, \partial x\, \partial y\, \partial z = 8\pi DA$$

the concentration C being expressed as the amount of diffusing substance per unit area of surface.

The concentration at a distance r from a point source in an infinite volume is:-

$$C = \frac{M}{8(\pi Dt)^{3/2}} \exp\left(- r^2 / 4Dt \right) \qquad (2.7)$$

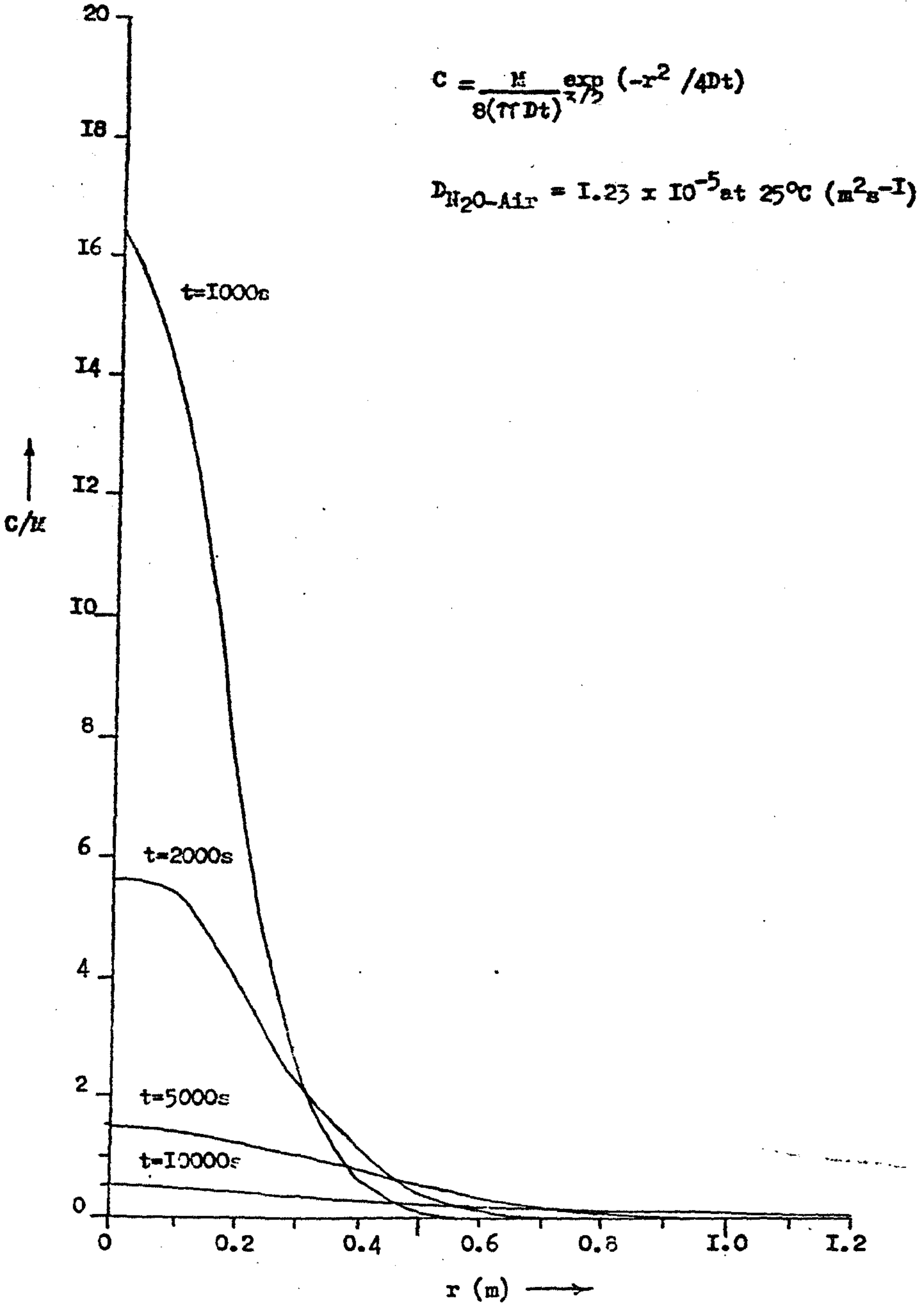
Equation (2.7), symmetrical with respect to r = 0, tends to zero as r approaches infinity positively or negatively for $t > 0$, and for $t = 0$ it vanishes everywhere except at $r = 0$, where it becomes infinite.

By substituting appropriate values of r,D,t into equation (2.7) the following concentration distribution curves have been plotted with two diffusion systems.

2.5 Conclusion.

The curves for an instantaneous point source as illustrated in Fig 2.2 and 2.3 for two mixtures of different diffusion coefficient show how quickly helium diffuses into the air, compared with the much slower nitrous oxide. For the purpose of the ventilation rate experiments, the diffusion rate of nitrous oxide is so small that it can be neglected. The air convection currents within the room would have a much more predominant role in mixing the gas, than the diffusion rate,and the latter would contribute only very slightly in the time of a test. Owing to the very low rate of diffusion of nitrous oxide into air, to achieve a uniform concentration from a point source, mechanical mixing is required. Without good mixing within the room, small pockets of tracer gas will exist which may give erroneous results.

NITROUS OXIDE - AIR MIXTURE



$$C = \frac{M}{8(\pi D t)^{3/2}} \exp\left(-r^2/4Dt\right)$$

$$D_{N_2O\text{-}Air} = 1.23 \times 10^{-5} \text{ at } 25°C \ (m^2 s^{-1})$$

Fig. 2.2 Concentration - distance curves for an instantaneous point source.

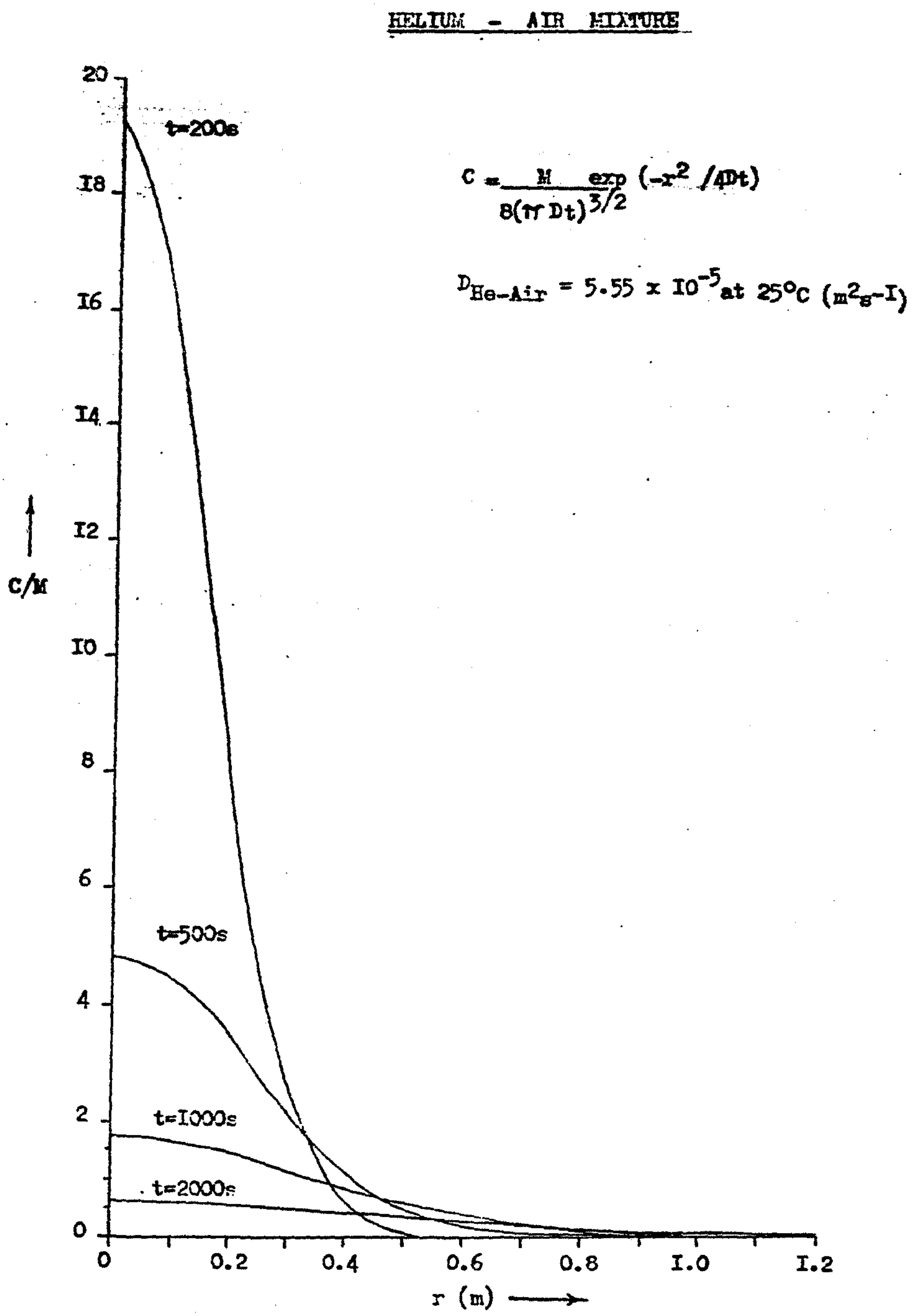


Fig. 2.3 Concentration - distance curves for an instantaneous point source.

3 Experimental Work

3.I
Introduction

There have been various methods to measure ventilation rate using an infra-red gas analyser, calibrated for the detection of nitrous oxide. "Hitchin and Wilson" (9) in their review of experimental techniques for the investigation of Natural Ventilation in Buildings mention four methods using the tracer gas techniques namely :-

A. Rate of decay
B. Equilibrium concentration
C. Transfer Index
D. Steady concentration

A. Rate of decay method - A quantity of tracer gas is released either at a number of points or at one point in a room near to a low speed fan to distribute the gas uniformly throughout the room. Assuming perfect mixing the concentration decay is exponential and by sampling the air at several points the apparent ventilation rate may be determined.

B. Equilibrium concentration method.- Tracer gas is continuously liberated into the room at a uniform rate and assuming perfect mixing, the gas concentration within the room will approach an equilibrium value if conditions are steady. Knowing the tracer gas liberation rate, the ventilation rate can be calculated.

C. The transfer index technique - This method of measuring ventilation rate resulted from the research by "O.M. Lidwell" in 1960 (10) from studies of infection in operating theatres. The procedure is to release a known volume of a gas at one point and to sample the concentration at several other points. The transfer index found is a function of the position of both points but does not depend on perfect mixing.

D. Steady Concentration method - This is similar to the equilibrium concentration method as tracer gas is injected at one point and the concentration is measured, but the gas liberation is controlled automatically so as to give a steady known concentration at the sampling point. Knowing the concentration at the detection point and the mean rate of tracer gas liberation, when the concentration is static, the transfer index can be calculated. Assuming perfect mixing the ventilation rate is the reciprocal of the transfer rate.

For all of the above methods, the concentration at the sampling point needs to be known in absolute terms ie. the gas analyser needs to be calibrated. The experimental work proceeding has been mostly based on the fact that as long as the analyser gives a linear reading the absolute value is of little importance.

Using a chart recorder from the electrical output on the gas analyser, a continuous record is plotted from which the ventilation rate can be found.

The two methods which have been used in this piece of work to determine ventilation rate are the

a) Rate of decay due to the pulse input of gas

b) Equilibrium concentration method due to a step input of tracer gas.

These two basic techniques were used to measure the ventilation rate within an experimental room, having a known supply of air which was measured using the pitot tube transverse method. The air change rates measured by the pitot-static tube and tracer gas methods were compared with various air flow rates into the room.

3.2 Methods used to analyse the results.

a) Rate of decay due to a pulse input of gas.

The decay equation is derived in terms of the rate at which tracer gas liberated, decays in a ventilated room under the influence of a diluting supply of fresh air, either by infiltration or by the mechanical ventilation system.

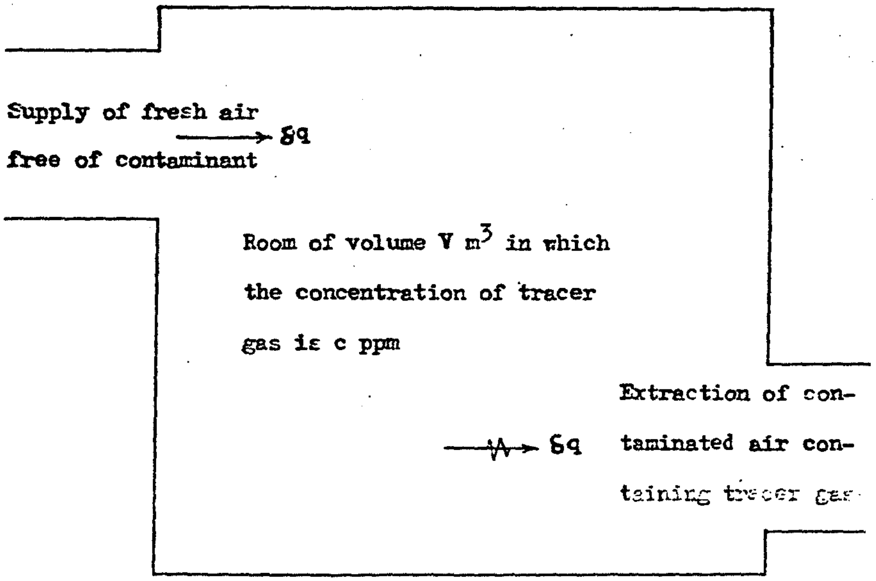
Consider a room as shown in Fig 3.I having a volume of Vm^3 in which the concentration of tracer gas is c ppm.(parts of tracer gas per million parts of air)

During a very short period δt, a small quantity of fresh air δq , enters the room and simultaneously a small quantity δq of contaminated air, is forced out of the room. Therefore the concentration of tracer gas within the room is reduced by an amount δc, which is defined as :-

$$\delta c = -\frac{\delta q}{V} . c$$

The negative sign is needed as the concentration is decreasing.

Fig 3.I



The rate of change of concentration in the room is defined as

$$\frac{dc}{dt} = - \frac{c\, dq}{V\, dt}$$

Let the room have a constant supply of fresh air Q (m^3/s)

$$Q = \frac{\partial q}{\partial t}$$

Therefore the rate of change of concentration of tracer gas is:-

$$\frac{\partial c}{\partial t} = -\frac{cQ}{V}$$

Integrating with respect to time

$$\int \frac{dc}{c} = -\frac{Q}{V} \int dt$$

$$\log_e c = -\frac{Qt}{V} + \log_e A$$

where $\log_e A$ is a constant of integration,

$$\text{Therefore} \quad \log_e c - \log_e A = -\frac{Q\,t}{V}$$

$$\log_e \frac{c}{A} = -\frac{Q\,t}{V}$$

$$\frac{c}{A} = \exp - (Q\,t / V)$$

$$\text{Therefore} \quad c = A \exp - (Q\,t / V)$$

Constant A is equal to the initial concentration c_o in the room at t = 0 (the instant that the ventilation begins)

$$\text{Therefore} \quad c = c_o \exp - (Q\,t / V) \qquad (3.1)$$

where c = concentration of tracer gas inthe air of the room at any instant,expressed as parts per million of air (ppm)

c_o = initial concentration of tracer gas in the air of the room, expressed as parts per million of air (ppm)

Q = fresh air supply rate (m^3 / s)

t = time variable (s)

V = volume of the room (m^3)

Equation (3.I) can be simplified by considering the time constant (T) for one air change within the room.

$$T = \frac{V}{Q} \left\{ \frac{m^3}{m^3/s} \right\}$$

where T = time constant for one complete air change within the room assuming perfect mixing (s)

From equation (3.I)

$$c = c_o \exp (- t / T) \qquad (3.2)$$

The number of complete air changes within the room in one hour is:-

$$AC/h = \frac{3600}{T} \qquad \underline{(Ih = 3600\ s)} \qquad (3.3)$$

To verify the method of calculating the air change rate per hour, consider a pulse input of tracer gas into a ventilated room.

Let the ventilated room have 2 complete air changes an hour and assume perfect mixing of a pulse input of tracer gas.

Therefore the time constant for one complete air change is from equation (3.3)

$$T = \frac{3600}{2} = 1800s$$

Substituting this value of T into equation (3.2)

$$c = co \exp\ (-t/1800) \qquad (3.4)$$

Let the value of c_o, initial concentration, equal an arbitrary value of unity. By substituting suitable values of time (t secs) in equation (3.4) the decay curve (concenration versus time) may be plotted. Fig 3.2 shows the decay part of the curve for a pulse input of tracer gas.

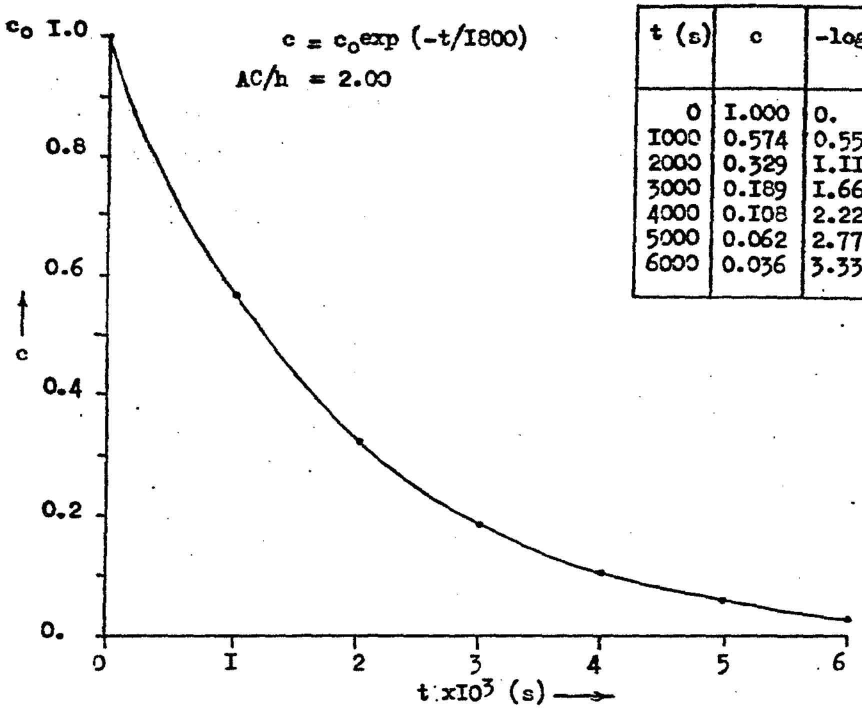
Rearranging equation (3.2)

$$\log_e \frac{c}{co} = -\frac{t}{T}$$

Therefore $t = -T \log_e \frac{c}{co}$ (3.5)

3.5 is a straight equation of the form $y = mx$ where T is the gradient of the line.

To verify correct calculation method for a pulse input of tracer gas.

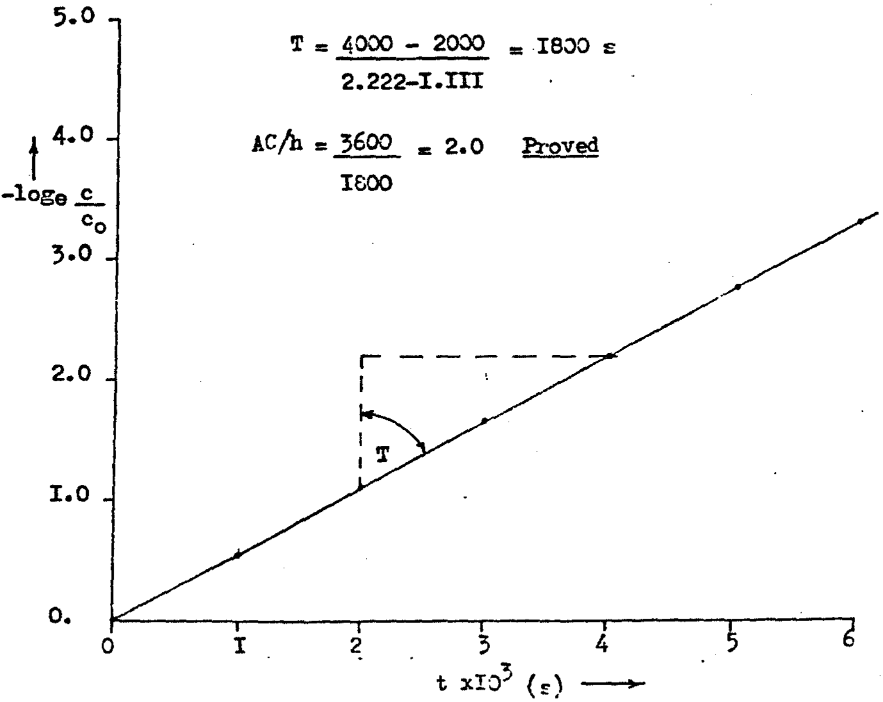


$c = c_o \exp(-t/I800)$

$AC/h = 2.00$

t (s)	c	$-\log_e \frac{c}{c_o}$
0	I.000	0.
I000	0.574	0.555
2000	0.329	I.III
3000	0.I89	I.666
4000	0.I08	2.222
5000	0.062	2.778
6000	0.036	3.333

Fig. 3.2



$T = \frac{4000 - 2000}{2.222 - I.III} = I800$ s

$AC/h = \frac{3600}{I800} = 2.0$ Proved

Fig. 3.3

By plotting t against $-\log_e \frac{c}{co}$, the time constant T can be obtained from the slope of the line, best fitting the points as shown in Fig 3.3.

It can be shown that the position taken from the initial concentration c_o is arbitrary as the time constant T will stay the same providing the final concentration when $t = \infty$ is known, and this should be the same concentration before the pulse input was liberated. The concentration decays rapidly, especially with a high ventilation rate, but even when the decay is slow providing there is sufficient curve to analyse there is no need to continue the test until the tracer gas concentration is equal to the initial value before the pulse input.

b) Equilibrium concentration method due to a step input of gas.

This technique requires a continuous release of tracer gas at a constant flow rate v (m^3/s) until a steady equilibrium concentration is reached within the room.

The theoretical explanation of the calculating method used is basically similar to the previous method, for the decay part of the curve. By considering the room in Fig 3.I the concentration of tracer gas within the room is increased at a rate of dc/dt. For simplicity assume that the steady supply of tracer gas is perfectly mixed with the supply of fresh air into the room.

Let c = concentration of tracer gas in the room at any instant, expressed as parts per million of air.

Q = rate of fresh air supply m^3/s

ca = concentration of tracer gas perfectly mixed with the supply air expressed in parts per million.

A gas balance equation can now be written.

Gas liberated in the room = Gas extracted from the room + Increase in gas concentration in room.

$$Q\frac{ca}{I0^6} = Q\frac{c}{I0^6} + \frac{V}{I0^6}\frac{dc}{dt} \qquad (3.6)$$

Let $D = \frac{d}{dt}$ (differentiation operator)

Multiplying by $I0^6$ and rearranging equation (3.6) becomes

$$ca = c\ \frac{(Q + VD)}{Q}$$

$$c = \left(\frac{I}{I + \frac{V}{Q}D}\right) ca$$

The time constant $T = \frac{V}{Q}$

Therefore $c = \left(\frac{1}{1 + TD}\right).\,ca$ (3.7)

Equation(3.7) is an anology to a first order transfer function, in control theory. Therefore with a step input the resulting first order step responce is written as

$$c = ca\ (I - \exp-(t/T)) \qquad (3.8)$$

To verify this method numerically consider a ventilated room of 2 complete air changes an hour and assume perfect mixing of a step input of tracer gas.
The time constant for one complete air change as before is

$$T = \frac{3600}{2} = I800s$$

Similar to the decay rate method the absolute values of tracer gas concentration can be ignored providing the electrical output from the gas analyser to the chart recorder is linear and the chart speed is known. Substituting the above value of T into equation 3.8 gives :-

$$c = ca\ (I - \exp -t/I800) \qquad (3.9)$$

Let the concentration of tracer gas be an arbitrary value of unity. By substituting suitable values of time (t) in equation 3.9 the step response curve may be plotted as shown in Fig 3.4

One method of analysing this type of curve is the fractional response method which considers all the readings on the curve.
By rearranging equation 3.8

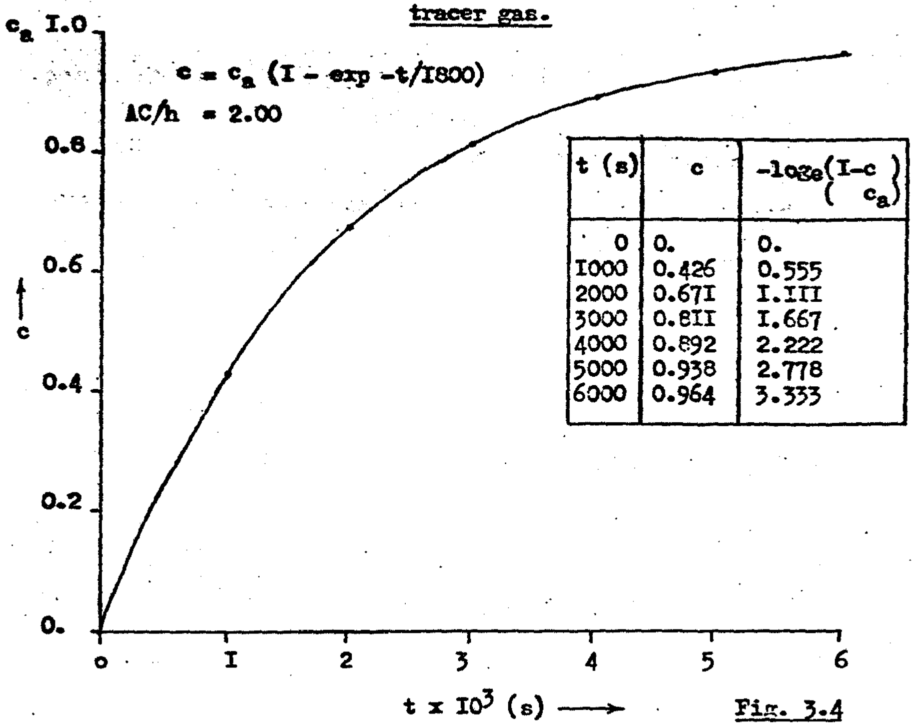
$$\log_e \left(I - \frac{c}{ca}\right) = \frac{-t}{T}$$

Therefore $t - -T \log_e \left(I - \frac{c}{ca}\right)$

this is a straight line equation of the form $y = mx$ where the time constant is the gradient.

By plotting $-\log_e \left(I - \frac{c}{ca}\right)$ against t, the time constant T can be obtained from the slope of the line best fitting the

To verify correct calculation method for a step input of tracer gas.

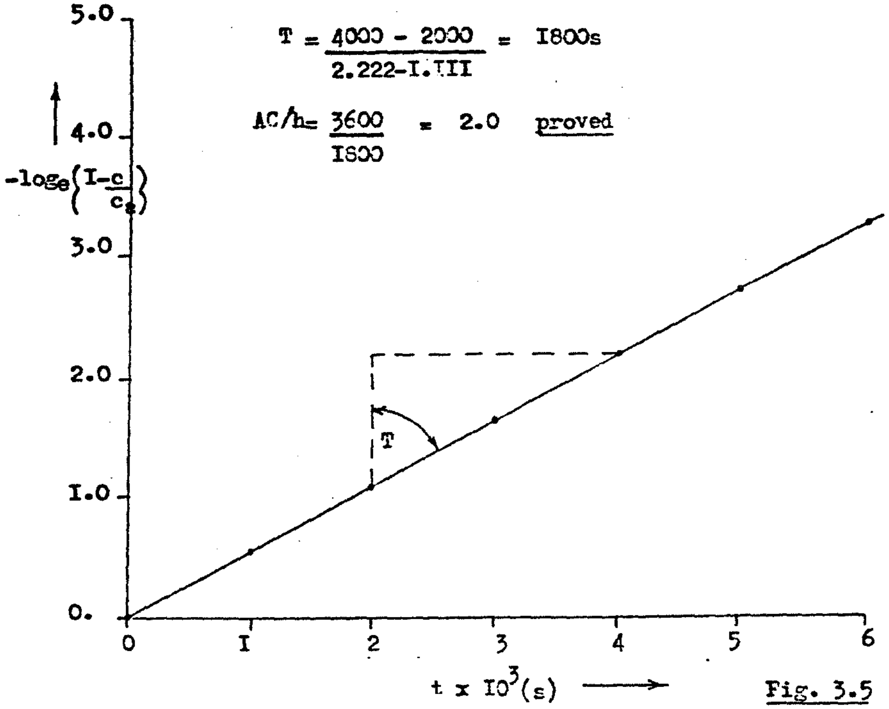


$c = c_a\,(I - \exp -t/I800)$

AC/h = 2.00

t (s)	c	$-\log_e\left(I-\frac{c}{c_a}\right)$
0	0.	0.
I000	0.426	0.555
2000	0.67I	I.III
3000	0.8II	I.667
4000	0.892	2.222
5000	0.938	2.778
6000	0.964	3.333

Fig. 3.4



$$T = \frac{4000 - 2000}{2.222 - I.III} = I800s$$

$$AC/h = \frac{3600}{I800} = 2.0$$ proved

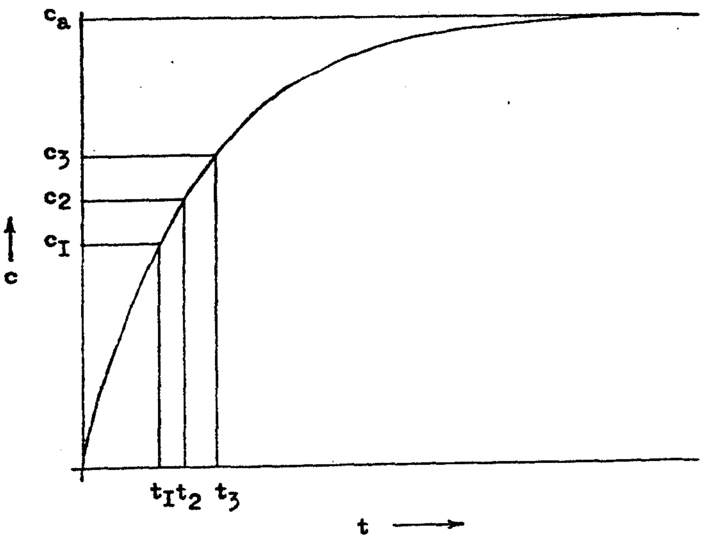
Fig. 3.5

points as shown in Fig 3.5

With this method the final concentration c_a is required to calculate the ventilation rate in the room and this can result in a long experimental period of several hours for very low air change rates and during this period the air infiltration rate into the room being variable, will probably have changed. An alternative to continuing the test until a steady condition is reached is to analyse the initial part of the plot using a computer program.

Fig 3.7 shows the computer program used for analysing the initial part of a step response curve. By considering two points on the curve (t_1, c_1) and (t_2, c_2) as shown in Fig 3.6

Fig.3.6



The equations for the two points respectively :-

Computer program to analyse the step response curves.

Language - BASIC

```
IO  PRINT "NAME & REFERENCE NO."  .   .   .   headings
20  PRINT "TI","CI","T2","C2","T"
30  S = 0
40  N = 0
50  LET T = IOOO .  .  .  .  .  .  .  .  .   initial value of T
60  DISP "INPUT TI(SEC), CI"
70  WAIT 2500
80  INPUT TI,CI     .  .  .  .  .  .  .  .   first co-ordinate on curv
90  DISP "INPUT T2(SEC), C2"
IOO WAIT 2500
I20 INPUT T2,C2     .  .  .  .  .  .  .  .   next co-ordinate on curve
I30 IF TI # 0 AND CI # 0 THEN I60
I40 LET TI = TI + 60
I50 LET CI = CI + 0.0005
I60 IF T2 = TI AND C2 = CI THEN 370
I70 R = CI/C2
I80 X = TI/T
I90 IF X> 230 THEN 2IO
200 GOTO 220
2IO X = 230
220 Y = T2/T
230 IF Y> 230 THEN 250
240 GOTO  260
250 Y = 230
260 LET RI = ((I-EXP(-TI/T))/(I-EXP(-T2/T))) --+
270 LET R2 = R - RI                             |
280 IF R2<0.0005 AND R2> -0.0005 THEN 3IO       +------ iteration to find T
290 LET T = T - (IOOO * R2)                     |
300 GOTO  260                       ------------+
3IO PRINT TI,CI, T2,C2,T
320 S = S + T
330 N = N + I
340 LET TI = T2
350 LET CI = C2
360 GOTO  90
370 LET M = S / N
380 PRINT "AVERAGE T = " M, "AC/E = " 3600/M
390 STOP
400 END
```

The above program was adapted to analyse the rate of decay curves.

Fig.3.7

$$c_I = c_a (I - \exp(-t_I/T)) \qquad (3.9)$$

$$c_2 = c_a (I - \exp(-t_2/T)) \qquad (3.IO)$$

A mean value of T can be found by considering pairs of points on the curve such as (c_I, t_I) and (c_2, t_2); (c_2, t_2) and (c_3, t_3). It was found that with a theoretical curve the time constant could be derived, but with a real curve which is not precisely exponential the values of time constant for each pair of points can be widely different, especially as $t \to 0$. This type of analysis was also adapted for the decay rate method, but due to the large scatter about the mean value the graphical method was used for analysing the majority of the readings.

3.3 Experimental Room Used for Air Ventilation Measurement Tests.

The experimental room and the test arrangement are shown in Fig 3.8. A 250mm diameter variable speed vane axial fan manufactured by "Woods" of Colchester was connected by a square metal duct to a blade type damper. The damper was adjusted by a finely threaded screw arrangement giving a good reproducible damper position.

From the damper the square ductwork abruptly transforms into circular ductwork to pass into the experimental room. To obtain very low ventilation rates within the room the extract duct was blocked off except for a I25mm diameter orifice, and this was found to be sufficient without an ex-

Experimental Room

Key

F - 250mm diameter supply fan

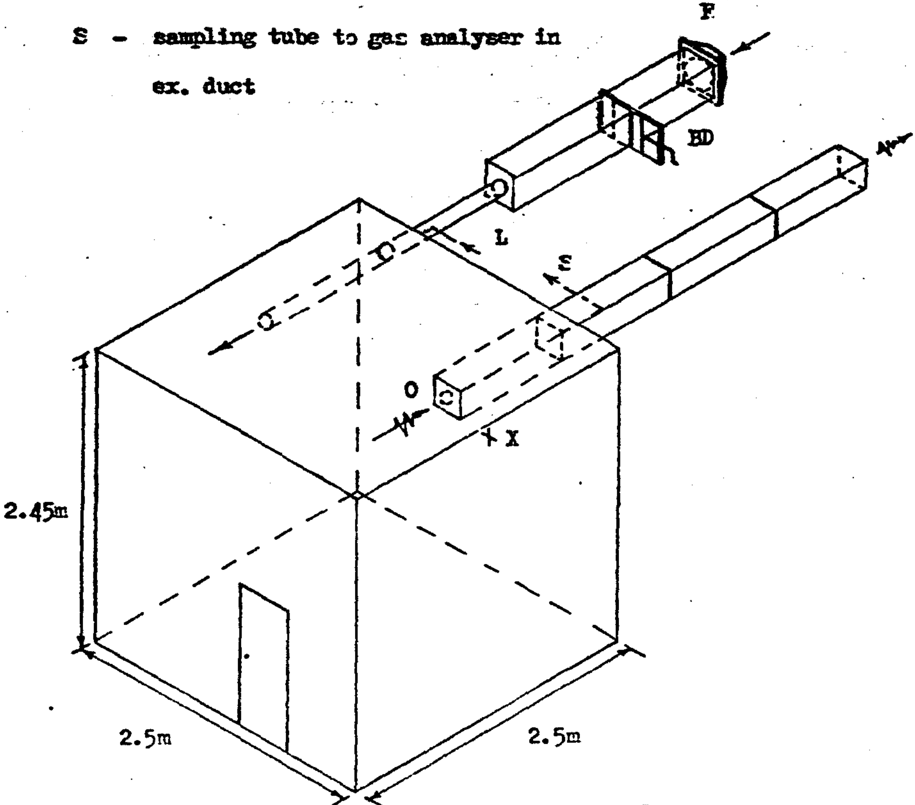
BD - blade damper

O - I25mm diameter orifice in ex. duct cover

X - balloon position for a pulse input of gas

L - tracer gas liberating point in sup. duct

S - sampling tube to gas analyser in
ex. duct



Ductwork

250 x 250 mm ductwork

I25 mm dia. ductwork

Fig. 3.8

tract fan.

The sampling tube to the gas analyser was placed in the extract duct as it was assumed that the tracer gas would be perfectly mixed with the air by then and this was the only place where air could leave the room as the latter was practically completely sealed within the limits of materials readily available. There must have been a small exchange of air between the experimental room and the outside due to the slightly higher pressure within the room, and that the room was constructed of porous materials.

The supply fan had a possible seven speeds giving a range from 600rpm to 1150rpm which, with suitable damper positions gave a ventilation rate within the room of between one and twenty air changes per hour assuming complete air changes and perfect mixing.

The experimental room, ductwork system and fan were situated in a larger room. So that air leaving the inner room was not re-circulated round the system, windows and doors were left open. Ideally no re-circulation was wanted, but due to the position of the extract duct, a little was unavoidable. Most of the tests were performed during calm weather conditions with low or no wind speeds, so that similar conditions for all tests were assured as could be practical.

The air flow distribution in the room was followed using a T E M Smoke Generator system for flow visualisation in air, and the instrument is discussed further in Section 7. The air flow currents were checked to ensure that the air was being reasonably mixed in the room before leaving via the extract duct. It was difficult to see the air flow patterns at very low velocities and a "puffer" type smoke probe was used which gave a better visual display of the air than the smoke generator.

3.4 Test Procedure.

A suitable range of damper positions with their appropriate fan settings were selected. The air velocity in the circular duct into the test room was measured using an electrical vane anemometer for the preliminary ventilation rates. To accurately measure the flow rate of air supply into the room a pitot tube was used according to BS 1042 Part 2A for the measurement of air flow rates in circular ductwork. Traverses were carried out over two diameters at right angles. On each traverse, measurements of the velocity pressure were made at ten points, located by the log-linear rule as shown in Fig 3.9

The ten point log-linear method of numerical integration by which the duct is divided into five zones of equal area, and velocity readings taken in each zone.

The pitot-static tube used was similar in construction to a N.P.L. modified ellipsoidal nosed standard pitot-static

Location of measuring points according to the I0-point log-linear rule. (BS I042 : Part 2A : I973)

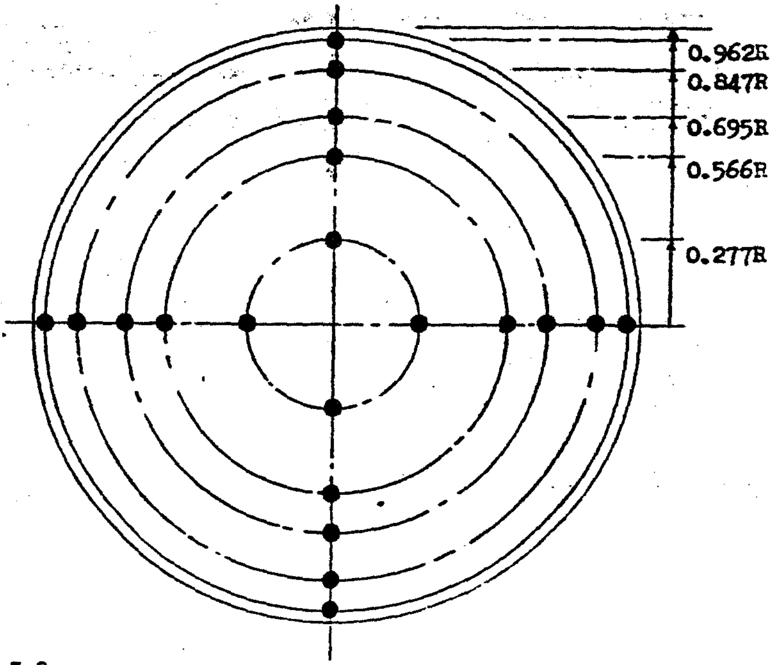


Fig.3.9

N.P.L. modified ellipsoidal-nosed standard pitot-static tube

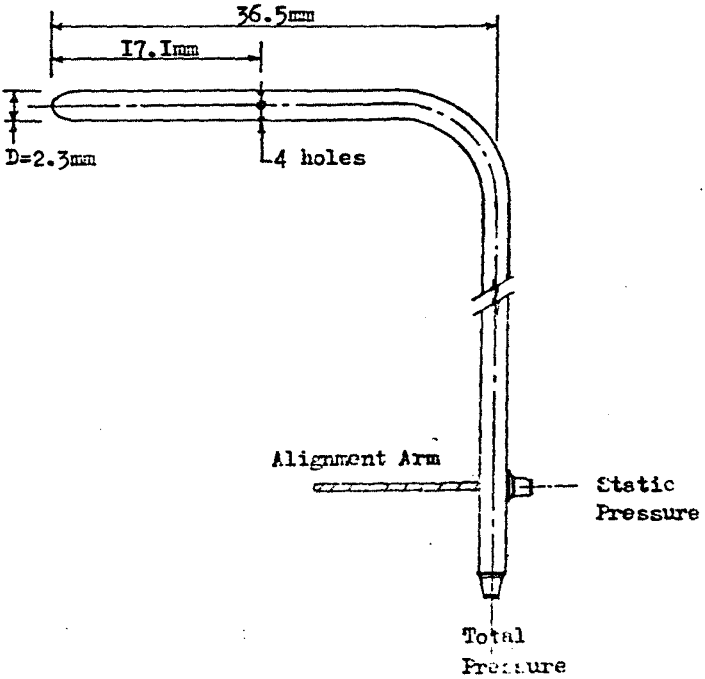


Fig.3.I0

tube and the dimensions of the one used given in Fig 3.10 The pitot-static tube consists of two concentric tubes, the inner one transmitting the total pressure while the annular space between the tubes transmits the static pressure.

The axis of the pitot tube was kept firmly positioned and parallel to the axis of the duct by an adjustable frame. In order to keep the blockage effect to a minimum the traverse on each diameter was carried out from each side so that the pitot-static tube was never more than half way across the duct.

As air velocity in the ductwork was low, below 7.5m/s, the resulting velocity pressure was only 3.5mm wg, a very accurate electronic micromanometer was used, manufactured by "Furness Controls Ltd" which is described more in section 7.

The electronic micromanometer was calibrated and then checked against a vernier reading manometer manufactured by "C F Cassella and Co Ltd" The manometer can be read by a vernier to 0.02mm wg over the whole range and has a much more damped response compared with the electronic micromanometer. The latter tends to produce more "noise" with the meter pointer.

During each test the temperature of the air was recorded using an ordinary mercury in glass thermometer and the barometric pressure was noted as both affect the velocity pressure recorded by the manometer.

For each air flow rate the fan speed was measured using a Strobatac which gave a direct reading in revolutions per minute.

When a suitable range of air flow rates had been measured and recorded the tracer gas methods were used to compare results. As the two methods using tracer gas differ in their test procedure they have been divided into seperate sub-sections.

The infra-red gas analyser used for all the tests was manufactured by "Grubb Parsons Co. Ltd." and calibrated to detect nitrous oxide as described in more detail in Section 7. The output from the analyser was connected to a potentiometer chart recorder manufactured by "Oxford Instrument Company Ltd." which has variable chart speeds from Icm/hour to 50cm/min. The chart speed chosen depended on the air flow rate into the room and the expected length of decay required to calculate the air change rate within the room. The sampling tube to the gas analyser was placed in the extract duct as all the air leaving the room was assumed to pass through this duct when the room had been sealed with adhesive tape. The sampling tube was similar to a pitot tube projected in the extract duct and parallel to the duct's axis.

3.41 Rate of decay due to a pulse input of gas.

As the quantity of tracer gas liberated into the room was of little importance, a balloon filled with the gas was considered to be a suitable input of point source. The balloon was placed in the room on the wall marked with an "X" in Fig 38 as this was a convenient position to burst the balloon by projecting a pin from the outside of the room and the air around the area was very turbulant as seen with the smoke probes.

The procedure for each test was to wait until the gas analyser was steady, which normally took at least forty five minutes. During this time the fan, at its selected speed could be running so that the whole system was settled. The windows and doors of the external room were kept open to remove the released nitrous oxide and to decrease the chance of recirculation within the system once the test had started.

A balloon was then filled with nitrous oxide from a gas cylinder, sealed and placed in the position marked X in Fig 3.8. Once the balloon was placed, the door of the room was securely closed and then the system was left a few more minutes depending on the air flow rate, to settle. During this period the chart recorder was switched on at the selected chart speed. When the system was completely steady, the balloon was burst by a pin penetrating the room wall.

When sufficient of the decay curve had been plotted on the chart recorder for the air flow rate to be determined, the recorder was switched off and the concentration in the room was reduced by increasing the air flow rate and opening the door. To reduce the concentration of nitrous oxide in the room to zero or the initial value, depending on the number of previous tests, normally took about thirty minutes, then another experiment could be performed. Besides using a balloon to create a pulse input, opening the regulating valve on the gas cylinder for a few seconds was also used. The gas was initially released at the same position as the balloons had been burst, but it was also liberated directly into the supply duct to the room.

Later tests were performed having an oscillating desk fan working in the room. This was to completely mix the tracer gas with the fresh air supply and to see if there was any significant difference in results.

3.4.2 Equilibrium concentration method

As the experimental room was very small, to produce a step input of gas which would create a steady response of below 100ppm concentration, so that the gas analyser could be used in its high sensitivity mode, presented the problem of producing a low, steady gas flow rate of below 100cc/min. This was achieved by using a fine vernier metering valve manufactured by "Munro Co." U.S.A.

between the gas cylinder and a rotameter manufactured by Platon Ltd which is discussed later in Section 7.

The setting up of the gas analyser and chart recorder was similar to the procedure for a pulse input. The windows and doors of the external room, were kept open and the door of the experimental room kept firmly closed. When the gas analyser and chart recorder were settled, a pre-calculated steady supply of tracer gas (N_2O) was introduced into the supply duct to mix with the incoming fresh air.

After a period of time, depending on the air supply rate into the room an equilibrium tracer gas concentration was reached at which point the gas was switched off. Depending on the time, the concentration was either left to decay by the selected air flow rate, or the air flow rate was increased and the room door opened, so that the next test could proceed within approximately thirty minutes.

As with the other method an oscillating table top fan was used in the room with some tests to completely mix the tracer gas with the incoming fresh air to see if there was any significant difference in results.

3.5 Results.

Air flow rate calculated by using a pitot-static tube.

In BS I042 Part 2A I973, many correction factors are mentioned to be applied to the measured differential pressure, but due to the uncertainties caused by the fluctuation of the electronic micromanometer meter which outweighed most of these minor corrections it was decided only to adjust the velocity pressure for temperature and atmospheric pressure measurements.

$$VP = \rho v^2/2 \qquad (3.II)$$

where VP = velocity pressure = differential pressure (N/m^2)

ρ = density of air (kg/m^3)

v = velocity of air (m/s)

Now ρ depends upon the temperature and pressure of the air. Strictly the air in the duct will be at a pressure B = SP where SP is the static pressure in the duct measured above or below the barometric pressure B; but this correction can be neglected where SP is much less than B.

Density of air at STP (0°C) = I.293 kg/m^3 so that for any temperature t°C and pressure B mm of mercury,

$$\rho = I.293 \times \frac{273}{273+t} \times \frac{B}{760} = 0.4644 \frac{B}{273+t} \qquad (3.I2)$$

The velocity pressure was measured in mm of water guage by the micromanometer and as

One pascal (Pa) = I N/m^2 = 0.1020 mm wg.

Let h = velocity head expressed in mm wg

$$VP = 9.807h \qquad (3.I3)$$

On substituting 3.I3 and 3.I2, equation 3.II becomes

$$v = 6.4988 \sqrt{\left(\frac{273 + t}{B}\right) h} \quad (m/s) \qquad (3.I4)$$

The mean air velocity in the duct is

$$v_m = \frac{I}{n}(v_1 + v_2 + \; .... \; + v_n)$$

where n = number of pitot-static tube readings. The air flow rate in the circular duct is :-

$$Q = \pi r^2 v_m \quad (m^3/s)$$

$$Q = \frac{\pi d^2}{4} v_m \quad (m^3/s)$$

The ten selected air flow rates were measured using the pitot-static tube and micromanometer, and the results were recorded. Using the tracer gas method a pulse input by a balloon was carried out on each air flow rate. More extensive tests were performed on only four selected air flow rates as tabulated in Table 3.2, assuming perfect mixing with complete air changes for the results.

$$AC/h = \frac{3600\ Q}{V} \qquad I\ h = 3600s$$

Where V = volume of experimental room (m^3)

The calculations of air flow rate using the tracer gas method have been divided into sub-sections.

3.5I Rate of Decay

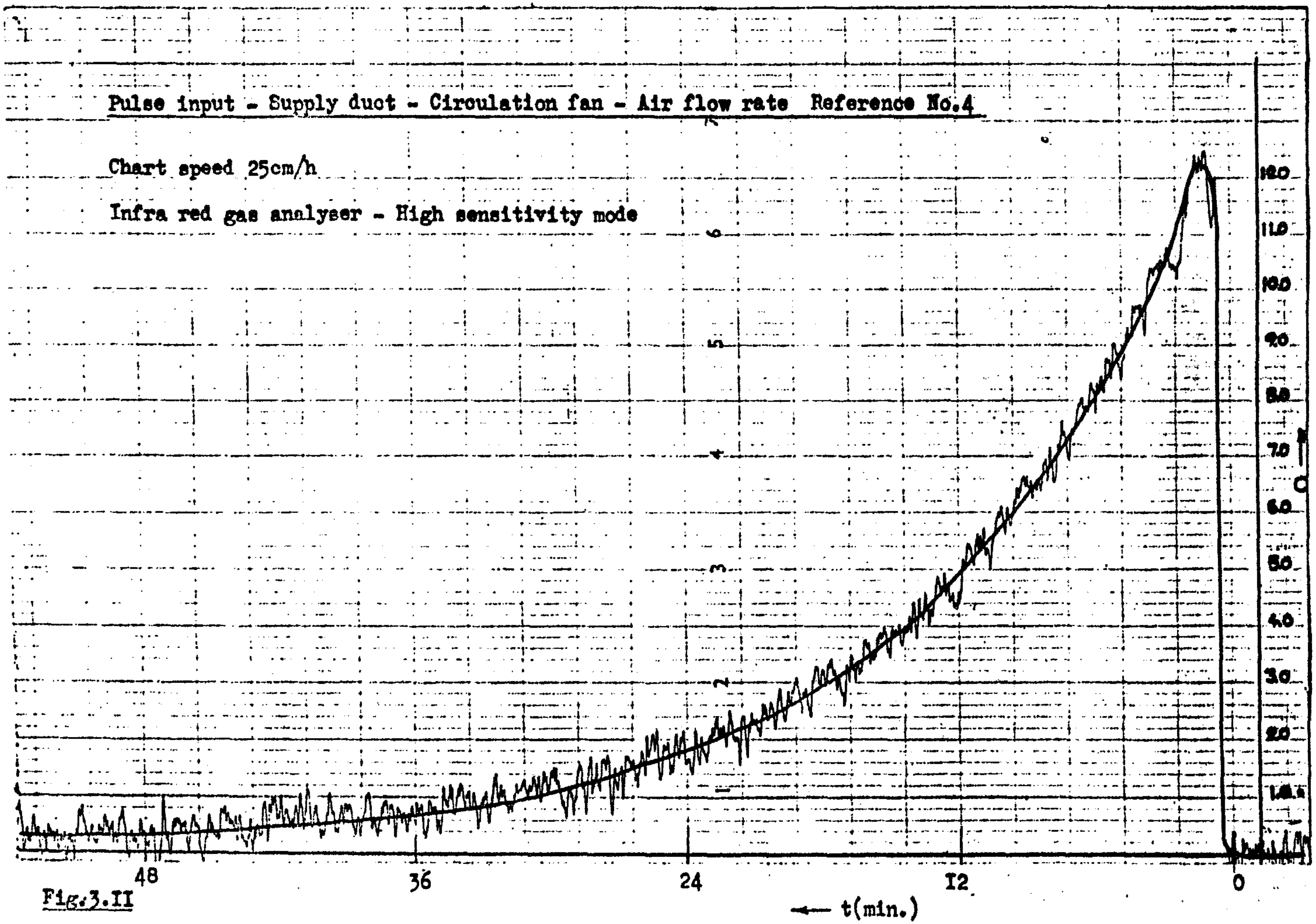
The calculation method for the air flow rate is the same whether the pulse input of the tracer gas was released in the supply duct or by bursting a balloon in the room. Fig 3.II shows a decay curve for a pulse input of tracer gas for a flow rate reference number 4 from Table 3.2 with a circulation fan in the room.

As the chart recorder used heat sensitive paper which easily marks, the curve was copied onto tracing paper.

The "Y" or "concentration" axis of the curve was given an arbitrary linear set of values as shown and a suitable number of points were located to apply the fractional response method. The time (sec) was plotted against -log $(\frac{c}{c_0})$ and the gradient of the straight line found, which is the time constant of one complete air change.

Therefore :- $AC/hrs = \frac{3600}{T}$

This exercise was repeated for all the decay rate curves to find the air flow rate in the room. Although the tracer gas concentration curve, shown in Fig3.II was allowed to decay nearly to its initial concentration, this was unnecessary providing there was sufficient curve to be able to plot time



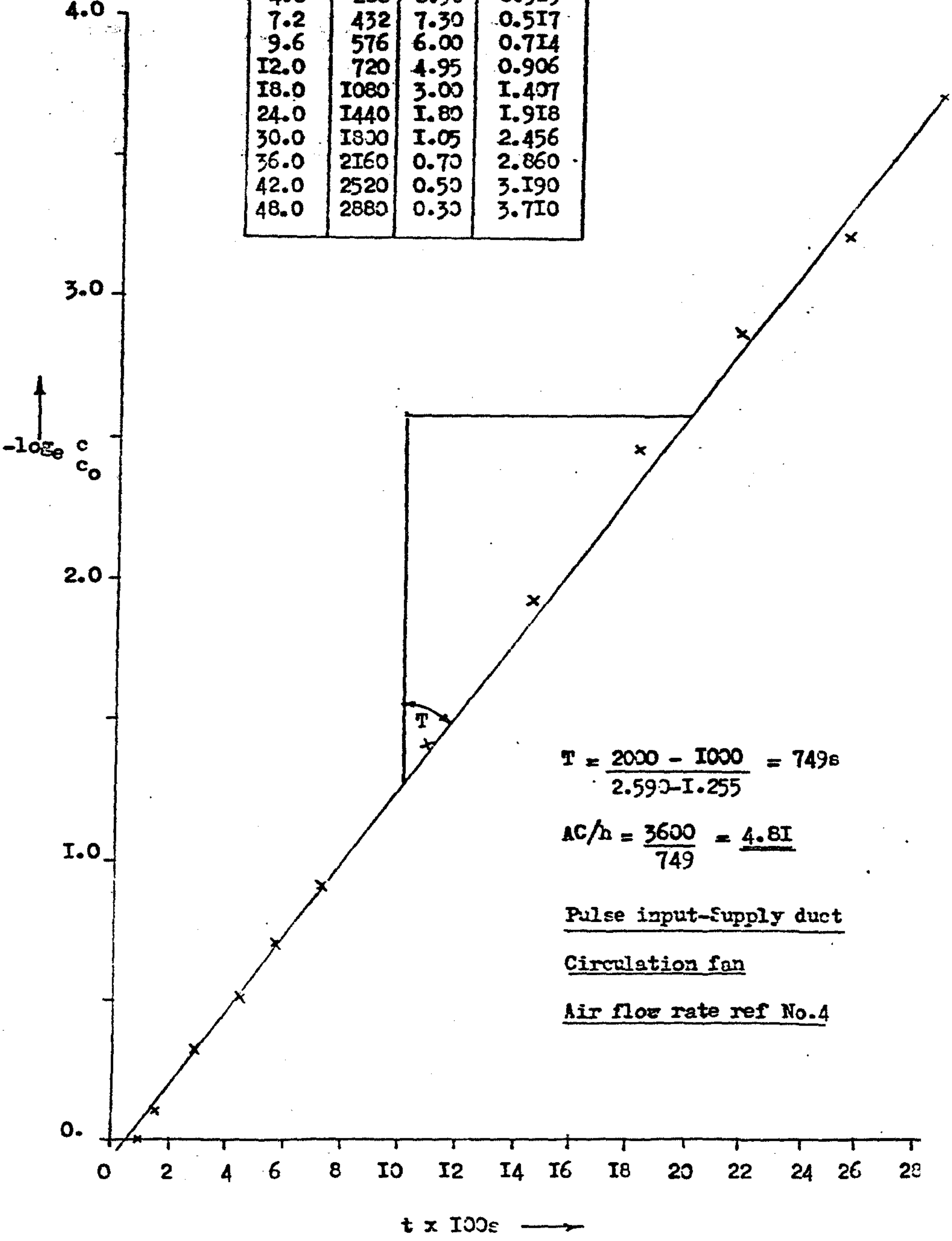
Pulse input - Supply duct - Circulation fan - Air flow rate Reference No.4

Chart speed 25cm/h

Infra red gas analyser - High sensitivity mode

Fig.3.II

t (min.)	t (sec)	c	$-\log_e \frac{c}{c_o}$
1.5	90	12.25	0.
2.4	144	11.00	0.107
4.8	288	8.90	0.319
7.2	432	7.30	0.517
9.6	576	6.00	0.714
12.0	720	4.95	0.906
18.0	1080	3.00	1.407
24.0	1440	1.80	1.918
30.0	1800	1.05	2.456
36.0	2160	0.70	2.860
42.0	2520	0.50	3.190
48.0	2880	0.30	3.710



$$T = \frac{2000 - 1000}{2.590 - 1.255} = 749s$$

$$AC/h = \frac{3600}{749} = \underline{4.81}$$

<u>Pulse input-Supply duct</u>

<u>Circulation fan</u>

<u>Air flow rate ref No.4</u>

Fig.3.11a

against $-\log \frac{c}{c_a}$ to find the time constant.

3.52 Equilibrium concentration method

Fig.3.I2 shows the response concentration curve to a step input of tracer gas of approximately 55 cc/min. with an air flow rate, reference 4, from Table 3.2. This particular test was with a circulation fan in the room, but the analysis of the curve is the same without such a fan. A tracing of the curve was made and a number of points of time against concentration were located. The time constant was found by plotting time against $-\log_e(I - c/c_a)$, and measuring the gradient of the best fitting straight line as shown in Fig. 3.I2.

With this method the steady concentration has to be known for calculation purposes so the test cannot be shortened as the decay rate method.

3.6 Experimental errors

The air flow readings from the pitot-static tube were used as a datum for comparing the different methods using tracer gas. Owing to the very low air flow into the room, the resulting velocity pressures were extremely small (0.00Imm to 4mm wg),andthe excessive air turbulence in the duct from the abrupt transformation pieces over a short length creating fluctuations in the electrical micromanometer readings.

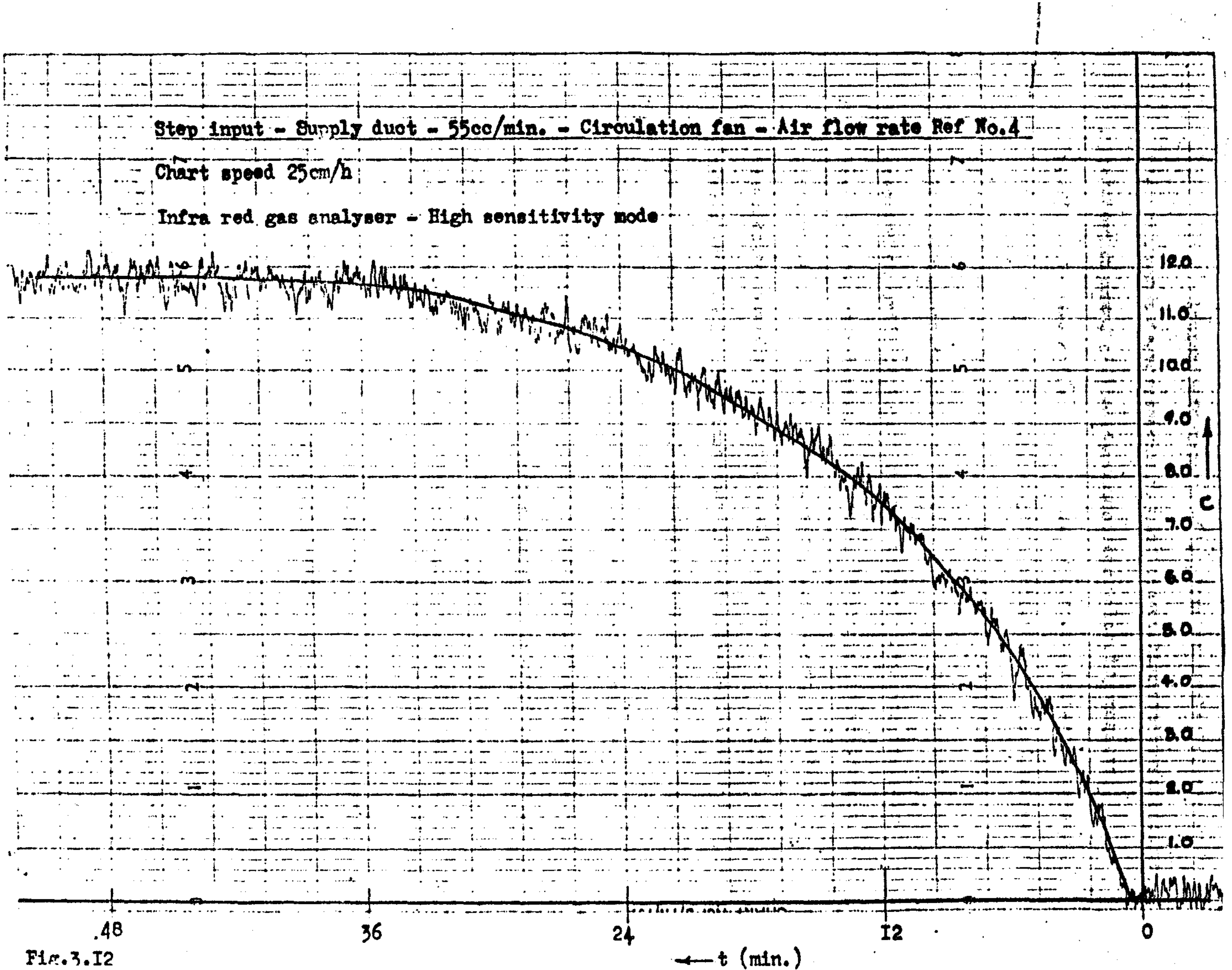

Step input - Supply duct - 55cc/min. - Circulation fan - Air flow rate Ref No.4
Chart speed 25cm/h
Infra red gas analyser - High sensitivity mode
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
C
.48
36
24
12
0
t (min.)

Fig.3.12

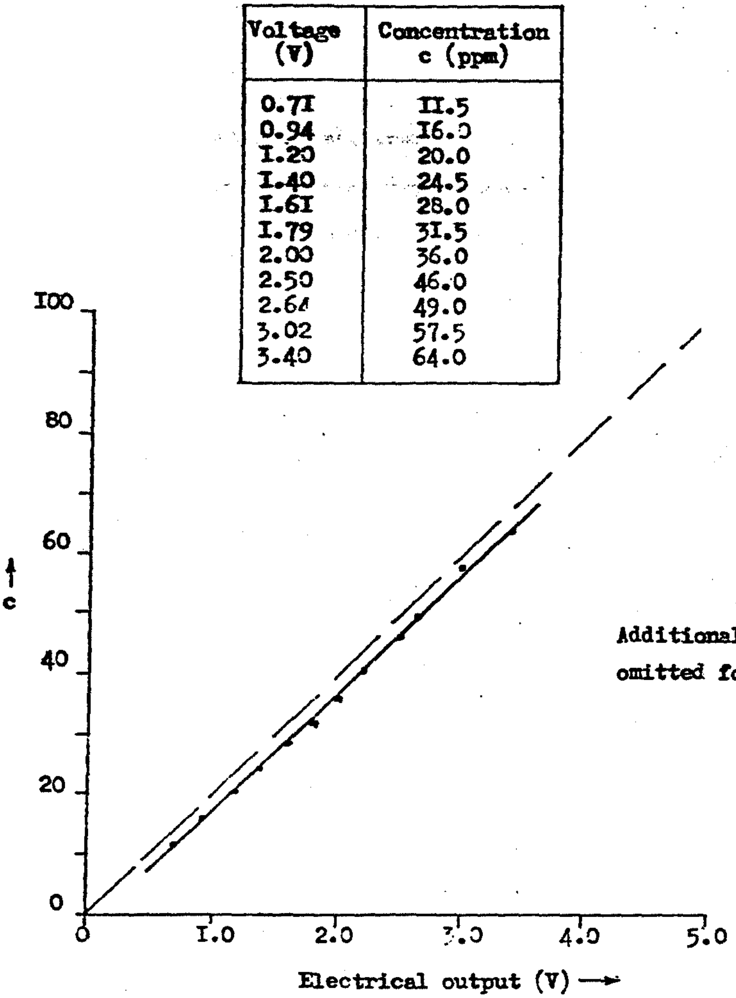
Approximate error (α), shown in table 3.I of the mean pitot traverse results has been calculated by assessing the deviation σ, of the micromanometer velocity pressure, reeding where $\alpha = \sigma/\sqrt{n}$ (n = number of points on traverse)

"Ower and Pankhurst" in their book "The measurement of Air Flow" advise using other forms of measuring device other than manometers below I5ft/s (4.57m/s) such as the vane anemometer, orifice plate, or the venturi tube, or, for very low speeds, the hot wire anemometer. Although the electronic micromanometer used could measure to 0.00I mm wg and there was nearly complete correlation with the vernier reading manometer. The former instrument is much more sensitive to pressure changes, but quick to take readings from.

As the tracer gas method depends entirely on the electrical output of the infra-red gas analyser, it was checked with a digital voltmeter against the front meter on the analyser and the graph of the readings is shown in Fig 3.I4. From the graph the electrical output is slightly out of phase with the front meter showing the concentration, but the output is linear and parallel with the ideal line and as the absolute concentration was not needed the output value was left uncorrected.

The absolute gas concentration should be read from the calibration curve, included with the analyser. The electrical output when the analyser is in the high sensitivity mode needs no correction applying to it for the absolute value.

Fig.3.14



Voltage (V)	Concentration c (ppm)
0.71	11.5
0.94	16.0
1.20	20.0
1.40	24.5
1.61	28.0
1.79	31.5
2.00	36.0
2.50	46.0
2.64	49.0
3.02	57.5
3.40	64.0

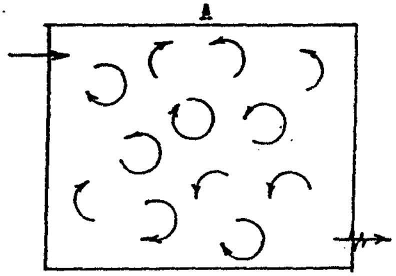
Additional points omitted for clarity

Additional Sources of Errors in Air Ventilation Measurements

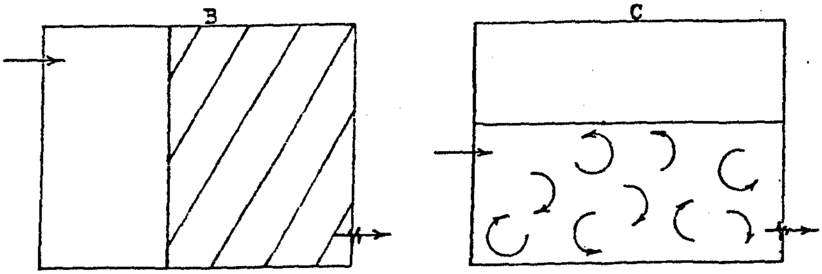
Effect of Non Uniform Mixing:- Air exchange rates based on tracer dilution rates and calculated as outlined previously have been based on the assumption of perfectly mixed complete air changes. The alternative conditions to this are illustrated in Fig 3.15.

In the non mixing model, fresh air enters as a front and pushes the air containing tracer gas ahead of it. "Hunt" in a paper for the A.S.H.R.A.E. proves that the average gas concentration over the entire volume is an inverse linear function of time.

With the second non uniform mixing model which is illustrated in Fig 3.I5(c) the upper volume contains completely stagnant air, whilst in the lower volume perfect mixing occurs.



Perfect mixing model.



Perfect non-mixing model.

Dead spot model.

Fig.3.I5

These models suggest that poor mixing could lead to air exchange rates measured by the tracer gas method which are either higher or lower than the true rate, depending on the type of mixing model which predominates.

Another source of error in the measurement of tracer concentration is drift in instrumental response with time, particularly when the instrument has just become operational after the "warming up" period. This can be minimized by checking against a reference (fresh air) to establish the drift, but as the concentration curve against time is needed in analysing the results this check can only be performed at the beginning or end of each test.

Additional errors arise when fitting a curve to the plot produced by the chart recorder owing to the "noise" produced by the recorder.

Another source of error was having the extract from the experimental room into the main room from where the supply was taken. Ideally the extract should have been ducted to the outside. The slight amount of recirculated tracer gas which resulted from the above system was probably the contributing factor to the high air exchange rate with the step input method.

The sampling tube to the analyser was placed in the extract duct, assuming that all the air would leave the room by this duct, but some air leaked into or out of the room from the unsealed cracks in the wall, floor and ceiling. The pitot-static tube was used to measure the supply air into the room assuming the same quantity left by the extract duct.

3.7 Conclusion.

The graphs of air exchange rates by the pitot-static tube, against the values calculated by the various tracer gas methods, shows close correlation with the ideal straight line up to about 7AC/hr. Above this, there is a large scatter of points and little can be concluded from the upper points owing to the few tests performed.

Below about 7AC/hr most of the results are the positively larger than the "datum" pitot traverse readings. This is particularly the case with the step input of tracer gas, but this is probably due to recirculation of the gas in the system which would result in a higher air change rate. Especially with the larger quantity of gas used with this method, making the difference even more predominant.

If recirculation of the tracer gas within the system existed, it would decrease the air change rate with the decay rate method. So, it can be concluded that the tracer gas method gives slightly higher results compared with the pitot traverse method.

The rate of decay method with a fan in the room to thoroughly mix the tracer gas and air, gave slightly better correlation than the other method which were reproducable. Because of this, and that it required less time, this was the method used in other rooms as described in the next section.

Comparison of methods in measuring the air change rate in the Experimental Room . Pulse input by a balloon - pitot tube traverse

Ref. No.	Fan speed (rpm)	Damper Position (mm)	Pitot traverse (20 Points)	Approx. Error	Tracer Gas Method		
					Pulse Input	Mean	Deviation with col.4
I	2	3	4	5	6	7	8
			AC/h	α	AC/h	AC/h	
I	605	I2	0.94	±0.049	I.I 0.82	0.96	+0.02
2	680	I2	I.50	±0.06	I.32 I.82	I.57	+0.07
3	620	50	3.I4	±0.080	3.2	3.2	+0.06
4	690	50	5.34	±0.085	5.55 4.68 5.50	5.24	-0.I
5	650	I50	4.0I	±0.II	4.29	4.29	+0.28
6	700	I50	6.68	±0.I4	6.52	6.52	-0.I6
7	740	I50	9.54	±0.I6	8.28 9.43	8.85	-0.69
8	8I0	I50	I3.2I	±0.23	I0.3I	I0.3I	-2.90
9	980	I50	I6.28	±0.I9	I2.39	I2.39	-3.89
I0	II20	I50	I9.I4	±0.32	30.48	30.48	+II.3

Table 3.I

Comparison of methods in measuring the air change rate in the Experimental Room. . Pulse and step inputs using tracer gas

Ref. No. I	Pulse input Sup. duct 2 AC/h	Mean 3 AC/h	Dev. with Pitot Traverse 4	Pulse input Sup. duct Circ. fan 5 AC/h	Mean 6 AC/h	Dev. with Pitot Traverse 7		Step input Sup. duct 8 AC/h	Mean 9 AC/h	Dev. with Pitot Traverse I0	Step input Sup. duct Circ. fan II AC/h	Mean I2 AC/h	Dev. with Pitot Traverse I3	Pitot Traverse Method I4 AC/h
I	I.07	I.07	+0.I3	I.26 I.I3	I.I9	+0.25		I.74	I.74	+0.80	I.44	I.44	+0.50	0.94
2	I.7I I.70	I.70	+0.20	I.80	I.80	+0.30		I.70	I.70	+0.20	I.60	I.60	+0.I0	I.50
4	6.25 4.76	5.5I	+0.I7	5.00 5.74 4.8I	5.I6	-0.I6		5.40 5.52	5.46	+0.I2	5.20 5.52 4.80	5.I7	-0.I7	5.34
7	8.I6	8.I6	-I.38	8.34	8.34	-I.20		9.86	9.86	+0.32	I0.62	I0.62	+I.08	9.54

Table 3.2

Tracer Gas Pulse Input Methods - Pitot Traverse Method

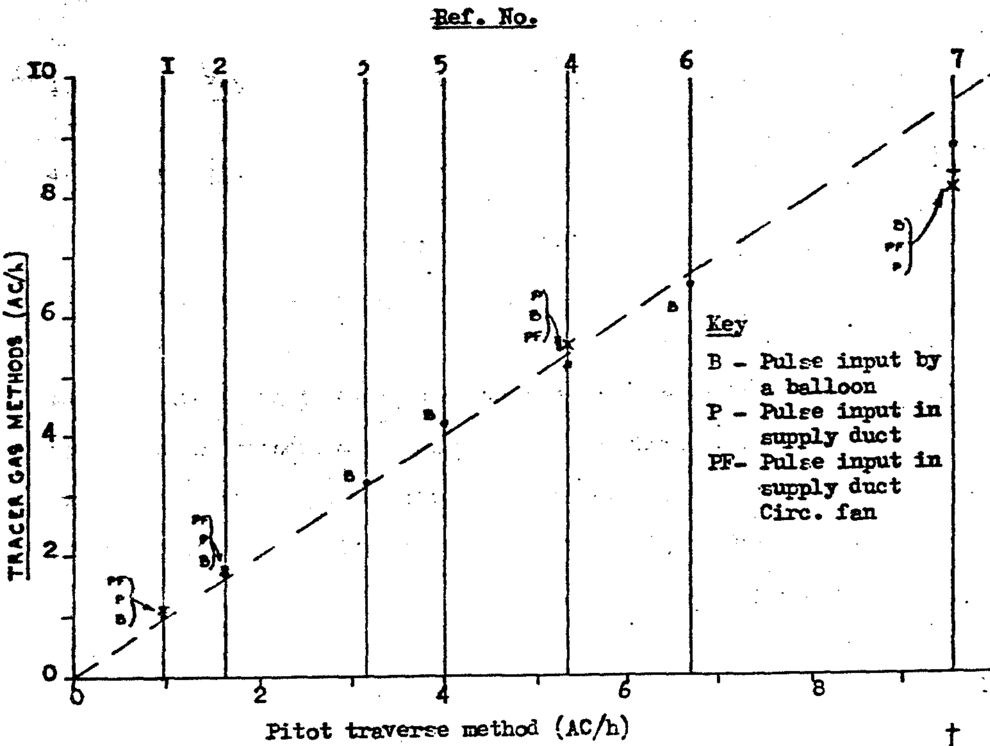


Fig. 3.16

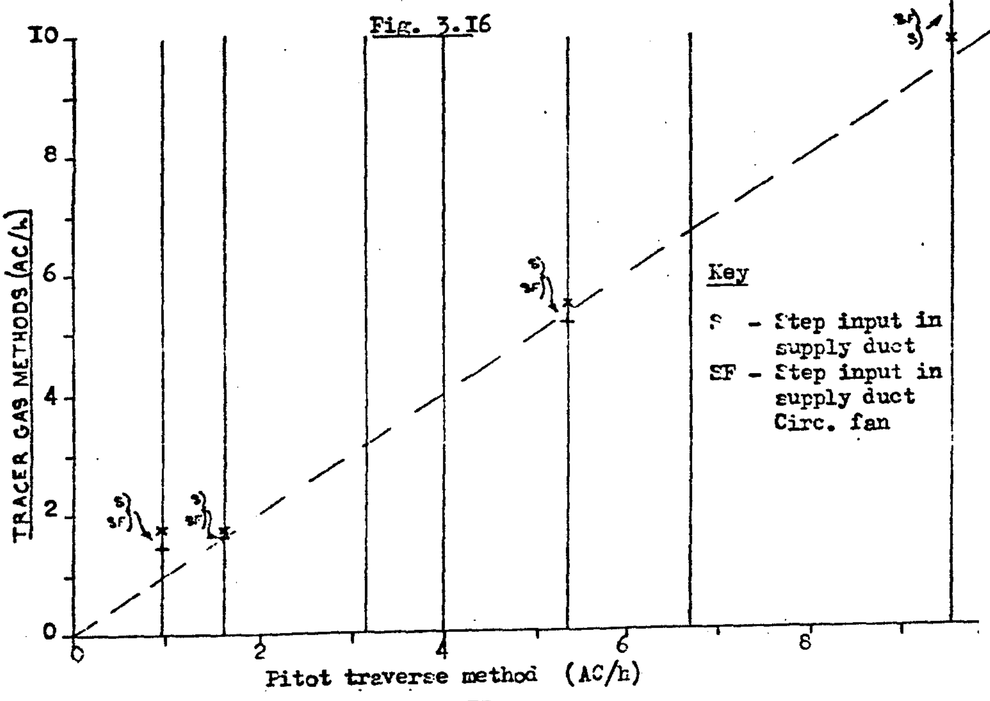


Fig. 3.17

Tracer Gas Step Input Methods - Pitot Traverse Method

Tracer Gas Pulse Input Methods - Pitot Traverse Method

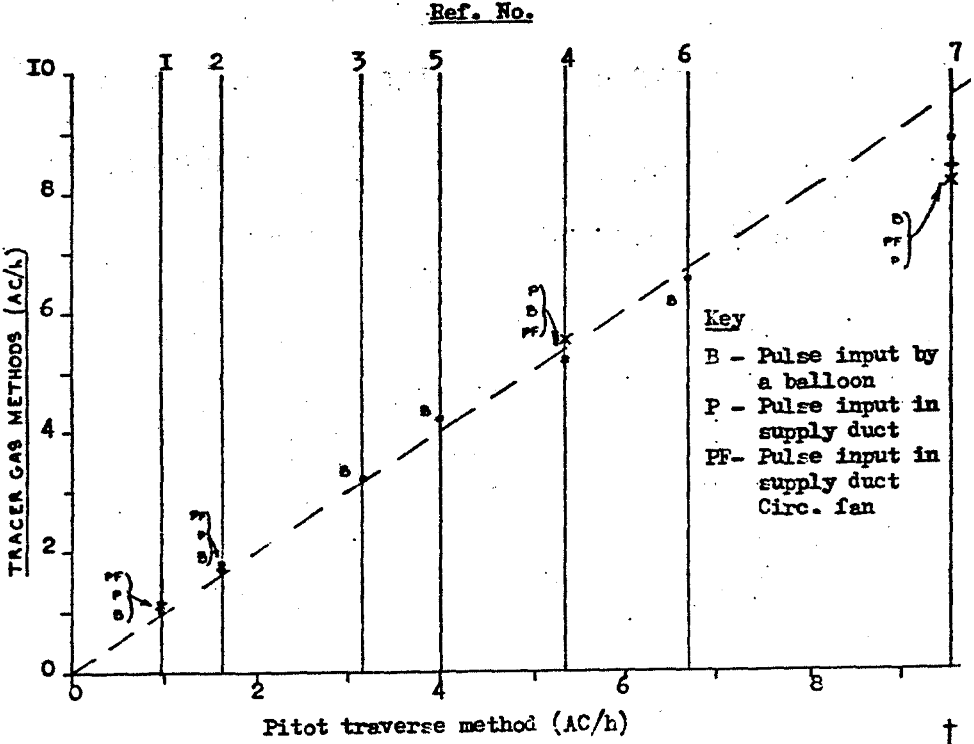


Fig. 3.16

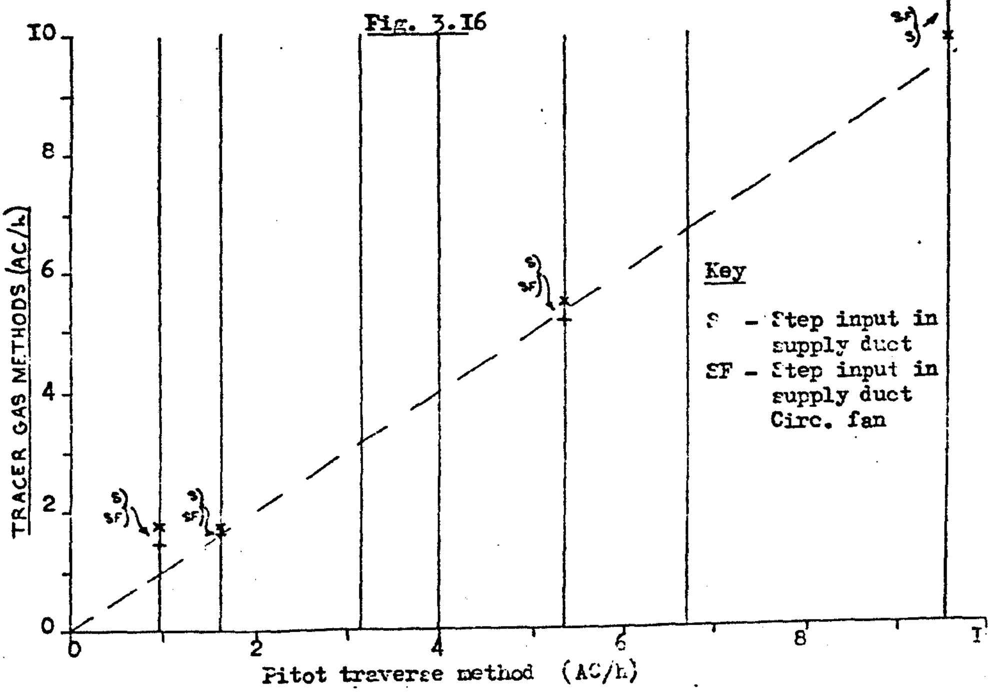


Fig. 3.17

Tracer Gas Step Input Methods - Pitot Traverse Method

4. Further Ventilation Rate Measurements in Different Rooms

4.1 Introduction.

The previous section was concerned with comparing different methods of measuring ventilation rate using tracer gas, with the air flow rate measured using a pitot-static tube. As the tests took so much longer using the equilibrium concentration method, especially at low air change rates, and much gas was required, the decay rate method was used in further test rooms. The pulse input being a balloon filled with nitrous oxide, or several balloons, depending on the room volume.

The method in the I.H.V.E. Guide, Section A4 for measuring infiltration rates using a tracer gas method requires a fan or some other method of mixing the tracer gas with the room air. When the mixing is complete the fan is switched off and the concentration of tracer gas is recorded for about one hour. The accuracy of this method is not mentioned in the Guide and during the hour the exterior weather conditions could have been varied considerably to change the air infiltration rate into the room.

The section A4 in the Guide goes on to describe a method of calculating the natural ventilation into a room using data and equations. The Guide also gives empirical values which are intended for use when calculations are impracticable or inappropriate.

The ASHRAE Guide publishes information on the infiltration occuring through window frames and construction materials so the ventilation rate can be calculated under certain exterior conditions.

The above methods have been used to calculate the ventilation rate for a few rooms and compare the results with those obtained by using the tracer gas method.

4.2 Calculation of Natural Ventilation

The three methods used to calculate the natural ventilation rate in a room discussed in this section are :-

a) The data, charts and equations presented in the IHVE Guide Section A4

b) The empirical values of infiltration as in the IHVE Guide Section A4

c) The tracer gas method using the decay rate procedure

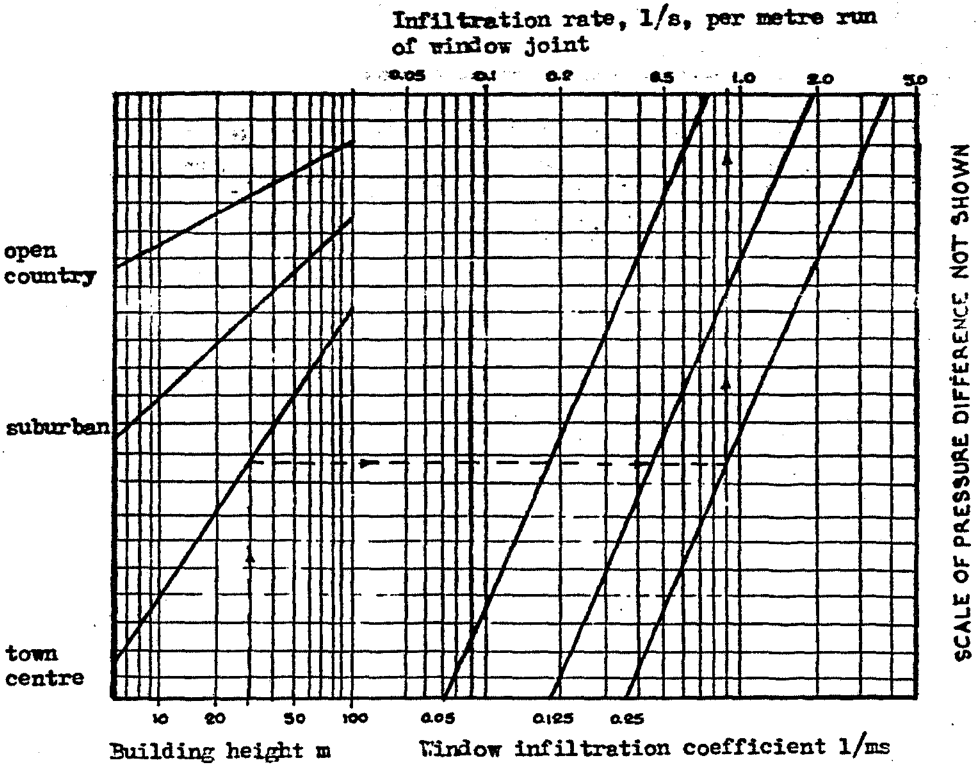
a) This method of predicting the rate of infiltration in a rectangular building is mainly for design purposes when sufficient information and the type of construction is known. The Guide presents an infiltration chart Fig 4.I which provides a simple infiltration estimation technique from the knowledge of wind speed and building height, location and window quality are known. Several correction factors are given to the infiltration chart for the type of internal resistance to air flow, such as partitions and corridors etc and for the stack effect which depends on the level of the room. The calculated infiltration rate is the maximum likely to occur in each room, there is a further equation to make allowances when calculating the total infiltration load on the central plant for the whole building. This considers that at any one time, outside air only enters the windward rooms and imposes a heating or cooling load upon them. The corresponding volume of air which must leave the building by passing through the leeward rooms is already at room temperature and so adds nothing to the total heat load of the building, assuming that all rooms are kept at the same temperature.

Example

The calculation of the natural ventilation of the first test room P/G/25 from the schedule of room details would proceed as follows :-

From the infiltration chart Fig 4.I the mean pressure difference is determined for the building height of 30m. The horizontal line is then traced until it crosses the line for the appropriate window infiltration coefficient, in this case 0.25 l/ms see table 4.I. A vertical line projected from the point of intersection to the right hand scale gives an infiltration rate per meter of window opening joint of 0.9 l/s. This value is adjusted by multiplying it by correction factors for internal air resistance. Therefore the average infiltration rate becomes within the building. In this case the correction factor

$f = I \qquad Q_b = 0.9 \times I = 0.9$



Infiltration chart. Reproduced from Fig.A4.2 IHVE A4

Fig.4.I

Window type	Window infiltration coefficient C for I N/m^2 (l/ms)
Horizontally or vertically pivoted-weather stripped	0.05
Horizontally or vertically pivoted-non-weather stripped	0.25
Horizontally or vertically sliding-weather stripped	0.I25
Horizontally or vertically sliding-non-weather stripped	0.25

Air infiltration through windows.

Table 4.I Reproduced from Table A4.3 IHVE A4

As this room is at the corner of the building, with openable windows on two adjacent walls, Q_b will be increased by I.5 times. Multiplying this value by the length of the windows opening joint in the external walls gives the infiltration rate

$$Q_r = 0.9 \times I.5 \times 25.I = 33.9 \text{ l/s}$$

The final adjustment is according to the level of the room resulting from wind conditions plus stack effect, assuming 20°C heating season. The percentage increase is approximately an additional 3% therefore Q_r for this room is :-

$$Q_r = 33.9 \times I.03 = 34.9 \text{ l/s}$$

Assuming perfect mixing in the room this gives an air change rate of :-

$$\frac{34.9}{I000} \times 3600 \times \frac{I}{94.0} = I.34 \text{ AC/hr}$$

b) The empirical values of the infiltration which may be expected in buildings of typical construction in normal use in winter.

The Table given in the IHVE Guide A4 give a value of I.0 h^{-I} for a general office and 2.0 h^{-I} for a classroom on a normal site. The room P/G/25 illustrated in the last example could be given a value of I.5 AC/hr, especially being a corner room. During periods when the room is unoccupied the infiltration rate can be taken as half that obtained above for normal use.

c) The method used with the tracer gas was the decay rate with either, no fans in the room, or, a maximum of two desk fans to mix the nitrous oxide liberated by bursting the balloon into the air. The positioning of the fans, sampling tubes and pulse input of tracer gas using a balloon are shown in the following plans. Other variations were, to have two sampling tubes to the analyser to try to average the concentration between two areas in the room.

Calculating the ventilation rate from the decay curve was the same as that used with the tests in the experimental room explained in Section 3. The outside weather conditions were also recorded to see the effect on the readings.

General

The above methods were repeated on a number of rooms with details as shown in the various schedules. With the Constant Temperature Room, only the tracer gas method was used as it was assumed to be a completely sealed room. The pulse input into this room was by opening the gas cylinder valve for a few seconds with a connected pipe passing into the room. The test on the constant temperature room was left to run for a few hours to determine whether the reading on the analyser would stay steady for such a time or if there was a calibration correction to be made to the readings.

Description of test rooms

The following room plans show where the apparatus for the tracer gas method was set up and the room schedules were used to calculate the rate of air infiltration by the other methods.

4.3 Experimental Procedure for the Tracer Gas Method.

The apparatus for each test was set up as shown in the plans of the rooms. The plans of every room tested are not shown as the test procedure for the other rooms was very similar to the ones shown. All the room except P/H/IO large laboratory were tested with the doors and windows closed, and once the apparatus had been set up and the balloons bursted the operator could leave the room. This method was impractical in the P/H/IO room as it was occupied during the experiments so all the doors remained open.

The balloons were held approximately a metre above the floor and in front of one of the desk fans to attain uniform concentration of gas within the room in the shortest possible time.

Three of the rooms GB/C/4/6/7 have ventilators incorporated into the window frames which are cord operated. Some tests were performed with the ventilators open to investigate the difference in ventilation rate in the rooms. Although these results were influenced more by the external weather conditions especially the wind speed.

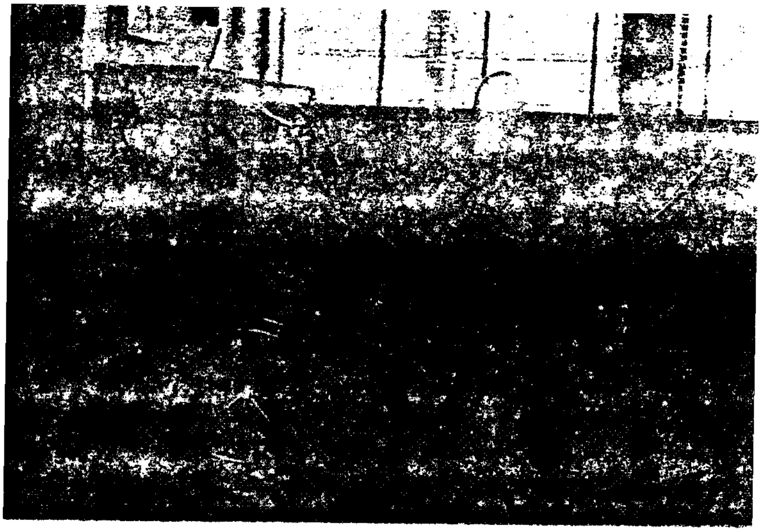


Plate I.

Typical set up of apparatus for the measurement of ventilation rate in a room.

In GB/C/6 some tests were performed with furniture in the rooms and others without it to see if there was any significant difference in the results. Tests without furniture usually gave better reproducible results. In this particular room where there were many tables, several different tests were performed with the fans and sampling points below and above the tables.

The volume of nitrous oxide required to fill one balloon was measured approximately by displacing water filled measuring cylinders over water, this was found to be between 4.2 to 5.0 litres depending on the balloon size and shape. This was used to assess the number of balloons required for a test room to achieve approximately 50-60 ppm concentration of nitrous oxide.

4.4 Results.

Examining table 4.2 with respect to the calculated ventilation rates using the tracer gas method, there appears to be very little deviation from the mean values for P/G/25 except, for Test No I with no mechanical mixing, but, there is a large scatter of values, for the other rooms.

The results shown in table 4.3 for the tracer gas method are only the values which had mechanical mixing in the room, continuously, throughout the test. The calculated values of rooms with open ventilators have also been omitted from the table as have the values which have depended largely on the position of the furniture.

In room P/H/10 which was occupied and functioning during the tests, and was the largest room tested, there were five balloons required, each filled with nitrous oxide and mechanically mixed to give good results. When only two balloons were used there was insufficient gas in the room, and even with mechanical mixing this resulted in an erroneous ventilation rate. With no mechanical mixing in the room, no decay curve of concentration was plotted. This would be as a result of nitrous oxide having a low diffusion coefficient as previously discussed in Section 2.

The doors in the room were kept closed to remove the complication of air exchange rates between the internal rooms and when the doors were opened accidentally the ventilation rate increased considerably, especially with the smaller rooms. This could have been due to (a) high convection currents in the corridors, (b) or the fans in the test rooms used to mechanically mix the tracer gas, contributing to higher exchange rates when internal doors were open, especially as there was no significant quantity of tracer gas liberated in the adjacent rooms.

4.5 Conclusion.

Considering the ventilation rate measured using tracer gas were measured during the summer months, although the external conditions show some low outside temperatures, for the time of year, the measured infiltration rates are all higher than for the other methods from table 4.3. The other two methods according to the IHVE Guide results, in the highest infiltration rate for rooms which is likely to occur duringthe heating season.

The high results obtained by the tracer gas method may have been due to relatively large flow into enclosed spaces such as furniture and fittings, but this would result in a non exponential curve. The results shown in Table 4.2 are from reasonably smooth first order decay curves over a period of approximately 20 to 30 minutes, from the time when the test commenced.

Furniture had a considerable influence on the results, when nitrous oxide was used with its low diffusion characteristics, as, if the gas is not uniformly mixed throughout the room, erroneous ventilation rates can result.

Method (a), table 4.3 is very much dependent on the type of windows fitted and this is evident in the results. With very low expected air change rates, with the rooms in the "George Begg" building, as the windows were weather stripped.

Two points that can be concluded are that mechanical mixing is required continuously during a test, which is contrary to the IHVE Guide Section A4 recommendation, which states that the fan should be switched off after the mixing is complete and then the concentration recorded, for about one hour.

Mechanical mixing is also required so that it can be assumed that perfect mixing and complete air changes occur for calculation purposes.

The second point is that using a balloon for a pulse input is relatively simple and gives a reasonably good decay curve from which the ventilation rate can be easily calculated.

Air infiltration tests using tracer gas - Rate of decay method

Table 4.2

Test No. 1	Room No. 2	Rm Temp °C 3	External condition Temp °C 4	Wind Speed 5	Wind Direction 6	Method of tracer gas liberation 7	Fan arrangement within room 8	Cal. ventilation Rate AC/h 9	Comments 10
I	P/G/25	I9.5	I3.5	2	SW	I balloon I S.P.	No fan	3.9	Insufficient mixing
2		20.0	I4.5	3	W	I balloon I S.P.	I DF run.cont.	I.84	Doors closed
3		20.0	I4.5	3	W	I balloon I S.P.	I DF run.cont.	I.80	" "
4		I9.0	I2.8	I	S	I balloon 2 S.P.	I DF run.initially	I.69	" "
5		20.0	I3.5	2	WNW	I balloon 2 S.P.	I DF run.cont.	I.83	" "
6		20.0	I3.5	2	WSW	I balloon 2 S.P.	I DF run.cont.	I.88	" "
7	CTR	20.0	-	-	-	pulse from gas cyl.2SP	I DF run.cont.	0.I2	Steady vent.rate for 3h.
8	P/H/II	I9.0	I4.2	I	E	2 balloons 2 S.P.	2 DF run.cont.	I.56	Door opened twice
9		I9.5	I4.5	2	W	2 balloons 2 S.P.	2 DF run.cont.	2.I6	Door opened 4 times
I0	P/H/I0	2I.5	I6.5	0	W	5 balloons 2 S.P.	2 DF & I CF run.cont.	3.09	Doors open
II		23.0	I7.0	3	SW	2 balloons 2 S.P.	2 DF run.cont.	9.76	Insufficient mixing
I2		24.0	I8.0	3	SW	5 balloons 2 S.P.	No fan	-	Insufficient mixing
I3	GB/C/4	22.5	I6.0	2	WSW	I balloon 2 S.P.	2 DF run.cont.	I.72	Ventilator closed-No furn
I4		I9.5	I5.0	3	SE	I balloon 2 S.P.	2 DF run.initially	2.73	As above & door open once
I5		23.5	I7.0	3	WSW	I balloon 2 S.P.	2DF run.cont.	2.07	Ventilator open-No furn.
I6	GB/C/6	20.0	I6.0	0	W	I balloon 2 S.P.	2 DF run.cont.	I.23	Ventilator closed-No furn
I7		22.0	I4.8	2	NE	I balloon 2 S.P.	2 DF run.cont.	I.40	As above
I8		20.0	I7.0	3	SW	I balloon 2 S.P.	2 DF run.cont.	3.I0	Ventilator open-No furn.
I9		22.0	I5.0	2	N	I balloon 2 S.P.	2 DF run.cont.	I.83	As above
20		2I.0	I8.0	3	SW	I balloon 2 S.P.	2 DF run.cont.	3.82	As above
2I		23.0	I9.5	I	S	I balloon 2 S.P.	2 DF run.cont.	0.57	Ventilator closed-furnitu
22		22.0				I balloon 2 S.P.	2 DF run.cont.	0.97	As above-fans below table
23		22.0				I balloon 2 S.P.	2 DF run.cont.	I.56	As above-fans above table
24	GB/C/37	27.0	I8.0	3	SW	I balloon 2S.P.	2 DF run.cont.	I.62	Ventilator closed-furnitu
25		27.0	I8.0	3	SW	I balloon 2 S.P.	2 DF run.cont.	2.70	Ventilator open-furniture

Air infiltration tests using tracer gas - Rate of decay method

Table 4.2

Test No. I	Room No. 2	Rm Temp °C 3	External condition Temp °C 4	Wind Speed 5	Wind Direction 6	Method of tracer gas liberation 7	Fan arrangement within room 8	Cal. ventilation Rate AC/h 9	Comments IO
I	P/G/25	I9.5	I3.5	2	SW	I balloon I S.P.	No fan	3.9	Insufficient mixing
2		20.0	I4.5	3	W	I balloon I S.P.	I DF run.cont.	I.84	Doors closed
3		20.0	I4.5	3	W	I balloon I S.P.	I DF run.cont.	I.80	" "
4		I9.0	I2.8	I	S	I balloon 2 S.P.	I DF run.initially	I.69	" "
5		20.0	I3.5	2	WNW	I balloon 2 S.P.	I DF run.cont.	I.83	" "
6		20.0	I3.5	2	WSW	I balloon 2 S.P.	I DF run.cont.	I.88	" "
7	CTR	20.0	-	-	-	pulse from gas cyl.2SP	I DF run.cont.	0.I2	Steady vent.rate for 3h.
8	P/H/II	I9.0	I4.2	I	E	2 balloons 2 S.P.	2 DF run.cont.	I.56	Door opened twice
9		I9.5	I4.5	2	W	2 balloons 2 S.P.	2 DF run.cont.	2.I6	Door opened 4 times
I0	P/H/I0	2I.5	I6.5	0	W	5 balloons 2 S.P.	2 DF & I CF run.cont.	3.09	Doors open
II		23.0	I7.0	3	SW	2 balloons 2 S.P.	2 DF run.cont.	9.76	Insufficient mixing
I2		24.0	I8.0	3	SW	5 balloons 2 S.P.	No fan	-	Insufficient mixing
I3	GB/C/4	22.5	I6.0	2	WSW	I balloon 2 S.P.	2 DF run.cont.	I.72	Ventilator closed-No furn.
I4		I9.5	I5.0	3	SE	I balloon 2 S.P.	2 DF run.initially	2.73	As above & door open once
I5		23.5	I7.0	3	WSW	I balloon 2 S.P.	2DF run.cont.	2.07	Ventilator open-No furn.
I6	GB/C/6	20.0	I6.0	0	W	I balloon 2 S.P.	2 DF run.cont.	I.23	Ventilator closed-No furn.
I7		22.0	I4.8	2	NE	I balloon 2 S.P.	2 DF run.cont.	I.40	As above
I8		20.0	I7.0	3	SW	I balloon 2 S.P.	2 DF run.cont.	3.I0	Ventilator open-No furn.
I9		22.0	I5.0	2	N	I balloon 2 S.P.	2 DF run.cont.	I.83	As above
20		2I.0	I8.0	3	SW	I balloon 2 S.P.	2 DF run.cont.	3.82	As above
2I		23.0	I9.5	I	S	I balloon 2 S.P.	2 DF run.cont.	0.57	Ventilator closed-furnitur
22		22.0				I balloon 2 S.P.	2 DF run.cont.	0.97	As above-fans below tables
23		22.0				I balloon 2 S.P.	2 DF run.cont.	I.56	As above-fans above tables
24	GB/C/37	27.0	I8.0	3	SW	I balloon 2S.P.	2 DF run.cont.	I.62	Ventilator closed-furnitur
25		27.0	I8.0	3	SW	I balloon 2 S.P.	2 DF run.cont.	2.70	Ventilator open-furniture

Summary sheet of air infiltration rates (AC/h)

Room No. I	Room description 2	(a) Calculation method using IHVE Data 3	(b) Empirical value from IHVE Guide 4	(c) Tracer gas method	
				Calculated values 5	Mean value 6
P/G/25	Seminar	I.34	I.5	I.84 I.80 I.83 I.88	I.84
CTR	Constant Temp. Rm. (sealed rm)	-	-	0.I2	0.I2
P/H/II	Advanced Laboratory	0.05	I.0	I.56	I.56
P/H/I0	Laboratory	0.04	I.0	3.09	3.09
GB/C/4	Seminar	0.04	I.0	I.72	I.72
GB/C/6	Seminar	0.06	I.0	I.23 I.40	I.3I
GB/C/37	Office	0.07	I.0	I.62	I.62

Table 4.3

SCHEDULE OF ROOM DETAILS.

Room Number .. P/G/25 Room Description .. Small Classroom (seminar room)

Dimensions .. Length (m) .. 5.8 Width (m) .. 4.7

Height (m) .. 3.45 Volume (m^3) .. 94.0

Orientation of External Walls .. I) North

2) East

Approx.Height of Bldg. .. 30m No of Floors .. 7

Height of Room above G.L. .. 2Im Floor Level .. 5th

Window Type .. Metal vertically pivoted non weather stripped
Window infiltration coefficient C = 0.25 l/ms

Glass Area (m^2) .. IO.98 Glass/Area of Window (m^2) Openable .. 6.57

Length of Window Opening Joint (m) .. 25.I

Glass Area / External Wall Area .. 30.3% Openable ..I8%

Construction Details ..

Walls I) Painted,plastered blockwork,brickwork outer leaf-two windows
2) " " " " " " -windows above
3) Painted plastered blockwork with internal door
4) " " " " " "

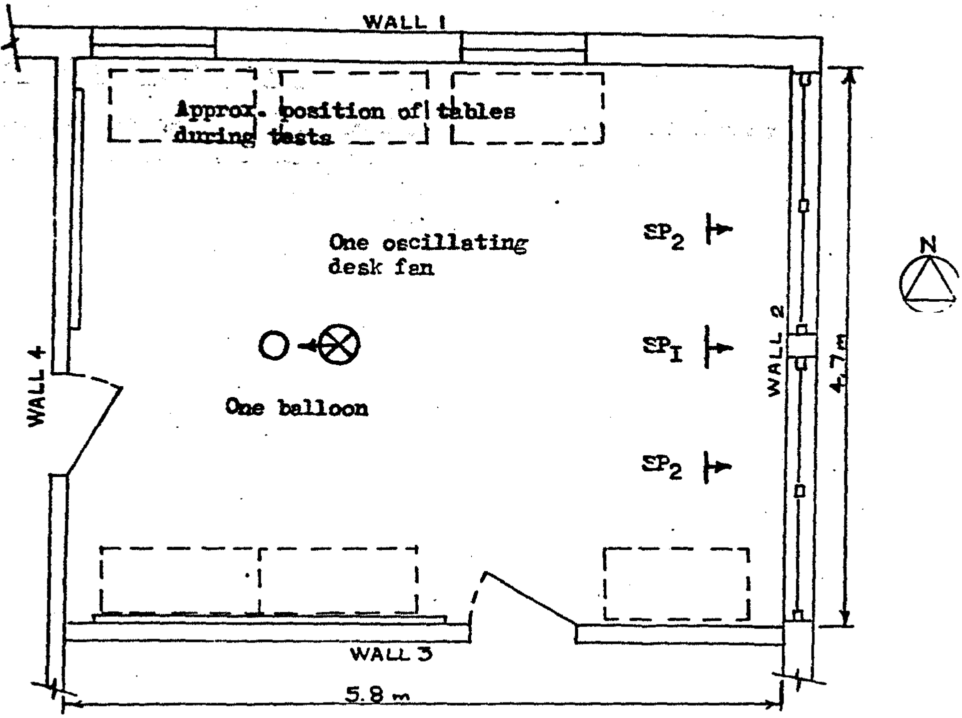
Floor .. Fitted Carpet

Ceiling .. Reinforced concrete beams,covered with insulation material.All painted

Furniture and Fittings.Details .. 6 tables and I2 chairs remained in the room during the tests.

Remarks .. No false ceiling.Some cracks around window frames.

Room No. P/G/25 **Room Description - Seminar room**



Test I - I balloon - I sampling point SP_I - no mechanical mixing

Test 2 - I balloon - I sampling point SP_I - I desk fan running continuously

Test 3 - I balloon - I sampling point SP_I - I desk fan running continuously

Test 4 - I balloon - 2 sampling points SP_2 - I desk fan running until steady peak concentration

Test 5 - I balloon - 2 sampling points SP_2 - I desk fan running continuously

Test 6 - I balloon - 2 sampling points SP_2 - I desk fan running continuously

Remarks

Tables and chairs remained in the room during the tests in the above positions.

SCHEDULE OF ROOM DETAILS.

Room Number .P/H/IO Room Description .. Large laboratory

Dimensions .. Length (m) .. I9.5 Width (m) .. 7.45

Height (m) .. 3.40 Volume (m^3) .. 494.0

Orientation of External Walls .. I) West

2) -

Approx.Height of Bldg. .. 30m No of Floors .. 7

Height of Room above G.L. .. 25m Floor Level .. 6th

Window Type .. Metal vertically pivoted - non-weather stripped
Window infiltration coefficient C = 0.25 l/ms

Glass Area (m^2) .. 30.7 Glass/Area of Window (m^2) Openable .. I3.I

Length of Window Opening Joint (m) .. 57.9

Glass Area / External Wall Area .. 46% Openable .. 20%

Construction Details ..

Walls I) Painted blockwork without plaster (internal)
2) " " " " and two internal doors to corridor
3) Partially glass partition with internal door
4) Painted blockwork, brickwork outer leaf - windows above

Floor .. Vinyl tiles

Ceiling .. Concrete beams with infill panels covered with insulation material and all painted.

Furniture and Fittings.Details .. Tables and benches with cupboards beneath

Remarks .. Volume of enclosed spaces = $35m^3$

SCHEDULE OF ROOM DETAILS.

Room Number .. P/H/10 Room Description .. Large laboratory

Dimensions .. Length (m) .. 19.5 Width (m) .. 7.45

Height (m) .. 3.40 Volume (m^3) .. 494.0

Orientation of External Walls .. 1) West

2) -

Approx. Height of Bldg. .. 30m No of Floors .. 7

Height of Room above G.L. .. 25m Floor Level .. 6th

Window Type .. Metal vertically pivoted - non-weather stripped
Window infiltration coefficient C = 0.25 l/ms

Glass Area (m^2) .. 30.7 Glass/Area of Window (m^2) Openable .. 13.1

Length of Window Opening Joint (m) .. 57.9

Glass Area / External Wall Area .. 46% Openable .. 20%

Construction Details ..

Walls 1) Painted blockwork without plaster (internal)

2) " " " " and two internal doors to corridor

3) Partially glass partition with internal door

4) Painted blockwork, brickwork outer leaf - windows above

Floor .. Vinyl tiles

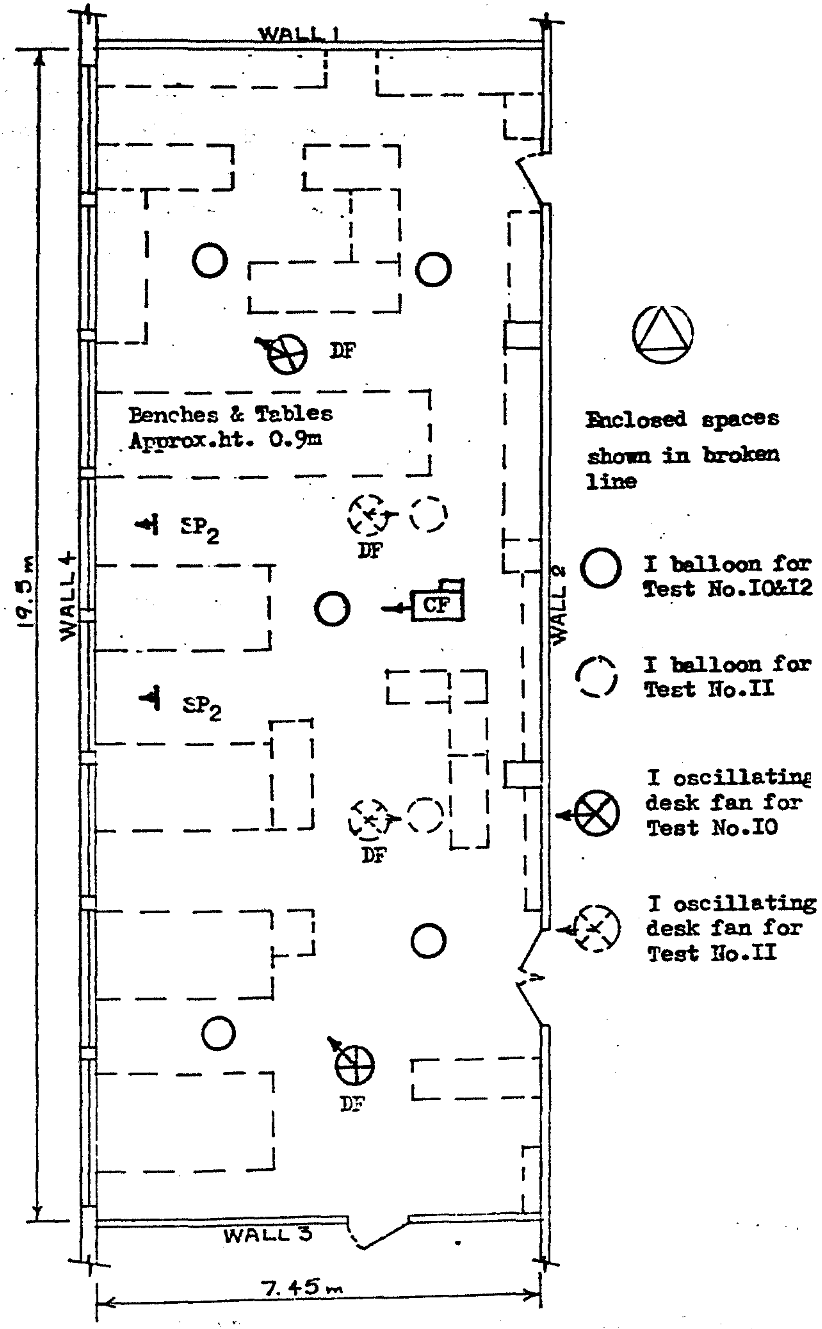
Ceiling .. Concrete beams with infill panels covered with insulation material and all painted.

Furniture and Fittings.Details .. Tables and benches with cupboards beneath

---

Remarks .. Volume of enclosed spaces = 35m^3

Room No. P/H/IO **Room Description - Large laboratory**



Test IO - 5 balloons - 2 sampling points SP$_2$ - 2 desk fans and a centrigugal fan running continuously

Test II - 2 balloons - 2 sampling points SP$_2$ - 2 desk fans running continuously

Test I2 - 5 balloons - 2 sampling points SP$_2$--no mechanical mixing

SCHEDULE OF ROOM DETAILS.

Room Number .. GB/C/6   Room Description .. Seminar room

Dimensions .. Length (m) .. 5.75   Width (m) .. 4.3

Height (m) .. 3.84   Volume (m^3) .94.9

Orientation of External Walls .. I) North

2) -

Approx.Height of Bldg. .. I4.0m   No of Floors .. 2

Height of Room above G.L. .. I0.0m   Floor Level .. 2nd

Window Type .. Metal vertically pivoted - weather stripped
Window infiltration coefficent C = 0.05 l/ms

Glass Area (m^2) .. 8.9   Glass/Area of Window (m^2)
Openable .. 3.65

Length of Window Opening Joint (m) .. I0.9

Glass Area / External Wall Area .. 54%   Openable .. 22%

Construction Details .

Walls I) Painted blockwork, brickwork outer leaf- windows above

2) Painted blockwork without plaster (internal)

3) Painted blockwork without plaster and internal door to corridor

4) Painted blockwork without plaster (internal)

Floor .. Vinyl tiles

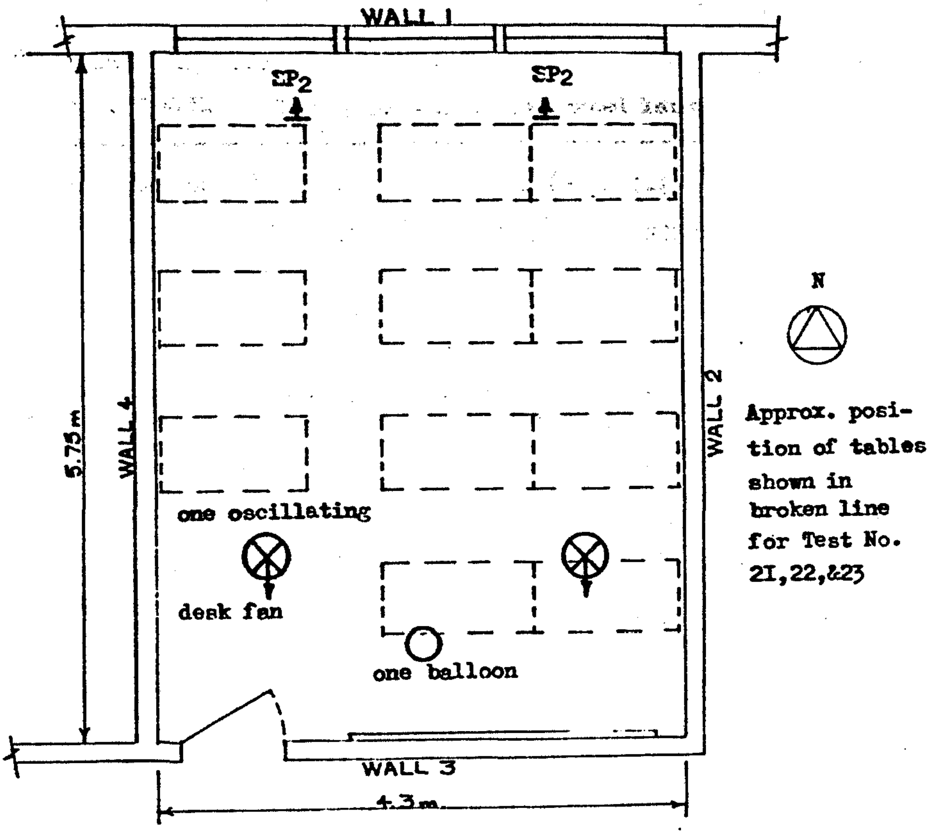
Ceiling ..- Roof - Metal decking with woodwool slabs between steel beams - all painted - no false ceiling.

Furniture and Fittings.Details .. I0 tables and 20 chairs - roll type blackboard

---

Remarks ..Slight shrinkage cracks between roof and walls especially at the junction with the internal walls. One cord operated ventilato incorporated into the window frame.

Room No. GB/C/6 Room Description - Seminar room



All Tests - I balloon - 2 sampling points SP_2 - 2 desk fans running continuously

Test I6 - window ventilator closed - no furniture

Test I7 - window ventilator closed - no furniture

Test I8 - window ventilator open - no furniture

Test I9 - window ventilator open - no furniture

Test 20 - window ventilator open - no furniture

Test 2I - window ventilator closed - furniture

Test 22 - window ventilator closed - furniture - fans below tables

Test 23 - window ventilator closed - furniture - fans above tables

SCHEDULE OF ROOM DETAILS.

Room Number .. P/H/II Room Description .. Advanced laboratory

Dimensions .. Length (m) .. 8.4 Width (m) .. 7.4

Height (m) .. 3.45 Volume (m^3) .222.0

Orientation of External Walls .. I) West

2) -

Approx. Height of Bldg. .. 30m No of Floors .. 7

Height of Room above G.L. .. 25m Floor Level .. 6th

Window Type .. Metal vertically pivoted - non-weather stripped
Window infiltration coefficient C = 0.25 l/ms

Glass Area (m^2) .. I5.35 Glass/Area of Window (m^2) Openable .. 6.54

Length of Window Opening Joint (m) .. 28.9

Glass Area / External Wall Area .. 47% Openable .. 20%

Construction Details ..

Walls I) Painted blockwork without plaster (internal)

2) " " " " and one internal door to corridor

3) " " " " (internal)

4) Painted blockwork, brickwork outer leaf - windows above

Floor .. Vinyl tiles

Ceiling .. Concrete beams with infill panels covered with insulatio material and all painted.

Furniture and Fittings. Details .. Tables and benches with cupboard beneath

Remarks .. Volume of enclosed spaces = I8m^3

SCHEDULE OF ROOM DETAILS.

Room Number .GB/C/4 Room Description .. Seminar room

Dimensions .. Length (m) .. 5.85 Width (m) .. 5.75

Height (m) .. 3.84 Volume (m^3) .. 129.2

Orientation of External Walls .. 1) North

2) -

Approx.Height of Bldg. .. 14.0m No of Floors ..2

Height of Room above G.L. ..10.0m Floor Level .. 2nd

Window Type ..Metal vertically pivoted - weather stripped
Window infiltration coefficient C = 0.05 l/ms

Glass Area (m^2) ..11.9 Glass/Area of Window (m^2)
Openable ..3.65

Length of Window Opening Joint .. 10.9
(m)

Glass Area / External Wall Area ..53% Openable ..16%

Construction Details ..

Walls 1) Painted blockwork, brickwork outer leaf - windows above

2) Painted blockwork, without plaster (internal)

3) Painted blockwork without plaster and internal door leading to corridor

4) Painted blockwork without plaster (internal)

Floor .. Vinyl tiles

Ceiling ..Roof - Metal decking with woodwool slabs between steel beams - all painted - no false ceiling.

Furniture and Fittings.Details .. 14 tables and 28 chairs - roll type blackboard

Remarks .. Slight shrinkage cracks between roof and walls especially at junction with the internal walls. Two cord operated ventilators incorporated into the window frames.

SCHEDULE OF ROOM DETAILS.

Room Number ..GB/C/37   Room Description .. Office

Dimensions .. Length (m) ..3.78   Width (m) .. 2.86

Height (m) ..3.84   Volume (m^3) ..4I.5

Orientation of External Walls .. I) West

2) -

Approx.Height of Bldg. .. I4.0m   No of Floors ..2

Height of Room above G.L. .I0.0m   Floor Level .. 2nd

Window Type ..Metal vertically pivoted - weather stripped
Window infiltration coefficient C = 0.05 l/ms

Glass Area (m^2) ..5.8   Glass/Area of Window (m^2) Openable ..I.73

Length of Window Opening Joint (m) ..5.32

Glass Area / External Wall Area ..53%   Openable .. 16%

Construction Details ..

Walls I) Painted blockwork without plaster (internal)

2) " " " " and internal door to corridor

3) " " " " (internal)

4) Painted blockwork, brickwork outer leaf - windows above

Floor .. Fitted carpet

Ceiling ..Roof - Metal decking with woodwool slabs between steel beams - all painted - no false ceiling.

Furniture and Fittings.Details .. II filing cabinets, desk and a few stacked chairs

Remarks .. Substantial shrinkage cracking between walls and ceiling. One cord operated ventilator incorporated into the window frame. Volume of enclosed spaces = $5m^3$

5. Use of Tracer Gas Technique to Measure Air Flow Rates in Ducts

5.I Introduction

The difficulty of making air flow measurements on site, is the presence of the large number of obstructions such as dampers, bends and fans which either mean a low standard of accuracy or a large number of readings; to measure air flow using conventional methods such as the pitot-static, anemometer etc. The tracer gas method can only be used where there are such obstructions or, mechanical mixing, to distribute the gas evenly throughout the air flow.

Various authors have written papers associated with the subject, especially with respect to measuring air flow in coal mines where most of the earlier research was performed.

The theoretical background of the methods used is very similar to measuring the air exchange rate in rooms as previously mentioned in the earlier sections. The main difference is that the absolute concentration value is needed to calculate the air flow rate. The theory to the methods used will be outlined seperately although the basic principles are the same as described in section 3.

5.2 Theory.

The technique of air flow measurements using a tracer gas depends upon releasing a known quantity of gas into the air stream either instantaneously or over a short period of time. When the tracer gas is evenly mixed with the air stream, the gas concentration can be determined, and, knowing the quantity of gas released, or its rate of release, it is possible to calculate the air flow.

5.2I Equilibrium Concentration Method.

This technique requires a continuous, known release of tracer gas given at a constant flow rate $v(m^3/s)$ until a steady equilibrium concentration is reached within the air flow at the sampling point. When a steady state is reached, the quantity of air flowing can easily be determined. Assuming there is no leakage from the duct and the air is at the same conditions at the release and sampling points.

After a steady state is reached

$$\frac{v}{Q} = (c_a - c_i)$$

Therefore $$Q = \frac{v}{(c_a - c_i)} \qquad (5.I)$$

where :- Q = volume flow rate of air (m^3/s)

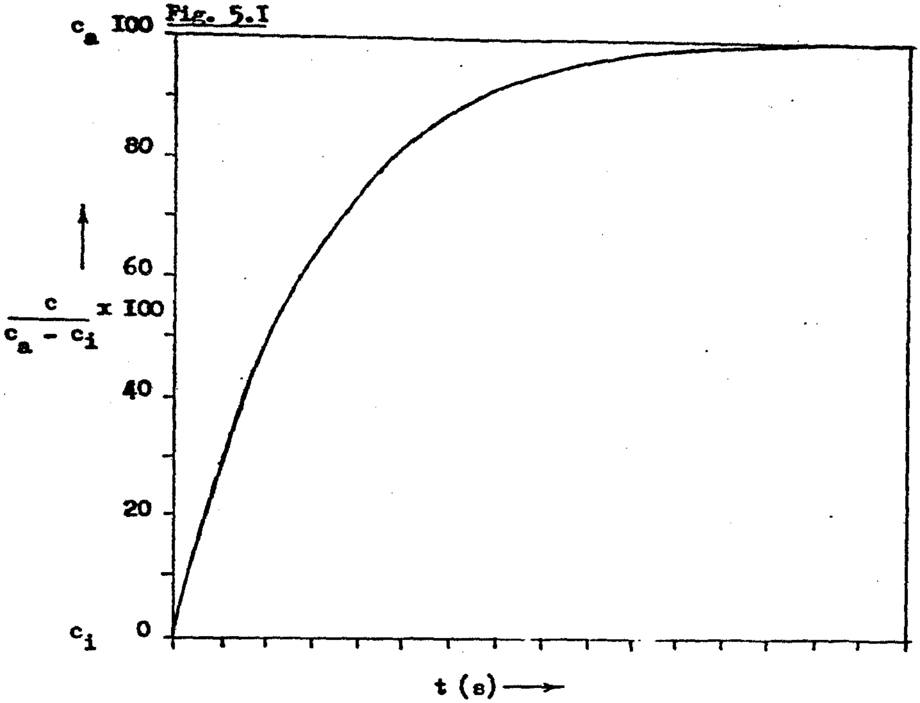
v = steady flow rate of tracer gas (m^3/s)

c_a = steady concentration at sampling point of tracer gas present in the air stream expressed in parts per million of air (ppm)

c_i = steady initial concentration at sampling point of gas present in the air stream (ppm)

Equilibrium Concentration Method

Fig. 5.I



The theoretical concentration increase is shown in Fig.5.I for a step input of tracer gas.

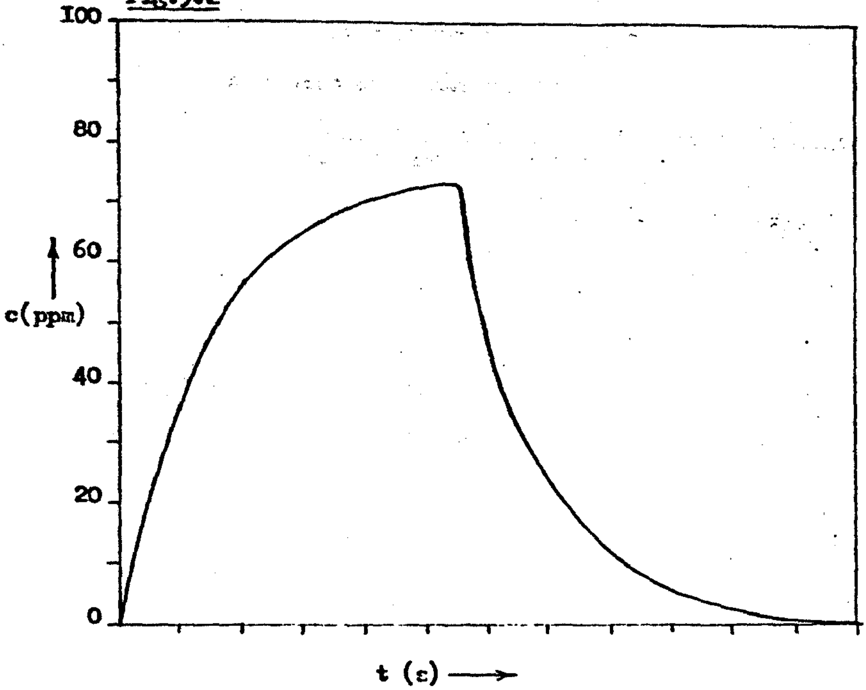
5.2.2 Decay Rate Method

With the decay rate technique a known quantity of tracer gas of mass m is released over a short period of time. The concentration of tracer gas at a point of uniform concentration is recorded using a chart recorder to plot a time concentration curve such as shown in Fig.5.2.

At time t the volume flow rate of tracer gas past the sampling point is: cQ

Pulse Input Method

Fig.5.2



Therefore the total volume of tracer gas past the sampling point is :-

$$\int_0^\infty c\,Q\,dt$$

Volume of tracer gas liberated $= m/\rho$

Therefore $$\frac{m}{\rho} = \int_0^\infty c\,Q\,dt = Q\,A$$

Therefore $$Q = \frac{m/\rho}{A} = \frac{v}{A}\ (m^3/s) \qquad (5.2)$$

where :- c = concentration of the tracer gas at the sampling point expresses in parts per million of air. (ppm)

Q = volume flow rate of air (m^3/s)

ρ = density of tracer gas (kg/m^3)

m = mass of tracer gas (kg)

v = volume of tracergas at atmospheric temperature and pressure (20°C, 1.013 bar)

A = area under the time concentration curve.

Again it is assumed that there is no leakage from the duct and the airflow is constant. It is also assumed that by introducing the tracer gas in the suction side of the centrifugal fan there will be complete mixing at the sampling point.

5.3 Experimental Procedure

All the experimental work in this section was performed on the sheet metal ductwork system shown in Fig 5.3 An additional length of ductwork was fixed to the inlet of the centrifugal fan so all of the tracer gas liberated into the system was thoroughly mixed by the fan to create a uniform concentration at the sampling point. "Higgins and Shuttleworth" in their experimental work, to measure air flow in coal mines headings using the tracer gas technique, calculated that a distance of 70 duct diameters on a straight ductwork system, is required to ensure that the concentration on the axis of the duct is within 1% of the mean concentration. With the ductwork system shown in the diagram there is a centrifugal fan and a damper to greatly assist the mixing process.

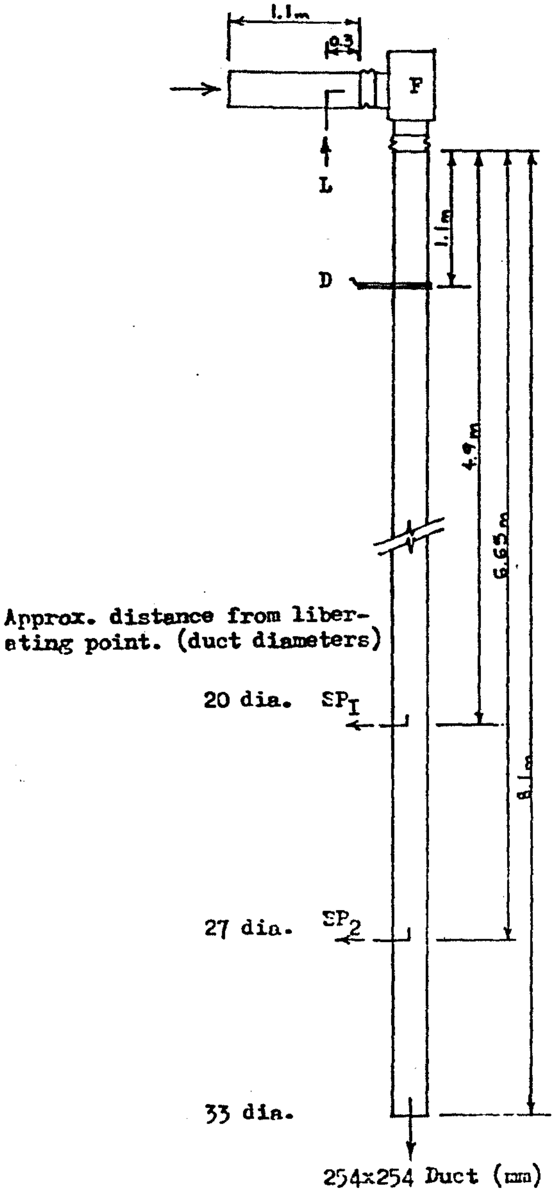
The joints between each length of ductwork had

Plate 2.

Ductwork system showing extract with frame for pitot-static tube.

Also shown :- Centrifugal fan to remove contaminated air to atmosphere

Ductwork System



Key

F - Centrifugal fan

D - Plate damper

L - Tracer liberating point

SP - Sampling tube to gas analyser

Fig.5.3

rubber gaskets and all the inspection points were sealed with tape so there was negligable leakage from the system.

The air flow rate in the ductwork could be varied either by the blade damper which had a fine threaded screw giving easily reproducible positions, or by the centrifugal fan with a variable pulley system giving a range of speeds which could be reproduced and checked with a Strobatac. A range of suitable air flow rates were selected using an electrical vane anemometer for the preliminary volume flow rates, for different damper and for fan speed settings.

As with the air flow measurements in the experimental room described in Section 3, the air flow was measured using a pitot-static tube and the electrical micromanometer manufactured by "Furness Controls Co." A frame was erected at the end of the duct to support the pitot-static tube. This kept the pitot-static tube parallel with the axis of the duct in each traverse position and also reduce the vibration to the tube.

From B.S.848 Part I. 1963 for rectangular airways the pitot tube should have been positioned as shown in Fig 5.4

This results in 48 observations which according to a short note by the "National Engineering Laboratory" in 1964, errors of 2% or more can still be measured in certain types of asymmetric velocity distribution.

Location of measuring points for rectangular airways according to BS 848 : Part I : 1963

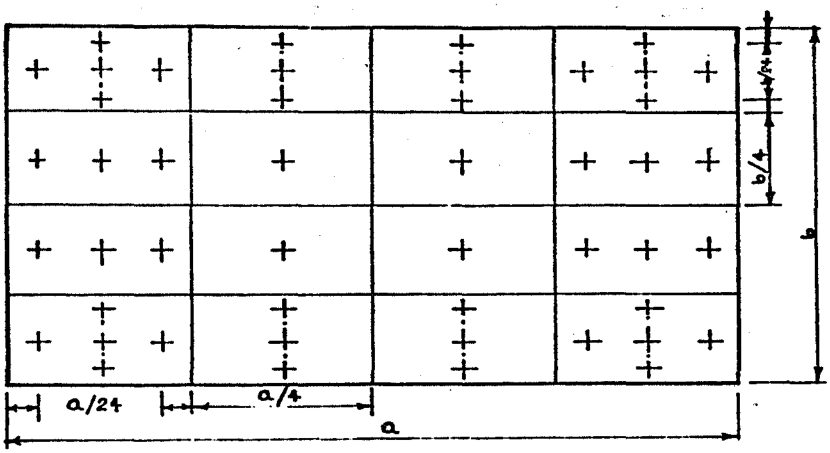


Fig.5.4

Location of measuring points used in experimental work

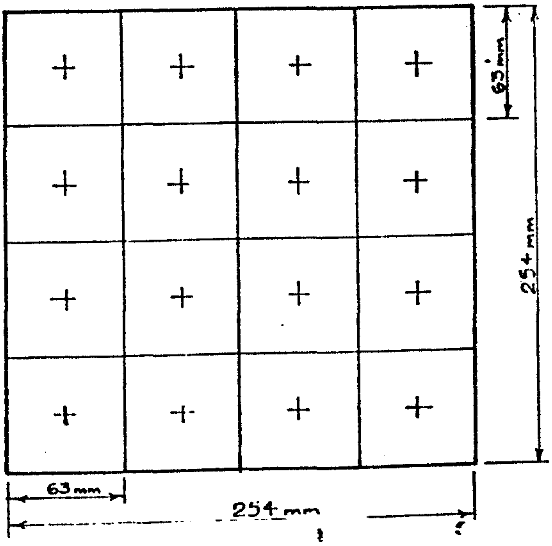


Fig.5.5

Considering this point, the duct was divided into I6 equal areas and a velocity pressure reading was recorded at the centre of each division (Fig 5.5) As a further check the traverse was repeated two or three times.

NPL modified ellipsoidal-nosed standard pitot-static tube was used to measure the velocity pressure. Where the velocity profile across the duct was extremely irregular further measurements were made, but only in those areas. The above velocity pressure measurements were made across the duct for each of the selected air flow rates.

As each of the tracer gas methods used to measure the air flow rate was different, they have been considered separately.

5.3.I Equilibrium Concentration Method.

The apparatus was set up as shown in the schematic Fig 5.6

Due to the low flow rate of tracer gas required the regulating value on the gas cylinder was not sensitive enough, so a needle value was used between the cylinder and rotameter. From the rotameter, two pipes. each with glass stop valves were used for adjusting the gas flow rate. One of these pipes was to the external fresh air so that to set the needle valve in its correct position , the gas was extracted with the stop valve on the liberating pipe closed.

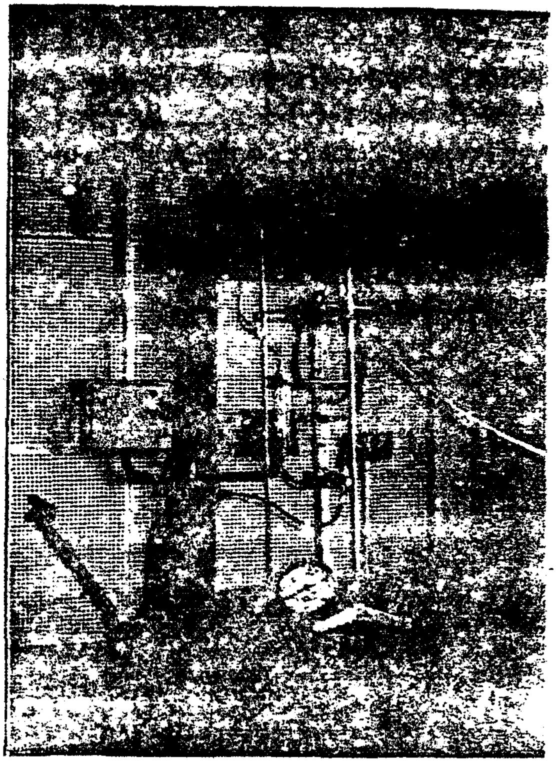
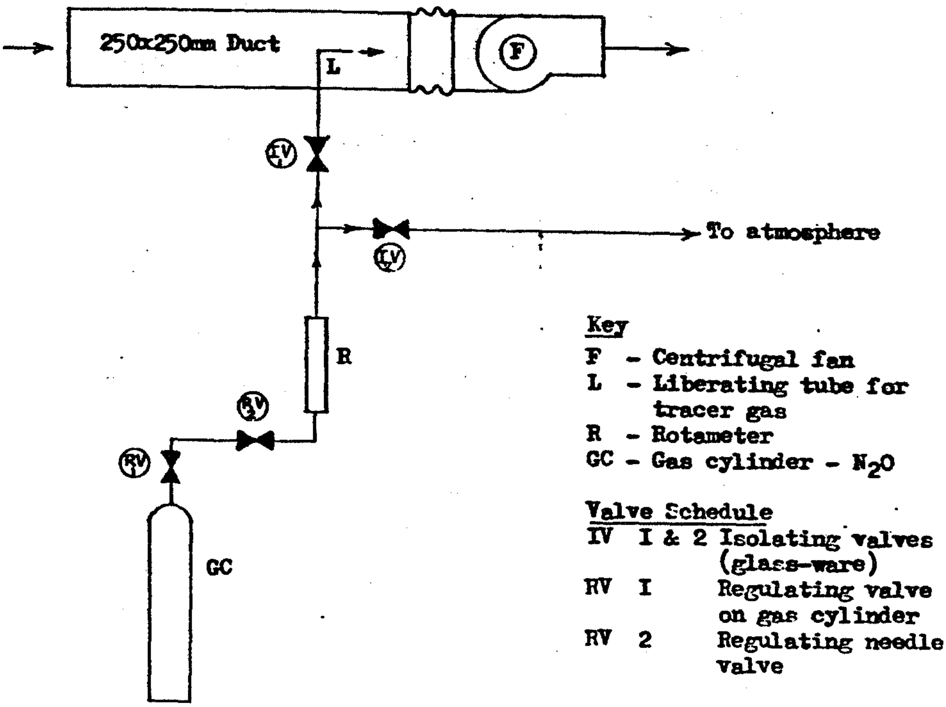


Plate 3.

Tracer gas liberation point to ductwork system

Schematic of tracer gas liberating point



Key
F - Centrifugal fan
L - Liberating tube for tracer gas
R - Rotameter
GC - Gas cylinder - N_2O

Valve Schedule

IV	I & 2	Isolating valves (glass-ware)
RV	I	Regulating valve on gas cylinder
RV	2	Regulating needle valve

Fig.5.6

When the tracer gas flow rate and the whole system was steady, including the gas analyser and chart recorder, the stop valve to the liberating point was opened and the other stop valve closed simultaneously. Within a few minutes the steady concentration level had been reached and the tracer gas flow was switched off leaving the concentration to decay to its initial level.

To assist this removal of contaminated air from the room where the ductwork was erected, all the windows and doors were kept open during the test period and a centrifugal fan was used close to one end of the duct.

This was to prevent tracer gas being recirculated within the system and affecting the results.

The samplig tube to the gas analyser was initially positioned at the end of the duct where the pitot traverses were performed. This particular position gave a very unsteady chart plot and therefore several other positions for the sampling tube were tried. Finally position SP_2 was selected as it gave a steady time concentration curve.

5.3.2 Decay Rate Method

The apparatus used for this method was similar to the previous method as shown in Fig 5.6 Releasing a known quantity of tracer gas over a short period to produce a pulse input, was achieved by having a steady flow of gas going outside to the atmosphere, then, when required opening the stop valve to the liberating tube and closing the other stop valve for a few seconds.
The pulse input was normally liberated over ten or fifteen seconds, then, the reverse procedure was applied, closing the stop valve to the liberating tube and opening the other to atmosphere. To reduce the uncertainty of inputting the exact quantity of gas the experiment was performed several times with different durations of tracer gas liberation.

5.4 Results.

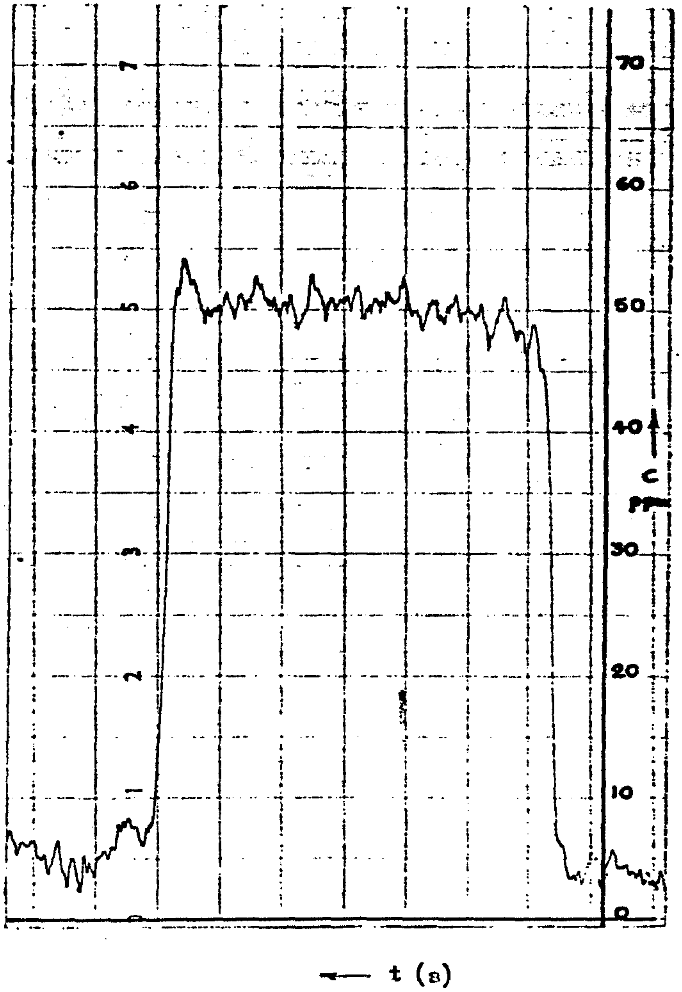
5.4I Pitot Traverse Method.

For each velocity pressure obtained the velocity at that point was computed using the formula, and correction factors for air temperature and atmospheric pressure, from section 3. The average velocity for the duct was calculated by the arithmetical average of the point velocities, and the volume flow rate was obtained by multiplying the area of duct by the average velocity as described before for the circular duct.

5.4.2 Equilibrium Concentration Method.

From the theory to calculate the volume flow rate of air, only the flow rate of tracer gas, and the rise in concentration to a steady level at the sampling point are required. The flow rate of the tracer gas was measured with a rotameter which was calibrated for air, so a correction factor was applied as discussed in further details in Section 7.

The typical ouput from the Oxford Recorder of one of the tests is shown in Fig 5. 7. Table 5.2 shows the results from all the tests and compares the volume flow rates with those oBtained by the pitot traverse method. From the plot in Fig 5. 7 it can be seen that the steady concentration is reached within the first minute. Most of the tests were run over at least five minutes to verify that the steady condition had been reached.



Equilibrium concentration curve for

a step input

Fig.5.7

Test No.4

Voloume flow rate of tracer gas liberated - $2.34 \times 10^{-6} m^3/s$

Initial concentration = c_i = 4.9 ppm

Steady concentration = c_s = 50.05ppm

Increase = $c_s - c_i$ =45.I ppm

Calculated air flow = $0.052 m^3/s$

5.4.3 Decay Rate Method

The area under the decay curve was measured with a planimeter which was calibrated to give the result in square centimeters.

The "y" axis of the decay curve is concentration of tracer gas expressed in parts per million of air (ppm). The Oxford Instrument Chart Recorder was calibrated in absolute terms to correspond to the moving coil meter of the infra-red gas analyser, and, this resulted in a scaling factor of 5ppm per cm. The "x" axis depends on the chart speed of the recorder calibrated in cm per min.

y axis Icm represents 5 ppm

x axis Icm represents $\dfrac{60}{\text{chart speed cm/min}}$ s

$$\text{Therefore Icm}^2 = \frac{5 \times 60}{\text{chart speed cm/min.}} \text{ s}$$

$$\text{Therefore Area(cm}^2) = \frac{300 \times A}{\text{chart speed cm/min}}$$

$$Q = V / A$$

$$\text{Therefore } Q = \frac{V \times \text{chart speed(cm/min)}}{300 \times \text{Area under decay curve(cm}^2)} \quad m^3/s$$

The area under the decay curve was measured two or three times and the average of the three readings was used in the further calculations. The flow rate of the tracer gas measured with the rotameter was corrected for measuring nitrous oxide as previously mentioned. A typical decay curve is shown in Fig 5.8 for the readings indicated in the table of results.

5.5 Experimental Errors.

The four chief sources of error with the tracer gas methods were :-

a) The possibility of recirculation of tracer gas within the room

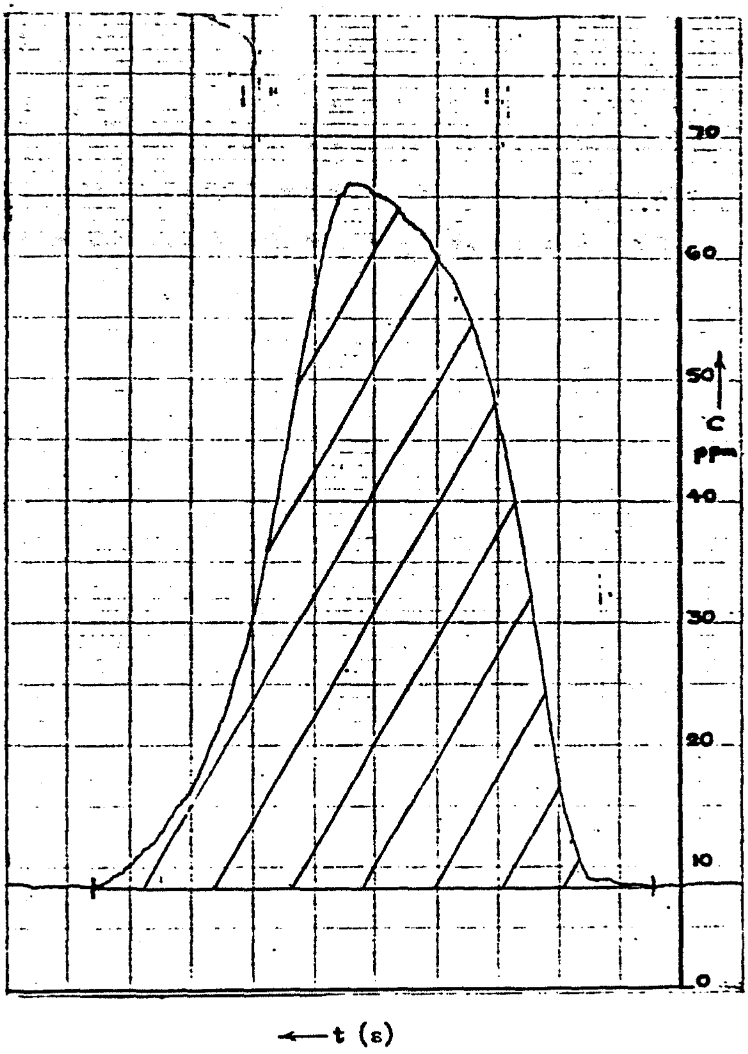
b) With the decay rate method , the difficulty of imputting an exact quantity of gas into the duct.

c) Obtaining a steady flow rate of gas with the rotameter

d) Calibrating the chart recorder to the electrical output of the infra-red gas analyser.

The first error applied particularly to the equilibrium concentration method where larger quantities of gas were used with the higher air flow rates. This was clearly shown when the tracer gas was switched off and the concentration did not decay to its initial value.

The decay rate method was repeated several times to reduce the uncertainty of inputting an exact quantity of tracer gas. Modifications to the apparatus were tried to input a pulse of gas, but none of these were as successful as using the glass stop valves.



Decay curve for a pulse input Fig.5.8

Test No.22

Chart speed = 25cm/min. Volume of N_2O released = $4.447 \times 10^{-4} m^3/s$

Area under curve (shaded area) measured with a planimeter

- 48.4 cm^2
- 48.7 cm^2
- 48.8 cm^2

Mean = 48.6 cm^2

Calculated air flow = 0.763 m^3/s

Another error associated with this method was obtaining a steady flow rate of gas with the rotameter to create the pulse input. This was also a problem with the equilibrium concentration method as there was some fluctuation with the rotameter even when the needle value was inserted between the gas cylinder regulating valve and the rotameter. The chart recorder was calibrated with the gas analyser at nearly full scale deflection and then checked at various other readings, but, there was the uncertainty of complete correlation.

The errors resulting from the pitot-static tube were of a similar nature to those arising when the electronic micromanometer was used to measure the air flow rate into the experimental room. As previously mentioned fluctuations in the velocity pressure readings resulted from the instrument being underdamped.

5.6 Conclusion

The graph of the air flow rates by the pitot traverse method against the mean values calculated by the two tracer gas methods, shows a distinct deviation from the ideal straight line. This has been concluded after several tests at each flow rate as shown in the tables of results. This may be due to systematic errors resulting from the instruments or ductwork system as previously mentioned.

The curve jointing the mean decay points gives closer correlation with the datum line from the pitot traverse method, than does the curve for the mean steady concentration points. As more tracer gas has to be released with the step input, some recirculation of the gas within the system would explain why the calculated air flow rates are lower.

Without more extensive tests with other ductwork systems, no conclusive explanation can be made as to why the tracer gas method was resulting in lower volume flow rates. What is evident is the speed of each test compared with the conventional method, especially with the pulse input which only took a matter of seconds to perform. This would be particularly important if the airflow to be measured had periodic fluctuations.

Volume flow rate of air measured with the pitot-static tube.

Test No. 1	Fan speed (rpm) 2	Damper position (mm) 3	Pitot traverse (16 points) (m^3/s) 4	Mean (m^3/s) 5	Deviation about mean 6	Vol. air flow ref. no. 7
1	940	51	0.049	0.050	-0.001	1
2	940	51	0.050		-0.	
					MD-0.0005	
3	940	150	0.182	0.182	0.	2
4	940	150	0.181		-0.001	
					MD-0.0005	
5	940	254	0.358	0.357	+0.001	3
6	940	254	0.355		-0.002	
					MD-0.0015	
7	1940	200	0.546	0.545	+0.001	4
8	1940	200	0.544		-0.001	
					MD-0.001	
9	1930	255	0.731	0.730	+0.001	5
10	1930	255	0.728		-0.002	
					MD-0.0015	

MD - Mean Deviation

Table 5.1

Comparison of methods of measuring air flow rate in ducts.

Equilibrium concentration using tracer gas and pitot tube met

Test No. I	Vol. air flow ref. no. 2	Vol flow rate tracer gas=V $10^{-6}m^3/s$ 3	$c_a - c_i$ ppm (10^{-6}) 4	Vol. flow rate air =Q = V/c_a-c_i m^3/s 5	Mean m^3/s 6	Deviation about mean 7	Pitot traverse (I6 points) m^3/s 8	Dev. of Q with col. 8 9	% Diff. I0
I	I	I.30	24.5	0.053		+0.0005			
2		I.30	25.2	0.052		-0.0005			
3		I.30	24.5	0.053		+0.0005			
4		2.34	45.I	0.052		-0.0005			
					0.0525	MD=0.0005	0.050	+0.0025	5
5	2	3.3I7	24.0	0.I38		-0.0I3			
6		8.383	52.7	0.I59		+0.008			
7		5.333	34.2	0.I56		+0.005			
					0.I5I	MD=0.009	0.I82	-0.03I	I7
8	3	I5.60	54.0	0.289		+0.005			
9		I3.00	49.2	0.264		-0.020			
I0		4.55	I5.7	0.289		+0.005			
II		8.45	28.5	0.296		+0.0I2			
					0.284	MD=0.0I0	0.357	-0.073	20
I2	4	I8.7I7	37.0	0.506		+0.033			
I3		I3.000	28.2	0.460		-0.0I3			
I4		I8.7I7	38.0	0.492		+0.0I9			
I5		8.450	I8.9	0.446		-0.027			
I6	"	I3.000	28.3	0.459		-0.0I4			
					0.473	MD=0.02I	0.545	-0.072	I3
I7	5	25.08	36.7	0.682		-0.0I4			
I8		25.08	37.0	0.678		-0.0I8			
I9		3I.20	45.0	0.693		-0.003			
20		37.70	5I.0	0.739		+0.043			
					0.696	MD=0.0I9	0.730	-0.034	4

Table 5.2

Comparison of methods of measuring air flow rate in ducts. **Rate of decay using tracer gas and pitot traverse methods**

Test No. 1	Vol. air flow ref. no. 2	Flow rate tracer gas 10^{-6} m^3/s 3	Duration of input s 4	Area under curve cm^2 5	Chart recorder speed cm/min 6	Vol. flow of air Q m^3/s 7	Mean m^3/s 8	Deviation about mean 9	Pitot traverse (16 points) m^3/s 10	Dev. of Q with col. 10 11	% Diff. 12
1	1	4.55	10	61.4	25	0.062		0			
2		4.55	10	63.9	25	0.059		-0.003			
3		4.55	10	59.2	25	0.064		+0.002			
4		4.55	15	89.4	25	0.064		+0.002			
5		4.55	15	95.7	25	0.059		-0.003			
							0.062	MD=0.002	0.050	+0.012	24
6	2	13.0	10	67.7	25	0.160		-0.006			
7		13.0	10	67.0	25	0.162		-0.004			
8		13.0	15	98.2	25	0.165		-0.001			
9		13.0	15	97.6	25	0.166		0			
10		13.0	10	60.8	25	0.178		+0.012			
							0.166	MD=0.005	0.182	-0.016	9
11	3	13.0	15	49.8	25	0.326		+0.025			
12		13.0	15	55.3	25	0.294		-0.007			
13		13.0	15	55.4	25	0.293		-0.008			
14		13.0	10	38.9	25	0.278		-0.023			
15		13.0	10	34.6	25	0.313		+0.012			
							0.301	MD=0.015	0.357	-0.056	16
16	4	44.47	15	4.7	1	0.473		-0.043			
17		44.47	15	21.2	5	0.524		+0.008			
18		44.47	15	201.4	50	0.552		+0.036			
19		44.47	15	107.6	25	0.516		0			
							0.516	MD=0.022	0.545	-0.029	5
20	5	44.47	15	82.9	25	0.670		-0.031			
21		44.47	10	55.4	25	0.669		-0.032			
22		44.47	10	48.6	25	0.763		+0.062			
							0.701	MD=0.042	0.730	-0.029	4

able 5.3

Tracer Gas Methods - Pitot Traverse Method

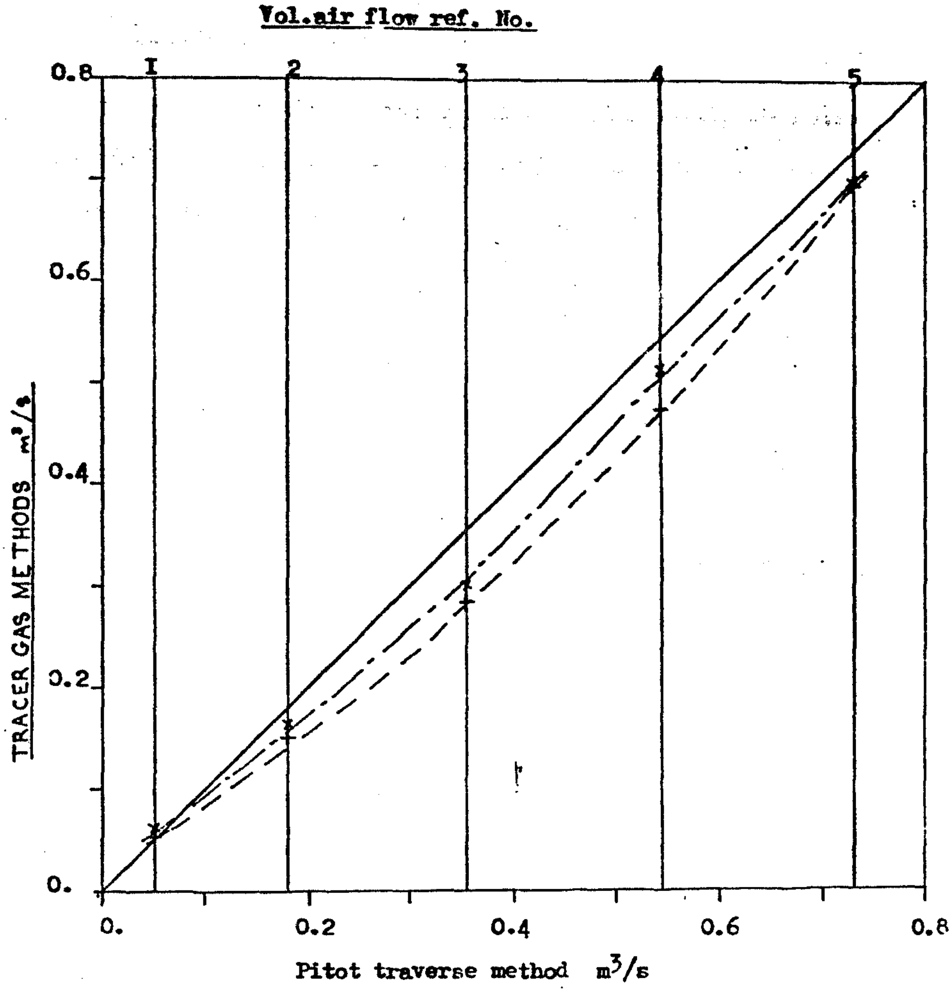


Fig.59

Key

+ = Mean equilibrium concentration points

X = Mean rate of decay points

6.0 General Conclusion.

Of the two methods of measuring ventilation rate in rooms, the rate of decay method requires relatively little time to give a result of the air change rate in an enclosure, assuming perfect mixing and complete air changes. Previous researches using nitrous oxide as a tracer have estimated the uncertainties of the method as being up to — ±15% in field conditions. This degree of uncertainty was found when comparing a pulse input of tracer gas with the pitot traverse method in the experimental room. This is assuming very few schematic errors with the pitot traverse technique, which was taken as a datum. This piece of work has shown how difficult it is to accurately measure low ventilation rates.

Further complications were involved when field tests were performed in other rooms with additional variables of the external weather conditions. Without more extensive tests to eliminate the random and systematic uncertainties, no conclusive result can be drawn as to why the field tests to measure the ventilation rate are so much higher than the calculation method recommended in the IHVE Guide.

All the ventilation rates have been calculated assuming perfect mixing of the tracer gas and air, within each room. This is probably a correct assumption for relatively small rooms with mechanical mixing, but for the large laboratory PG/H/10 even with three fans, this may have been insufficient mixing.

The technique of plotting the rate of decay of nitrous oxide in a room has shown that results are reasonably reproducable, providing, sufficient mechanical mixing is present in the room and the external variables are similar.

The infra-red gas analyser easily detected low concentrations (0 - 100 ppm) of nitrous oxide, and this resulted in small quantities of the gas being used. Nitrous oxide is a suitable tracer gas as it is easily obtainable, and has the advantage over many other tracers, of being non toxic, and non explosive.

The work in Section 5 on measuring air flow in ducts using a tracer gas method illustrated how much quicker the volume flow rate could be calculated compared with the conventional method of using a pitot-static tube. In view of the time involved in accurately measuring the air flow in ducts using conventional methods the tracer gas technique could have an exciting future in the Building Services Industry. The main disadvantage is the high cost of the infra-red gas analyser.

7. Schedule of Apparatus

7.I Luft-type infra-red gas analyser 20

Model A.AI 600 Type U Serial No I28I

Manufactured by Sir Howard Grubb Parsons and Co Ltd.

Specifications.

Weight - approximately 23kg

Range - High sensitivity - 0-I00ppm v/v of N_2O in N_2

Low sensitivity - 0-500ppm v/v of " " "

This particular non dispersive infra-red analyser has been designed and calibrated to measure concentration levels of nitrous oxide. Measurement of the absorption of infra-red radiation enables the quantity of many gases in a complex gas mixture to be measured in this way. The function diagram of the analyser is illustrated in Fig 7.I

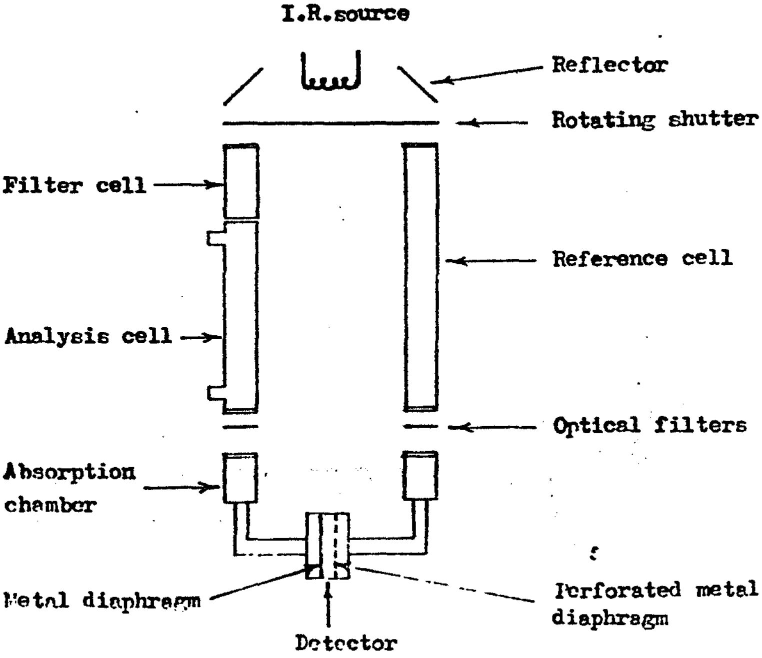


Fig.7.I

Plate 4.

Infra-red gas Analyser

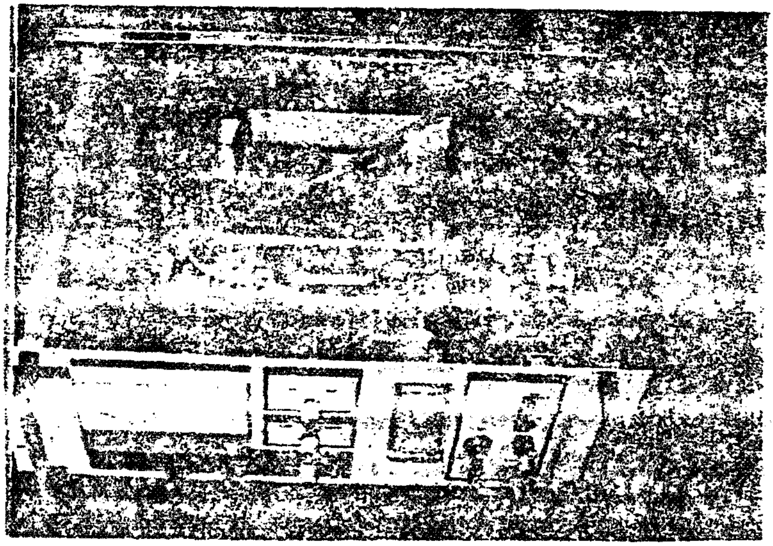


Plate 5.

View showing tube assembly of Infra-red gas Analyser

Two beams of infra-red radiation of equal energy are interrupted by a rotating two bladed chopper driven at constant speed which allows the beams to pass intermittently, but, simultaneously through an analysis(sample) cell assembly and a parallel reference cell, and onto a Luft pattern detector. The reference cell is normally filled with dry carbon dioxide free air, circulated by the pump through an absorber. The detector consists of two sealed absorption chambers separated by a thin metal diaphragm. This diaphragm with an adjacent perforated metal plate, forms an electrical capacitor. The two chambers are filled with the gas to be tested so that the energy characteristic of the gas to be measured is selectively absorbed. When the sample is passed through the analysis cell, the measured gas present absorbs some of the energy to which the detector is sensitised, resulting in an imbalance of energy causing the detector diaphragm to be deflected and so change the capacitance. This out of balance mode is corrected so as to be proportional to theconcentration of the sample and a corresponding reading is obtained on the meter and an electrical output is produced.

Another gas also present in the sample, will not affect the result unless its absorption bands which overlap those of the gas being determined. Filter tubes are fitted containing the interfering gas which minimizes the effect of these other gases.

The length of the absorption tube is designed for the gas being detected and the concentration required.

Normal Operating Instruction.

a) Switch on.,and check that function switch is in operate position which activates the pump and chopper.
b) Allow instrument to settle which normally takes 45mins
c) Set to gas sensitivity required as specification. Nearly all the experimental work was carried out using the high sensitivity range.
d) With suitable non-absorbing gas flowing in analysis cell, check zero setting. Set zero control if necessary Ordinary air was used for this but carbon dioxide free oxygen, oxygen,nitrogen or any gas that does not absorb infra-red radiation could have been used.

For further details such as gas connections, zero unobtainable minimum adjustement etc the manual supplied with the analyser should be consulted.

Calibration

As this particular infra-red gas analyser was nearly new and the "fine gain" control had been calibrated by the manufacturers it was assumed to be correct, especially as there was no available suitable gas mixture to test the instrument.

To check calibration a test gas should be introduced into the analyser to give between 50-IOO% F.S.D. for both "high" and "low" sensitivity settings of the concentration switch.

From the meter scale and the calibration chart any small errors should be corrected according to the appropriate instruction in the operating manual.

7.2 Chart Recorder

Type :- Oxford Instruments 3000 Chart Recorder

The six way plug at the rear of the infra-red gas analyser provides D.C. output of zero to five volts for a potentiometer recorder.

The potentiometer Recorder could be switched to provide a suitable sensitivity from the analyser output. The recorder could also be calibrated against the meter scale of the analyser to give an absolute reading or plot of the concentration as required. There is a range of chart speed from Icm per hour to 50cm per minute giving ample range for all the tests. For further details of calibration and adjustment, the operating manual should be consulted.

Another chart recorder used for only one ventilation rate measurement was the following :-

Level Recorder Type 2305

Manufactured by "Brüel and Kjoer"

This is a much more sophisticated recorder, with the appropriate Logarithmic Range Potentiometer which gives a straight line output in this case, considerably reduced the time of analysing the results. The recorder was only used once because on subsequent tests, the two recorders were connected in parallel to the output of the gas analyser which resulted in overloading the analyser. Also the level recorder weighs 25kg which makes it unsuitable for field work.

7.3 Micromanometer

Electronic Micrpmanometer MDC

Manufactured by "Furness Controls Ltd"

The MDC Micromanometer is a sensitive pressure measuring device capable of measuring a gas pressure equivalent to 0.00I mm wg to I0 mm wg. It has five ranges which are :-

0.00I - 0.I, 0.3, I, 3.0, I0 (mm wg)

The instrument is fitted with a linear scale which can be read to 0.5% F.S.D. but as it is under damped the fluctuation of the meter needle resulted in a lower accuracy than could have been achieved with such a micromanometer. A damping switch is provided which increases the time constant of the measuring circuit, but even with this, in the "slow Position"the meter was considerably fluctuating and the observed mean was assumed. The instrument has a warm up time of approximately 30 mins, but it can be used during this period if the zero is checked occasionaly and adjusted accordingly. For further details of the operating and calibration of the instrument, the instruction manual should be consulted.

Vernier Reading Micromanometer.

Manufactured by "C.F. Cecille and Co Ltd" London

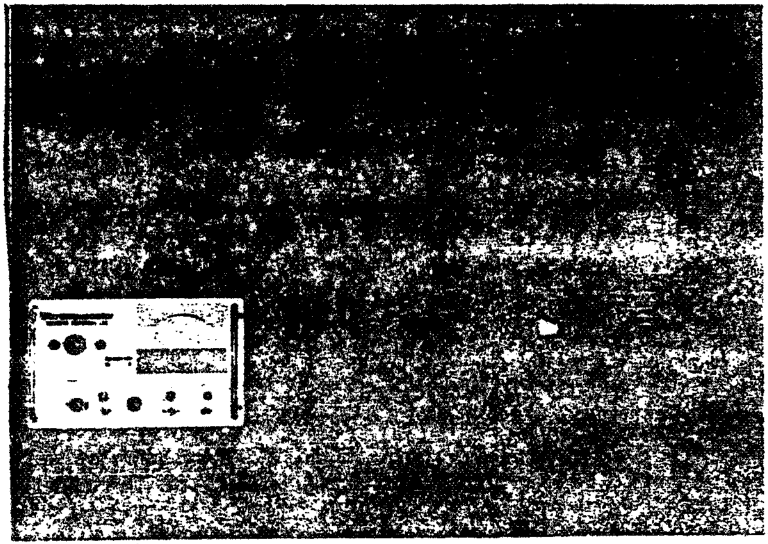


Plate 6

a) Electronic Micromanometer

b) Vernier Reading Micromanometer

c) Electrical vane Anemometer

The vernier micromanometer was used as a final check on the calibration of the electronic micromanometer manufactured by "Furness Controls. The instrument has a range of 0-200 mm wg and the vernier can be read to 0.02 mm wg.

The instrument consists of a flexible "U" tube manometer with one end connected to a reservoir and the other to a measuring chamber. Both the chamber and reservoir containing water may be moved vertically and the movement accurately measured. The measuring chamber contains a stainless steel needle which is fixed, point upwards and the needle and its reflection, produced by internal reflection, can be viewed at 45° from a window in the bottom. When the tip of the reflection just touches the tip of the needle, the needle is just in contact with the underside of the water surface. So the position of the water surface is accurately determined.

The vernier manometer was only used for checking the calibration of the electronic micromanometer and was not used for taking readings of velocity pressure, from the pitot-static tube traverses across the duct as the former is overdamped which results in a long delay between readings. The vernier is more difficult to read than a meter dial also resulting in a long experimental time for each pitot tube position in the duct.

7.4 Smoke Generator System for Flow Ventilation in Air.

H.P.L. Design. Manufactured by " T.E.M. Engineering Ltd"

The smoke generator was used to examine the air flow patterns in the experimental room. With this particular smoke, generator oil is forced through a small diameter tube to the smoke probe which has an integral electrical heating coil which vaporizes the oil immediately before the exit orifice. The volume flow rate of smoke is controllable according to the air velocity being traced.

7.5 Rotameter

Gapmeter Lab-kit Any flow from 25 to IOO,000cc/min Air
Manufactured by Platon Flow Control

The rotameter consists of a long graduated tube having an internal uniform taper, with the smaller cross sectional area at the bottom, and the axis of the tube vertical. A float shaped according to the flow rate and density of the fluid to be measured, moves freely within the tube. As the rate of flow through the instrument increases, the float rises in the tube increasing the area of the annular space and keeping the differential pressure across the float at a fixed value.

The rotameter used in the experimental work are calibrated for air at normal temperature and pressure. (20°C, I.OI3 bar)

When the rotameter was measuring nitrous oxide at (ATP) atmospheric pressure and temperature (20°C I,OI3 bar) the observed flow rate Q_{OBS} cc/min was corrected for nitrous oxide by :)

$$Q\ CORR = \sqrt{\frac{\rho\ AIR}{\rho\ N_2O}} \times Q\ \ OBS$$

where Q Corr = Corrected flow rate for nitrous oxide cc/min
Q OBS = Observed " " calibrated for air cc/min
ρ N_2O = Density of Nitrous Oxide at ATP (kg/m^3)
ρ Air = " " Air " " "

$$Q\ \text{CORR} = \sqrt{\frac{I.205}{I.98}} \times Q\ \text{OBS}$$

$$= \underline{0.780 \times Q\ \text{OBS}}$$

As the density of the float is so large compared with the gases involved, the former can be neglacted and no further factor is necessary in the above calculation

7.6 Miscellaneous

Strobatac Type I33I-A
Manufactured by General Radio Co

Fans.

I2" Oscillating Blade Sweep Desk Fans 55 watts input
Manufactured by "H. Frost and Co" - 2 Off

Fan for experimental room
250mm diam Frame motor no. F 844
Electrical Input I00W - output - 50W I380 rpm max
Manufactured by "Woods" of Colchester.

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