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A SURVEY OF RESEARCH INTO SOME ASPECTS OF AIR INFILTRATION

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J. Dewsbury B.Eng.

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DECLARATION

No part of the work contained in this dissertation has been submitted in support of an application for another degree or qualification of U.M.I.S.T. or any other university or other institution of learning.

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THE AUTHOR

The author received his degree of Bachelor of Engineering in mechanical engineering from the University of Sheffield in 1973. After a period of industrial training with Courtaulds Engineering Limited, Coventry, he became assistant to the Divisional Chief Engineer of Courtaulds Northern Weaving Division, Manchester, with responsibility for specific items of new installations and maintenance together with coordination and information services for the works engineers.

In 1977 he moved to Norway, where he worked for mechanical services consulting engineers. He returned to England in October 1979 to study at U.M.I.S.T.

He is now employed as a Senior Project Engineer at the Building Services Research and Information Association, working largely on the design and construction of a solar heating test installation.

SUMMARY

This survey of some aspects of research into air infiltration falls into four parts.

Chapter 1 sets the problem of infiltration in its historical context, explains its importance for air quality, energy consumption and condensation and describes its mechanisms.

Chapter 2 discusses methods of measurement of ventilation rates and of building leakiness, with special emphasis on the author's criticism of the work of Card et al. and Sherman et al. on the infrasonic method of leakage testing. The author's analysis of the infrasonic method is presented. It is concluded that this method is difficult to apply but worth further study. The other methods discussed are the pressurisation method of leakage testing, thermography and tracer gas methods of measuring ventilation rates.

Chapter 3 describes the available techniques for predicting leakiness and infiltration rates and discusses their ease of application and accuracy. It is concluded that buildings' leakage properties vary so much that it will probably prove impossible to find methods which are both simple and accurate.

Chapter 4 presents the author's conclusions that the achievements of research to date are sound methods of measuring leakiness and infiltration rates. It is suggested

that what is required to make further progress towards more refined prediction is a programme of testing of leakage properties to derive mean values for different types of buildings, which could be used as data for computer calculations of infiltration rates under different conditions. Action to reduce infiltration by occupiers who are becoming aware of its importance for heat loss is likely to precede the development of a generally applicable method for calculating the resultant heat savings.

An appendix on permeable buildings, where ventilation air is drawn in through permeable walls or roofs and expelled by an extract fan, is included.

A bibliography is provided. For further references the reader is referred to the Air Infiltration Centre.

Chapter 1 INTRODUCTION

1.1 General Remarks

During the preliminary stages of the work for this dissertation the author collected approximately four hundred references relevant to the study of infiltration. This meant that it was only possible to examine a fraction of them in the time available, so the result of the work is discussion of a sample rather than a comprehensive guide to the literature. The pace of new publications at present is so fast that any comprehensive guide would be out of date before it was completed. Those sources that have been discussed in detail have generally been those which presented some significant advance or novel approach.

1.2 Definition of Terms

Ventilation is the movement of air into and out of a space, whether caused by natural or artificial forces.

Mechanical ventilation is ventilation caused by artificial forces. Usually these are produced by fans, although the House of Commons once had an extract system powered by a fire in the base of an extract tower (18). The ventilation induced by a flued combustion appliance must be regarded as a special case of mechanical ventilation, in that the ventilation is caused by an artificial agency which is under the user's control and it does not depend much on the weather (assuming a well-designed appliance and flue).

Natural ventilation and infiltration are ventilation caused by the forces which are the result of the very presence of the building: differences in wind pressure between different parts of the envelope and differences in hydrostatic pressure due to the difference in density between the air inside and outside.

It is common to draw a distinction between natural ventilation proper which is caused by natural forces through openings provided for the purpose, and infiltration or adventitious ventilation which takes place through cracks and other accidental openings. Some writers use "natural ventilation" to include infiltration, but the distinction is a useful one and will be adhered to in this dissertation.

"Infiltration" is generally used to denote the movement of air both into and out of a building, but when the direction of movement is important "infiltration" is used for air entering and "exfiltration" for air leaving.

"Ventilation" without any qualification will be used to denote the sum of mechanical ventilation, natural ventilation and infiltration, although not all these need be present.

1.3 Historical Background

For many years it has been recognised that significant quantities of air enter and leave buildings through openings which are not made purposely for ventilation, but which are the result of attention not being paid to making the structure airtight.

Until recently there were many advantages in having leaky buildings. Open fires and stoves required large amounts of air for combustion (about 400 m^3/h for an open fire), whilst gas or oil lamps and candles required plenty of fresh air to replace the oxygen consumed and to dilute the combustion products. Densities of occupation were higher and standards of hygiene lower than they are today, requiring higher ventilation rates to control body odour.

In a leaky building the necessary fresh air enters at many widely-scattered points, which although not giving draught-free ventilation does not cause as severe winter draught problems as unheated air entering through a large opening. The problem of how to reduce draught from ventilators has been studied by Tipping & Tickner (65) and Michel (47), but the only way known at present of introducing cold air without causing discomfort is at high velocity above the occupied zone, so that the jet is well mixed with room air before it can fall very far. Only a mechanical air supply system can achieve the necessary velocity, and this is still regarded as a luxury by most building operators. In any case, the cost of adding a heater battery to a mechanical air supply system so that the fresh air is supplied at near room temperature is quite small compared to the cost of the rest of the system.

The major disadvantage of leakiness is that the ventilation rate is determined by the effects of wind and the temperature difference between the inside and outside of the building rather than by the quality of the air inside. Thus at some times the ventilation rate may be much more and at other times much less than is necessary.

When the ventilation rate is too low the air quality deteriorates. A higher ventilation rate than is necessary to maintain the freshness of the inside air is only an advantage when the inside temperature is too high and the outside temperature is lower, otherwise it adds to the load on the heating or (in hot countries) cooling plant. The conditions under which a high ventilation rate is an advantage often occur during the summer in temperate countries, when people respond by opening windows and the building's leakiness becomes insignificant compared to the effect of the open windows. In sub-tropical and tropical countries these conditions can prevail for most or all of the year, buildings being provided with large permanent ventilation openings if they do not have mechanical cooling. This dissertation is concerned largely with the problems of temperate countries during the heating season.

Ventilation requirements are now less than they were and still falling, owing to various factors some of which are mentioned below:

(1) Candles, gas and oil lamps have been almost completely replaced by electric lighting.

(2) Open fires and stoves are being replaced by central heating, balanced-flue appliances and electric heating, which draw little or no air from the building. Even if the central heating boiler is not a balanced-flue type and is placed inside the heated space, its greater efficiency and lower air to fuel ratio mean that it requires much less air than the appliances it replaces.

(3) Densities of occupation are lower. The introduction of central heating, particularly, means that the whole dwelling is used as a living space and not just one or two rooms.

When the ventilation rate is higher than necessary energy is wasted in heating the extra air to room temperature. In the past the required ventilation rates were, as explained, higher and the ventilation heat loss was a smaller fraction of the total heat loss since few buildings were insulated against conduction heat loss. Even in Norway, with its severe winters, there are many buildings built before 1940 which are without insulation.

Figure 1 shows the conduction and ventilation heat losses from a typical semi-detached house for different types of construction. The ventilation rates are selected on the basis of what is currently known about winter infiltration rates (20, 68). New houses generally have lower infiltration rates than old ones, but no proper survey of a large number of typical British dwellings has yet been published. It can be seen that although the better-insulated houses have been assigned lower ventilation rates, ventilation is responsible for a larger fraction of their total heat loss. This trend can be expected to continue as better insulation becomes economic or required by Building Regulations. (A U-value of 0.6 $W/m^2\ ^oC$ for outside walls will soon be required, as against 1.0 $W/m^2\ ^oC$ at present). It is therefore becoming more important to be able to estimate infiltration accurately in order to calculate heating loads and energy consumption. In order to reduce energy consumption it will in future be worth paying much more attention to reducing infiltration.

However, to be able to make accurate predictions we must answer the following questions:

(1) How do we measure the leakiness of buildings?
(2) How do we measure ventilation rates?
(3) How do we predict the leakiness of buildings?
(4) How do we predict ventilation rates?

The answers to (1) and (2) are by now sufficiently well understood to be approaching standardisation. The answers to questions (3) and (4) have been the subject of extensive research but as yet no way of making accurate predictions has been found. Much attention has been directed to the problem of finding a relationship between measured leakiness and ventilation rates.

Several countries are now preparing to follow Sweden's lead in setting leakage standards for buildings in order to reduce infiltration, although at present it is not possible to accurately predict the reduction in energy consumption brought about by a given reduction in leakiness in order to assess its cost-effectiveness (40).

The justification for the Swedish standard seems to be partly a belief that energy prices will continue to rise relative to other prices, and partly a policy of saving energy on ecological grounds.

It is probable that at a certain degree of leakiness, that which gives just enough infiltration to result in acceptable air quality most of the time, a reduction in leakiness will result in an increase in energy consumption as a mechanical ventilation system must be installed or windows or ventilators left open to ensure a sufficient infiltration rate. Open windows can give very high ventilation rates (21).

In principle there is no reason why a "topping-up" mechanical ventilation system with a capacity of say 50 m^3/h should not be installed in a small building such as a dwelling. In practice it would be little cheaper than one with a capacity of 200 m^3/h, and a client who wanted to save capital cost would choose to open windows whereas one who was prepared to pay for mechanical ventilation would choose the greater comfort afforded by the full-size system.

Thus if infiltration is to be reduced below the level which, on average, gives acceptable air quality it must be reduced to a very low level if the change is not to be counter-productive. Mechanical ventilation must then be installed, which gives improved comfort but increased capital and maintenance costs. This is the policy that has been adopted in Sweden.

Blomsterberg (7) found that most dwellings constructed with industrialised building systems met the new standard, as their joints were carefully designed,the components precisely made. Few tradesman-built dwellings met the standard, and considerable alterations to design and site practice will be necessary to enable them to do so (43).

Most of current research on air infiltration is concentrated on dwellings. This is because they are fairly standardised buildings which are found in large numbers, so results which are obtained have general application. Industrial, commercial and institutional buildings, by contrast, are fewer in number and exhibit greater variety.

1.4 Condensation

An aspect of infiltration which has received less attention than its contribution to heat loss is its contribution to condensation. When warm moisture-laden air from inside the building passes through the envelope in winter, it cools off. Condensation will take place if the initial moisture content of the air is high enough and the temperature to which it is cooled low enough.

Some workers (25, 51) have investigated the significance of in- and exfiltration for condensation, but the topic is as yet poorly documented. Work in Sweden by Paljak and Pettersson (51) has shown the crucial importance of detailing of vapour barriers and insulation by both the designer and the builder for the avoidance of cold bridges and air leaks leading to condensation. The technique of infra-red photography, or thermography, is generally used to reveal areas of high heat flux when searching for defects in existing buildings. These areas of high heat flux result from cold bridges and air leaks.

It has been common for ventilating engineers to adjust plant so that the supply air flow is greater than the extract air flow, as most leakages will then be outwards and draughts will be reduced (38). It is now realized that this makes condensation in the structure likely, and that it is better that the supply air flow is less than the extract air flow. The problem is made more difficult by the fact that both supply and extract air flow rates change as filters become blocked and ducts dirty (50). This reference reports a doubling of the flow rate in an extract system after cleaning.

1.5 The Causes of Infiltration

The causes of natural ventilation and infiltration are wind pressure and the hydrostatic pressure difference due to the difference in density between the air inside and outside the building. Even in "unheated" buildings the effect of the building envelope is to make the air temperature inside different from that outside, hence the densities will be different.

A great deal of work has been done on wind pressures, most of it with a view to assessing maximum pressures in order to calculate the necessary structural strength (12). The usual pattern is a positive pressure on the wall facing the wind, a negative pressure on the other three walls and a larger negative pressure on the roof.

The pressure difference due to the difference in density of air inside and outside the building is known as "stack effect". It produces a pressure difference which varies linearly with height, and tends to draw air into the base of the building when the air inside is warmer than that outside. See figure 2.

The line on the surface of the building where the pressure difference across the envelope is zero is known as the neutral zone, although it is in fact a line and not a zone. Its height depends on the disposition and relative sizes of the openings in the building envelope. If any one opening is so large in relation to the others that there is a negligible pressure difference across it, it is known as the dominant opening.

The effect of wind is to move the neutral zone up on those faces of the building which are exposed to a positive, and down on those faces which are exposed to a negative wind pressure.

The effect of flues and mechanical extract systems is to move the neutral zone up on all faces of the building. The effect of mechanical air supply systems is to move the neutral zone down.

Wind, flues and mechanical ventilation systems can have such an effect that the neutral zone moves off a wall entirely, so that the whole of the wall is passing air in the same direction.

Even if the positions and sizes of all openings, the inside and outside temperatures and the wind pressure distribution are known, the combination of wind and stack effect is a complex task. The rate of flow of air through almost all leakage paths in buildings is a non-linear function of the pressure difference across them, and the internal pressures can therefore not be derived immediately. They must be found by trial and error: making initial estimates of them, calculating the flows in and out and revising the estimates accordingly, until the calculated flow in is equal to the calculated flow out within an acceptable margin or error.

The general problem to be solved is shown in figure 3. This can be represented by the system of nodes and resistances shown in figure 4.

The groups of equations that must be satisfied are:

1) The leakage equations

2) The flow balance equations

The leakage equations are usually written

$$Q_{12} = C_{12} \operatorname{sgn} (P_1 - P_2) \; |P_1 - P_2|^{n_{12}}$$

$$Q_{27} = C_{27} \operatorname{sgn} (P_2 - P_7 - r_i(h_7 - h_2)) \, |P_2 - P_7 - r_i(h_7 - h_2)|^{n_{27}}$$

Q_{12} is the flow from node (1) to (2), C_{12} is the flow coefficient and n_{12} the exponent, r_i the density of air inside and h_2, h_7 the heights of nodes (2) and (7). $(\Delta P)^n$ is written as $(\operatorname{sgn} \Delta P) |\Delta P|^n$ in order to account for the possibility of some flows being in the opposite direction from that assumed.

The flow balance equations are:

$$\Sigma Q_2 = 0$$

i.e. $Q_{12} + Q_{S2} = Q_{23} + Q_{27} + Q_{e2}$

$$\Sigma Q_3 = 0$$

i.e. $Q_{23} = Q_{34} + Q_{38}$

etc., since the quantity of air in each cell must remain constant.

Strictly speaking all flows and flow balances should be expressed in mass units, but at present the other errors involved in the calculations are so large that it is common to use volume units and neglect the changes in density of the air in order to save calculating time.

It is usually assumed that the mechanical ventilation flows are constant. This is a good approximation for modern systems, where the fan pressures are ten or even a hundred times greater than the wind and stack effect pressures.

For flow through the duct system

$$Q = k\sqrt{(\Delta P)}$$

$$\frac{dQ}{d\Delta P} = \frac{-k}{2\sqrt{(\Delta P)}}$$

Thus the larger the pressure drop through the system the smaller absolute (not only proportionate) difference to the flow rate results from any change in the pressure drop. Only if the pressure drop through the system is comparable to the pressures produced by wind and stack effect will the mechanical ventilation flows be significantly affected by these.

The pressures at the external nodes (1), (6), etc. are found from the following equations:

$$P_1 = 0 + C_{P1} P_W$$

$$P_6 = -r_o (h_6 - h_1) + C_{P6} P_W$$

etc.

r_o is the density of the air outside, h_1 and h_6 the heights of nodes (1) and (6), C_{P1} and C_{P6} the wind pressure coefficients for nodes (1) and (6) and P_W the wind's velocity pressure. It is assumed that the leakage flows through the building are insufficient to affect the pressure distribution around it.

The solution of even a relatively simple flow network such as that shown is best performed by a computer. The topic is further discussed in Section 3.3, "Prediction of Infiltration".

Chapter 2 METHODS OF MEASUREMENT

2.1 General Remarks

The following quantities are usually of interest to workers in the field of air infiltration:

(1) Inside and outside air temperatures

(2) Wind speed and direction

(3) Mechanical ventilation flows

(4) Leakiness of building, room or component

(5) Ventilation rate

Number (5) is the result of the interaction of numbers (1) to (4). Numbers (1) to (3) are measured by conventional methods which will not be discussed here, but the measurement of numbers (4) and (5) will be covered in some detail.

2.2 The Pressurisation Method

The pressurisation method is the first of the two methods of measurement of leakiness that will be described.

The essentials of the method are shown in figure 5. The equipment consists of a fan, a manometer for measuring the pressure difference produced, a means of measuring the flow through the fan and a means of controlling the flow.

It is usual to arrange the apparatus so that the flow can be reversed and measurements taken for both pressurisation and depressurisation.

It is necessary both for this method and for the infrasonic method to consider carefully which leakage one wishes to measure, and to seal the other possible leakage sources thoroughly. The Swedish standard for leakage testing of buildings (SP 1977:1), for instance, is concerned with whether the building envelope meets the required standard of airtightness when deliberate openings have been sealed. Untrapped drains, ventilators, chimneys, etc. must therefore be carefully sealed with tape (40). Skinner (60) mentions that he does <u>not</u> seal chimneys, presumably because he is interested in the leakiness of the building in its normal operating condition.

The pressure at which the test is carried out is necessarily a compromise. It is desirable that the leakiness of the building or component be measured at a low pressure comparable to those produced by natural forces (e.g. a wind of 4 m/s has a velocity pressure of about 10 Pa.) in order to avoid a change of leakiness as, for instance, windows close more or less tightly under the influence of the applied pressure. Newman (49) studied the variation in leakiness of several types of windows and doors used in British dwellings, and found the leakiness to be little affected by the applied pressure up to about 10 Pa. On the other hand, in order to be able to distinguish the pressure difference and airflow produced by the fan from those produced by natural forces, the artificial pressure and flows must be several times larger than the natural ones. This difficulty is partly resolved by the infrasonic method, described in Section 2.3.

American practice (62, 64) has been to use a pressure of 0.3" w.g. (about 75 Pa) but tendency in Europe is to somewhat lower pressures. Kronvall (40) quotes the draft for the Swedish standard SP 1977:1 as requiring tests to be done at four pressures from 20 to 55 Pa, with the final result stated at a pressure of 50 Pa. This is becoming accepted as a standard method also in other countries. Kronvall reproduces a diagram from Lind et al. (42) showing the influence of wind on the measured leakage rate: for a wind-induced error of 10% at 50 Pa the wind speed should not exceed 8 m/s. For dwellings the errors due to stack effect are quite small: a height of 4 m and a temperature difference of 20°C produce a pressure of only 3.5 Pa. Kronvall recommends that testing should not be carried out when the temperature difference exceeds 30°C.

It was previously mentioned that the apparatus should be reversible, to allow both pressurisation and depressurisation. Usually the average of the two results is taken in order to reduce the effects of both any changes in building leakiness in response to the pressure applied and also any natural pressures and airflows which may be present. Since for most buildings exfiltration must equal infiltration the outward leakage characteristic is as important as the inward. More information about the building is conveyed if the inward and outward leakages are stated separately rather than just their average, since if the two differ much then it will be the smaller which dominates the natural in- and exfiltration.

It is important to realise that the result of a pressurisation test is only very indirectly related to a building's natural infiltration rate, although they may be expressed in the same units. When the result of a pressurisation test is expressed in, for instance, m^3/h or ac/h, it obtains only under the test conditions, which should be stated. An infiltration rate in m^3/h or ac/h obtains under a different (natural) set of conditions, which should also be stated as exactly as possible.

It seems reasonable to suppose that buildings which are leakier when pressure tested will have higher infiltration rates, but the relationship is not simple. For instance, the two buildings shown in figure 6 could have the same leakiness measured by pressurisation, but different infiltration rates. The one whose openings are at the top and bottom on the same side would have an infiltration rate determined by stack effect, the one whose openings are at the same height but on opposite sides would have an infiltration rate determined by wind. Most real buildings lie between these two extremes. The problem is discussed further in Section 3.2 "Prediction of Infiltration".

The results of pressurisation tests are presented in one of three ways:

(1) As a flow rate at some specified pressure difference.

(2) As coefficient C and exponent n in the equation $Q = C\,(\Delta P)^n$, where Q is the air flow rate and ΔP the pressure difference. C and n are found by fitting a curve to a set of pairs of values of Q and ΔP. It is important that the units of Q and ΔP be stated so as to define the units of C, which are for instance $m^3/h\ (Pa)^n$ or $ft^3/min\ ("w.g.)^n$, n is dimensionless.

(3) As an equivalent open area. Some workers (62, 64) have used the area of an orifice giving the same flow rate at the same pressure drop, but the value of n for most buildings and components is around $\frac{2}{3}$ whereas for an orifice it is $\frac{1}{2}$. (This is because the flow through a building's leakage paths is a mixture of laminar flow (n = 1) and turbulent flow ($n = \frac{1}{2}$) whereas that through the equivalent orifice would be turbulent). Thus

the area of the equivalent orifice was dependent on the pressure, which was clearly unsatisfactory.

Etheridge (23) showed how by using crack flow equations of the type

$$\frac{1}{C^2} = M\frac{Z}{d} \cdot \frac{1}{R} + N$$

equivalent open areas could be found that did not vary with the pressure.

C = discharge coefficient $\doteq \frac{V}{A} \frac{r}{2\Delta P}$

V = volume flow rate

A = cross-sectional area of crack

r = density of air

ΔP = pressure drop through crack

Z = total distance through crack

d = 4A/ wetted perimeter

R = Reynolds number $\doteq$ Vd/Av

v = kinematic viscosity of air

M and N are constants whose value depends on the shape of the crack

It is necessary in the method he describes to make certain assumptions about, for instance, the length, depth and shape of cracks. For cracks around windows and doors this is not difficult, whereas it is very hard to decide what values should be used for the "background" crackage through walls and floors, electrical fittings, etc. This is, in any case, an assembly of many cracks and other openings each with its own size and shape. Etheridge uses a process of trial and error to produce estimates of an equivalent crack whose dimensions are independent of pressure to an accuracy sufficient for infiltration calculations.

Method (1) is the usual one for assessing whether a building or component complies with a leakage standard, such as the Swedish SBN 1975:3 or the Canadian NAAMM standard for windows (48). For this purpose it is satisfactory, but it tells us very little about the building's leakiness at other pressures.

Method (2) has the advantage of describing the building's leakage properties over the whole of the pressure range tested, and can be extrapolated at the risk of inaccuracy. It has the disadvantage, already mentioned, that the units of C are dependent on the units chosen for Q and ΔP.

Etheridge suggests that his version of method (3), finding an equivalent crack, is superior to method (2) because the coefficients in the crack flow equation are dimensionless. The writer feels that this advantage is somewhat small (the units of the dimensions of the equivalent crack must after all be stated) compared with the extent to which the derivation of the crack dimensions is not reproducible by other workers. The values of C and n are found by standard statistical techniques, whereas the dimensions of the equivalent crack are found by trial and error and human judgement. It is conceivable that another worker could take the same experimental data and derive an equivalent crack with very different dimensions but similar flow characteristic. The differences in the stated crack dimensions would then obscure the fact that they both were intended to summarise the same experimental data.

2.3 The Infrasonic Method

The infrasonic method of measuring the leakiness of buildings has been described by Card et al. (14) and by Sherman et al. (58).

2.3.1 Card et al's. Account

Card's apparatus is shown in figure 7. It consists of a rigid cylinder, one end of which is closed rigidly. The other end is closed by a diaphragm which is moved alternately in and out by a connectingrod and crank coupled to an electric motor.

As the diaphragm moves in and out the effective volume of the building increases and decreases, so the pressure falls and rises and air is sucked in or expelled through the leakage openings in the envelope. The pressure difference across the envelope is measured by a micro-manometer.

The apparatus is placed inside the building to be tested, and run at a number of speeds between about 0.1 Hz. and 5 Hz. to obtain a characteristic curve of amplitude of pressure fluctuations against frequency.

The amplitude of the pressure fluctuations produced is small, of the order of 10 Pa, but the signal from the manometer is analysed by filtering out all components except that at the forcing frequency, an almost noise-free output thus being obtained.

The displacements and frequencies of oscillation of the diaphragm and the pressure differences produced being known, it is possible to calculate the leakage coefficient and exponent. The picture is, however, confused by dynamic effects.

The difference in travel time of the pressure wave from the test machine to different parts of a large building means that air can be flowing out at maximum rate at some places whilst it is flowing out at less than maximum rate or even flowing in at others, and the pressure difference

They define a leakage function as the ratio of flow rate to pressure difference, and find that it becomes very large as the pressure difference becomes very small. They suggest that this is a physical phenomenon which explains why several workers (5, 20, 46) have predicted non-zero infiltration rates at zero pressure difference by extrapolating their results from measurements under real conditions.

This must be criticised on two grounds. Firstly, viscosity damps out all motion of real fluids unless a pressure difference exists which can maintain the flow. Secondly, if the authors are correct in supposing that flow rate is proportional to the square root of the pressure difference at very low pressure differences, then the tendency of the leakage function to infinity as the pressure difference tends to zero is merely a consequence of the way it is defined.

$$L\ (\Delta p) \triangleq \frac{Q}{p}$$

$$Q = C\sqrt{\Delta p}$$

$$\therefore\ L\ (\Delta p) = \frac{C\sqrt{\Delta p}}{\Delta p} = \frac{C}{\sqrt{\Delta p}}$$

$$\text{As}\quad p \longrightarrow 0,\ \frac{1}{\sqrt{\Delta\ p}} \longrightarrow \infty$$

$\therefore L(\Delta p) \longrightarrow \infty$

$L(\Delta p)$ is the leakage function

Δp is the pressure difference

Q is the flow rate

C is a constant

Unfortunately they do not report any of their actual measurements, so their derivation of conclusions from experimental results can not be checked.

They make some interesting remarks about the effect of wind turbulence on ventilation. Measurement of ventilation rates by tracer-gas methods while conducting infrasonic tests of airtightness gave lower ventilation rates at high test frequencies than were predicted by considering the amount of air being forced into and out of the building. Observations with smoke sticks confirmed that at the higher test frequencies air was being sucked into the building, failing to mix with the other air inside and then being pushed out again through the same crack, thus reducing the effective infiltration rate. This may mean that only low-frequency wind turbulence need be taken into account in ventilation studies, but more research is needed on this topic.

2.3.3 Resonance and Flexing

The effect of resonance in flues etc. is considered by Card et al. They find that it will contribute a peak to the curve of pressure against frequency for a constant test displacement, and confirm this by experiment. It has little effect on the response at low frequencies where the leakage properties are studied.

The effect of flexing of the building envelope is considered by both Card et al. and Sherman et al.

Card et al. consider it to be unimportant on the basis of a metre of air being more resilient than a studded partition. They go on to predict by means of a more detailed analysis considering both the mass and stiffness that the vibration of a wall will give a dip in the curve of pressure against frequency. They do not find any such dip and therefore conclude their presumption that flexing is unimportant to be justified.

Sherman et al. compare the flexibility of the structure not to the compressibility of air but to the displacement of the test apparatus. They point out that the resonant frequency of most buildings is approximately 15 Hz, which is much greater than the test frequencies used. This means not only that dynamic effects involving structural resonance are unlikely to be important (confirmed by Card et al.) but also that the flexing of the structure will be very nearly in phase with the pressure difference across it. For the purpose of analysis they assume that the change in volume of the structure is proportional to the pressure difference across it. It is found in Section 2.3.5 that this flexing has little effect on the low-frequency response. Sherman et al. state that they correct the low-frequency response for flexing, although it is not clear how they do this.

2.3.4 Non-Linearity

The unavoidable disadvantage of the infrasonic method compared with the pressurisation method is that the air leakage through a building envelope is in general not a linear function of pressure. Thus the pressure produced by wind effect, stack effect and the test apparatus acting simultaneously will not be the sum of the pressures they each produce when acting individually.

The pressurisation method overcomes this problem by using a test pressure which is much larger than the wind and stack pressures. The infrasonic method is intended to be used at low pressures, so it cannot solve the problem in the same way.

One effect of the non-linearity will be that the flow produced by the test apparatus will take place mostly through leakage paths where little natural flow exists. This is because the test method produces the same change in pressure difference across all leakage paths, and n is less than 1 in the leakage equation $Q = C(\Delta p)^n$. The same change in Δp produces a smaller change in Q when Δp is large than when Δp is small. Thus the leakiness which is measured will be dominated by those leakage paths where little natural air flow takes place!

More experimental work is needed to determine to what extent variations in wind and stack effects actually affect the results obtained by the infrasonic method, so that recommendations can be drawn up such as Kronvall (40) gives for the pressurisation method.

The leakage through the envelope can be non-linear in several ways.

Describing the leakage as $Q = C(P_o - P_i)^n$, the value of n can be not equal to 1 (usually about 0.7), the value of C can be different for $P_o > P_i$ and $P_o < P_i$, and the value of n could be different for the cases $P_o > P_i$ and $P_o < P_i$.

The first type of non-linearity, $n \neq 1$ but not dependent on the direction of leakage, has been partly dealt with by Card et al., and an adaptation of their analysis is reproduced in Section 2.3.5 using thermodynamic quantities instead of their electrical analogue. The analysis does not take account of the effects of natural air flows.

The other type of non-linearity, variation in the value of C and possibly n as the direction of leakage changes, is not considered by Card et al. Sherman et al. try to take account of it by using the expression

$$Q = L(\Delta P) \quad (1 + \alpha \Delta P) \ \Delta P$$

where $L(\Delta P)$ is an even function of the pressure, and α is an "asymmetry parameter".

They go on to make a linear approximation by replacing $L(\Delta P)$ by its mean value during a cycle. However, the above expression gives an inappropriate shape for the variation of $|Q|$ with $|\Delta P|$, which is sketched in figure 9.

It can be seen that when $|\Delta P| > \frac{1}{2\alpha}$, $|Q|$ <u>decreases</u> as $|\Delta P|$ increases for $\Delta P < 0$, which is clearly unrealistic. The authors report a value of α of the order of 0.015 Pa^{-1},

$$\longrightarrow \frac{1}{2\alpha} = 33 \text{ Pa.}$$

This is not much greater than the range of pressure used in the tests ($\pm$ 20 Pa) both by these authors and by Card et al., so it seems likely that the use of this method of accounting for asymmetry will introduce errors of its own.

That asymmetry can be important is shown by Kronvall's listing of the results of pressurisation tests, where differences of up to 25% of the larger value are reported between leakage rates on pressurisation and depressurisation.

If the leakage coefficients and/or exponents are not the same for leakage in both directions, then the mean pressure inside the building will change when the test is started. This test-induced difference will be quite small (of the order of 5 Pa, see Section 2.3.5) and is thus of the same order of magnitude as the pressure differences produced by wind or stack effect. (A breeze of 4 m/s has a velocity pressure of 10 Pa, a height of 4 m and a temperature difference of 20°C give a stack pressure of 3.5 Pa.)

Sherman et al. have attempted to measure this test-induced difference although it is not obvious how they have distinguished it from wind and stack effects.

Indeed, in attempting to do this one is abandoning the greatest advantage of the infrasonic test method over the pressurisation test method. This is that measurements at low pressures can be distinguished from wind and stack effects by filtering out those components of the pressure signal which are not at the same frequency as the drive. Therefore the writer is of the opinion that an attempt to assess the asymmetry of the building's leakage by measuring the difference between the mean inside pressure and the outside pressure is almost certain to fail. Rather, it must be accepted as an inherent limitation of the infrasonic method that it averages the inward and outward leakage characteristics.

2.3.5 Analysis of Infrasonic Method

Assume that the process is adiabatic. Neglect kinetic and potential energy. Neglect resonance effects. Assume temperatures inside and out are similar.

Consider a small movement of the piston dV:

The first law of thermodynamics states that

Heat transfer into system - Net work done by system
= Increase of internal energy.

Heat transfer into system = 0

Net work done = $P\,(dV + \lambda\,dP) - RTdn$

Increase of internal energy = $(n + dn)\,(T + dT)\,C_v - (nTC_v + dnTC_v)$

$$RTdn - PdV - \lambda PdP = ndTC_v + dndTC_v$$

$$RTdn = PdV + \lambda PdP + nC_v dT \quad (dndTC_v \approx 0)$$

But $PV = nRT$

$$T = \frac{PV}{nR}$$

$$dT = \frac{\partial T}{\partial V}\,(dV + \lambda\,dP) + \frac{\partial T}{\partial P}\,dP + \frac{\partial T}{\partial n}\,dn$$

$$dT = \frac{P}{nR}\,(dV + \lambda\,dP) + \frac{V}{nR}\,dP - \frac{PV}{n^2R}\,dn$$

$$RTdn = PdV + \lambda PdP + nC_v \left(\frac{P}{nR} (dV+\lambda dP) + \frac{V}{nR} dP - \frac{PV}{n^2 R} dn \right)$$

$$= PdV + \lambda PdP + C_v \left(\frac{P}{R} (dV+\lambda dP) + \frac{V}{R} dP - \frac{PV}{nR} dn \right)$$

$$= PdV + \lambda PdP + \frac{1}{\gamma - 1} \left(P(dV+\lambda dP) + VdP - \frac{PV}{n} dn \right)$$

$$dn \left(RT + \frac{PV}{n(\gamma-1)} \right) = (PdV+P\lambda dP) \left(1 + \frac{1}{\gamma-1} \right) + \left(\frac{V}{\gamma-1} \right) dP$$

$$dn \left(RT + \frac{nRT}{n(\gamma-1)} \right) = (PdV+P\lambda dP) \left(\frac{\gamma}{\gamma-1} \right) + \left(\frac{V}{\gamma-1} \right) dP$$

$$RTdn \left(\frac{\gamma}{\gamma-1} \right) - (PdV+P\lambda dP) \left(\frac{\gamma}{\gamma-1} \right) + \left(\frac{V}{\gamma-1} \right) dP$$

$$RTdn = PdV + \frac{1}{\gamma} VdP + \lambda PdP$$

$$Q \triangleq v \frac{dn}{dt} = \frac{RT}{P} \frac{dn}{dt}$$

$$Q = \frac{dV}{dt} + \frac{1}{\gamma} \frac{V}{P} \frac{dP}{dt} + \lambda \frac{dP}{dt}$$

$$V \approx V_o \qquad P \approx P_o$$

$$Q = \frac{dV}{dt} + \left(\frac{1}{\gamma} \frac{V_o}{P_o} + \lambda \right) \frac{dP}{dt}$$

Linear approximation solution

For this method of solving linear differential equations by means of Laplace transforms see almost any introductory book on control systems, e.g. (56).

Suppose $Q = L\,(P_o - P)$

then $L\,(P_o - P) - \frac{dV}{dt} - \left(\frac{1}{\gamma}\,\frac{V_o}{P_o} + \lambda\right)\frac{dP}{dt} = 0$

$$P - P_o = \Delta P$$

$$dV = \Delta V$$

$$\frac{1}{L}\left(\frac{V_o}{\gamma P_o} + \lambda\right) = k = \frac{V_o + \lambda\gamma P_o}{L\gamma P_o}$$

$$\rightarrow \quad -\Delta P(t) - \frac{1}{L}\,\frac{d}{dt}.\,\Delta V(t) - k\,\frac{d}{dt}\,\Delta P(t) = 0$$

Taking Laplace transforms:

$$-\quad P(s) - \frac{1}{L}\,S\,\Delta V(s) - k\,s\,\Delta P(s) = 0$$

$$\longrightarrow \quad P(s)\,(-1 - ks) = \frac{1}{L}\,S\,\Delta V(s)$$

$$\longrightarrow \quad \frac{\Delta P(s)}{\Delta V(s)} = \frac{-s}{L\,(1+ks)}$$

If $\Delta V(t) = \sin wt$ (unit amplitude)

$$\Delta P(t) = \frac{-\,jw}{L(1+kjw)} \quad \text{(standard result)}$$

$$\left|\frac{\Delta P}{\Delta V}\right| = \left|\frac{-\,jw}{L(1+kjw)}\right| \qquad (|\Delta V| = 1)$$

$$= \frac{w}{L}\,\frac{1}{\sqrt{1+k^2w^2}}$$

$$\log \left|\frac{\Delta P}{\Delta V}\right| = \log w - \log L - \log \sqrt{(1+k^2w^2)}$$

$$L \approx 0.02 \ m^3/\text{sec Pa} \qquad \lambda \approx 3 \times 10^{-3}$$

$$V_o \approx 280 \ m^3$$

$$\gamma = 1.4$$

$$P_o \approx 10^5 \ \text{Pa} \qquad \longrightarrow k \approx 0.25$$

When $kw \ll 1 \qquad \sqrt{(1 + k^2w^2)} \approx 1 \qquad (\log 1 = 0)$

When $kw \gg 1 \qquad \sqrt{(1 + k^2w^2)} \approx kw$

The asymptotes intersect at $w = \frac{1}{k} = 4$

At low frequencies $\left|\frac{\Delta P}{\Delta V}\right| \approx \frac{w}{L}$

$$\longrightarrow \qquad L \approx w \left|\frac{\Delta V}{\Delta P}\right|$$

At high frequencies $\left|\frac{\Delta P}{\Delta V}\right| \approx \frac{1}{Lk} \qquad = \frac{\gamma P_o}{V_o + \lambda \gamma P_o}$

Thus the low frequency amplitude depends on the leakiness of the enclosure and not its volume or flexibility. The high frequency amplitude depends on the enclosure's volume and flexibility and not on its leakiness.

If the leakage is very small we have only adiabatic compression and expansion. Thus we can check our expression against PV^{γ} = constant.

$$\left|\frac{\Delta P}{\Delta V}\right| = \frac{w}{L\sqrt{(1 + k^2w^2)}}$$

$$= \frac{w}{L}\frac{1}{\sqrt{1 + \left(\frac{w}{L}\left(\frac{V_o}{\gamma P_o} + \lambda\right)\right)^2}}$$

$$= \frac{w}{L}\frac{1}{\sqrt{1 + \left(\frac{wVo + w\lambda\gamma P_o}{L\gamma P_o}\right)^2}}$$

$$= \frac{w}{L}\frac{L\gamma P_o}{\sqrt{L^2\gamma^2 P_o^{\,2} + (wVo + w\lambda\gamma P_o)^2}}$$

$$= \frac{w\gamma P_o}{\sqrt{L^2\gamma^2 P_o^{\,2} + (wV_o + w\lambda\gamma P_o)^2}}$$

As $L \rightarrow 0$ and $\lambda \longrightarrow 0$

$$\left|\frac{\Delta P}{\Delta V}\right| \longrightarrow \frac{\gamma P_o}{V_o}$$

Also, if PV^{γ} = constant = A

$$P = \frac{A}{V^{\gamma}}$$

$$\frac{dP}{dV} = -\gamma \frac{A}{V^{\gamma+1}}$$

$$= -\gamma \frac{P_o V_o^{\gamma}}{V^{\gamma+1}}$$

But $V \approx V_o$

$$\longrightarrow V^{\gamma+1} \approx V_o^{\gamma+1}$$

$$\longrightarrow \frac{dP}{dV} \approx -\gamma \frac{P_o}{V_o}$$

$$\longrightarrow \left|\frac{dP}{dV}\right| \approx \gamma \frac{P_o}{V_o}$$ as previously obtained.

(The negative sign in $-\gamma\frac{P_o}{V_o}$ indicates that as V increases P decreases).

The phase angle between the driving piston and the pressure oscillation is less easy to measure than the amplitudes, but it can be predicted as follows:

$$\measuredangle \Delta P(t) = \measuredangle \frac{-jw}{L(1+kjw)}$$

$$= \measuredangle(-jw) + \measuredangle\left(\frac{1}{L}\right) + \measuredangle\left(\frac{1}{1+kjw}\right)$$

$$= -90^{o} + 0^{o} + \tan^{-1}(-kw)$$

$$= -\left(90^{o} + \tan^{-1}(kw)\right)$$

where $k = \frac{1}{L}\left(\frac{V_o}{\gamma P_o} + \lambda\right)$

As $w \rightarrow 0$, $\measuredangle \Delta P(t) \longrightarrow -90^{o}$

As $w \rightarrow \infty$, $\measuredangle \Delta P(t) \longrightarrow -180^{o}$

As $L \rightarrow 0$, $\measuredangle \Delta P(t) \longrightarrow -180^{o}$

Symmetric Non-linear analysis for $n \neq 1$, adapted from Card et al

The linear approximation analysis shows that for low frequencies

$$\left|\frac{\Delta P(t)}{\Delta V(t)}\right| \approx \frac{w}{L}$$

i.e. the compressibility of the air and the flexibility of the building are negligible.

Thus we can write $Q = C\,(\mathrm{sgn}(P_o - P_i))\,|P_o - P_i|^{n}$

and $Q_{max} = C\,|\Delta P|^{n}_{max}$

C is used as the leakage coefficient to distinguish it from L used in the linear case. The subscript $_{max.}$ is used to show that the quantities do not necessarily vary sinusoidally.

$$\longrightarrow w|\Delta V| = C|\Delta P|^{n}_{max.}$$

$$\longrightarrow |\Delta P|_{max.} = \left(\frac{w|\Delta V|}{C}\right)^{\frac{1}{n}}$$

$$\longrightarrow \left|\frac{\Delta P}{\Delta V}\right|_{max.} = \left(\frac{w}{C}|\Delta V|^{1-n}\right)^{\frac{1}{n}}$$

$$\longrightarrow \log \left|\frac{\Delta P}{\Delta V}\right|_{max.} = \frac{1}{n}\log w + \frac{1}{n}\log \frac{|\Delta V|^{1-n}}{C}$$

$$\longrightarrow \log \frac{|\Delta P|}{|\Delta V|}_{max.} = \frac{1}{n}\log w - \frac{1}{n}\log C|\Delta V|^{n-1}$$

Compare for the linear case $\log \frac{|\Delta P|}{|\Delta V|} = \log w - \log L$

The linear approximation analysis shows that for high frequencies the effect of leakage is negligible. Thus we can write as for the linear case

$$\frac{|\Delta P|}{|\Delta V|} \approx \frac{\gamma P_o}{V_o + \lambda\gamma P_o}$$

These two lines intersect at the break point, where

$$\left(\frac{w_b}{C}|\Delta V|^{1-n}\right)^{\frac{1}{n}} = \frac{\gamma P_o}{V_o + \lambda\gamma P_o}$$

$$\longrightarrow \frac{w_b}{C}|\Delta V|^{1-n} = \frac{\gamma^n P_o^{\,n}}{(V_o + \lambda\gamma P_o)^n}$$

$$\longrightarrow w_b = \frac{\gamma^n P_o^n \, C \, |\Delta V|^{n-1}}{(V_o + \lambda \gamma P_o)^n}$$

When n = 1 and C = L

$$w_b = \frac{\gamma P_o \, L}{(V_o + \lambda \gamma P_o)} = \frac{1}{k}$$

the same as the breakpoint found by the linear approximation.

The shape of the frequency response in the region of w_b can not be found from an explicit expression, but must be determined numerically. Card et al. offer an approximate expression:

$$\frac{|\Delta P|}{|\Delta V|} \text{max.} = \frac{\gamma P_o}{V_o} \frac{\left(\frac{w}{w_b}\right)^{\frac{1}{n}}}{\sqrt{1 + \left(\frac{w}{w_b}\right)^{2/n}}}$$

When w is large, $\frac{|\Delta P|}{|\Delta V|} \text{max.} \rightarrow \frac{\gamma P_o}{V_o}$, as previously found

When w is small, $\frac{|\Delta P|}{|\Delta V|} \text{max.} \rightarrow \frac{\gamma P_o}{V_o} \left(\frac{w}{w_b}\right)^{\frac{1}{n}}$

$$\frac{\gamma P_o}{V_o} \left(\frac{w}{w_b}\right)^{\frac{1}{n}} = \frac{\gamma P_o}{V_o} \left(\frac{w \quad V_o^{\,n}}{\gamma^n P_o^n C \, |\Delta V|^{n-1}}\right)^{\frac{1}{n}}$$

$$= \left(\frac{w}{C \, |\Delta V|^{n-1}}\right)^{\frac{1}{n}}$$ as previously found.

When n = 1, $$\frac{|\Delta P|}{|\Delta V|} = \frac{\gamma P_o}{V_o} \frac{\left(\frac{w}{w_b}\right)}{\sqrt{1 + \left(\frac{w}{w_b}\right)^2}}$$

$$= \frac{\gamma P_o}{V_o} \cdot \frac{wV_o}{\gamma P_o L} \cdot \frac{1}{\sqrt{1 + \left(\frac{wV_o}{\gamma P_o L}\right)^2}}$$

$$= \frac{w}{L} \frac{1}{\sqrt{1 + k^2 \; w^2}}$$

as previously found for the linear case.

The approximate expression is stated to agree within 5% with the numerical solution.

Asymmetric analysis

Suppose $Q = C_1 \ (P_o - P)^{n1}$ for $P_o > P$

and $Q = -C_2 \ (P - P_o)^{n2}$ for $P_o < P$

Card et al's analysis has shown that at low frequency the pressure amplitude is given by $|\Delta P|_{max.} = \left(\frac{w \, |\Delta V|}{C}\right)^{\frac{1}{n}}$

$$P_o - P = \Delta P_1 \qquad (P_o > P)$$

$$P - P_o = \Delta P_2 \qquad (P_o < P)$$

$$|\Delta P_1|_{max.} = \left(\frac{w\,|\Delta v|}{C_1}\right)^{\frac{1}{n_1}}$$

$$|\Delta P_2|_{max.} = \left(\frac{w\,|\Delta v|}{C_2}\right)^{\frac{1}{n_2}}$$

Let us assume that we can measure the mean amplitude $\frac{|\Delta P_1|_{max} + |\Delta P_2|_{max}}{2} = |\Delta P|_{max}$ (i.e. one half of the peak-to-peak amplitude), and also the mean pressure difference across the envelope, which will be given <u>approximately</u> by

$$\Delta P_m = \frac{|\Delta P_1|_{max.} - |\Delta P_2|_{max}}{2}$$

Thus
$$|\Delta P_1|_{max} = |\Delta P|_{max} + \Delta P_m$$
$$|\Delta P_2|_{max} = |\Delta P|_{max} - \Delta P_m$$

$$|\Delta P_1|_{max} = \left(\frac{w\,|\Delta v|}{C_1}\right)^{\frac{1}{n_1}}$$

$$\longrightarrow \log\,|\Delta P_1|_{max} = \frac{1}{n_1}\log w + \frac{1}{n_1}\log\left(\frac{|\Delta v|}{C_1}\right)$$

$\longrightarrow \frac{1}{n_1}$ is the slope of a plot of $\log|\Delta P_1|$ against $\log w$.

Similarly $\log\,|\Delta P_2|_{max} = \frac{1}{n_2}\log w + \frac{1}{n_2}\log\left(\frac{|\Delta v|}{C_2}\right)$

and $\frac{1}{n_2}$ is the slope of a plot of log $|\Delta P_2|$ against log w.

When w = 1, log w = 0

$$\longrightarrow \log |\Delta P_1|_{max} = \frac{1}{n_1} \log \left(\frac{|\Delta V|}{C_1}\right)$$

$$\longrightarrow |\Delta P_1|_{max}^{n_1} = \left(\frac{|\Delta V|}{C_1}\right)$$

$$\longrightarrow C_1 = \frac{|\Delta V|}{|\Delta P_1|_{max.}^{n_1}}$$ at w = 1 on the low frequency asymptote.

Similarly $C_2 = \dfrac{|\Delta V|}{|\Delta P_2|_{max}^{n_2}}$

at w = 1 on the low frequency asymptote.

The magnitude of ΔP_m can be estimated as follows: assume that $n_1 = n_2 = 0.7$, $C_1 = 0.02$ m^3/sec $Pa^{0.7}$, $C_2 = 0.015$ m^3/sec $Pa^{0.7}$, $V = 0.1$ m^3, w = 2 rad/sec.

$$|\Delta P_1|_{max} = \left(\frac{w|\Delta V|}{C_1}\right)^{\frac{1}{n_1}}$$

$$= \left(\frac{2 \times 0.1}{0.02}\right)^{\frac{1}{0.7}}$$

$$= 26.83 \text{ Pa}$$

$$|\Delta P_2|_{max} = \left(\frac{w\ |\Delta V|}{C_2}\right)^{\frac{1}{n_2}}$$

$$= \left(\frac{2 \times 0.1}{0.015}\right)^{\frac{1}{n_2}}$$

$$= 40.46 \text{ Pa}$$

$$\frac{|\Delta P_2|_{max} - |\Delta P_1|_{max}}{2} = 6.82 \text{ Pa}$$

2.4 Other Conceivable Methods of Leakage Testing

The pressurisation test method is equivalent to a ramp change of volume of the building under test. The infrasonic method imposes a sinusoidal change of volume.

The third input commonly used in system testing is the step change. As far as the writer knows this has not been used by ventilation researchers. It could be approximated by, for instance, driving the piston of the infrasonic test apparatus by a pneumatic actuator instead of a rotating motor and crank. It would give a trace of pressure against time such as is shown in figure 13.

From the shape of the curve it would in principle be possible to determine the leakage properties of the building. In practice the shape would be obscured by noise, unless the change in volume was large enough to produce a pressure difference comparable to that used in pressurisation testing. This would again introduce the problem of the testing not being carried out at pressures representative of the pressures driving infiltration.

A series of alternately positive and negative steps of the same magnitude but varying length can be arranged to form what is known as a pseudo-random binary sequence. By use of appropriate statistical techniques a plot of magnitude of pressure oscillation against frequency can be drawn, even when the step changes of volume are so small that the changes of pressure they produce are comparable to the naturally occurring noise. This plot is equivalent to that produced by the infrasonic test method. This and other statistical methods of testing are apparently hitherto unused in leakage testing, but could well repay investigation (56).

2.5 Thermography and other qualitative methods

Some mention must at this point be made of thermography.

Thermography can not be used for measurement of air leakage or heat loss, but it can be used to give a qualitative understanding of their distribution over the building envelope.

The principle of thermography is that a special camera is used to take a picture of the area of interest using infra-red radiation. The amount of infra-red radiation emitted by a surface depends upon its temperature and upon its emissivity, and thus the picture produced by the camera depends upon both these things. If the emissivity of the surface is known then the calibration of the camera can be used to determine the temperature of the surface to less than $1^{o}C$.

Such precision in measuring surface temperatures is, however, rarely necessary in building applications, as the rate of heat loss from a surface depends also on air temperature, air velocity and radiant temperature of surroundings. These are rarely known with any accuracy (54, 61).

Thermography is applied in building by taking photographs from either inside or outside the building in winter. Most building materials (except metals) have similar emissivities, so on photographs taken from outside, insulation defects and air leaking outwards show up as warm areas. On photographs taken from inside, insulation defects and air leaking inwards show up as cold areas. The usual method is to use the fan of the pressurisation method of airtightness testing to draw air out of the building so that all the leaks are inward, and take photographs from the inside. Insulation defects tend to show up with rounded edges, air leaks with jagged edges.

A comprehensive guide to the application of thermography in building is given by Paljak and Pettersson (51).

Keast and Hsien-Sheng (37) have described the use of sound for locating infiltration openings in buildings. Openings are located by the change in sound reflection as a sound source and microphone pass across them. The sound reflected can also vary grèatly in the absence of openings, so the method is difficult to apply.

These qualitative methods of studying heat loss are not measurements, but are useful tools for locating defects.

2.6 Measurement of ventilation rates

The accepted method of measuring ventilation rates is by means of a tracer gas, a small quantity of which is released inside the space and whose variation of concentration with time is observed.

The ideal tracer gas would have the following properties:

- cheap
- easily available
- stable
- non-toxic
- non-inflammable
- similar density to air
- normally occurring in negligible concentrations
- small concentrations easily measured
- not absorbed by building materials or furnishings

No one gas has yet been found which combines all these properties. Hydrogen was used by some early workers (19). Other gases used include carbon dioxide (33), carbon monoxide, ethane and water vapour (31). The usual choices now are nitrous oxide, sulphur hexafluoride and to a lesser extent halogenated hydrocarbons.

The concentration of hydrogen is measured using a katharometer, where the temperature of a heater element inside a small chamber varies with the conductivity of the air in the chamber, which depends upon the concentration of hydrogen. This method gives a continuous measurement of tracer gas concentration.

The concentration of gases such as carbon dioxide, water vapour and nitrous oxide is measured by infra-red absorption, where the sampled air is drawn through a tube down which a beam of infra-red radiation passes. The beam falls on a detector cell, and the proportion of the radiation which is absorbed by the air depends upon the concentration of tracer gas in it. This method also gives a continuous measurement of tracer gas concentration. The apparatus responds to all those gases which absorb infra-red radiation, so if it is desired to measure the concentration of nitrous oxide but not water vapour or carbon dioxide then the influence of the other gases must be removed. This is done by passing the sampled air through a chemical drier to remove water vapour, and passing the infra-red radiation through a cell filled with carbon dioxide to ensure that all the radiation that can be absorbed by carbon dioxide is so absorbed. The apparatus is generally constructed to compare the absorption in the test tube with the absorption in a reference tube through which is pumped outside air.

The concentration of sulphur hexafluoride and halogenated hydrocarbons is measured by electron capture chromatography. The air to be sampled is pumped through a fractionating column, where the constituent gases are delayed for varying periods of time. The gas leaving the fractionating column passes through an electron capture detector, where the current between two electrodes varies according to the tendency of the gases molecules to capture the free electrons. Each gas is delayed for a characteristic time by the fractionating column and thus the concentration of a particular gas can be found by observing the output of the electron capture detector at the appropriate time. Thus it is possible to use this method to simultaneously measure the concentrations of several different tracer gases when studying air movements between rooms as well as infiltration from outside. Because the fractionating column works by separating discrete samples of air this method gives a measurement of tracer concentration at intervals rather than continuously.

The three common methods of using tracer gases are the concentration decay method, the constant concentration method, and the constant rate of supply method. Assuming perfect mixing within the space, the analyses of the three methods are as follows:

2.6.1 Concentration decay method

Consider a room of volume V, containing tracer gas in air at a concentration c_r m^3/m^3. Suppose fresh air containing $c_o m^3/m^3$ of tracer gas enters at a rate of f m^3/sec, and an equal volume of room air leaves. If no correction for the change in volume of the fresh air as it is heated or cooled to room temperature is made then all volumes are automatically expressed as corrected to room temperature.

Thus in a short time dt seconds, quantity of tracer gas entering $= c_o f\,dt\ m^3$, quantity of tracer gas leaving $= c_r\ f\ dt\ m^3$, quantity of tracer gas in room at time t $= Vc_r\ m^3$ and quantity of tracer gas in room at time t + dt $= V\,(c_r + dc_r)\ m^3$

$$Vc_r + c_o\ fdt - c_r\,f\,dt = V\,(c_r + dc_r)$$

$$f\ (c_r dt - c_o\ dt) = V\,(-\,dc_r)$$

$$\frac{f}{V} = \frac{-1}{C_r - C_o}\ \frac{dc_r}{dt}$$

(The negative sign is the result of a positive ventilation rate giving a falling tracer gas concentration, i.e. $\frac{dc_r}{dt}$ negative).

The concentration of tracer gas in the room is measured at intervals or continuously, and the ventilation rate $\frac{f}{V}$ derived by numerical or graphical methods from the results. When using graphical methods it is usually necessary to wait until the concentration of tracer gas has fallen to about one half of the original value in order to obtain enough curve to analyse. Abel & Sundström (1) have developed a method based on automatic measurement of the tracer gas concentration at frequent intervals (ca. 1 second), the concentration measurements for the last minute or so being analysed by a microprocessor each time a new measurement is taken. When three or four successive calculations give the same ventilation rate the test is stopped, which saves a great deal of time.

The concentration decay method is sufficiently fast for normal purposes, is economical of tracer gas and equipment, but can give results which are difficult to analyse if the ventilation rate is changing.

2.6.2 The constant concentration method

The concentration of tracer gas in the room is measured automatically, and used to control the rate of release of tracer gas v_t so that the concentration c_r is held constant.

$$f\ c_r = f\ c_o + v_t$$

$$f = \frac{v_t}{c_r - c_o}$$

The method gives a continuous measurement of the ventilation rate and the results are easy to analyse, but it requires complex and expensive equipment for controlling and measuring the small release of tracer gas which is required. The method is also subject to control system errors

2.6.3 The equilibrium concentration method

The rate of release of tracer gas, v_t, is constant. When equilibrium is reached

$$f\,c_r = f\,c_o + v_t$$

$$f = \frac{v_t}{C_r - c_o}$$

The equipment is less complex than that required for the constant concentration method, but it is difficult to ensure a constant rate of release of tracer gas. Large quantities of tracer gas are consumed as equilibrium is approached, and equilibrium may indeed never be attained as the outside weather conditions, and hence the ventilation rate, are constantly changing.

2.6.4 The problem of mixing

Throughout the foregoing analyses it has been assumed that the air and tracer gas are thoroughly and rapidly mixed in the room. In practice this ideal is approached to varying degrees according to the characteristics of the air movement in the room (45).

It is possible to distinguish three different types of mixing in rooms: perfect non-mixing, perfect mixing and partial mixing. See figure 15.

In a room where a perfect non-mixing air movement pattern exists and the tracer gas is originally thoroughly mixed with the room air, a sensor would record first a constant tracer gas concentration and then a step change to zero concentration, corresponding to zero and infinite ventilation rates in a perfectly mixed room.

The variation of tracer gas concentration in a perfectly-mixed room has already been described.

In a room where partial mixing takes place a sensor placed in the stagnant zone would record a constant tracer gas concentration, corresponding to zero ventilation rate. A sensor placed in the mixed zone would record a tracer gas concentration which decayed as if the volume of the room were the mixed volume.

The rate at which a tracer gas diffuses through still air is very much lower than the rate at which it is mixed by air movements normally present in rooms.

Dick (19) was of the opinion that the tracer gas should be allowed to mix with the room air under the influence of the normal air movement during the test, but this gave rise to the possibility that the air being sampled by the concentration meter was not representative of the average condition. It is possible to use a manifold which draws air from many points simultaneously, but if the flow rate through the meter is not increased in proportion its response becomes very slow. If the flow rate is increased and the number of sampling points is made large in order to obtain a good average, then the flow rate through the meter becomes large enough to alter the pattern of air movement in the room. Thus we are unable to measure the average condition of the room air without altering the air movement pattern and probably altering the rate of in- and exfiltration (26). Honma (32) attempted to overcome this difficulty by means of a sensor which detected the concentration of tracer gas between an infra-red emitter and receiver without drawing the air through a machine, but technological difficulties meant that as yet the device can only be used for water vapour, which is a very poor tracer gas.

Most workers now resolve the problem by using fans to mix thoroughly all the air in each space and measuring the tracer gas concentration at one point in each space. Buildings with air conditioning or warm-air heating systems using recirculated air lend themselves particularly well to this approach, as the quantities of air circulated are large, the tracer gas concentration can be measured at the central plant and the circulation of air induced is present during normal operation as well as testing (35). In other buildings it is usual to employ free-standing oscillating fans such as are used to create air movement for summer cooling.

An additional problem is introduced by the presence of furniture containing significant volumes of air which will not be well-mixed with that in the room. The only solution to this is to remove the furniture, but as a compromise fixed cupboards, etc. can be left in place with their doors open (71).

Chapter 3 METHODS OF PREDICTION

3.1 General Remarks

Prediction of leakiness and of infiltration rates is very difficult, and no easy and accurate methods have yet been found. The source of the difficulty is the great variation in position and size of leakage openings among even nommally identical buildings, and the variation in the wind pressures to which they are exposed. The geometry of a building's surroundings can radically alter the distribution of wind pressures on its surface (2) so not only the building but also its environment within a radius of up to several kilometres must be described if infiltration is to be predicted.

3.2 Prediction of leakiness

The hitherto most used method of predicting leakiness is the "crackage" method described in the ASHRAE Handbook and CIBS Guide. This method is also standard in Germany (22).

The lengths of cracks around opening windows, doors etc. are multiplied by their leakage coefficients per unit length to find the total leakage for each part of the building. The leakage coefficients for windows, doors etc. are obtained from the manufacturer, or more usually from the the tables of typical values in the Handbook and Guide. The number and type of parts into which the building is divided depends upon how detailed the infiltration prediction calculation is to be.

A minor defect of this method is that the leakage coefficients given in the tables are not always correct. Sasaki (55) in 1965 tested a number of windows. He found that whilst the wooden windows had leakage coefficients similar to those given in the ASHRAE Handbook, the metal windows were generally much leakier. The most likely solution to this problem is that, as the importance of limiting infiltration becomes generally realised, maximum leakage coefficients for windows and doors will increasingly be specified by architects and stated by manufacturers.

A fundamental fault of the method is that it takes no account of adventitious openings or "background" leakage. These are for instance cracks between floorboards and around skirtings, openings for services, cracks between door and window frames and walls, permeability of certain types of walls, etc. Several workers (60, 23) have found that the background leakage can be as large as or larger than the leakage which is taken account of by the crackage method.

Skinner (60) tested the airtightness of 25 British dwellings. One of these was a Victorian house with many sash windows and chimneys, which was much leakier than the other more modern buildings. It is therefore excluded from the following remarks. From Skinner's graph it can be deduced that the sample as a whole had a mean leakage of 9.4 m^3/h per m^2 floor area with a variance of 26%. 10 nominally identically dwellings had a mean leakage of 9.7 m^3/h per m^2 floor area with a variance of 27%. (Air leakage stated at 10 Pa pressure difference). Skinner suggests that the variation amongst the nominally identical dwellings must have been due largely to variations in the background leakage. This is because although individual windows and doors vary in their leakiness, the chance of getting all tight or all leaky specimens in one house is quite low.

Howard (34) measured the ventilation rate in several Australian dwellings, and found that it was unaffected by whether the ventilators were open or closed. This suggests that the background leakage was very large.

Kronvall (40) gives in his appendix 1 a summary of measurements that have been made on about 400 Swedish buildings, but does not draw any conclusions from them.

The first 21 examples given are all 1½ storey detached houses with a volume of ca. 380 m^3, built of prefabricated wooden volume elements with a suspended ground floor, having mechanical extract systems. 2 sets of results are given for some of the dwellings, but there is no obvious difference between the conditions for the two sets so they are all lumped together here. With a positive pressure of 50 Pa the mean air change rate is 4.22 ac/h and the variance 18%, with a negative pressure of 50 Pa the mean air change rate is 4.27 ac/h and the variance 19%.

Brunsell and Uvsløkk (11) tested 61 Norwegian detached houses of traditional wood-frame construction, and found a mean air leakage of 4.7 ac/h at 50 Pa with variance 32%. They also tested 34 flats in blocks built of concrete with light-weight external walls, and found a mean air leakage of 1.3 ac/h at 50 Pa with variance 31%. All dwellings were between 1 and 5 years old. Brunsell (10) earlier tested four groups of nominally identical dwellings for airtightness, with the following result:

Type of dwelling	Type of construction	No	Variance
Detached	"Multi" prefabricated panels	9	20%
"	Other prefabricated panels	8	18%
Terrace	Traditional timber frame	8	19%
Flat	Concrete with light-weight external walls	4	23%
"	After draughtproofing	4	15%

The mean values of airtightness are not stated, but from Brunsell's chart it can be seen that the flats after draughtproofing were the tightest, then flats before draughtproofing, then "Multi" prefabricated houses, then the houses of other prefabricated and traditional construction. Brunsell suggests that as the variance appears to bear little relation to airtightness it must be due to variations in workmanship rather than materials. The fact that draughtproofing of the flats decreased the variance tends to support this conclusion.

Brunsell and Uvsløkk searched for leaks by thermography, and found that they tended to occur at joints between different constructions, e.g. window/wall, wall/roof.

Very little work has been done on the variation of airtightness with the seasons. Siviour and Mould (59) found that in their test house, where the infiltration was stack effect dominated, the infiltration was larger in summer than in winter. This they attributed to the boards of the suspended ground floor drying out so that the joints between them opened up.

So far as the writer is aware, no study has been or is being made of the effect of ageing of buildings on airtightness. Presumably this is because no workers have yet had the time and resources to take a number of buildings and follow them for many years.

Thus we can draw four main conclusions:

1) It is not possible to make an accurate estimate of airtightness by the crackage method, because this does not take account of the important background leakage.

   The estimate obtained by the crackage method has hitherto been sufficient for plant sizing purposes. If the ventilation heat loss is 30% of the total heat loss and is estimated to be only half of the actual figure, the underestimate of the total heat loss will be only 15%. This is easily absorbed by normal oversizing of plant and casual gains from cooking, lighting, people, etc.

In order to calculate whether it is worth investing in better airtightness we must be able to estimate infiltration more accurately, especial the effect of reducing the background leakage (not accounted for by crackage method).

If more accurate and easily applicable methods of estimating airtightness can be found in order to estimate energy consumption, it may also be possible to use them for more accurate plant sizin This aspect will be more important in future as the infiltration heat loss represents a larger proportion of the total heat loss in well-insulat buildings.

2) Information about airtightness of buildings can only be gained by a properly-designed testing programme, in order to find means and variances for different types of buildings. There would also be a need for frequent programmes of testin of new buildings, in order to take account of changes in building practice.

3) The effect of changes in design or in construction methods can perhaps be roughly estimated beforehand, but the variation in airtightness of nominally identical buildings is such that testing of many completed buildings will always be necessary to prove or disprove the estimates.

4) Finally it should be noted that the variation in leakiness of individual sections of the building envelope may be expected to be greater than the variations in the leakiness of the whole building. This is because, as Skinner (60) pointed out, it is likely that a building will contain some tight and some leaky components rather than all tight or all leaky. Leaks at the top and bottom of a building have most importance for stack-effect induced infiltration, whilst leaks on the sides have most importance for wind-induced infiltration. Thus it is possible that the variation in infiltration rate between nominally identical buildings under the same conditions will be different from the variation in their total leakiness. The expense of a climatic chamber to test several buildings under identical conditions has excluded any experimental test of this proposition, as no two buildings outside the laboratory are ever exposed to identical conditions.

3.3 Prediction of Infiltration

There exist a variety of methods for predicting infiltration. Generally it can be stated that the accurate methods are very complex and the simple methods rather inaccurate.

Methods of predicting infiltration can be divided into three main groups:

1) those which give a round number for use at the plant design point,

2) those which present an empirical correlation between wind speed, temperature difference and infiltration rate,

3) those which solve flow networks of varying complexity based on data concerning wind pressures, temperature difference and the building's leakage properties.

The first group consists of the variants of the "air-change" method included in the ASHRAE Handbook (3), CIBS Guide (15) and VVS-håndboken (67). These suggest numbers of air changes per hour to allow for infiltration at the plant design point, dependent on type of construction, exposure, number of windows and doors, etc. (not all factors are included by every handbook). They have proved to be adequate up to now, probably more because plant has been oversized than because the infiltration has been estimated accurately. Stöcher (63) has pointed out how the heating load may be greater on a mild windy day than on the cold calm day usually used as the design condition, and suggested a method for plotting heat loss against probability curves for both outside temperature and wind speed to enable the critical condition to be found.

The second group are few in number. For a single given building, several researchers have produced quite close correlations of infiltration rate with wind speed and temperature difference (8, 28, 68). A pattern which is commonly found is, for a given temperature difference, an infiltration rate which is approximately constant up to a certain wind speed and thereafter approximately proportional to wind speed. The transition between the stack-effect-dominated and wind-effect-dominated regimes is quite sharp. This phenomenon has been used by some workers in their infiltration calculations in the third group to simplify the calculation so that only the greater of the two effects is taken account of.

The extension of this approach to cover many buildings is much more difficult.

Peterson (52) reduces results from a wide variety of other workers to two tables from which infiltration rates in dwellings can be predicted. However, these must be regarded as being of limited value as no indication is given of the size of possible errors.

The methods of predicting infiltration on which most work is now being concentrated belong to the third group, where the infiltration rate is calculated from the pressure distribution over the surface of the building and the building's air leakage properties.

The oldest of these methods is the crackage method. This finds the leakage properties of the building from standard tables, as previously described, and the wind-induced pressure drop across the walls from an approximate formula based on the wind speed. The infiltration (and exfiltration) rate is then found from the leakage properties and the calculated pressure drop. It is important to note that this method as usually applied does not adjust the pressure inside the building in order to balance the infiltration rate with the exfiltration rate, but requires that this be estimated at the start. Janssen et al. (36) report that the accuracy of the crackage method is similar to that of the air change method, i.e. good enough for plant sizing hitherto but not for accurate predictions of energy consumption or air quality under conditions of average or little infiltration.

The other methods of calculating the infiltration rate from the pressure distribution over the building's surface and its leakage properties all involve an iterative solution of the problem, and are therefore intended for computer use. They take an estimate of the pressure inside the building (or each room) and correct this on each iteration until the calculated rate of infiltration equals the calculated rate of exfiltration (to an acceptable degree of accuracy).

It may be noted here that calculations of natural ventilation (as opposed to infiltration) have been performed by hand for many years. Natural ventilation is dominated by a few large openings, so the number of simultaneous non-linear equations to be solved is within the capabilities of a human being. Aids to calculation have also been devised (9, 13). An effect which is especially important for large openings but which has been neglected in natural ventilation calculations is that turbulence can result in air flowing both in and out simultaneously through the same opening (16, 24, 69). This problem is yet unsolved. It has been reglected in the past because turbulence tends to increase the ventilation rate, and designers have been largely concerned with ensuring some minimum rate of ventilation rather than some mean or maximum. For the effect of turbulence on infiltration see later in this section.

The most elaborate of the computer infiltration models is the British Gas model presented by Alexander and Etheridge (2). The leakage properties of all the building's surfaces and partitions are expressed as equivalent cracks, and the flow equations used are the crack-flow equations of Etheridge (23). Account is taken of the effect of turbulence on large openings such as ventilators based on the work of Etheridge and Nolan (24). The position of the neutral plane on each surface is found rather than assumed. The model is capable of considering each room in the building individually and calculating the flows between rooms, rather than merely regarding the building as a single cell.

The disadvantage of such an elaborate model is that it requires so much data both on the leakage properties of the building and on wind pressure distributions. Alexander and Etheridge found from wind tunnel studies of a model of their test house and its surroundings that the standard wind pressure coefficients were substantially in error. This was due to the sheltering effect of neighbouring buildings. In their calculations they therefore used wind pressure coefficients derived from their wind tunnel studies.

They measured actual ventilation rates using an automated constant tracer-gas concentration apparatus, and found a mean ratio of predicted tomeasured ventilation rate of 1.04 with a variance of 18%. This included cases where the house's mechanical ventilation systems were off and run as supply only, extract only and balanced. There was a slight tendency for the model to underestimate infiltration rates upstairs and overestimate them downstairs. They measured airtightness by the pressurisation method, and found good agreement between predicted and measured airtightness at low pressures (up to ca. 30 Pa). At higher pressures the agreement was less good. They suggest that this is because their crack flow equations were losing their validity. The effect is unlikely to be important as pressures over 30 Pa seldom occur naturally.

Their results show that it is possible to achieve quite accurate prediction of infiltration if a sufficiently elaborate calculation method is used. The disadvantage of the method is that it requires comprehensive information about the leakage and aerodynamic properties of the building and its environment, which is difficult and time-consuming to obtain for existing buildings and (in the case of leakage properties) impossible for projected ones.

Many other simpler infiltration models have been developed (6, 17, 22, 41, 57, 68). They make simplifying assumptions about one or more of wind pressure distribution, crack distribution, crack flow characteristics and internal partitioning of the building.

As yet no model has appeared as the one which makes the right simplifications, enabling the accuracy of the British Gas model to be approached without requiring such detailed data.

No models apart from Alexander and Etheridge's model take specific account of turbulence. They refer to Van der Held's paper (66) as being highly significant, but the present author was unable to obtain a translation.

Potter (53) describes an experiment designed to investigate the effect of turbulence on infiltration. A room with windows in both ends was sealed off from the rest of the dwelling as well as possible. Micromanometers were installed to measure the pressure differences across the windows. The infiltration rate was measured by use of a tracer gas technique.

The infiltration rate was calculated from the data-logged output of the micromanometers and the known leakage characteristics of the windows, thus taking account of turbulent fluctuations in wind pressure, and found to agree closely with the measured infiltration. The infiltration rate was then calculated from the time-averaged wind pressures using the Building Services Research and Information Association's CRKFLO computer program. This was found to underestimate the infiltration rate by 20% to 80%, most at low infiltration rates.

Handa (30) presents a theoretical model which predicts the effect of wind turbulence on infiltration. In all cases the effect is to increase the rate of infiltration as the turbulence of the wind increases. The increase is greater if the flow through the leakage openings is laminar rather than turbulent, and greater if the size of the building is small compared to the scale of the wind turbulence.

Handa's figure 2.8 gives an intensity of turbulence of approximately 0.25 for a semi-urban site such as the site of Potter's test building. Assuming further that the size of the test building (a dwelling) was small compared to the scale of the wind turbulence, Handa's figure 7.3 (b) predicts an increase in the wind-induced infiltration rate of from 22% (for fully turbulent leakage flow) to 50% (for fully laminar leakage flow), as compared to the infiltration rate which would result if wind pressures were constant. At high infiltration rates the leakage flow will tend to fully turbulent, and at low infiltration rates to fully laminar. Handa's predictions are thus of the same order of magnitude as Potter's measurements and exhibit the right tendency of increasing importance of turbulence in the wind as the wind speed falls.

Much more work is needed on this question.

Chapter 4 CONCLUSIONS

The unsolved problem in the study of infiltration is that of prediction.

The mechanisms driving infiltration, wind and stack effects, are well understood and it is possible to make accurate calculations of infiltration rates provided that one has sufficient information about the properties of the building and of the wind (2).

The methods of measuring infiltration rates and their limitations are sufficiently well researched to be approaching standardisation. The problems that remain in this field are those of improving the accuracy and flexibili of the instruments without extravagent cost.

The pressurisation method of measuring leakiness is now almost standardised. Those variations in practice which do exist are the consequence of differences in the use to which the information obtained is to be put.

The infrasonic method of measuring leakiness is a new method which has not yet been thoroughly explored. It has several advantages over the pressurisation method, but the inherent difficulty of anlysing the results of the infrasonic test may prove to outweigh the advantages. Further research is needed to settle this question.

The prediction of leakiness and infiltration rates is far more difficult than their measurements. This is because even nominally identical buildings exhibit large variations in leakiness, which are compounded by variations in wind pressures to produce variations in infiltration rate.

Thus it does not seem to be possible to make an accurate prediction of what the infiltration rate into a particular building will be without performing many measurements on it, which is of course impossible for buildings still on the drawing board.

What is feasible is to measure the leakage properties of samples of different types of buildings, and to use this sample data to construct means for each type. Computer programs which had been tested on real buildings could then be used to predict the infiltration rates of these hypothetical mean buildings under different conditions. The effect of extra airtightening measures could then be calculated. By study of the variation of the leakiness of the different parts of the sample buildings and investigation of the importance of these variations for infiltration with the help of the computer program, it would be possible to derive a "worst likely case" for plant sizing purposes.

Since we now know the order of magnitude of infiltration rates to expect, there is little point in making measurements of infiltration rates except as a test of a predictive model, since the results will otherwise simply augment the mass of undigested data on infiltration rates which has been collected over the years.

Only when an accurate predictive method has been developed will it be possible to know whether it is cost-effective to change methods of construction and improve workmanship in order to cut down infiltration. The high rate of interest which must be paid now means that it is unlikely that we can expect any voluntary raising of standards for new construction, unless the associated costs can be shown to be fully offset by lower running costs. It is more probable that retrospective airtightening work will be done by occupiers although its economic benefit can not be rigourously demonstrated, in the same way as occupiers now install double glazing.

APPENDIX

Permeable Buildings

Permeable buildings embody a novel approach to the problems of ventilation and infiltration. They have been used mainly in Sweden and Finland, for industrial, agricultural and sports buildings but not yet for dwellings. They have been used in Russia for cold stores (4, 39).

The principle of the construction is that ventilation air passes into the building through the insulation, which is not provided with any vapour barrier or other airtight layer. This is known as a counterflow construction as the ventilation air flow is counter to the heat flow.

Solution of the equation relating the conductivity and thickness of the insulation, the velocity, density and specific heat of the air and the temperature difference between inside and outside shows that the temperature profile through the insulation will take up the form shown on the right in figure 16 (39).

It can be seen that the temperature gradient near the outer surface of the insulation is very small, and thus the conduction heat loss is also very small. Provided that there is a need for the ventilation then significant energy savings are possible (how much depends on the size and use of the building, its location, etc.)

The practical details of the installation vary from case to case. For industrial and agricultural buildings it is usual to have a fan or fans supplying outside air to a loft or roofspace used as plenum above a counterflow ceiling. Korsgaard (39) suggests the use of counterflow walls for dwellings. Some applications require that exhaust air be extracted from the building by fans, whereas Græe (29) states that these can often be dispensed with in agricultural buildings with leaky walls.

Anderlind and Larsson (4) state that a minimum airflow inwards is always required to avoid condensation on the cold side of the insulation. Græe states that he has found in practice in cattle buildings that condensation damage can be avoided by ensuring that the plenum loft is always well-ventilated, even when the ventilation requirement of the building is reduced and little air is passing through the insulation. This is done by keeping the supply fan(s) running and opening damper(s) to dump the excess air to the outside.

Nothing appears to have been published about the effect of varying wind and temperature on the airflow through these buildings.

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Figure 1 - Heat Losses from Semi-detached House

Type of Construction	ac/h Vent.rate	Heat Losses W/°C Conduction	Ventilation	Total	Vent.%
220 mm solid brickwork with 15 mm hard plaster, single glazing, linoleum on floor.	2	383	167	550	30%
105 + 50 + 105 mm cavity brickwork with 15 mm hard plaster, single glazing, carpet on floor.	2	342	167	509	33%
105 + 50 + 100 mm brick/block cavity wall with 15 mm hard plaster, single glazing, carpet on floor, 50 mm loft insulation.	1½	226	125	351	36%
105 + 50 + 100 mm brick/block cavity wall with 15 mm hard plaster, double glazing, 50 mm floor insulation, 100 mm loft insulation, 50 mm cavity insulation.	1	114	84	198	42%

Floor area 100 m^2, glazed area 20 m^2, outside walls (excl. glazing) 80 m^2, suspended timber ground floor.

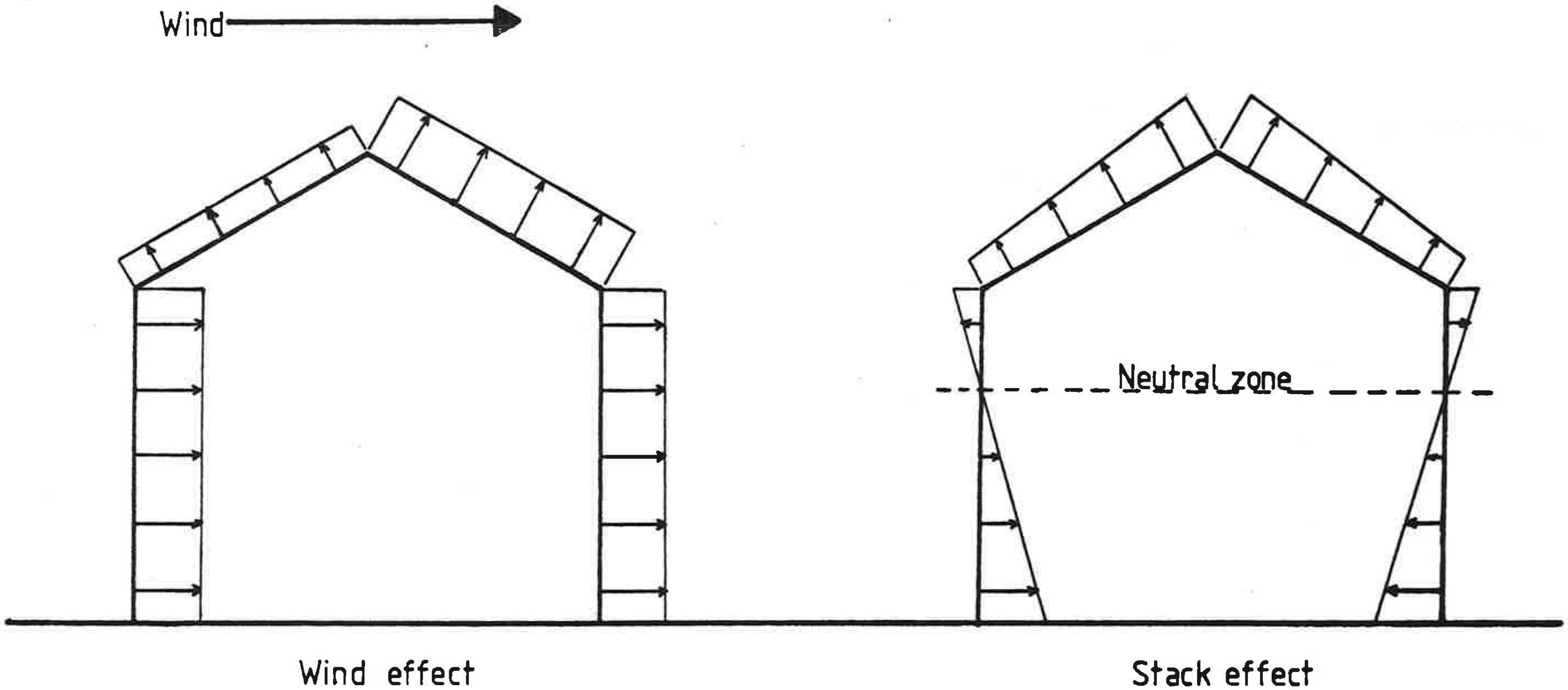

FIGURE 2 - Pressure differences across building envelope

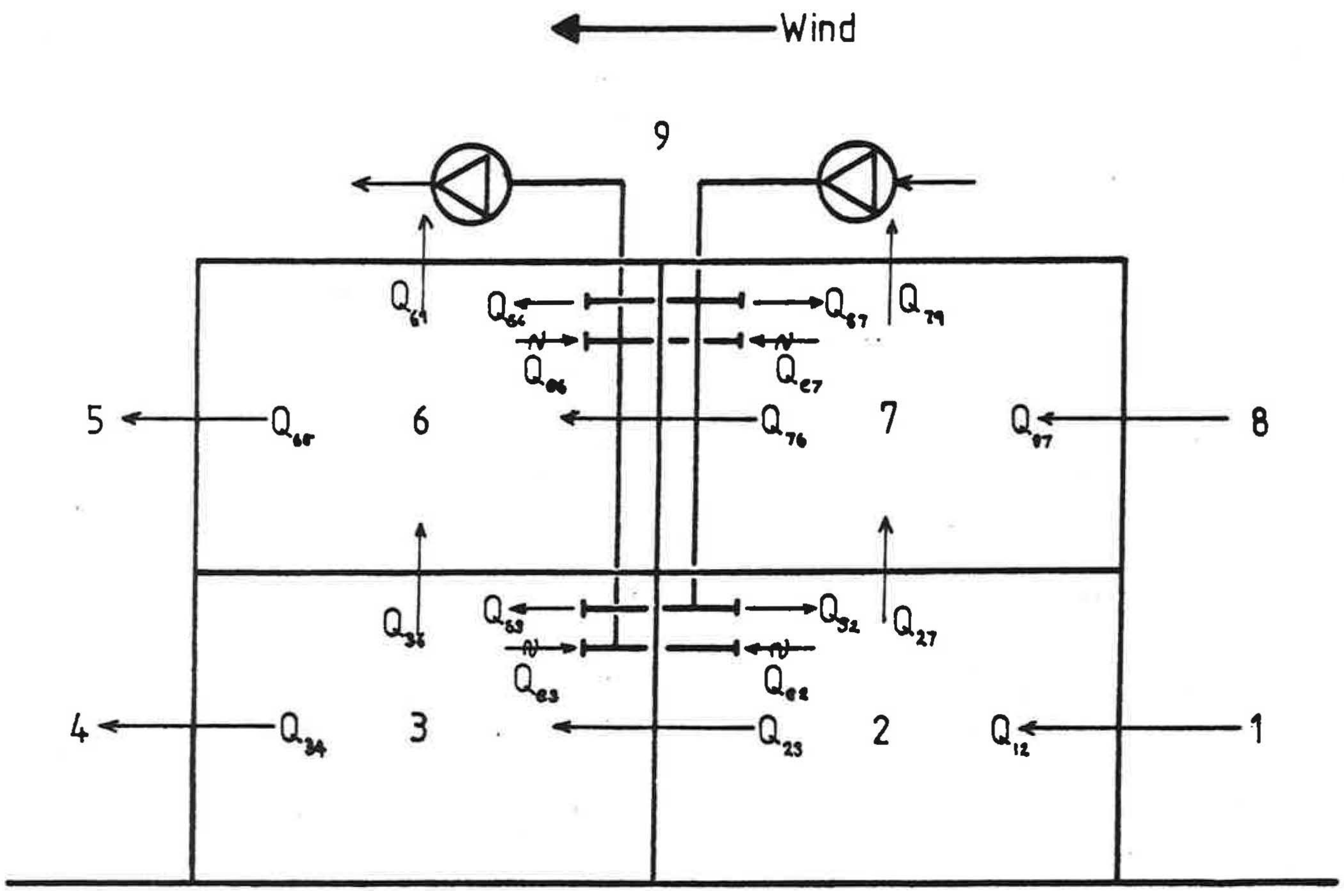

FIGURE 3 - Airflows through a building

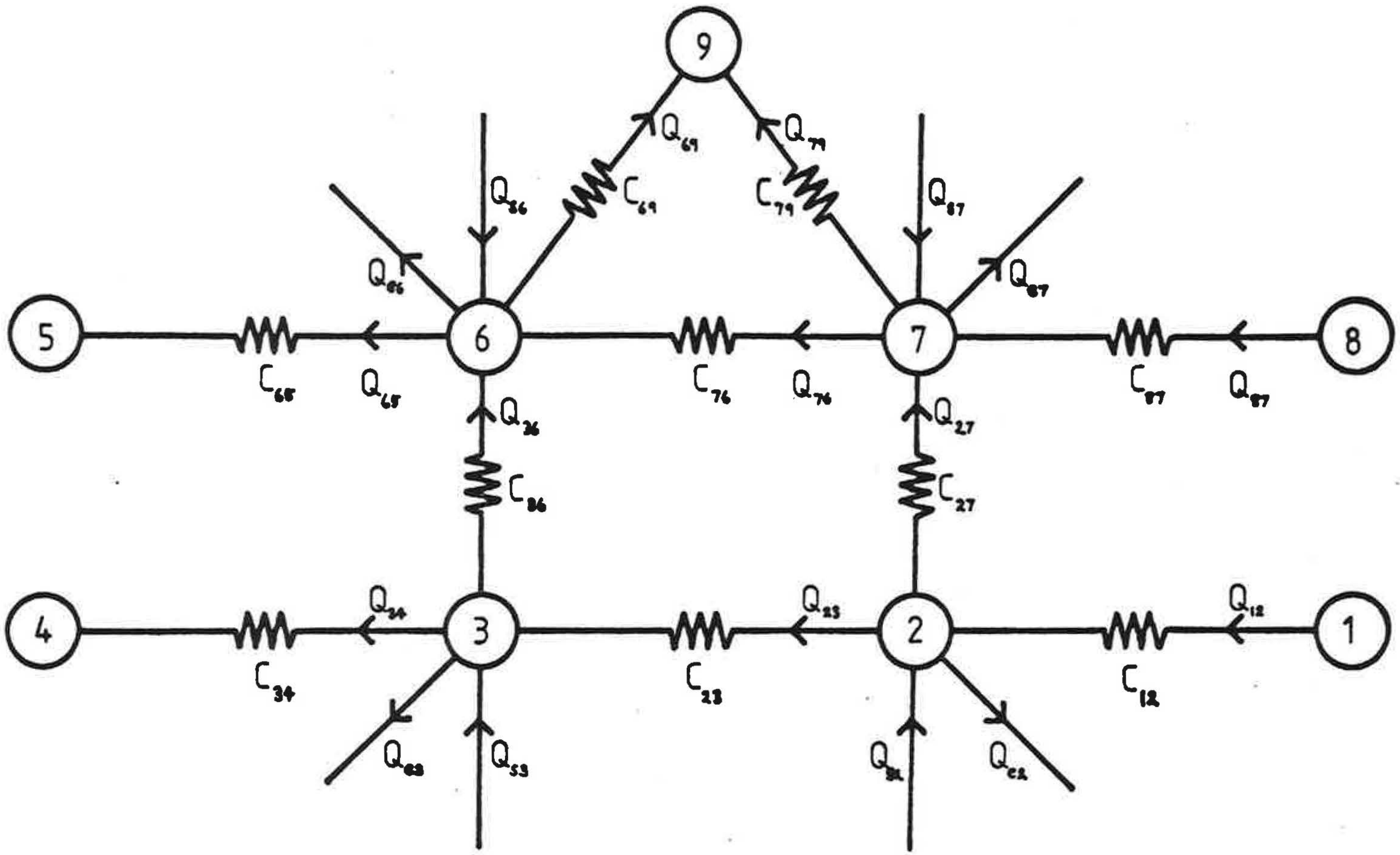

FIGURE 4 - Network representing airflows through a building

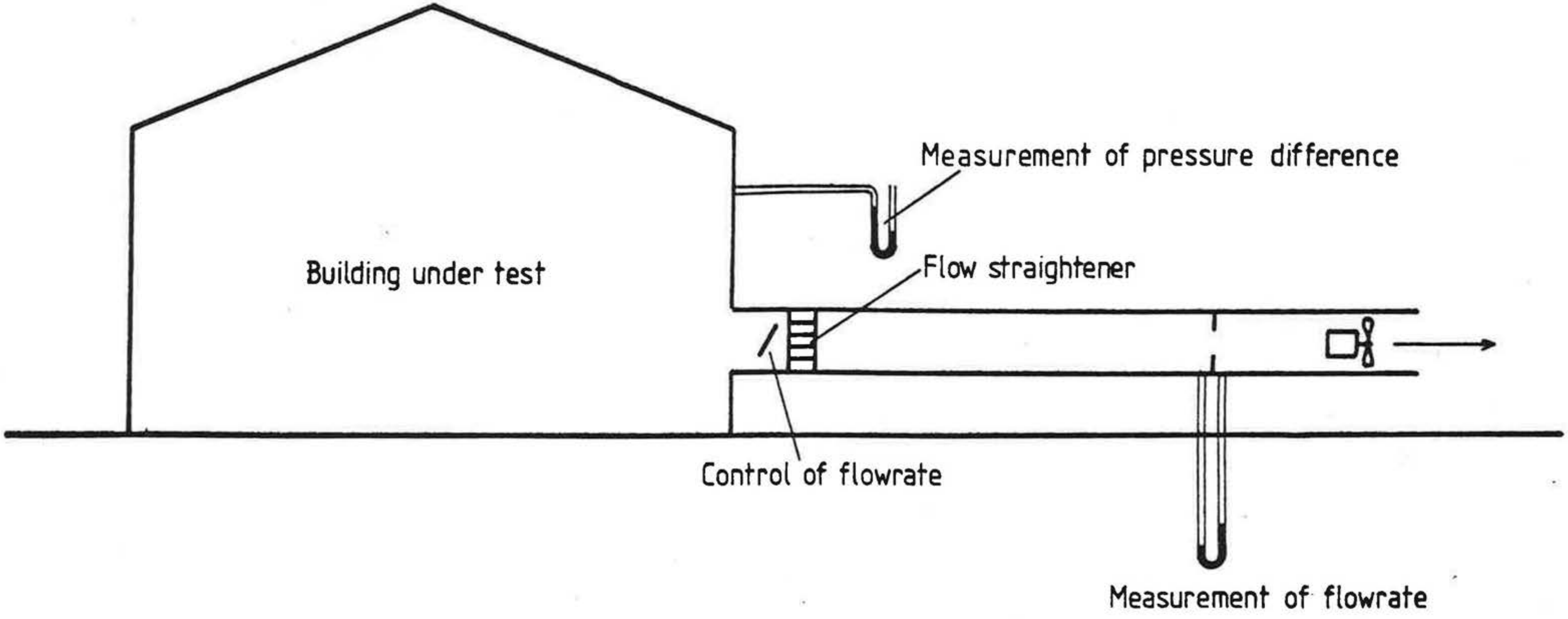

FIGURE 5 - Pressurisation method of leakiness measurement

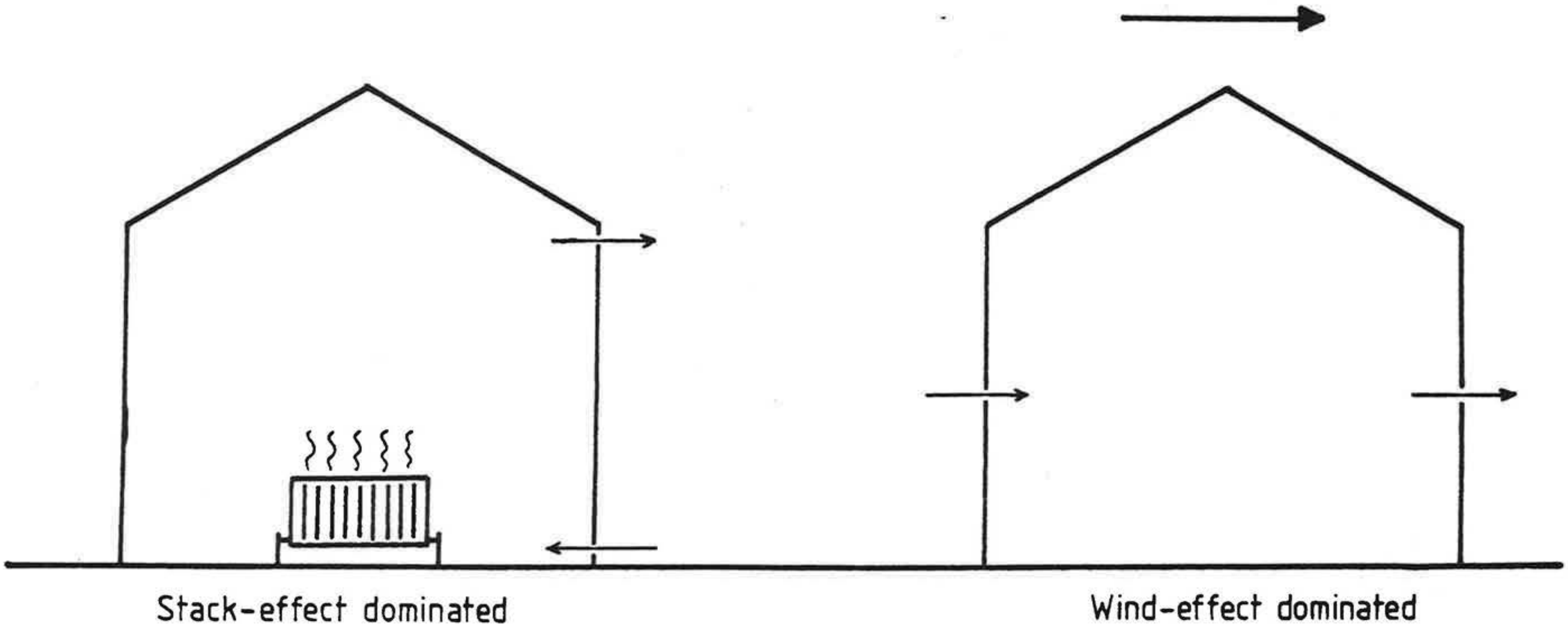

FIGURE 6 - Buildings with stack- and wind-effect dominated infiltration rates

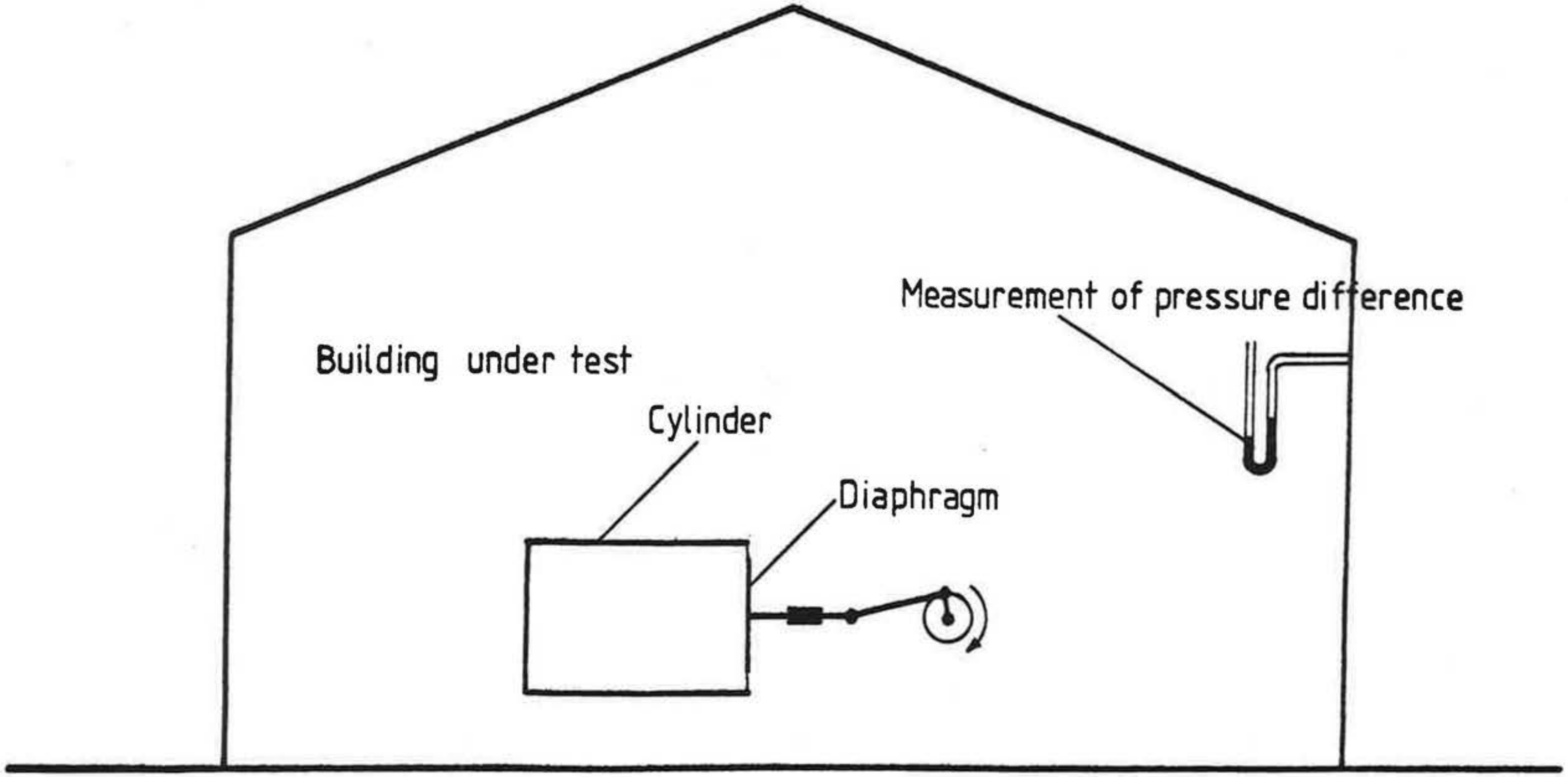

FIGURE 7 - Infrasonic method of leakiness measurement (Card et al.)

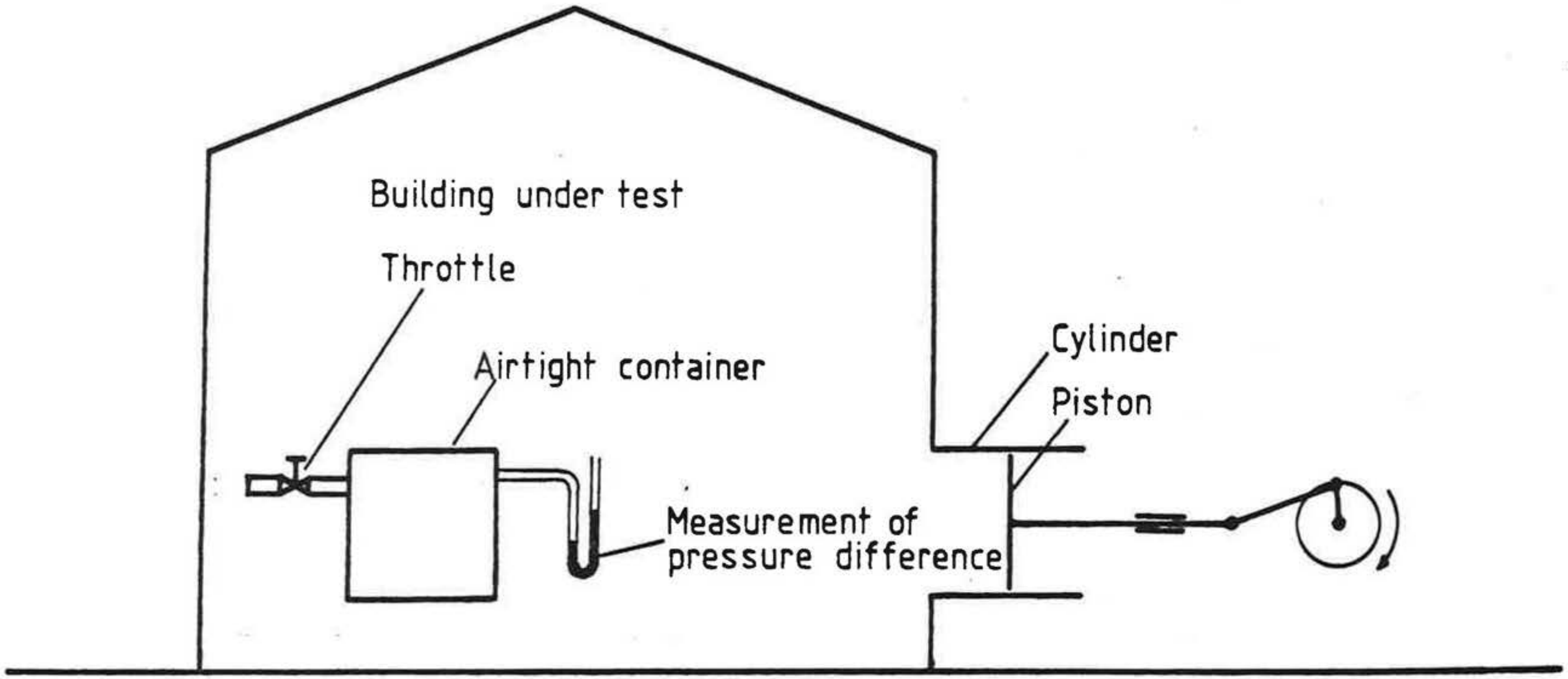

FIGURE 8 - Infrasonic method of leakiness measurement (Sherman et al.)

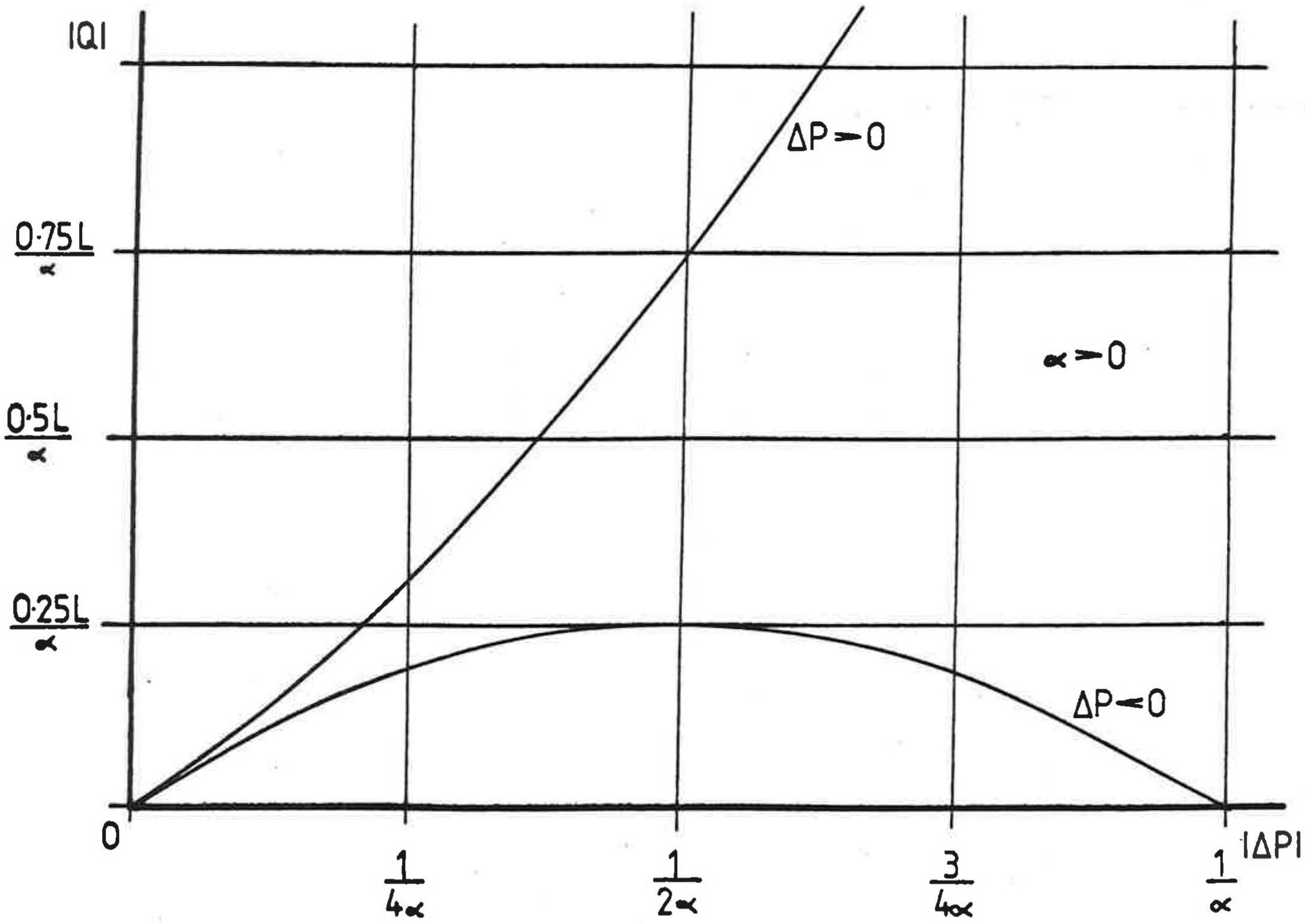

FIGURE 9 - Sketch of $Q = L(1+\alpha\Delta P)(\Delta P)$

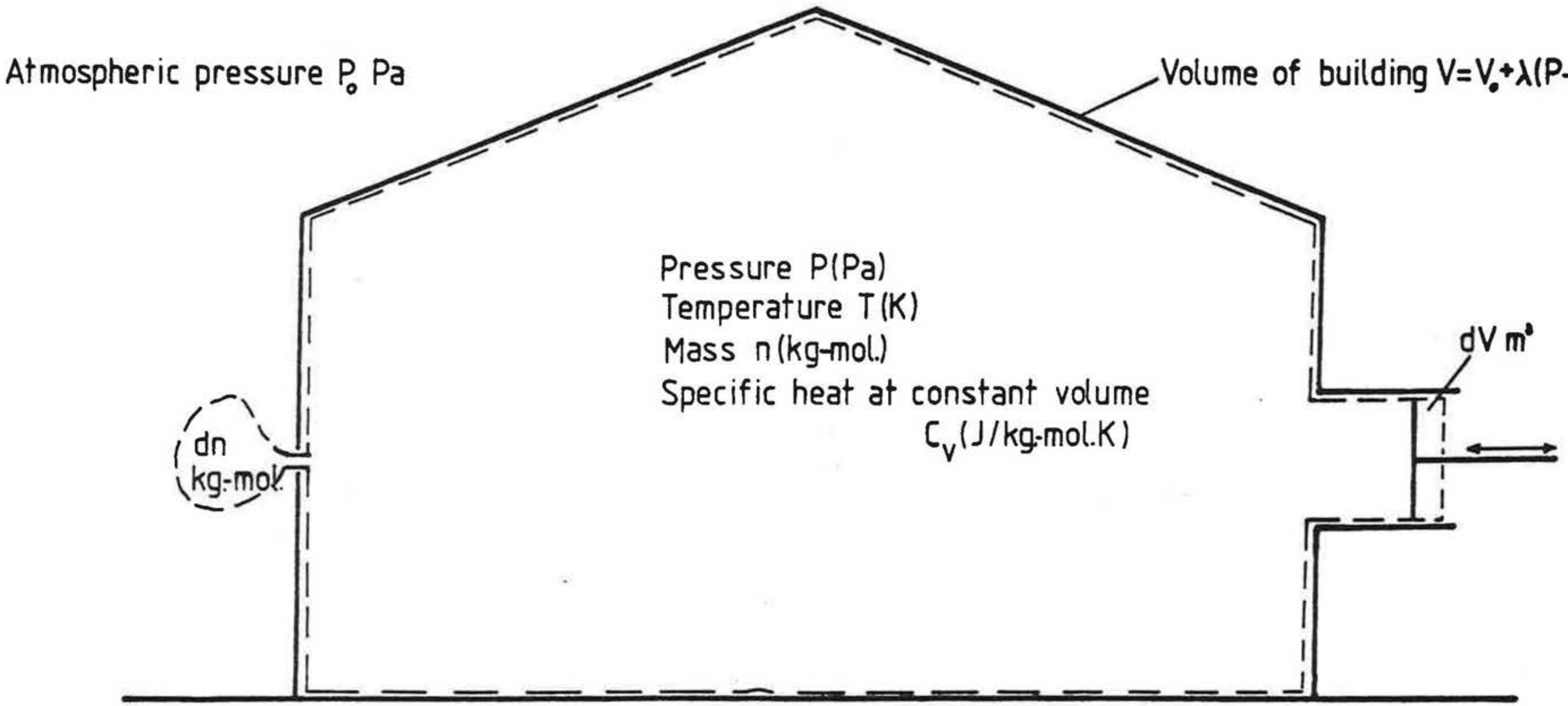

FIGURE 10 - Model of infrasonic method

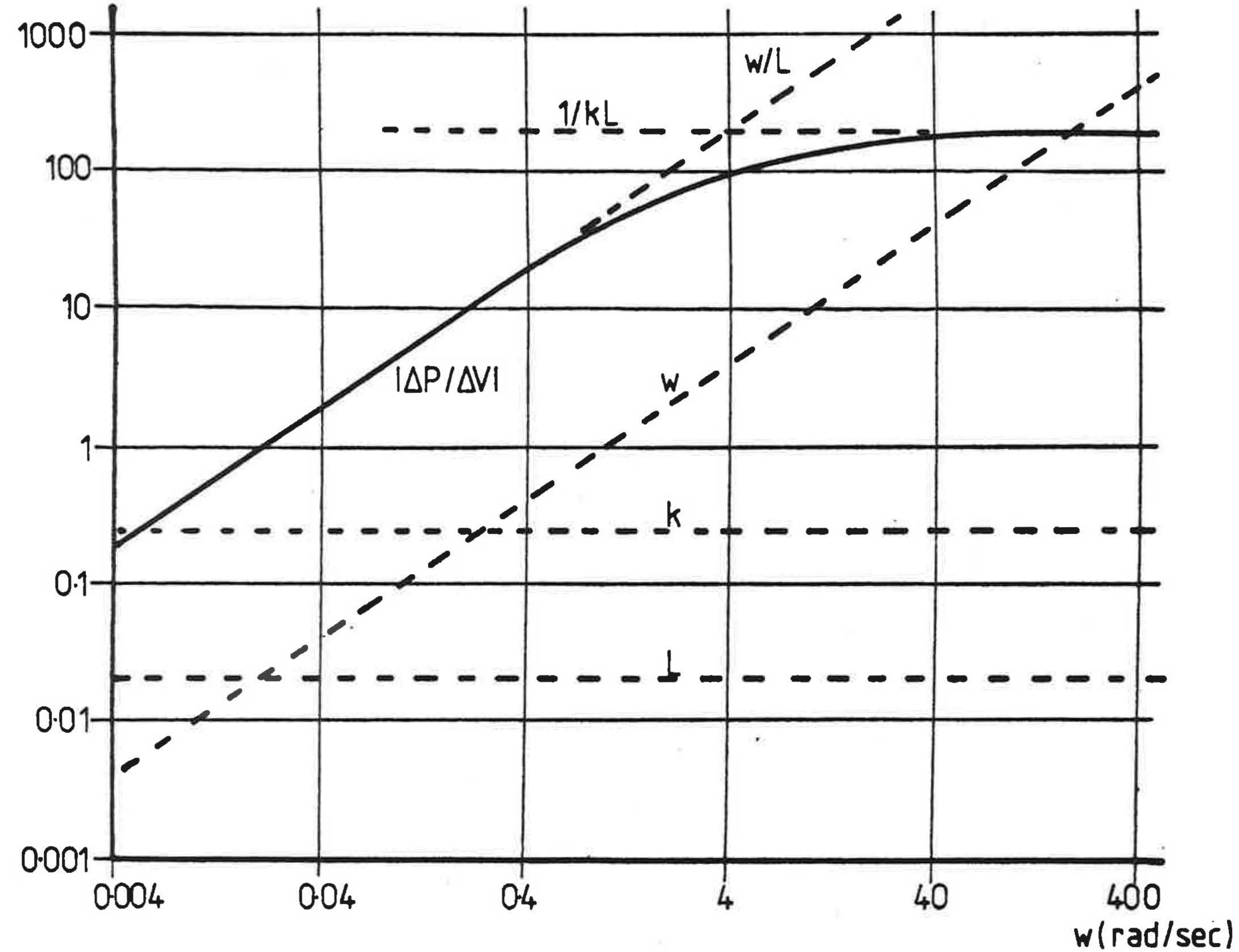

FIGURE 11 - Sketch of |ΔP/ΔV| against w

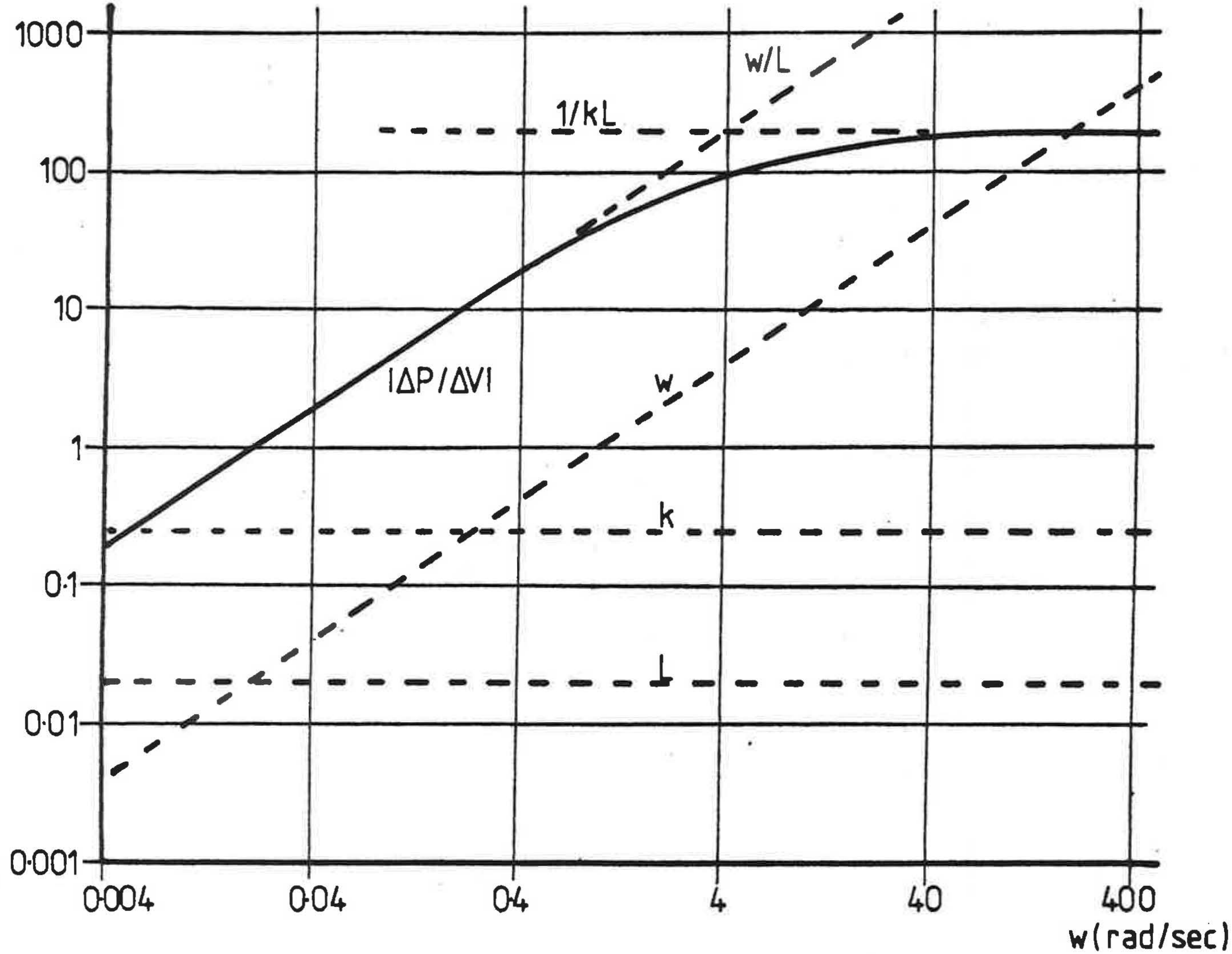

FIGURE 11 - Sketch of |ΔP/ΔV| against w

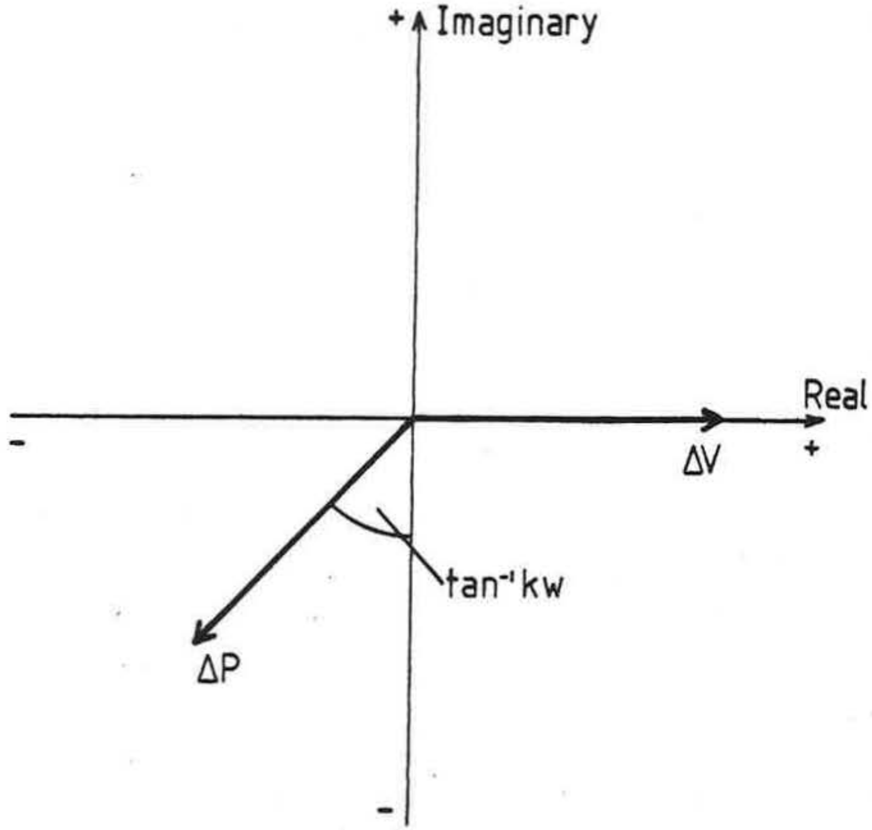

FIGURE 12 - Phase angle between ΔV and ΔP

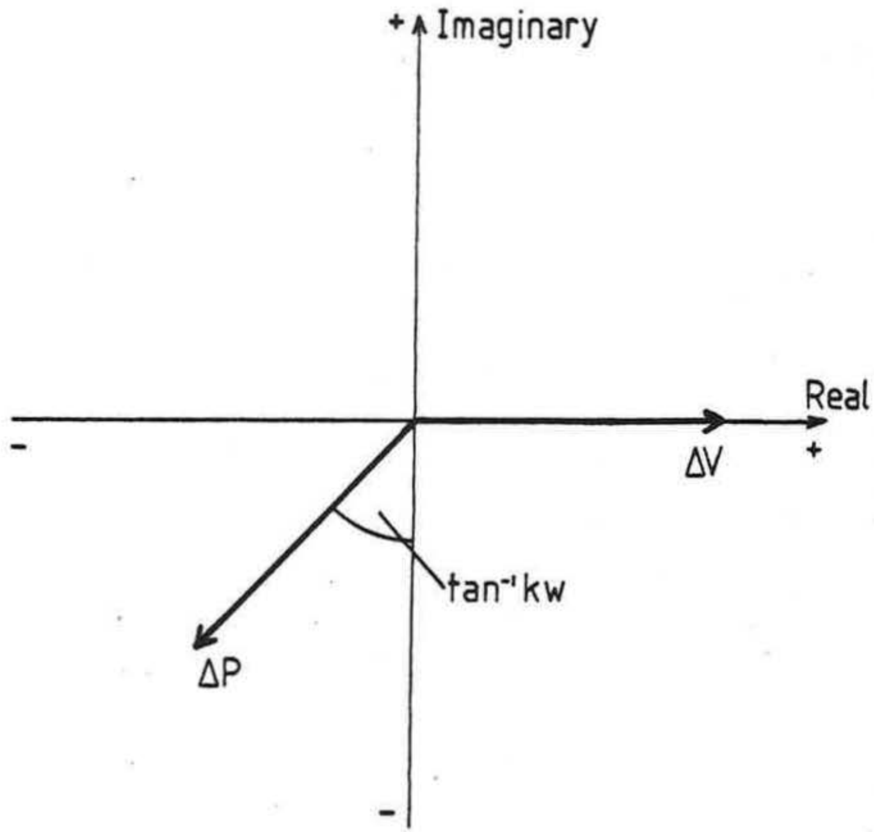

FIGURE 12 - Phase angle between ΔV and ΔP

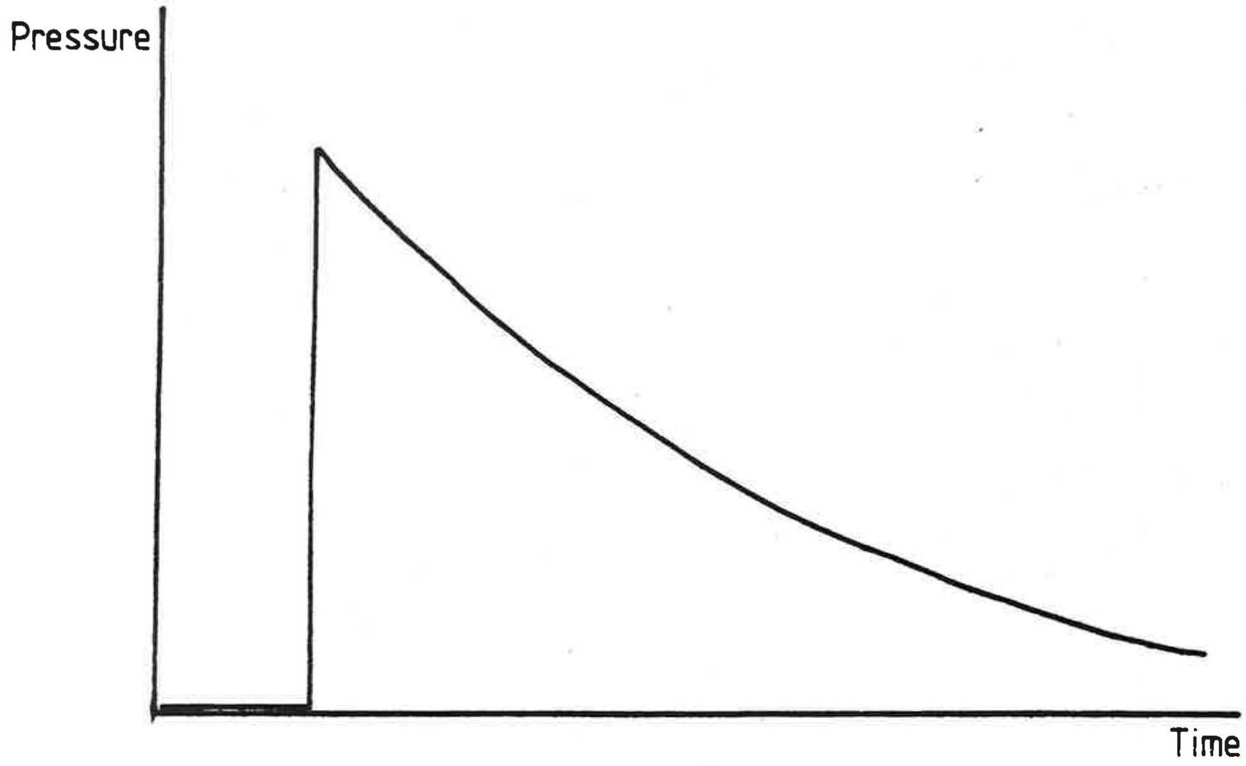

FIGURE 13-Response to a step change of volume

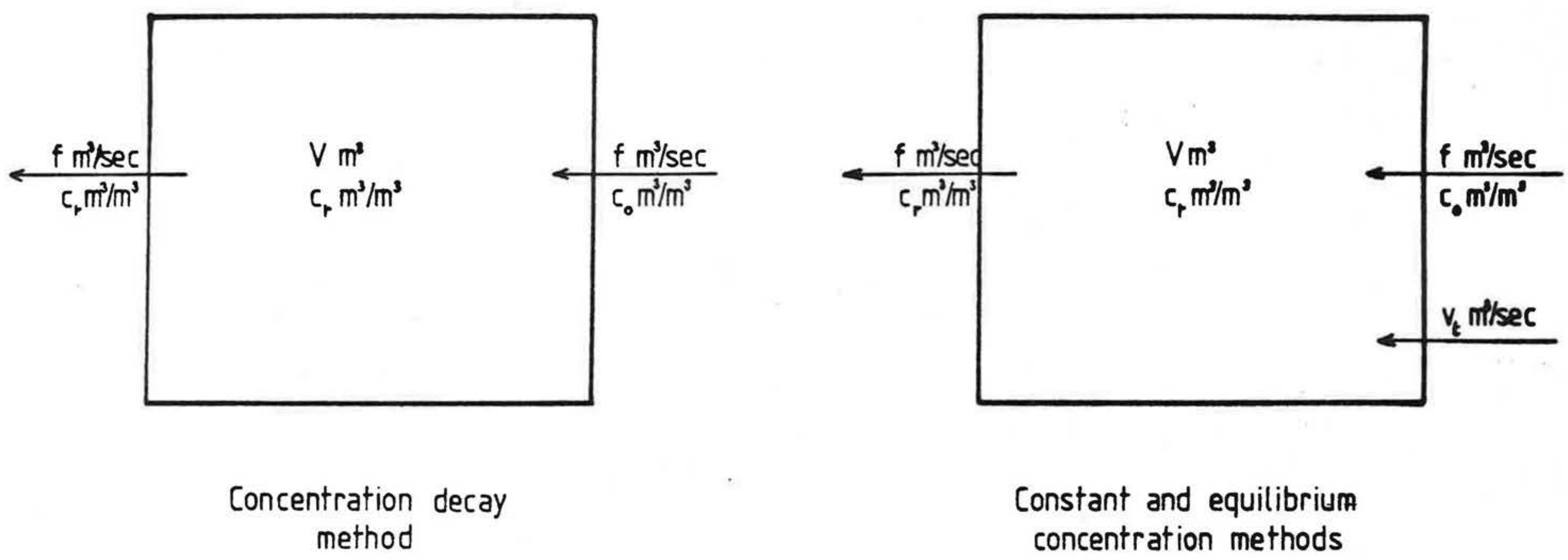

FIGURE 14 - Tracer gas methods

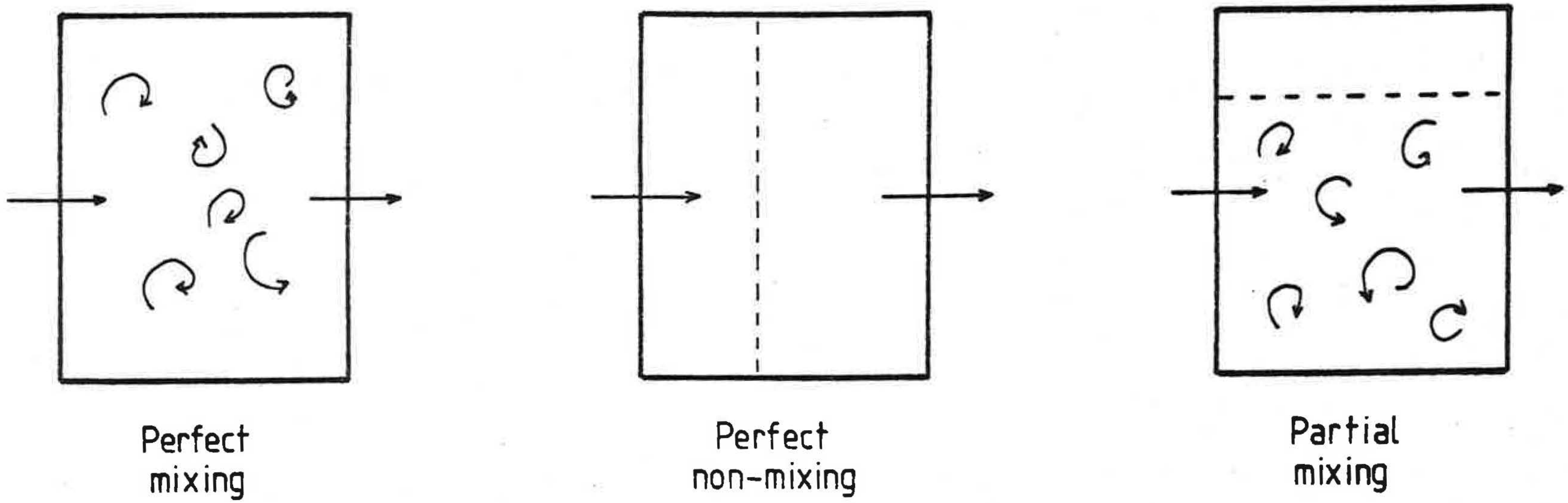

FIGURE 15 - Types of mixing

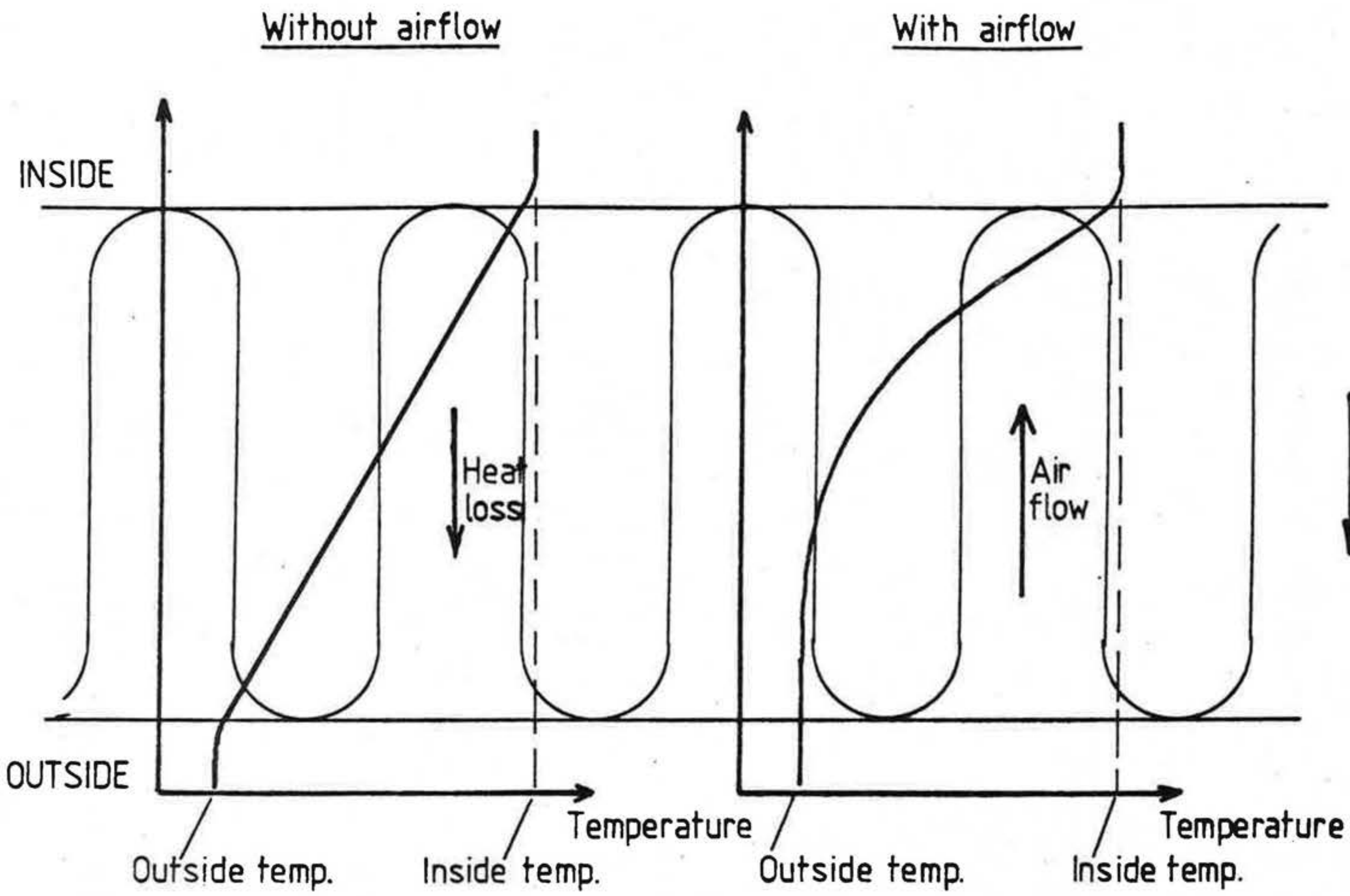

FIGURE 16-Counterflow construction