THE PREDICTION OF AIR INFILTRATION THROUGH BUILDING COMPONENTS; THE ASSEMBLY OF A DEVICE TO MEASURE AIR INFILTRATION THROUGH COMPONENTS WITH A SUGGESTED METHOD OF PRODUCING DATA WHICH COULD BE USED TO FORM THE BASIS OF A PREDICTION MODEL

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by

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PRÉCIS

This text is an investigation into air infiltration through building components. The term building components in this text is confined to windows and doors. A description of a device to measure flow rate of air through components and the method on how to use it are described in later chapters.

After a short introduction the text starts with a review of the fundamentals of air infiltration. This briefly discusses pressure and then discusses in more detail methods of measuring air infiltration in rooms or houses. The methods discussed are tracer gas methods and the pressurisation method.

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The following is a list of the salient points discussed in the text.

(i) The pressure difference exponent does not tend towards a particular value.

(ii) No discernable relationship between flow rate and crackage area is found.

(iii) It is very difficult to accurately measure crackage area.

(iv) The work performed at British Gas may be limited in its use in British Gas researchers because of assumptions made about crackage area being proportional to flow rate for a particular crack.

(v) Tight fitting components exhibit similar pressure difference exponents for suction and pressure tests.

(vi) Loose fit components have differing flow characteristics for suction and pressure tests.

(vii) For low pressure testing (i.e. less than 20 Pa) calm weather conditions are necessary.

(viii) Draught-stripping components can reduce air infiltration to very small quantities.

(ix) By correctly maintaining components, their functional lives can be greatly extended.

(x) Poor maintenance of components has an adverse effect on air infiltration which can result in either excess heat losses or condensation and fungus growth.

(xi) Loft traps could be a significant source of moisture-laiden air to loft spaces.

(xii) Leakage through false ceilings could be a serious problem.

It is hoped other researchers who refer to this text will find its content useful in the context of their own work.

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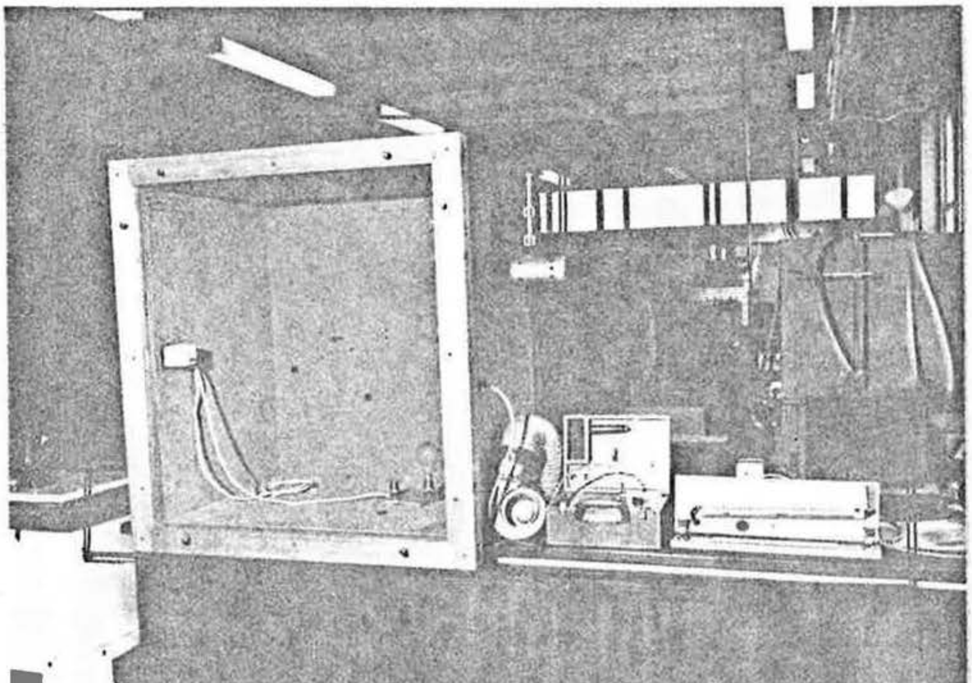

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CHAPTER I

INTRODUCTION

I INTRODUCTION

The ingress of outside air into a building is essential for the purposes of ventilation for occupants, combustion processes, removal of odour/moisture, cooling etc. Methods used to ventilate most buildings are either by mechanical or by natural ventilation, the latter being found in nearly all domestic dwellings.

During the Victorian era and the early twenties before electricity was commonplace, and when coal was plentiful, a fire could be found burning in every room of the house in Winter. Consequently the ventilation rate was generally very high. However with the advent of electricity (for lighting), central heating, high efficiency solid fuel systems and the energy crisis the ventilation rate was greatly reduced. However, because most of the U.K's housing stock was built before the realisation of the need to save energy, subsequently air leakage into and out of a building (hereinafter called the leakiness) only marginally improved by comparison to the reduction in the ventilation requirement.

Flow paths through a building are too extensive to list but consideration of the following will serve to illustrate the nature of the problem; cracks around door and window frames, gaps between window sashes and frame and door and frame, joints between floorboards, loft traps, holes in the external wall for telephone or ariel cables and purpose made openings i.e. air-bricks. Adventitious air-flow through porous walls, also called background ventilation, is another source of ventilation and is not directly measurable. It is not discussed in this text.

Infiltration of air gained importance after the Arab-Israeli war when escalating energy prices highlighted the loss of energy from leaky houses. This source of loss has a much greater importance in low energy dwellings where ventilation losses can account for the largest proportion of heat loss. Moreover, the passage of moisture laden warm air into a well insulated loft space may cause condensation and cause dry-rot to appear if the ventilation rate in the loft space is too low. Thus the flow of air through a building is seen as a problem requiring a balance of our needs.

This text reviews the present work on prediction of whole house ventilation rates and is followed by an experiment. The experiment investigates the possibility of ascribing an exponent to a pressure-difference which when multiplied by a coefficient will reveal air flow through a particular building component. The exponent and coefficient are peculiar to a particular component. The construction of a device and the method to follow when using the device to measure air flow is described.

The results are presented as tables and graphs in the Appendix. The notation of +ve. and -ve. pressure is used in the text to simplify the description of a test. The term +ve. pressure means air is being blown onto a component and would tend to open it. The term -ve. pressure means air is being sucked from a component and would tend to draw it shut.

The experimental data is used to find an exponent and coefficient (previously described) and to compare the usefulness of work being performed at British Gas with the traditional method. The results of the experiment are discussed in Chapter 6 from which conclusions are drawn in Chapter 7. The following is a summary of the detail highlighted in the discussion;

(i) The pressure difference exponent does not tend towards a particular value.

(ii) No discernable relationship between flow rate and crackage area is found.

(iii) It is very difficult to accurately measure crackage area.

(iv) The work performed at British Gas may be limited in its use to British Gas researchers because of assumptions made about crackage area being proportional to flow rate for a particular crack.

(v) Tight fitting components exhibit similar pressure difference exponents for suction and pressure tests.

(vi) Loose fit components have differing flow characteristics for suction and pressure tests.

(vii) For low pressure testing (i.e. less than 20 Pa) calm weather conditions are necessary.

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(ix) By correctly maintaining components, their functional lives can be greatly extended.

(x) Poor maintenance of components has an adverse effect on air infiltration which can result in either excess heat losses or condensation and fungus growth.

(xi) Loft traps could be a significant source of moisture-laiden air to loft spaces.

(xii) Leakage through fabric ceilings could be a serious problem.

It is hoped other researchers who refer to this text will find its content useful in the context of their own work.

CHAPTER II

FUNDAMENTALS

II FUNDAMENTALS

Unlike fabric losses where heat flow by conduction is proportional to the internal-external temperature difference, ventilation losses are proportional to temperature difference and air-flow i.e. mass flow rate due to a pressure difference and/or a temperature difference. Subsequently the prediction of ventilation losses is theoretically difficult because the magnitude and direction of flow through networks of resistances in a house are unknown. In early work presented by Dirk (1) it was noted because the head at the beginning of each crack was equal, flow through them could be considered as flow through a parallel duct system and therefore proportional to the area of the cracks.

The primary driving force of air is pressure different which is dependent on wind effects and on stack effects. Both these variables are considered in the next sections below.

2.1.1 Wind; in open areas e.g. moorland, pressure is approximately proportional to the square of the wind speed. In a dwelling the pressure difference is heightened by the suction on the leeward side, which is approximately one third of the pressure on the windward side. Furthermore, there may be local effects caused by chimnies where the suction produced on the flue can be of the same order as the velicity head (Fig. 1).

In built-up areas there is a shielding effect which either reduces wind pressure or causes local increases. This is a problem when trying to predict pressure difference and will be discussed in later sections.

2.1.2 Stack effect

Pressure due to temperature difference has gained importance with the introduction of central heating and open-plan housing. Its effect is dominant at low wind pressures but at higher wind pressures the stack effect is of little importance. Combining the two pressures is difficult since straight addition reveals erroneous answers due to the interaction of wind and temperature. Subsequently there exists various formulae for combining the effect. An example given by Tamura (2) is as follows:-

$$\frac{Q_{ws}}{Q_{lrg}} = 1 + 0.24 \quad \frac{Q_{sml}}{Q_{lrg}}$$

where Q_{ws} = infiltration rate caused by wind and stack effect.

Q_{lrg} = larger value of Q_s and Q_w

Q_s = infiltration due to stack effect

Q_w = infiltration due to wind effect

Q_{sml} = smaller value of Q_s and Q_w

Further reference to the flow rate is given in the original paper. An equation put forward by Etheridge in a separate paper (3) can be used for finding the stack effect but little is said about combining the two.

Other factors affecting infiltration rate are:-

(i) Building height

(ii) Internal/External temperature difference

(iii) Surrounding terrain and the vicinity of other buildings.

(iv) Mode of heating, i.e. open fire, electricity,etc.

2.2. Air Infiltration Measurement

The measurement of air movement in a building may be performed by one of two methods:

(i) Tracer gas methods; where the concentration of a particular gas in the air serves as the indicator to the number of air-changes, as the concentration decreases.

(ii) Pressurisation method; where a room or a building is subjected to a positive or suction pressure and the flow rate measured.

Both methods are widely used but the interpretation of the results yields differing kinds of answers. The tracer gas method is performed at atmospheric pressure, therefore the ventilation rate at a particular weather condition is measured. The pressurisation method, because it is performed at elevated pressures is a measure of the air-tightness of a building or a room at a given pressure difference and interpolation is required to find the air flow at lower pressure differences.

2.2.1. Tracer gas methods

The effectiveness of tracer gas methods as a measurement of the ventilation rate, depends on the degree of mixing that can be achieved.

The mixing of outdoor air with room air has three different modes (Fig. 2)

(i) Perfect mixing

(ii) Perfect non-mixing where room air is pushed out like a front.

(iii) Dead spot model where there is a degree of mixing in a clearly defined volume.

Tamura (6) states with doors and windows closed most rooms would act as condition 'iii' unless otherwise compelled to by the use of a small fan(s) but under other conditions i.e. an open door or window, mixing may be near perfect. If perfect mixing is assumed the main ingredients of the method are;

(i) Suitable tracer gas
(ii) A gas analyser
(iii) Chronometer or a watch.

If these are present there are three recognised methods of measurement,

(i) Decreasing gas concentration
(ii) Constant gas concentration
(iii) Constant gas emission

2.2.1.1. Decreasing gas concentration

As the title suggests the gas concentration is allowed to decrease once a uniform mixture has been achieved i.e. by use of a fan. The ventilation rate of the test volume can be found from the following equation (4)

$$n = \frac{1}{t} \ln \frac{C_o}{C_t} \qquad (2)$$

where n = number of air changes per unit time
t = unit time
C_o = initial gas concentration
C_t = gas concentration at time 't'

Because perfect mixing cannot be achieved at one point a number of alternative methods of collection are available;

(i) Air is collected at several points and mixed. The resulting mixture is used to find the ventilation rate

(ii) The decrease in concentration is simultaneously measured at several points. The point which most represents the average is used, thereafter.

(iii) The decrease in concentration is measured as above and an average value is used in the calculation.

Although method 'i' is affected by a time dependent displacement error, which is affected by how incoming air mixes with room air, it is the most often used method. If an average value is required then method 'ii' or 'iii' are more reliable.

The advantages of the decreasing gas concentration method are;

(i) It is easy to perform

(ii) Analysis of the results is simple

The disadvantages are;

(i) The measured results may not reliably reflect the result

(ii) Gas may get trapped in pockets and the resulting decrease may not be exponential (an inherent disadvantage which applies to all methods)

(iii) Difficulties in ensuring simultaneous uniform discharge of gas at several points.

2.2.1.2 Constant gas concentration

This method enables continuous monitoring of the ventilation rate of the test volume. By measuring the gas concentration at one point with respect to gas emmission, the concentration of room mixture can be kept constant by the use of automatic control devices. In the ideal case of perfect simultaneous mixing the ventilation rate can be calculated from the concentration and the rate of gas discharge thus (4);

$$n = \frac{q}{C.V} \qquad (3)$$

where n = number of air changes per unit time (h^{-1})

C = gas concentration (p.p.m.)

q = gas flow rate ($m^3.h^{-1}$)

V = test volume (m^3)

Measurements cannot be taken until a constant gas concentration is reached, the time for which is proportional to the ventilation rate. The equation for the gas concentration at time 't' is given by the following (4);

$$C = \frac{q}{n\,v}\,(1 - e^{-nt}) \qquad (4)$$

notation as before.

Figure three shows the behaviour of the term $(1 - e^{-nt})$ for differing values of ventilation rate (n). Thus equilibrium can take some time to be reached.

An alternative is to allow the concentration to oscillate between an upper and lower limit and let the time between topping-up be a measure of the ventilation rate.

The advantage of this method is that continuous monitoring of the ventilation rate is possible.

The disadvantages are;

(i) A greater amount of and more complex equipment is required.

(ii) Errors may be introduced by a time-lag between gas release and analysis at the gas analyser.

2.2.1.3 Constant gas emission

This method is similar to the previous method and therefore suitable for continuous monitoring of the ventilation rate. The gas concentration, read from a gas-analyser, serves as the indicator to the ventilation rate. A reduced ventilation rate would yield an increased gas concentration and vice-versa for an increased ventilation rate.

For a constant ventilation rate at the time of gas emission, using equation four the transient response will be as shown in fig. 3. For large values of 't' equation four becomes (4)

$$C = \frac{q}{V n} \qquad (5)$$

notation as before

Where the concentration 'C' is inversely proportional to the ventilation rate. Therefore the flow rate of gas emission 'q' must be chosen such that it remains within the scale of the instruments.

The advantages of this method are;

(i) Continuous measurement of the ventilation rate is possible.

(ii) The instrumentation is simpler than that used in the constant gas concentration method.

The disadvantages are;

(i) Few gas analysers have a scale range long enough to cope with the variation in gas concentration due to changeable weather.

(ii) Wasteful on gas because of the long period required for reaching a constant gas concentration.

(iii) Difficult to arrange an absolutely constant rate of gas emission.

2.2.2.1 Tracer gases

Although there exists a wide range of tracer gases i.e. acetone, argon, helium, ethane, hydrogen (obsolete), etc. the commonest used in the U.K. is nitrous oxide and occasionally carbon dioxide, whilst in America sulphur hexafluoride is the most common. Ideally a tracer gas should have the following properties;

(i) A concentration in air which can be accurately measured at high and low concentrations.

(ii) Unaffected by atmospheric gases

(iii) Adsorption and absorption of gas into walls, furniture, etc., should be negligible

(iv) Chemically stable

(v) Chemically stable

(vi) Inexpensive and plentiful

(vii) Non-toxic

(viii) Non-flammable and non-explosive

(ix) A density close to air density

(x) Not normally present in air

(xi) There should not be another source of the tracer gas in the test volume.

There is not a known tracer gas which meets all of these requirements. It is possible a 7-8% difference may occur between results of tests using SF_6 and tests using N_2O, however, this is not greater than the 10-15% uncertainty associated with tracer gas measurements and therefore may not be reflected in the final result (5). The advantage of using SF_6 is that concentrations as low as 10^{-9} p.p.m. can be measured. The advantage of N_2O is it is cheap but the volume required for a single family dwelling is approximately 0.3 m^3, whereas, using SF_6 the required volume would be approximately 3 cm^3.

2.2.2.2 Comment

In the U.K. N_2O is most widely used because it has always been cheaper than SF_6. With respect to method of measurement, the decreasing gas concentration method is the most popular because it is simple to perform and simple to calculate the ventilation rate.

2.3.1 Pressurisation method

The pressurisation method, which reveals information on the infiltration of external air and infiltration of internal air, is a method widely written about (ref. 6 et al) and will be briefly explained in the following sections;

2.3.2 Equipment

The following equipment is essential for most tests;

(i) Control fan capable of producing a pressure of 55 Pa. and delivering the required flow i.e. 1200 - 2000 m.s for an apartment or a single storey house, respectively

(ii) Flowmeter capable of reading the working flow rate

(iii) Micromanometer capable of measuring the working pressure differences within an accuracy of $\pm$ 2 Pa.

2.3.3 Test conditions for air-tightness test by pressurisation method

Internal and external temperatures should be recorded together with wind velocity and direction. Testing should not proceed if the temperature difference is greater than $30^{o}C$ or the wind speed is greater than $8.m.s.^{-1}$.

2.3.4 Procedure

(i) All ventilation openings are sealed before the test i.e. cooker fan, windows, fireplaces, letterboxes etc. All areas heated to a temperature of greater than $10^{o}C$ should be included in the test volume.

(ii) One external door or window is left and replaced by a wood panel, in which holes exist for the passage of air from the fan and measurement of pressure.

(iii) A number of readings are taken (at least four) and the results expressed in volumetric units. When measuring the volume of a dwelling internal dimensions are used with reductions for internal walls and floors but not for cupboards.

(iv) The results should be displayed on a graph of air flow-rate V's pressure difference for a range of 20 - 55 Pa. (Fig. 4. note non-linearity).

2.3.5 Comment

The pressure differences under normal conditions are less than 20 Pa., therefore (usually 2 - 10 Pa) extrapolation of the results is necessary to find the air flow under normal conditions. Moreover, because the result is a value for the leakiness of a building it is of little value when assessing air change rates under natural conditions. This is because the pressure difference under test conditions is of the same order on every face whereas under natural conditions the pressure on any face of the house is dependent on the wind, which will often cause pressure on one side of a building and suction on another. However the method does produce quick reliable results, which can be used as a measure of the building's airtightness, specification of a standard and/or a direct comparison between buildings even though there is not an indication of the leakage.

2.4 Other Methods

Infrasonic method: is a method by which a leakage coefficient of a building is determined by pumping air into and sucking it out at a given frequency. The method is claimed to be simple but the interpretation of the results is difficult. The subject is examined by Dewsbury (7) when comparing Card's et al and Sherman's et al accounts of the method and he concludes the subject is still in its infancy but, nevertheless, worthy of further investigation because the working pressures are closer to those experienced in natural conditions.

Other methods include the use of heat sensitive film to locate warm air escaping into a cold atmosphere. This method is limited in its application to air infiltration measurement but would prove useful in an initial study when identifying areas of a building for further investigation.

CHAPTER III

PREDICTION METHODS

III PREDICTION METHODS

3.1.1 C.I.B.S. prediction method

Most prediction methods are based on, essentially, empirical results because of the lack of uniformity between separate buildings. The C.I.B.S. method is based on the following equation for infiltration through cracks around windows:

$$Q = C(\Delta P)^n \qquad (6) \qquad \text{(ref. 8)}$$

where Q = volume flow rate per metre of window opening joint.

C = window infiltration coefficient defined by volume flow rate per unit length of crack per unit pressure difference.

ΔP = pressure difference across the crack

n = exponent (for windows = 0.6)

The coefficient C, can be determined from tables after which the basic infiltration can be found from a chart of pressure difference V's infiltration rate per metre run of window opening. The pressure difference is calculated knowing its heights and location i.e. city, suburb or countryside. The basic infiltration rate once found can be used to calculate the total infiltration rate from;

$$Q_{TOT} = Q_b \quad \Sigma L \quad \frac{(a^2 + b^2)^{\frac{1}{2}}}{2.a.b} \qquad (7)$$

where Q_{TOT} = total infiltration rate

Q_b = basic infiltration rate

ΣL = total crack length of buildings

a & b = plan dimensions of building (glazed facade)

3.1.2 Comment

The C.I.B.S. method is not accurate enough for the present calculations because it is assumed all window facades are uniform within a small bandwidth, whereas, the total open area of crackage around a window is unpredictable. Furthermore the pressure difference across the external envelope is not as uniform as is implied by the method.

3.2 Early Work

In an early treatment of the subject by Dick (9) the air change rate of each room was examined and the following equation postulated:-

$$n = A + B\,v \qquad (8)$$

where n = ventilation rate for the room

A = constant relating to stack pressure

B = constant

v = wind velocity

Using the above equation as a basis another equation for the ventilation rate of a house is postulated which attempts to consider the pressure difference according to wind direction;

$$n = A + B\,v\,(C.\cos\Theta + D.\sin\Theta)v \qquad (9)$$

where A,B,C,D = constants

Θ = wind direction

In the conclusion of this work Dick found the wind direction did not significantly affect the ventilation rate, generally a linear correlation existed between wind speed and the ventilation rate. This becomes significant when, in his appendix, it is stated the total ventilation rate can be found if, for each room in the house the fraction of air passing through to the exterior is known i.e.

$$n = \frac{1}{V_T} \Sigma Y_i V_i \qquad (10)$$

where: V_T = volume of the house

V_i = volume of room 'i'

Y_i = measure of air lost to the exterior in room 'i'

3.3 Pressure

In the above the assumption is that the pressure difference is approximately equal to the velocity pressure. Thus, for a given velocity profile a pressure difference can be found. However, this assumption may lead to serious errors because of the effects of major factors like topography, immediate buildings, trees, etc., are not considered. A large number of variables affect the pressure difference across a building in a natural wind. The interaction of wind and pressure difference and the control difficulty has led to the use of scale models as the main source of information. Much of this work is concerned with turbulent flow over rough surfaces with the building considered as an element on the rough surface. The factors affecting pressure difference can therefore be classified into two main groups;

(i) factors relating to the building form

(ii) factors relating to the property of the wind

The main properties affecting the above factors are the separate formation of groups of buildings and the form of each building in the group, the latter of which may be broken down into size, shape and permeability (of the building). In open areas i.e. open countryside, derelict sites, etc., if a building is isolated and the wind velocity gradient is relatively undisturbed, prediction of a pressure difference can be a simple matter. But in urban areas, where building density is greater the properties of the wind, building geometry and group form make the prediction of pressure difference difficult. If, on the basis of a full scale measurement of atmospheric boundary layer flow over suburban terrain, the properties of the wind can be adequately modelled a set of relationships can be established, by measurement at the model, between wind pressure forces on a building and the form factors which describe the building and its immediate surroundings.

Lee, Hussain and Soliman (10) investigated the above factors and demonstrated their importance in the calculation of pressure difference. In an earlier report Lee and Soliman showed how wind might be expected to behave when flowing over cubes (Fig. 5) and identified three main flow patterns. Further work in a wind tunnel enabled a coefficient to be found from graphs, which when applied to the velocity pressure, calculated from the wind velocity profile, produced a value for pressure difference for use in equation 6:

$$\Delta P = C_p . 0.5 . \rho . v_g^2 \qquad (11)$$

where: ΔP = pressure difference

C_p = coefficient, found graphically

ρ = density of air

v = velocity gradient of an area for which a given wind speed will not be exceeded for a given percentage of the year.

The above work has produced a valuable contribution to the prediction of ventilation rates, however, the determination of a coefficient for use with the pressure difference is not an easy matter.

3.4.1 British gas model

In work by Hopkins and Hansford (11) they state in much of the early work a relationship of the following is assumed;

$$Q = C.\Delta P^{n} \qquad (6)$$

notation as before;

where n is a value close to 0.5 and in more recent times the C.I.B.S. method also uses this form. This simple relationship also holds for flow through a thin orifice plate with a coefficient of discharge equal to 0.65;

$$Q = 0.845.A.(\Delta P)^{\frac{1}{2}} \qquad (12)$$

where Q = flow rate ($m^3.S^{-1}$)

A = area (m^2)

ΔP = pressure difference (Pa)

From the above a straight line relationship can be assumed to exist. Most of the openings (cracks) in a building are of the type shown in Fig. 6. Hopkins and Hansford investigating crack flow found the square law relationship was not strictly true for the following reasons;

(i) The open area of the crack increases due to distortion caused by pressure difference.

(ii) It could not be applied for all types of cracks, crack geometries and pressure differences.

Since equation 6 was not accurate enough for the computer technique employed by British Gas an investigation into the derivation of an equation, which considered the variation of discharge coefficient with Reynold's Number was started. From the Navier-Stokes equation the following equation was derived:

$$\frac{1}{C_Z{}^2} = B.\ \frac{Z}{d_h}\,\frac{1}{R_{e_h}} + C \qquad (13)$$

where C_Z = discharge coefficient

B = apparent coefficient

Z = centre line distance through crack (m)

d_h = hydraulic diameter (m)

R_{eh} = Reynold's No. based on hydraulic diameter

C = empirical constant.

By modifying equation (6);

$$\Delta P = \frac{K}{A^2}\ Q^{1.65} \qquad (14)$$

Hopkins and Hansford suggested an iterative solution for C_Z. However, later work by Etheridge (12) indicated equation 14 would not work "because it was not dimensionally homogenous" (but this depends on the units of K). The flow of air through a crack is dependent on the Reynolds No. such that flow can be described by:

$$C_Z = F(R_{e_h}) \qquad (15)$$

$$^{*}C_Z = C_a = \frac{Q}{A}\sqrt{\frac{\rho}{2.\Delta P}}$$

where ρ = density

notation as before

and $R_{eh} = \frac{\bar{\mu}\ d\,h}{r}$

*see note opposite

N.B.
The original paper by Etheridge defines eqn. 15 as

$$C_z = \frac{Q}{A}\sqrt{\frac{\rho}{2\,\Delta P}}$$

this text introduces C_a to simplify the comparison of eqns 13 & 15 in the discussion where $\overline{\mu}$ = flow rate/Area (Q/A)

r = kinematic viscocity

d_h = defined by 2 Y where Y = the width of the crack

In practice there are a large number of cracks of differing kinds and a large number of $F(R_{e_h})$ but by introducing a geometric parameter this number may be reduced to a manageable size. Moreover, by analogy to pipe flow, the ratio Z/d_h suggests itself as a parameter. Thus the crack flow equation has the form as described in equation 13. For the case of turbulent flow Etheridge found the Reynold's No. in equation 13 becomes $(R_{e_h})^{0.25}$.

When considering all types of flow processes, equation 13 is a simplification but some degree of simplification is unavoidable because the room which just has uniform cracks does not exist. Despite the problems, Etheridge states the crack flow equation has been successful in describing flow through real life components and estimating the open areas around the components. The advantages of the equation are;

(i) it is dimensionally homogenous, therefore, the value of C_Z does not vary with units.

(ii) it considers the effect of Reynold's No.

Consequently the open areas are independent of flow rate, which permits the insertion of the area into the equation where it can be accurately measured.

For the prediction of ventilation rates it is necessary to know the open area of each room component. Although direct measurement of full scale areas is generally not possible, it is possible to get an indirect measurement given the pressure difference and crack type from;

$$\frac{A^3 \, 2 \Delta P}{\rho \, Q^2} - A.C - \frac{B_Z \, L^2 \, r}{4 \, Q} = 0 \qquad (16)$$

where L = crack length

C & B = constants obtained from experimental data gathered by Etheridge.

In a later paper by Etheridge and Alexander (ref. 3), the above equations were incorporated into a computer method for predicting house ventilation rates. The basis of this method is the solution of simultaneous equations describing air flow through a network of openings across the dwelling coupled with the continuity equation.

3.4.2 Fluctuating pressure difference

Hitherto pressure difference has been considered as steady state. However, in practice the pressure generated at the surface is unsteady which is transmitted through cracks in the building fabric to the interior (13). If the pressure difference at time 't' is considered, its solution is given by;

$$\Delta P_i(t) = P_{ei}(t) - P_{Ii}(t) \qquad (17)$$

where ΔP = pressure difference

subscripts I = interior

e = exterior

i = the i^{th} crack

By assuming that the internal and external pressures can be expressed as a mean, which is independent of time over a long period (T), the mean difference becomes;

$$\Delta\overline{P}_i = \Delta\overline{P}_e - \Delta\overline{P}_I \qquad (18)$$

where $\Delta\overline{P}_i$ = mean pressure difference

subscript I = interior

e = exterior

i = ith crack

the bar denotes a mean value over the same period

the net mass flow rate into the house is assumed to be zero;

$$\Sigma \rho_i \; Q_i = 0 \qquad (19)$$

where e = density

Q = flow rate

subscript i = internal

Although there will be differences in the density due to temperature variation these differences will be small in the context of the continuity equation. Thus equation 19 becomes

$$\Sigma Q_i = 0 \qquad (19a)$$

Quasi steady flow is assumed such that equations 19(a) and 18 can be solved using the crack flow equations. Essentially $\Delta\overline{P}_i$ can be expressed in terms of Q_i permitting the solution of equations 18 and 19(a).

At higher frequency pressure fluctuations and higher flow rates the relationship becomes non-linear which leads to error, hitherto, not investigated. Moreover because there is a fluctuating pressure component, ΔP_i, flow reversal may occur through larger openings and is not accounted for by the steady-state equations. By assuming $\Delta P_i(t)$ has a gaussian distribution and a low flow rate if equation 16 is multiplied through by Q^2 the term '$A.C.Q^2$' becomes negligible and enables the mean flow rate over period 'T' to be estimated from;

$$Q_{Ti} = F.0.4 \quad \frac{2}{\Pi} \quad \frac{\Delta P_{i(r.m.s.)}}{\Delta \overline{P}_i} \quad \overline{Q}_i \qquad (20)$$

where Q = flow rate

ΔP = pressure difference

subscript i = internal

r.m.s = root mean square

the bar denotes mean

F is a factor relating to pressure

The above equation relates to low flow rates underwhich condition

$$\overline{Q}_i = \frac{8\ A^3}{B\ Z\ \ell^2\ \mu} \qquad (21)$$

where Q = flow rate

A = area of crack

Z = depth of crack

ℓ = length of crack

μ = kinematic viscosity

In equation 20 the term F accounts for the occurrence of large mean pressures where flow reversal will not occur and $\overline{Q}_{Ti} = 0$. This is the case when $\Delta\overline{P}_i > 3\Delta P_{i(r.m.s.)}$ (approx.) thus linear interpolation can be used between this case and when $\Delta\overline{P}_I = 0$. The term $\Delta\overline{P}_i$ can be found from equation and if $\Delta P_{i(r.m.s.)}$ us known an estimate of $\overline{Q}_{Ti}$ can be made. However, the term $\Delta P_{i(r.m.s.)}$ is not generally known; though, by choosing an arbitrary figure it was found that

$$\Delta\overline{P}_{i(r.m.s.)} = 0.5 \quad \Delta P_{i(r.m.s.)} \qquad (22)$$

Tests indicated this is a reasonable value.

3.4.3 Stack pressure

The effect of stack pressure modifies the internal pressure but this effect is only significant at external wind speeds of less than 2.5 $m.s^{-1}$ (13, quoting other references).

3.4.4 Predicted V.s. measured a.i.r.s.

For the purpose of comparison Etheridge (3) chose a detached house in a suburban area. The wind direction varied from 70^o to 170^o (0^o - N.) at speeds of 1.0 $m.s.^{-1}$ to 6.0 $m.s.^{-1}$, with temperature differences between 1^oC to 17^oC.

Extensive information was gathered from a large number of tests and predictions made on the collected data. The area of the background cracks was calculated from the measurements and it found these values produced the best predictions from the distributions that were tried. The results are very promising because the ratio of the predicted rate to the measured rate is 1.02 with a standard deviation of 0.4. More recent tests, which were not fully examined, under differing weather conditions, with all internal doors closed, then open gave the same ratio but the standard deviation was reduced to 0.19. The improvement in accuracy is ascribed to the improved method of measurement.

3.4.5 Comment

The above method has much potential for the investigation of ventilation rates in domestic buildings. If pressure differences can be accurately predicted for any dwelling, from a scale model the problem of predicting ventilation rates may be nearer to solution, though more work in this area is needed first i.e. distribution of pressure on the faces of a house and its effect on internal pressure differences.

3.5.1 American prediction models

The situation in America is not as advanced as the British gas model because most of their work is concerned with predicting ventilation rates from data collected from tracer gas experiments, though there are exceptions. The following is an example of one of the models being investigated.

Sepsey, McBride and Reeves (14) worked on the development of a model for hourly infiltration rate whilst considering weather, orientation, crack size, combustion processes and door and window openings. Previous work on modelling used an equation of the general form;

$$n = A + B.\Delta T + C.\mu \qquad (23)$$

where n = ventilation rate

ΔT = temperature difference

μ = wind speed

A, B & C = constants derived by regression analysis

But agreement about the consistency of the results of various experiments was poor (see 14 for list). In the model described by Sepsey et al, wind-pressure, stack effect and equivalent crack lengths were the main parameters for which an equation existed to describe the separate effect. The equations used to describe the aforementioned were drawn from the A.S.H.R.A.E. handbook (15) and used in seven different models which had the general form of;

$$n = \beta_o (A) \qquad (24)$$

where n = ventilation rate

A = $F(C_i . \Delta P_i)$

C = equivalent crack length

ΔP = pressure difference

β_o = statistical regression constant

subscript i = index for front, back, left or right surface

Most of the models failed but the simplest and most successful took the form of;

$$n = \beta_o . C_T (A.\Delta P_T + B.\Delta P_W)^{0.5} \qquad (25)$$

where n = ventilation rate

C_T = total equivalent crack length

ΔP_T = theoretical temperature pressure difference

ΔP_W = theoretical wind pressure difference

A & B = weighting constants

β_o = statistical regression constant.

In their conclusion a model is presented as a copy of a computer programme with suggestions on data collection. The authors finish by indicating the areas where more information is needed.

3.5.2 Comment

From the discussion of the British gas model equation 25 will fail on two counts because it resembles equation 6. Moreover, because of the differing nature and form of the medium causing the pressure difference, the arithmetic addition of pressures could be at fault, even with weighting constants, because they too would be functions of temperature.

CHAPTER IV

FLOW THROUGH COMPONENTS OF THE BUILDING

IV FLOW THROUGH COMPONENTS OF THE BUILDING

The implication of Etheridge's work is that if crack flow equations could be set-up for the component parts of the building it would be possible to predict the ventilation rate for any pressure difference and the energy consumption over a given heating season with the proportion of energy losses due to ventilation in an existing building. The measurement of flow through the open area around components of a building is a subject which little has been written of.

A laboratory investigation by Dick (16) of infiltration through gaps around window sashes produced some interesting results for pressure differences of 1.2 Pa. to 120 Pa (0.005 to 0.5 in.s. w.g.) and flow rates of 0.74 $cm^3 . s^{-1} . m^{-1}$ to 0.23 $m^3 \, s^{-1} \, m^{-1}$ (0.3 $Ft^3 \, hr^{-1} \, Ft^{-1}$ to 900 $Ft^3 \, hr^{-1} . Ft^{-1}$) though there is little indication to the length of the gaps. Dick noted flow rates depended on the applied pressure, the crack width and crack depth. In the analysis of the results the flow rate could be calculated from a quadratic equation;

$$\Delta P = A Q + B Q^2 \qquad (26)$$

where ΔP = pressure difference (in. s.w.g)

Q = flow rate ($Ft^3 \, hr^{-1}$)

A & B = constants

The derivation of the above equation is not given and the constants were found by empirical means. In concluding this work a graph of predicted results V.s measured results showed that reasonable agreement could be achieved by using equation 26 but to apply this work to present prediction would require an assumption to be made regarding crack length since this is not covered in detail.

A more recent investigation by Shaw (17) on in-situ components using a fan capable of delivering 0.2 $m^3 s^{-1}$ at 2 K.Pa (Fig.7) connected to a plywood sealing chamber found considerable lateral leakage (Fig.7) occured if the chamber was not balanced with either the adjacent rooms or adjacent area, as appropriate. Furthermore, it was found the background leakage contributed only 5% of the total leakage through the walls. This was found by comparing the results of the pressurisation of the whole wall and the pressurisation of the individual components, which may be of importance where it is not possible to measure background leakage on site.

4.1 Comment

Although, Shaw does not postulate an equation for calculating the flow rate through building components he does indicate overall infiltration of a building can be calculated from the component parts with reasonable accuracy. If this degree of accuracy is applied to the British gas model the possibility of finding an effective means of predicting ventilation rates becomes more real.

4.2.1 Kronvall

In a recent paper by Kronvall (18) into the study of air flow through building components he closely considers the theory of fluid flow relevant to building. The initial treatment of flow is based upon the Weisback formula (not read) or general friction formula;

$$\Delta P = \lambda \frac{\ell}{d_h} \underline{\rho}\, v^2 \qquad (29)$$

where ΔP = pressure difference (Pa)

ℓ = length of flow (m)

d_h = hydraulic diameter (m)

ρ = density ($kg.m^{-3}$)

v = velocity ($m.s.^{-1}$)

λ = friction factor

This equation is similar to equation six in its nature. Unlike Etheridge, Kronvall considers friction in the cracks and resistance due to restrictions i.e. where a door meets the frame, when calculating a coefficient for use with the velocity (or pressure difference) though he does not mention how to measure the area of the restrictions. Moreover, in using this method he suggests that for hand calculations (i.e. for an initial estimate on site) it is easy to get bogged down because the method is iterative, using the following equation;

$$\Delta P = (\varepsilon_{ext} + \lambda \frac{\ell}{d_h} + \varepsilon_{int}) \frac{e v^2}{2} \qquad (28)$$

where ε_{ext} = $K - (1 - \sigma)^2$

σ = ratio of constriction area to frontal area

ε_{int} = $(1 - \sigma)^2 + K$

K_e & K_c are found from graphs $K_{c/e}$ versus Reynolds No.

λ = friction factor

ℓ = length of flow (m)

d_h = hydraulic diameter (m)

Essentially a first estimate of the Reynolds is used to find or calculate the above factors from which the pressure difference can be found using equation 28. If the first value calculated from equation 28 disagrees with the measured pressure difference the Reynolds number is changed (and subsequently K_e & K_c) in order to bring the calculated value closer to the measured value. Iteration is used until an acceptable value is reached.

4.2.2 Comment

For more complicated shapes than a rectangular, or straight-through crack, for which equation 28 describes the flow, finding the coefficients becomes more complex (as the complexity of the flow increases). Moreover, the guesswork about how big a restriction in a building component crack may be and the respective surface roughness, the accuracy applied to finding earlier coefficients (i.e. ε, λ or K) may be lost.

CHAPTER V

THE EXPERIMENT

V THE EXPERIMENT

5.1 Objective

It is well established that air will flow through cracks and gaps in the building fabric under a pressure difference. Previous attempts to introduce a prediction method to this phenomenon are wide and varied in their approach but, as yet none are widely acclaimed. The purpose of this experiment is to gain an insight to the solution of predicting ventilation rates by examining the coefficient defined in equation six and making a comparison with present work being undertaken at British gas by Etheridge. Thus the objectives of the experiment can be defined as follows;

to construct a device capable of measuring air flow through a building component under a given pressure difference and to investigate the existence of a coefficient which, when multiplied by the pressure difference, raised to an exponent, will yield the air flow through that component.

5.2 Apparatus

The choice of apparatus for the experiment was based upon the technique described by Shaw and others (Fig. 7) though for this experiment the rigid airtight chamber was replaced by a heavy duty polythene sheet, hereinafter called 'the tent', which was held in place around the component by either struts and masking tape or masking tape alone. The reason for using polythene was that time could be saved on dismantling and erecting the tent over an opening. Where an opening was too big (2.5 x 2.5 m) or the use of tape to secure the tent would damage the decor around an opening then bracing and a rubber gasket would be used (Fig. 8). The struts were made from screwed rod, 19 mm hollow, square-section tubing and nuts (Fig. 8) and the bracing from either 25 mm angle iron or lengths of 19 x 80 mm timber according to what was available.

The fan used to deliver the air was an Air Flow Development 40 BTFL capable of delivering 2.75 $m^3 s^{-1}$ at 50 Pa The working range of the tests was to be from 0 Pa. to 50 Pa. as recommended by Kronvall and other researchers for whole house testing.

The static pressure difference was read using an Air Flow Developments inclined manometer capable of reading down to 0.5 Pa. on the scale. A length of 12 mm. i.d. tubing connected the manometer to the 'tent' and the opposing face of the component.

Two transitions pieces (Fig 9/10) were made for the fan/duct interface and duct/tent interface. The duct/tent interface included a facility to secure the air flow meter and a connection for the tube from the manometer. The static pressure at the end of the transition piece is the same as the static pressure in the tent for most purposes, subsequently the tap for the tube to the manometer was at the end of the Transition Piece. The loss of air from the tent/duct transition piece was eliminated by using gaskets cut from closed-cellular, rubber matting and stuck to the metal with a solvent glue ('Evo Stick'). Air loss from the fan/duct transition piece was not a problem since it was necessary to disconnect the ducting from the fan in order to regulate the pressure difference. This crude method of regulation using tape to block the flow at the fan's exit instead of a purpose-made damper enabled readings at very low pressure differences to be taken which for short-term use was adequate.

5.3 Method

In essence the method of testing is to place an air-tight cover over an opening and measure the air flow through the building component under differing pressure differences. Although this is what is understood to be the test method, in practice an air-tight seal is not always possible because of difficulties in sealing the text at corners or the point where the rubber gasket seal stops and the tape seal begins. The method used for testing in this experiment will be explained in the following paragraphs.

Before a test starts all the cracks of interest are identified and their dimensions measured or approximated, after which they can be covered with masking tape to seal them. These cracks are usually the visible cracks whose area can be estimated. In the case where all routes of escape are of interest and a tent can be erected to form a tight seal, it is not necessary to tape the cracks. The purpose of taping the cracks is to isolate air-flow through background cracks and/or escape from the test from flow through the relevant cracks to enable comparisons to be made with predicted values at a later stage.

The tent membrane is made from heavy-duty polythene sheeting cut to size such that it covers the opening and, with the edges sealed will contain a pressure differenc causing air to flow through the cracks. The stop-nut shown in Fig. 8 has a 25 m.m. length of angle-iron welded to it to match the brace but if a softer material is required to preserve the decor wood can be used and plain nuts used as stops. The wood used during this experiment was from old 5" x ¾" floor-boards which were split and cut to size for braces. For most of the tests it was possible to tape at least two sides without damaging the decor. However, the purpose of the struts was often two fold because they took the weight of the transition piece and ducting on the tent, which is often necessary when little tape is required to seal the edges.

When connecting the duct and fan to the tent the transition piece plates (Fig. 10) can be fixed to the polythene sheet either before or after the tent has been erected. If the plates are fixed after the polythene is fitted in place slits can be cut in the sheet, to insert the inner plate, and sealed using packaging tape. Before attaching the transition piece to the transition piece plates the impeller of the air flow meter is fitted into the transition piece. This saves a lot of effort when trying to keep the interfaces air-tight whilst the transition piece is awkwardly positioned on the tent. Once the transition piece is fixed to the tent the manometer and air-flow meter connections can be made.

When reading pressure differences across a building component it may be necessary to use a long length of tubing to make the connection. The inside diameter of the tubing used in this experiment was greater than the outside diameter of the manometer (an air tight joint was effected) but the precaution was unnecessary because static pressure difference was being measured over relatively long periods. Before starting to take readings the required direction of pressure should be decided. The description which follows assumes both directions of air-flow are of interest but for the case when one direction is of interest the principle is the same. With the joints taped readings of air flow and pressure difference are taken in stages from 4 $\pm$ 2 Pa to 45 $\pm$ 10 Pa for 7 $\pm$ 2 (No.) differing pressure differences for air flow in one direction. The choice of pressure differences depends on the behaviour of the air flow. For example, if air-flow increased rapidly at low pressures for a small increase in pressure difference the number of readings taken would be seven, say, with an emphasis on the lower end of the pressure scale. After one set of readings are taken the fan is switched off for a few minutes to allow the tent system to return to its natural position. This is repeated until three separate sets of results, which are in approximate agreement, are collected. The precaution of allowing the system to return to its natural position proved to be useful because it is possible to guess air flow, for a given pressure difference after the first run, which if found to differ greatly may be the result of a fault in the system i.e. a blow-out in the seal. By taking three sets of results the best curve can be drawn for the results with reasonable confidence. The starting point of a run i.e. 0 or 50 Pa., was not found to be important to the shape of the resulting curve.

To test for flow in the opposite direction with the joints taped the duct is connected from the fan inlet (or outlet) and connected to the fan outlet (or inlet) and the aforementioned procedure repeated. For testing with the joints open slits are cut in the tent to allow the operator to remove the tape covering the cracks to leave the joints open. The slits can be repaired using packaging tape to stick the flaps back together. When the slits in the tent have been repaired the first set of results of air-flow through open cracks can be recorded without changing the position of the duct on the fan from the previous set of results. The number of points recorded and number of runs (usually three because all faults should have manifest themselves at this stage) follows the procedure previously described for air-flow with the joints taped. The final set of results of open joint testing, with flow in the opposite direction (to the previous set of results), can be recorded by changing the direction of air flow as previously described.

The testing of the building component is now completed and the operator should have at least twelve sets of data which can be split into four sets of three then paired into pressure differences of the same sign with flow for joints taped and joints open i.e. the results of two tests with flow in both directions.

5.4 Calibration of the Device

The method used to calibrate the device was a simple one using tracer gas as its technique. The transition piece and flow meter were assembled and the transition piece bolted over a 20 m.m. hole at the centre of one side of the test chamber (see plate I). The fan and ducting were connected to the transition piece and air was blown through the box at a constant rate and pressure. Nitrous oxide was introduced through another hole, into which the sampling tube for the gas analyser was fitted, immediately after the introduction of the nitrous oxide, and the chamber's atmosphere was continuously sampled and analysed.

The results of the calibration tests are presented in Tables I and II from which it can be seen there is close agreement in the two resulting ventilation rates. The difference of 11% between the two methods is acceptable because the accuracy which can be achieved using tracer gas methods is around 10 - 15% (19). The tests were performed at high pressures (50 Pa) because previous researchers i.e. Kronvall on house air tightness used this pressure as their upper reference level and the author initially intended 50 Pa. to be the upper reference level of this experiment (40 Pa. was actually used).

5.5 Problems, Delays and Experiences

Problems encountered during the initial stages were generally minor i.e. buying materials from outside the university or failing to ensure an air-tight seal on the tent, etc., but their total effect was notable. In the following section a small number of the problems will be related to the reader in order to be of assistance in future tests.

The first test was perhaps too ambitious in its size, being a 2.1 m x 2.1 m window opening. In order to effect a seal a 12 m.m. x 12 m.m. closed cellular rubber strip was to be braced against the wall adjoining the window. The material for the bracing was, at first a length of 25 m.m. x 3 m.m. mild steel strip which was useless for its chosen purpose. Its successor was 25 m.m. x 6 m.m. angle iron which proved successful but needed a special stop at the strut/ brace interface to prevent it toppling over (using the gasket as a fulcrum) as the strut was tightened (Fig. 8).

During the first test it was discovered a perfect seal could not be achieved using a series of struts and rubber gasketting. In fact towards the end of testing the tent was sealed using adhesive tape alone because it is quicker and does not require two people to erect the tent. However, the struts and gasketting system are invaluable where tape cannot be used and these situations are many.

Towards the end of testing it was decided to test air flow through ceiling roses and small openings. Using a large, plastic bucket with a rubber gasket stuck to edges of the open end and the transition piece fixed to the other (a hole needed to be cut in the bottom to allow air-flow), a suitable tent was made to go over the hole. The tent/ bucket was held in place using struts. However, because the air flow meter would not record air-flow of less than 200 litres per second the tests could not be completed.

5.6 Results

The test results are presented as graphs and tables in Appendix II. The flow rate through a component was found as the difference between the curve representing air flow through the background alone, with the joints taped and the total air flow with the joints open. The term background in the previous sense applies to all passages of escape other than the cracks. The range of pressures, analysed by four equations to yield five different flow characteristics, was from zero to 10 Pa, the range of pressures most frequently met in the domestic situation. The equations used for the analysis are:

$$Q = C_p \Delta P^n \qquad \text{- Eqn. 6}$$

which revealed the coefficient C_p and the exponent of ΔP by plotting $\ell n.Q$ V's $\ell n.\Delta P$.

$$\frac{A^3 2\Delta P}{Q^2 \rho} - \frac{BZ\ell^2 r}{4Q} - CA = 0 \qquad \text{Eqn. 16}$$

By measuring 'ℓ' and 'Z' and using Etheridges values for 'B' and 'C' the crackage area is found from Newton's "method of improving an approximation", given the first approximation is the product of the measured values of crack length and width:

$$x_2 = x_1 - \frac{F(x_1)}{F^1(x_1)} \qquad (29)$$

when x_1 = the first or the $(n-1)^{th}$ approximation

x_2 = the second or the nth approximation.

Once the crackage area is found the coefficients C_Z and C_a are calculated from:

$$\frac{1}{C_Z^2} = \frac{BZ}{d_h R_e} + C \qquad \text{Eqn. 13}$$

$$C_a = \frac{Q}{A}\sqrt{\frac{\rho}{2\Delta P}} \qquad \text{Eqn. 15}$$

The values of 'C_p' and 'n' in equation six were found by using values taken off the graphs in Appendix II and analysing them in a regression analysis computer programme. The values for Eqn. 13, Eqn. 15 and Eqn. 16 were calculated on a computer programme.

In the treatment of the British gas work Etheridge indicates that two constants (B & C) exist for a particular crack type and where there are two crack types in a single component it may be possible to obtain a reasonable approximation using only one pair of constants. During the tests rarely was the crack type found to be uniform throughout the component. It was also found the dimensions i.e. Z or w, varied as the crack type varied. These problems were overcome by combining the various dimensions into a single length weighted dimension to enable input of a single value into a computer programme which calculated the separate crack-type results, using the appropriate constants, for comparison at a later stage.

CHAPTER VI

DISCUSSION

Table 1. Summary of Experimental Results

The results in this table are referred to throughout the discussion chapter (6).

Test	A_m ($x\ 10^3\ m^2$)	A_c → "	Q(10 Pa) ($x\ 10^3 m^s.s^{-1}$)	C_p ($x\ 10^3$)	n → "	C_z → "
1	3.542	4.497	1.97	0.96	0.37	0.096
2	16.46	14.66	21.20	4.75	0.69	0.40
3	16.63	10.06	18.20	2.58	0.85	0.44
4	1.26	1.33	1.13	0.16	0.95	0.57
5	15.82	7.45	19.20	5.40	0.51	0.66
6	6.07	2.55	7.04	1.66	0.63	0.76
7	8.82	1.93	2.51	0.64	0.61	0.54
8	1.83	3.39	8.13	1.06	0.48	0.13
9	too small		2.46	0.33	0.95	-
10	1.40	4.45	1.97	0.67	0.60	0.03
11	"	4.68	3.45	0.55	0.73	0.04
12	4.25	7.55	17.70	2.71	0.84	0.29
13	"	6.70	16.70	2.48	0.85	0.34
14	8.41	9.79	20.70	4.52	0.66	0.38
15	"	13.52	32.00	5.52	0.80	0.39
16	16.46	12.00	14.04	3.38	0.66	0.36
17	7.17	9.92	18.20	3.37	0.76	0.37
18	"	11.33	22.60	4.30	0.75	0.31
19	16.52	9.05	12.30	1.40	0.95	0.41
20	"	8.44	7.39	2.48	0.47	0.39
21	6.14	9.24	16.70	2.68	0.57	0.25
22	"	8.97	15.30	2.60	0.78	0.24
23	too small		1.97	0.22	0.92	-
24	"		2.46	0.29	0.96	-
25i	0.57	3.35	7.88	1.07	0.72	0.09
25ii	1.40	5.47	19.70	2.13	0.74	0.53

In the above the values are multiplied by a given value and need to be divided to find the actual value e.g. Test 1, A_c = 4.497 but the true value is 4.497 x 10^{-3} m^2. See Over-

A_m = Measured area (by hand)

A_c = Calculated area (on a computer)

Q(10 Pa) = Flow rate at 10 Pa.(m^3 s^{-1})

C_p = Coefficient as defined by Equation 6

C_z = Coefficient as defined by Equation 13

n = Power exponent as defined in Equation 6

VI DISCUSSION

6.1 British Gas

From the results a number of points emerged, which will be discussed in the following section. After comparing the calculated areas (hereinafter denoted A_c) with the measured area (denoted A_m) it was found A_c significantly differed from A_m, by an amount, which was up to 300% in some cases. The reason for this discrepency is probably due to the difficulty in accurately measuring the crackage area around a building component. This difficulty is twofold in reality because a crack's width will vary over its length and the open crack width is often different to the crack width in the depth of the crack. During testing many cracks whose widths were less than a millimetre were estimated. This estimation can only be approximate because surface roughness will vary the crack width at this size of crack.

After comparisons were made of the areas of various crack types a trend did not emerge but it was seen that the area (A_c) was proportional to the flow rate. The variation in area as measured by the standard deviation was $\pm$ 8% (for a 0 - 10 Pa. pressure difference range). Hopkins and Hansford (11) indicate the possibility of crackage area variation with flow but do not produce any values from experimental data or references to support this statement. Since the form of equation 16 has the area proportional to the flow rate the values obtained will follow the previous statement by Hopkins. (This is not discussed in detail by this text). Thus the basis for questioning the validity of equation 16 is formed because;

(i) the degree of movement will vary from one crack to another and cannot be accurately measured.

(ii) the answers obtained are calculated using empirically found constants for a specific crack type, whereas in most components the crack type varies.

However the degree of accuracy required for ventilation rate predictions is 10 - 15%, which could embrace the errors of equation 16. Comparisons between predicted and measured ventilation rates are outside the scope of this work.

The value of the coefficient C_z is defined as the ratio of the actual velocity through a crack to the theoretical velocity. In the results this ratio is annotated as C_a. After comparisons were made between C_z and C_a it was noted that the majority of values of the ratio C_z/C_a were between 0.75 and 1.3 with a small but noticeable number outside this range and even fewer near unity. In order to trace this discrepancy the two respective equations need to be analysed. From equation 15 it can be seen that C_a is the coefficient that is most readily understood. The derivation of equation 15 (i.e. a ratio) shows the final value to be independent of crack width, subsequently if A_c is an acceptable value the coefficient C_a will be used to predict air flow through a building component. The derivation of equation 13 on the other hand is not as readily understood especially as it uses two empirical constants. However, as these constants are subsequently used in equation 16 it follows that any error involved should balance out.

$$\frac{1}{C_z^2} = \frac{B.z}{d_h.R_e} + C \qquad \text{Eqn. 13}$$

In the above the first term relies on an input value for crack width (Y), directly ad d_h = 2Y and indirectly in R_e. Therefore if A_m and A_c differ greatly the difference will probably lie in the crack width if the measured crack width (ωm) is used as Y. If the crack width calculated from A_c (ωc) is used instead of ωm the difference in C_z will take the sign of $(A_m - A_c)$ and the new C_z will increase or decrease approximately in the ratio of ω_m/ω_c. The results from the experimental data generally needed correcting in the opposite direction to the sign of $(A_m - A_c)$ i.e. if $(A_m - A_c)$ was negative then C_z needed increasing to make $(C_z/C_a = 1)$, therefore to use the crack width derived from A_c would only aggrevate the problem. This seriously questions the validity of equation 16 because subsequent values derived therefrom or equation 13 should correct errors relating to the ratio C_z/C_a.

6.2 Traditional Method

The traditional method using equation 6 was analysed using a regression analysis computer programme and the velocity shown on the air-flow meter. However, this method was not satisfactory and the coefficient (C_p) and pressure difference exponent (n) were later found by plotting ℓn. Q V's ℓn ΔP from which C_p and n could be found. Although there was not any distinct relationships to emerge from the results a number of interesting points did appear. Hopkins and Hansford (11) suggested the pressure difference exponent would be approximately 0.65 but this was not confirmed by the results.

There was not an obvious relationship between either A_c or A_m with C_p or n. The values of C_p and n did not show a particular trend with flow rate. On the positive side of matters, equation six generally produced a value which was very close to the flow rate curve (graphs 1 to 25).

6.3 Pressure Difference

The results in this experiment were all based on the assumption that pressure difference was constant for any one reading. In section 3.4.2 it was stated that pressure difference is unsteady in practice and the discussion of Potter's work indicated that the fluctuations in pressure difference, under certain conditions would be random in their behaviour. In most of the tests a steady pressure difference was maintained but during a number of tests the fluctuating pressure difference was a nuisance and the test had to be abandoned. It was especially noticed during test 1 where the component was near the top of a seven storey building, however, during tests 12 and 22 in the suburbs of Manchester, difficulties were also experienced.

For the pressure difference to fluctuate noticeably the wind velocity at ground level was just noticeable (the author suggest $0.45\ m.s^{-1}$). At higher wind speeds the fluctuations were a nuisance. The weather condition during the tests was usually dry, warm and calm which allowed doors to remain open without discomfort and subsequently eliminate the need to account for stack pressure. On occasions when there was wind the pressure difference could easily fluctuate by $\pm$ 7 Pa. (as the wind blew, stopped and sucked). Moreover the frequency of the fluctuations was as random as the value of the pressure difference.

As future work on air flow through building components becomes clearer the present work on fluctuating pressure difference and modelling will be useful. Its use will be proved when calculating air flow through building components for a given pressure difference. However, unless the subsequent distribution and direction of pressure difference through the building is known prediction of ventilation rates may be confined to whole house ventilation rates.

6.4 Summary (of the experimental data)

Of the four buildings where more than two tests were performed it was seen the three storey, Victorian terrace house was the leakiest. The property in Wales, a 17th century slate cottage was expected to be leaky but lack of care during painting and decorating had effectively sealed the cracks around a lot of the components. This is most noticeable when comparing the flow rates at 10 Pa. for tests 4 and 7 (table 1) (windows) with test 23 (purposely, air-tight window). However the windows which were openable had little effect on reducing infiltration of cold external air. Although the windows at Fairfield are small in comparison to the windows at Peel Ave., when test 5 is compared with test 17 it is seen the flow rates at 10 Pa. are comparable. The windows in the Pariser Building have all been treated with an epoxy resin between sash and window frame for the purposes of draught exclusion. The effect of the treatment is to make the window as air-tight as a brand new, purpose made, air tight window (see tests 1 and 22 and 23). If it is assumed each window had the air-tightness of the door in tests 12 and 13 (which maybe generous) before treatment then the overall effect of each of the eight windows on energy consumption must have been considerable.

The effect of draught stripping a door is indicated when comparing tests 10 and 11 with test 3. Although the two components are of differing design the crack lengths are similar and the crack depths are reasonably close for the purpose of this comparison (Table Lll). Clearly by comparing tests 12 or 13 with test 1 and tests 10 and 11 with test 3 the beneficial effect of draught proofing can be recognised. Conversely to make a component effectively air-tight by intentional means or otherwise i.e. poor maintenance is likely to cause condensation and fungus growth. Some of the components at Fairfield were an example of this where window frames had been painted so as to seal the cracks and make the component effectively air-tight. Poor maintenance at Fairfield also had an opposite effect on infiltration where part of the component had rotted over the years. This can be seen in test 5 where the component is comparatively small but the air flow, is large. Thus the effect of poor maintenance of components is realised to be wider spread in its consequences.

The effect of draught proofing is to effectively reduce the area of crackage from which one might deduce that flow rate is proportional to crackage area. However, it is not strictly true. After comparing the calculated area of tests 1 and 11 it was found they were nearly equal but their flow rates at 10 Pa. were different (1.97×10^{-3} m.^{3} s^{-1} and 3.45×10^{-3} m^3.s^{-1}, respectively). When comparing the measured areas the same was true for tests 2 and 3. Mindful of the previous examples graphs of flow rate V's crackage area were plotted for measured and calculated areas. The subsequent curve confirmed there is not a simple relationship between crackage area and flow rate (this is supported by Shaw, ref. 17).

After examination of the coefficient and pressure difference exponent of equation 6 it was found that the exponents of pressure and suction tests on the same component were equal (for a majority). This is true for tests 25i and 25ii, 23 and 24, 17 and 18, 12 and 13. Exceptions were found where the component was a loose fit in its frame as noted for tests 10 and 11 (door) and tests 14 and 15 (window). The implications of similar pressure difference exponents are;

(i) The shape of the leakage curve will be practically the same for both pressure and suction tests and the difference in the magnitude of flow, controlled by the coefficients for good fit components.

(ii) For loose fit components the magnitude of flow will be dependent on the degree of movement in the component and the direction of flow.

The loose fit phenomena described may be the reason for the difference in the results of tests 2 and 16. Although the two tests were on the same component the flow rates at 10 Pa. were $21.2 \times 10^{-3}\ m^3\ s^{-1}$ and $14.04 \times 10^{-3}\ m^3.s.^{-1}$ (tests 2 and 16 respectively). However Carruthers and Newman (20) found there was often wide variation in the data recorded by different workers performing the same test on the same component. The author tentatively agrees with Carruthers and Newman and believes the difference can be ascribed to the operator's unfamiliarity with the test procedure. This was sorted out by test 3 or 4.

The results of tests 18 and 19 explores a weakness in using the false-ceiling height for air change rate calculations because it is not air-tight. Graphs 19 and 20 show there is significant flow through the four tile section which could not be reduced by pressing the tile and frame surfaces together. This was tested by placing a brick (approx. 1 kg.) behind each tile. The test has shown it is possible a significant proportion of warm air may escape through to the ceiling void and further if there is passage.

The results of test 25 indicate the possibility that significant quantities of warm air can escape through loft trap-doors and subsequently to the exterior. The trap in this text had been treated with neoprene draught-stripping which probably made it less leaky than an untreated loft trap. The effectiveness of the draughtstripping was more than doubled by placing a brick on the back of the trap-door (graph 25). A beneficial effect of decreasing infiltration to the roof space is to reduce the amount of moisture penetration and subsequent condensation problems with the roof timber.

It should be noted that the characteristic curve changed shape, in the aforementioned tests, at a definite pressure area. This change is believed to be the point where the component has been lifted off its frame and is suspended above the frame by the air flow.

6.5 Summary of the Discussion

To close this chapter the subjects highlighted in the discussion will be listed as follows;

(i) Pressure difference exponent of equation 6 does not tend towards a particular value.

(ii) There is not a UNIQUE relationship between the flow rate and crackage area of differing cracks.

(iii) It is very difficult to accurately measure crackage area.

(iv) Work at British gas may be limited in its use because:

(a) The area calculated from equation 16 is proportional to the flow rate.

(b) The ratio C_z/C_a does not tend to unity.

(c) The errors relating to the ratio C_z/C_a are not corrected by equation 16 (an equation derived from the relationship of $C_z \equiv C_a$).

(v) Tight fitting components (i.e. whose crackage area is effectively constant) exhibit similar pressure difference exponents for suction and pressure tests.

(vi) Loose fit components have differing flow characteristics for suction and pressure tests.

(vii) For reasonable accuracy at low pressure testing i.e. less than 10 Pa., calm weather conditions are necessary.

(viii) Great care is required when performing a test in order to eliminate errors and make the test reproducible.

(ix) Draught stripping components can reduce air infiltration to a negligible quantity if it is done properly using durable materials.

(x) Poor maintenance of components has an adverse effect on air infiltration which can result in either excess heat losses or condensation and fungus growth.

(xi) Loft traps could be a significant source of moisture-laiden air to loft spaces.

(xii) Leakage through fabric ceilings could be a serious problem.

CHAPTER VII

CONCLUSIONS

VII CONCLUSIONS

From the previous chapter there are a number of interesting points to emerge from which conclusions may be drawn.

7.1 British Gas

The obvious conclusion about the work performed at British gas is that it is of limited value. The reader may support this statement by quoting item iv from section 6.5. However, although the results of the experiment have found flaws in the British gas work it would be an error to absolutely conclude their work is of little value. The reason for this is that the method used to find air flow through the components differed in this experiment from the method used at British gas. Bearing in mind the work of Carruthers and Newman the author suggests this conclusion be treated with qualification about the method used to arrive at it before quoting conclusively.

7.2 Crackage Area

With respect to crackage area the author concludes there is not a unique relationship between area and flow. This was supported by plotting both the measured area (A_m) and the area calculated using the British gas equation (eqn. 16.A_c), against the respective flow rate. Shaw's work implies there is not a relationship between flow rate and area. Moreover, the difficulty of finding a unique relationship for crackage area is aggrevated by the nature of cracks and their measurement in real life comcponents.

7.3 Reducing Crackage Area

Draught stripping of components reduces crackage area.

to the point where air flow is limited. Although the method of draught stripping used on the door to G.10 (test 10) was sticky-back foam its effect was noticed by comparison to test 3. The mastik seal placed in the metal frames (tests 1 & 8) also proved effective when compared with other more leaky components. However to effectively seal a room (by intentional means or otherwise) is folley and can only produce disasterous results. Finally, tight fitting components with small crackage areas have low infiltration rates.

7.4 Traditional Method

There is not a discernable relationship between either the coefficient or the pressure difference exponent with any of the physical dimensions of the component. The accuracy of equation 6 to describe the air leakage curve is good (generally better than 90% accurate) and may be considered excellent if one is mindful that the curve is the best fit in a band of results. This is contrary to Etheridge's belief that equation 6 is not accurate enough to describe air flow through components for the computer model used by British gas. Etheridge's reason for dismissing equation is that it is not dimensionally homogenous. However, because equation 6 accurately describes the characteristic flow curve indicates its dimensions have not been successfully derived. It is possible that future work in this area will reveal a mathematical derivation of this equation.

Using equation 6 the author believes it is possible to predict whole house ventilation rates for a given weather condition. This would be found using the basic principle of 'what flows in must flow out' through the component parts of a house, for example. However for this principle to be a useful tool all the relevant escape passages must be identified and external pressure difference distribution found. The latter point may rely on the success of the present work on modelling for its success.

7.5 The Experiment

The primary conclusions of this text must answer the objectives set out at the beginning. The objectives set out in section 5ii have been answered in the affirmative up to now but the following will be a confirmation.

The experiment has shown it is possible to construct a device which is capable of measuring air-flow through a building component under a given pressure difference. The accuracy of the device is acceptable and it can be used for investigative work on building components.

With respect to the existence of a coefficient for use in conjunction with the pressure difference, raised by an exponent, equation 6 is acceptable. This is contrary to work done by British gas and the author believes the additional accuracy may be just academic in the light of the distribution of points of the air leakage curves.

Finally, the experiment has shown it is possible to perform pressure/air flow tests quickly and efficiently. Similar work is required to enable comparisons to be made to show which method is the most reliable. This work in conjunction with work on pressure difference distribution will form the basis of a useful prediction model.

7.6 Air-tightness of Building Components

The performance of tight-fitting components in their frame is far superior than loose fitting components with respect to air-tightness. A clear example is the windows at Spur Walk (tests 22 and 23) compared with those at Fairfield (test 5). The effect of draught stripping is to reduce infiltration by reducing crackage area. When draught stripping and a tight fit (by use of extra weight) are applied to loft-trap doors there is an improvement in air-tightness. The effect of the draught stripping is enhanced by a tight fit.

The basis to question the use of false ceiling height in air infiltration calculations has been formed, although much depends on a tile's finish, its properties (i.e. weight) and the frame on which it sits. If on the assumption that all false ceilings (without obvious differences) behave in a similar fashion this is a subject which merits further investigation because of its far reaching implications.

7.7 Summary of Text

In summary of this text it has been seen that assumptions about the air-tightness of false ceilings and loft traps are probably incorrect and significant flow occurs through these components.

With respect to prediction models this text favours the traditional method but is mindful that more work is required in the area pressure difference distribution in order to produce a useful model. The author feels if this problem is solved a useful prediction model will result.

List of Tests

Test/graph No.	Description
1.	5th window from R.H. corner, looking West, room H.8, Pariser building, U.M.I.S.T. + ve. pressure.
2.	Door-opening to room H6, Pariser building U.M.I.S.T., + ve. pressure.
3.	Front door, 'Fairfield', Llanfair Talhaiarn; + ve. pressure.
4.	Front window, back-room, 'Fairfield', Llanfa Talhaiarn; + ve. pressure.
5.	Back kitchen window, Fairfield, Llanfair Talhaiarn; + ve. pressure.
6.	Rear-window, backroom, Fairfield Llanfair, Talhaiarn; + ve. pressure.
7.	Parlour window, Fairfield, Llanfair Talhaiar + ve. pressure.
8.	R.H. window to G.10, Pariser building, U.M.I.S.T., + ve pressure.
9.	Downstairs toilet window, 5 Peel Ave., -ve. pressure.
10.	Door to G.10, Pariser building, U.M.I.S.T., -ve. pressure.
11.	As test 10 but +ve. pressure.

Test No.	Description
12.	Attic bedroom door, 5 Peel Ave., -ve pressure.
13.	As test 12 but with +ve. pressure.
14.	Front attic window, 5 Peel Ave., -ve. pressure.
15.	As test 14, but with +ve. pressure.
16.	See test 2.
17.	Front bedroom window, 5 Peel Av. -ve. pressure.
18.	As test 17 but with +ve. pressure.
19.	A four square section of false ceiling on Prot. Ward, Pinderfields Hosp., +ve. pressure
20.	As test 19 but -ve. pressure and unrestricted flow only.
21.	Front small-bedroom door, 4 Spur Walk; +ve. pressure.
22.	As test 21 but with -ve. pressure.
23.	Front small-bedroom window, 4 Spur Walk, +ve. pressure.
24.	As test 23 but with -ve. pressure.
25.	Loft trap, 7 Maes-Y-Llan, Llanfair Talhaiarn, +ve. pressure.

Fig. 1 Surface Pressure for differing building geometries

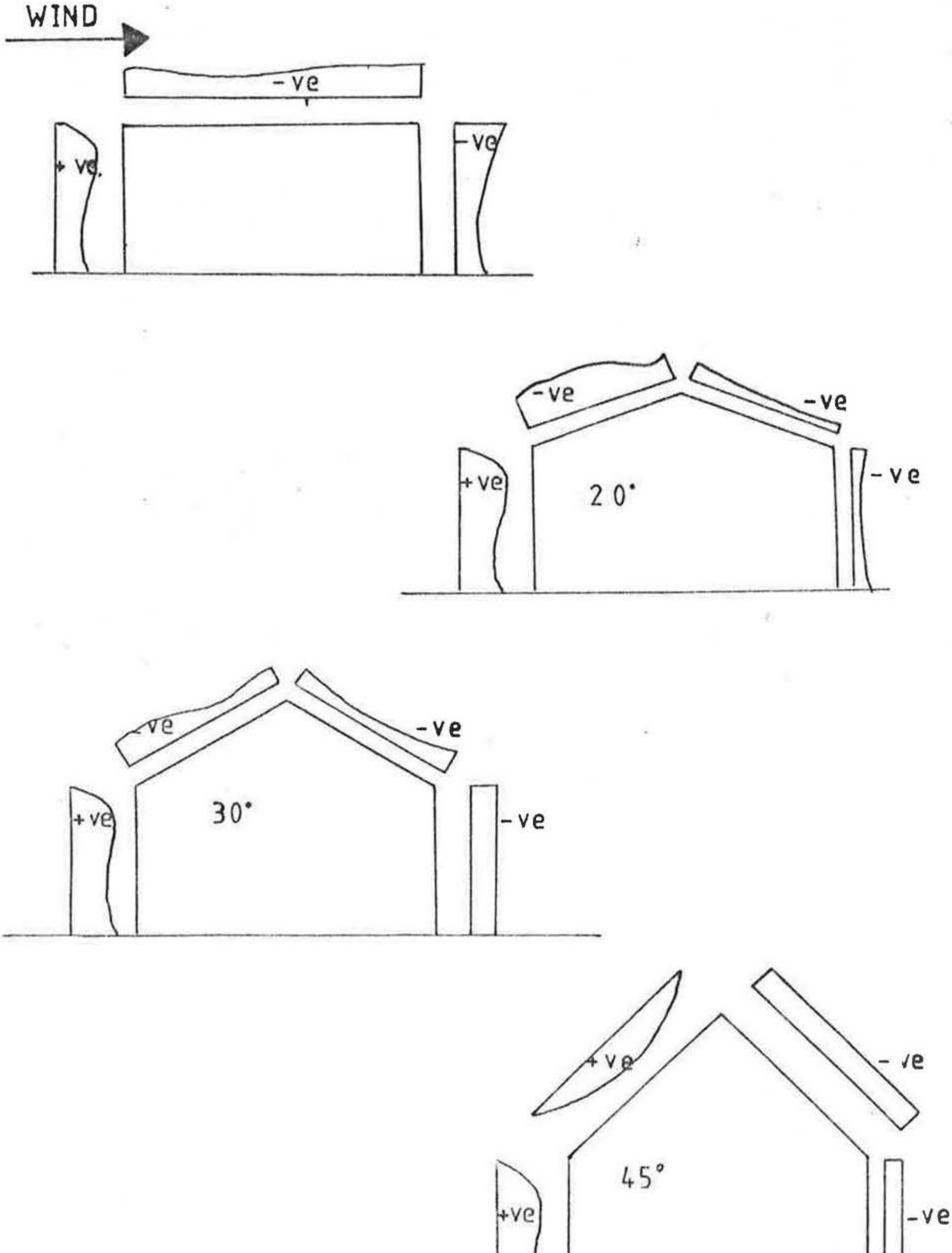
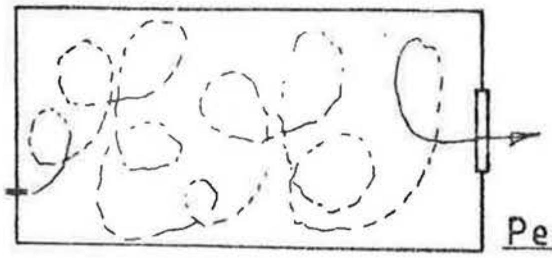
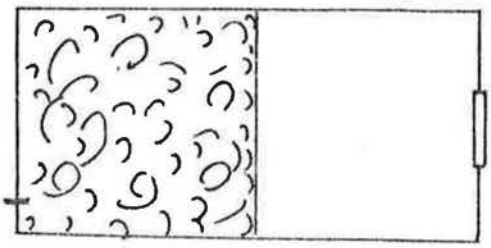


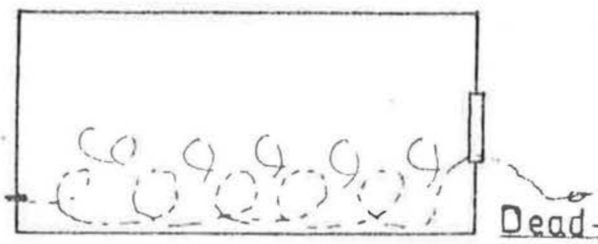
Fig 2 Tracer gas mixing patterns



Perfect mixing



Perfect non-mixing



Dead-spot mixing

Fig. 3 Concentration response curve

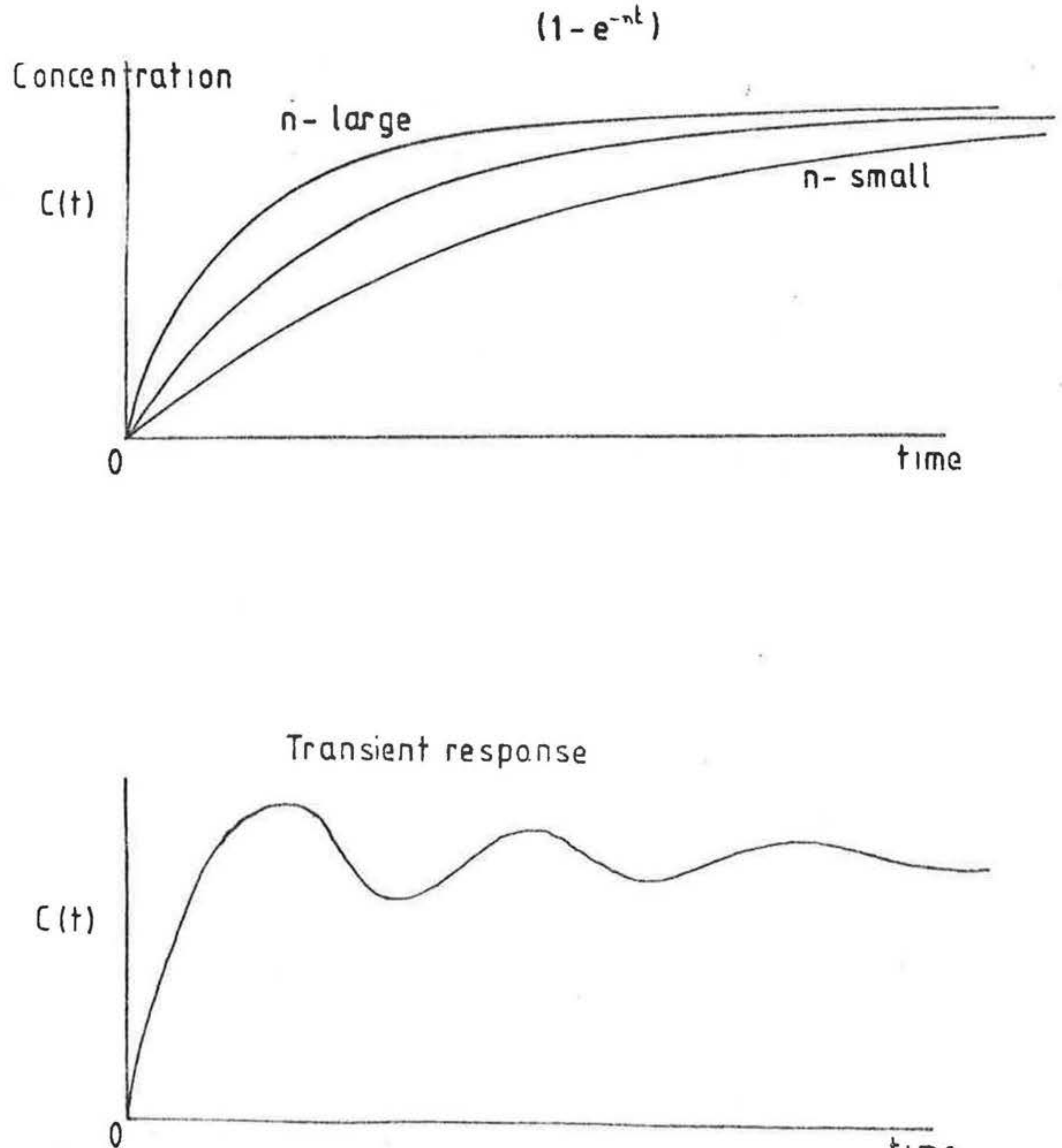


Fig 4 Flow rate V's Pressure diff.

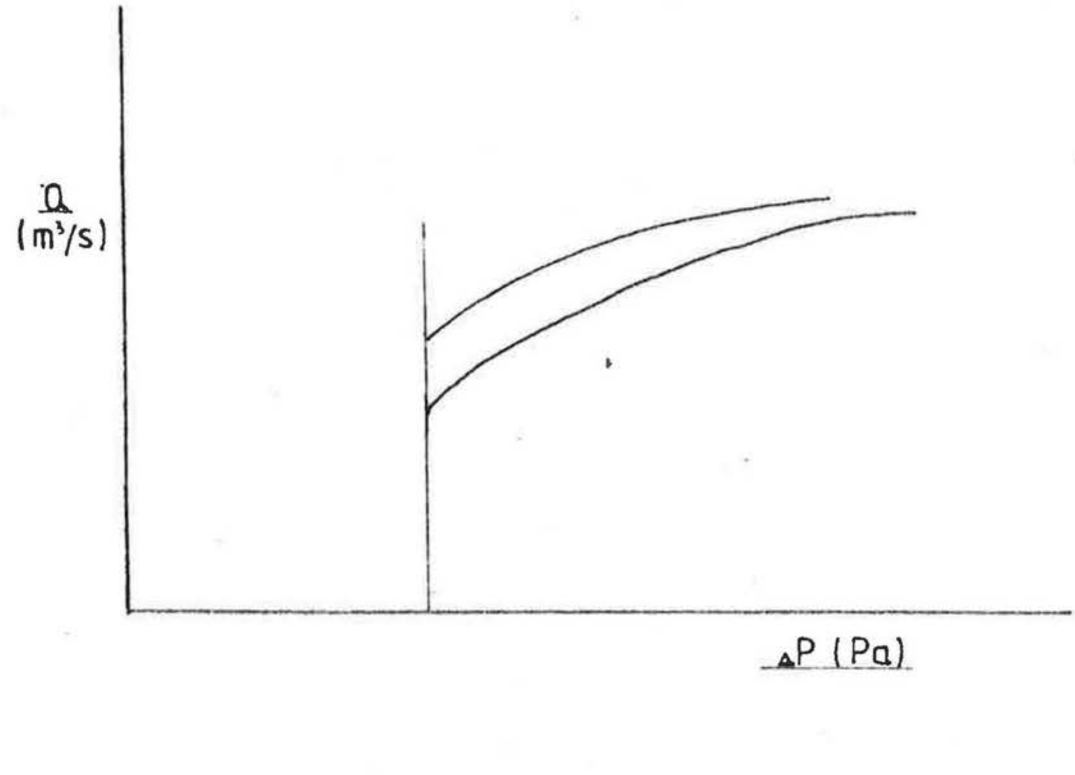


Fig 5 Wind patterns over cubes

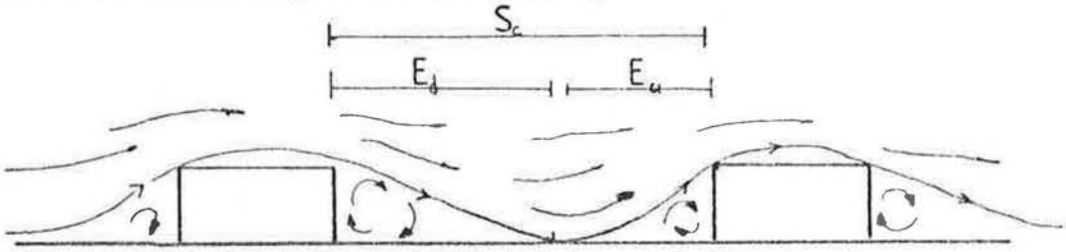
Key
E_u = upstream seperation distance

E_d = downsteam ——"——

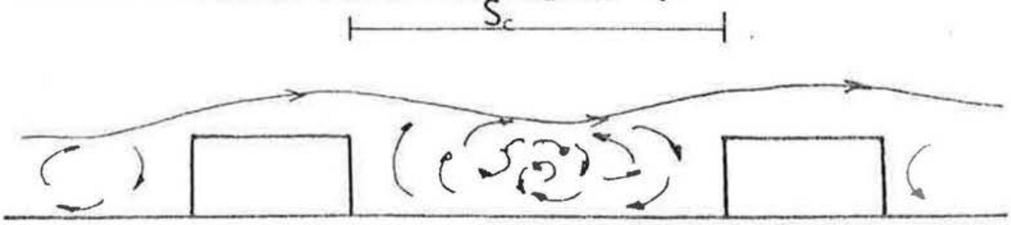
E_v = maximum size of gap for the existence of a stable vortex

$E_t = E_u + E_d$

i Isolated roughness flow $S_c > E_t$



ii Wake interference flow $E_u < S_c < E_t$



iii Skimming flow $S_c \leq E_v$

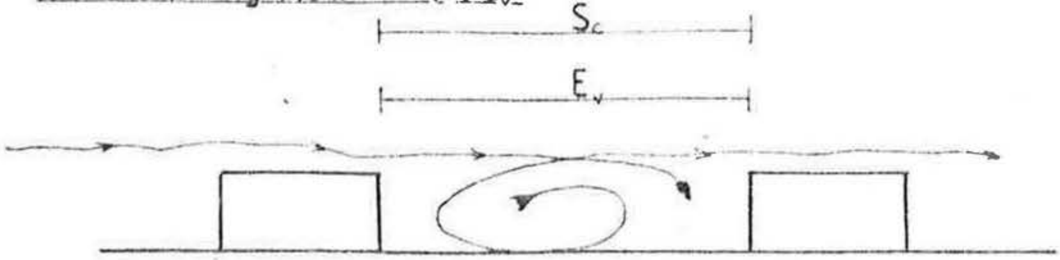
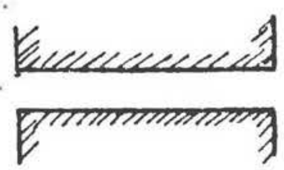
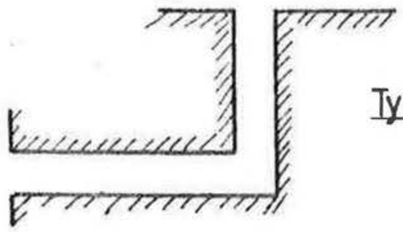


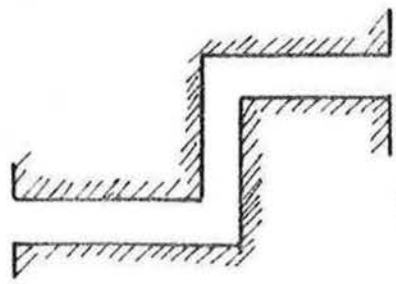
Fig 6 Crack-types



Type 1 Straight through

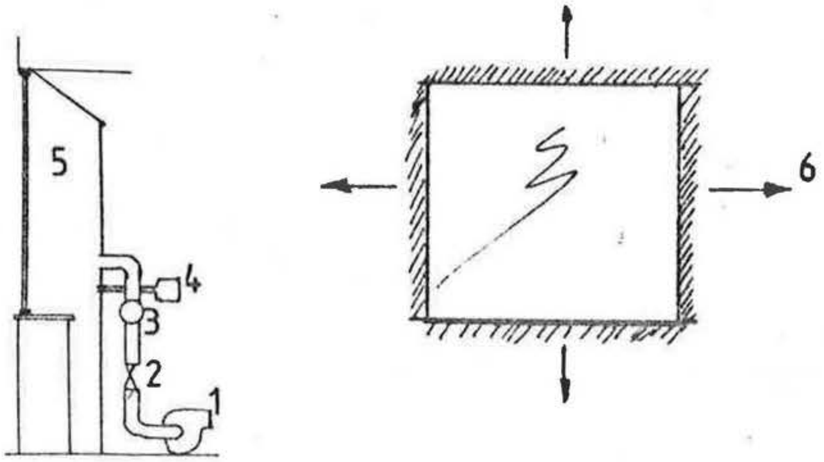


Type 2 Single bend



Type 2 Double bend

Fig 7 Pressure test apparutus



1 Fan

2 Damper

3 Flow-meter

4 Manometer

5 Air-tight test chamber

6 Lateral leakage to unpressurised areas

Fig. 8 Strutting of the tent

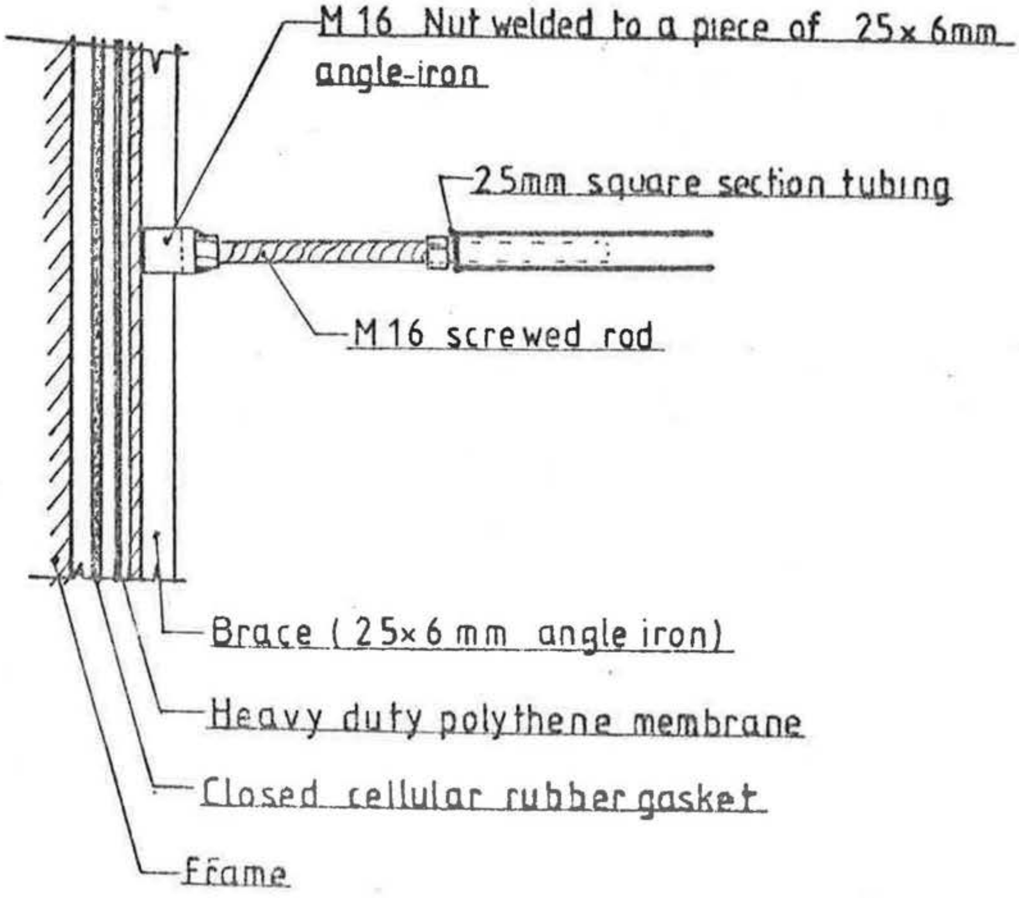


Fig.9 Duct/Tent transition piece

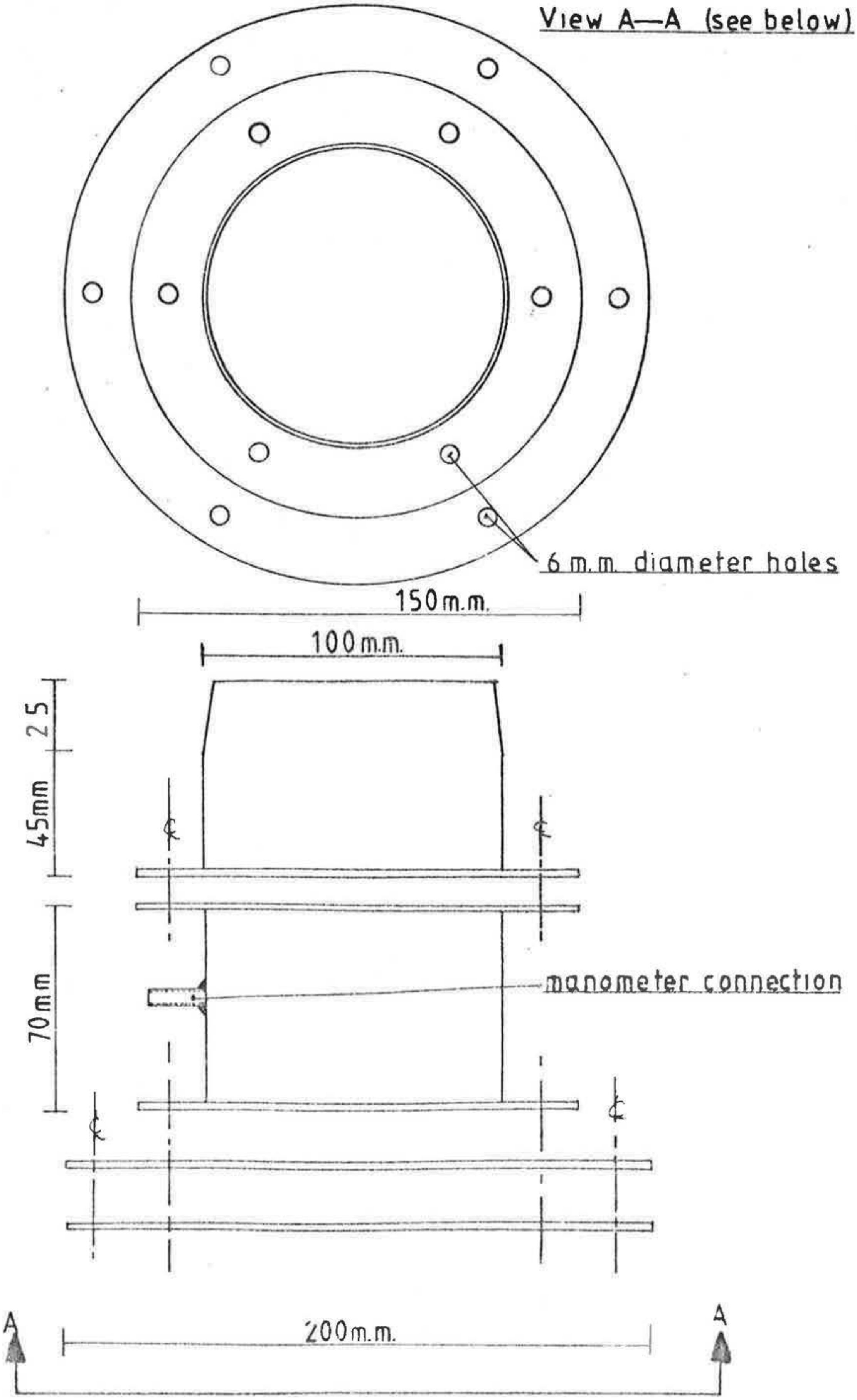
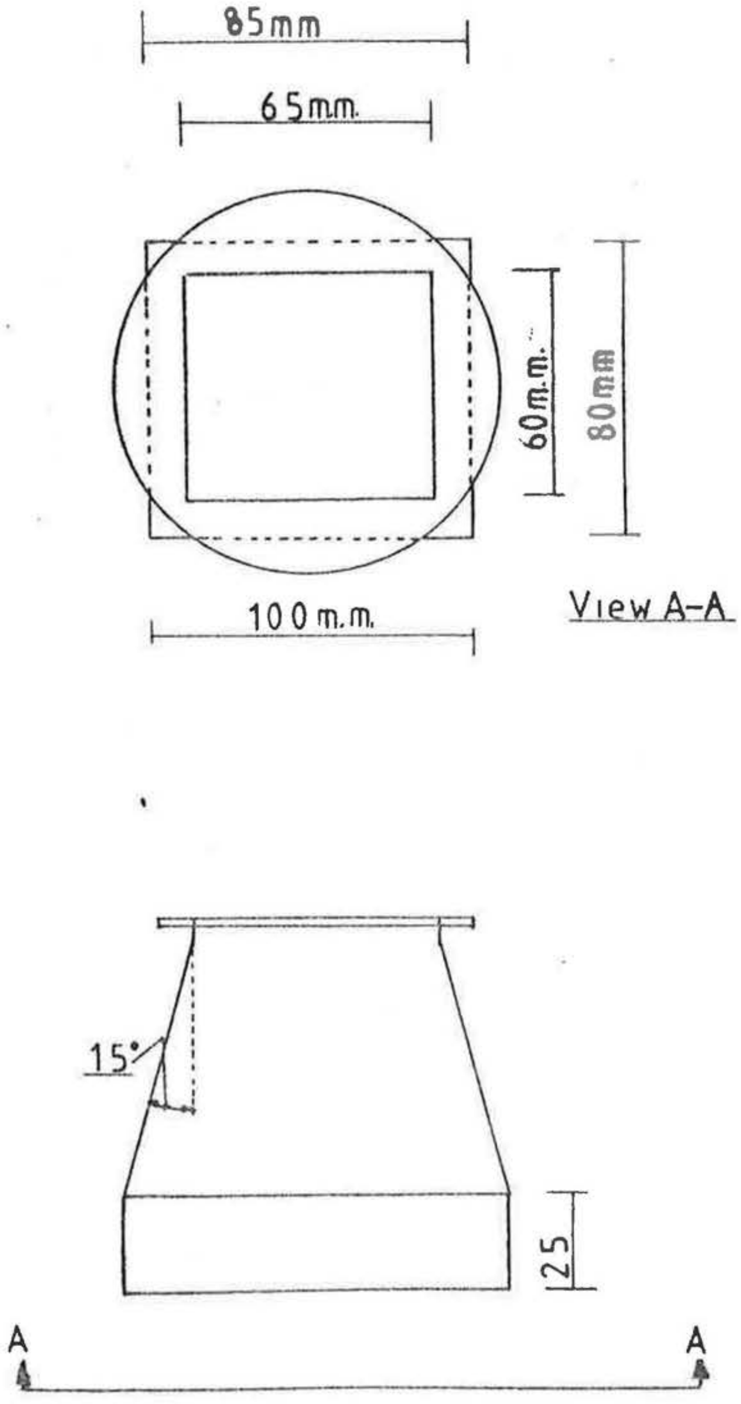
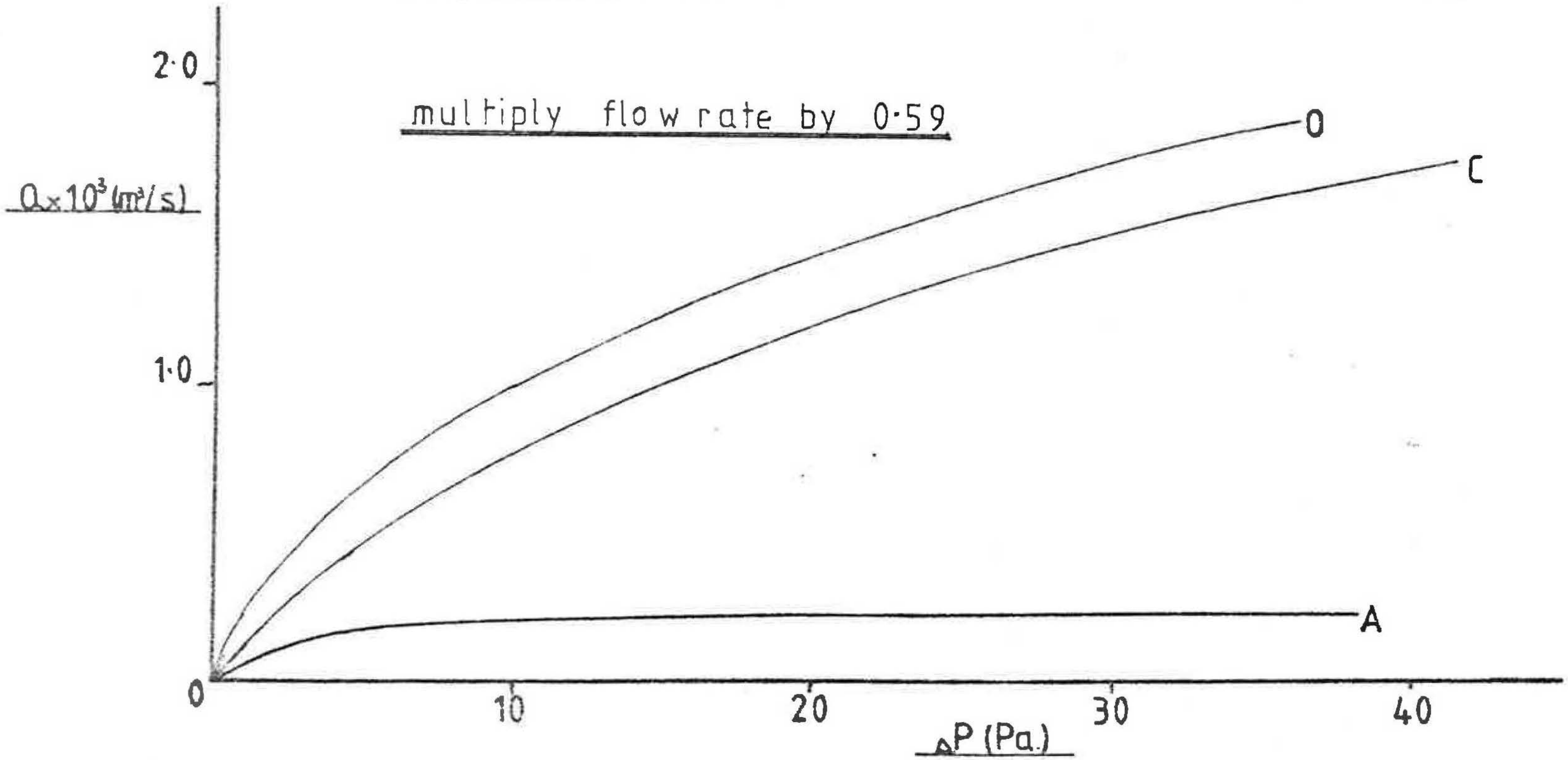


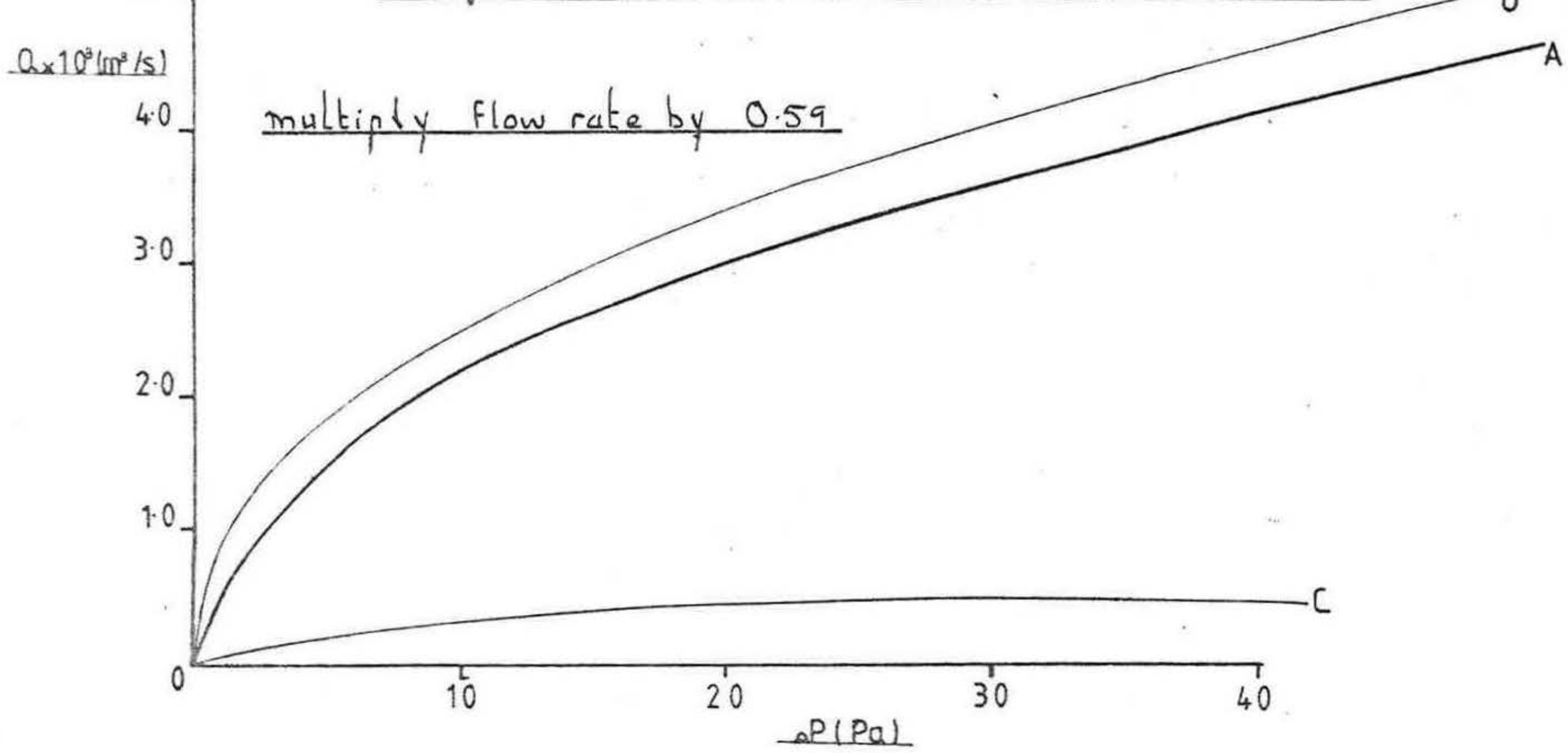
Fig.10 Fan Duct transition piece



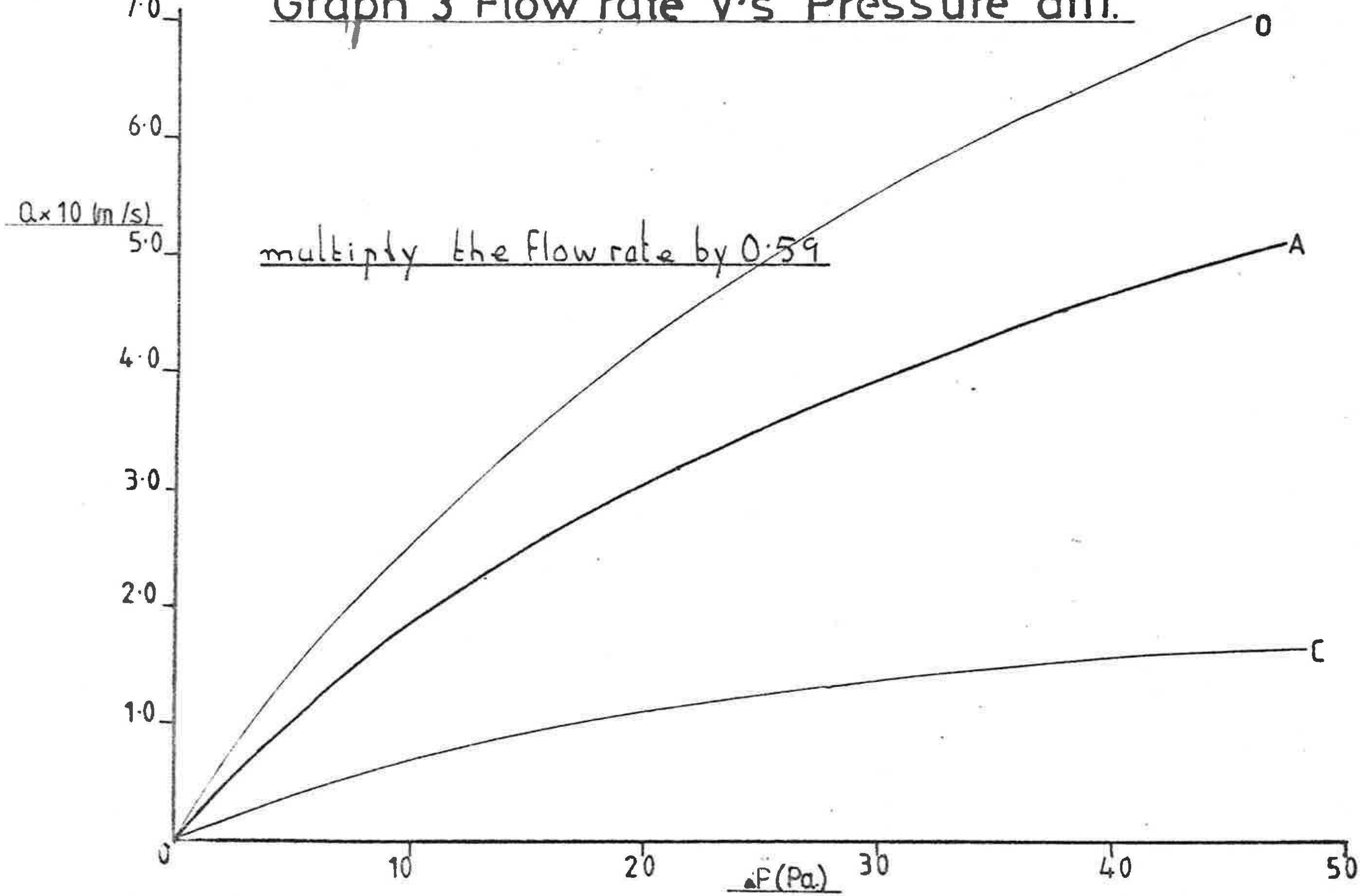
Graph 1 Flow rate V's Pressure diff.



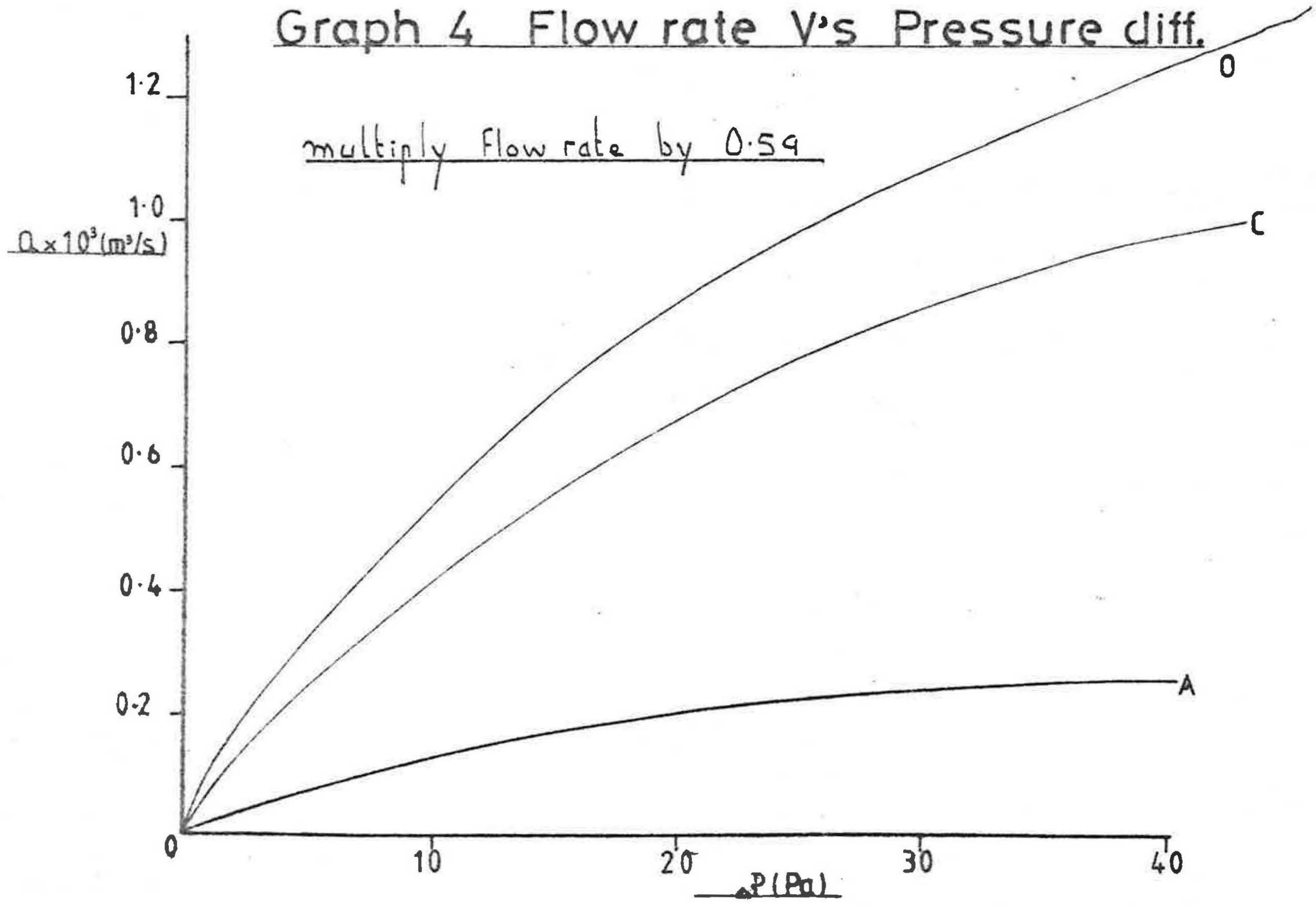
Graph 2 Flow rate V's Pressure diff.

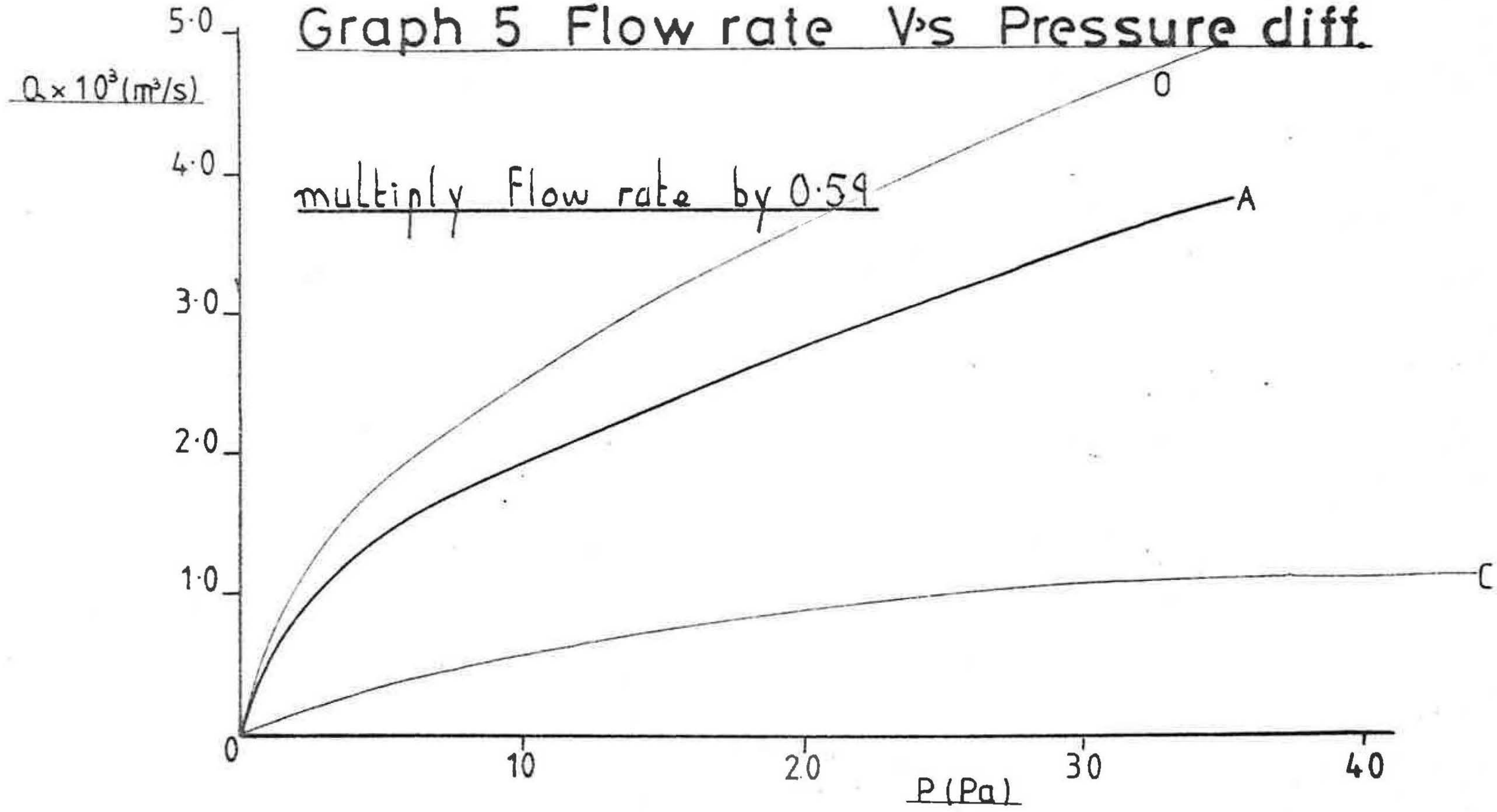


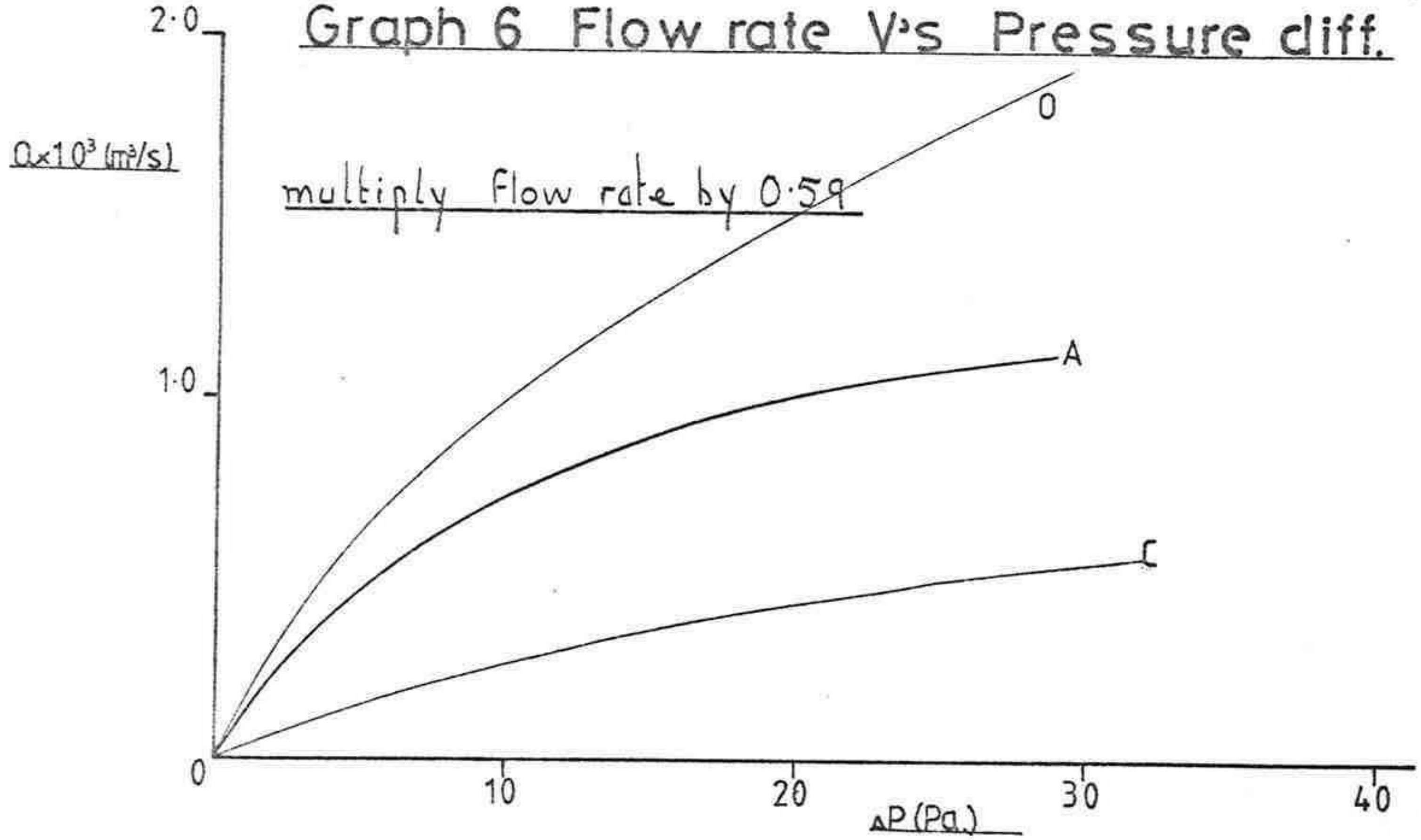
Graph 3 Flow rate V's Pressure diff.

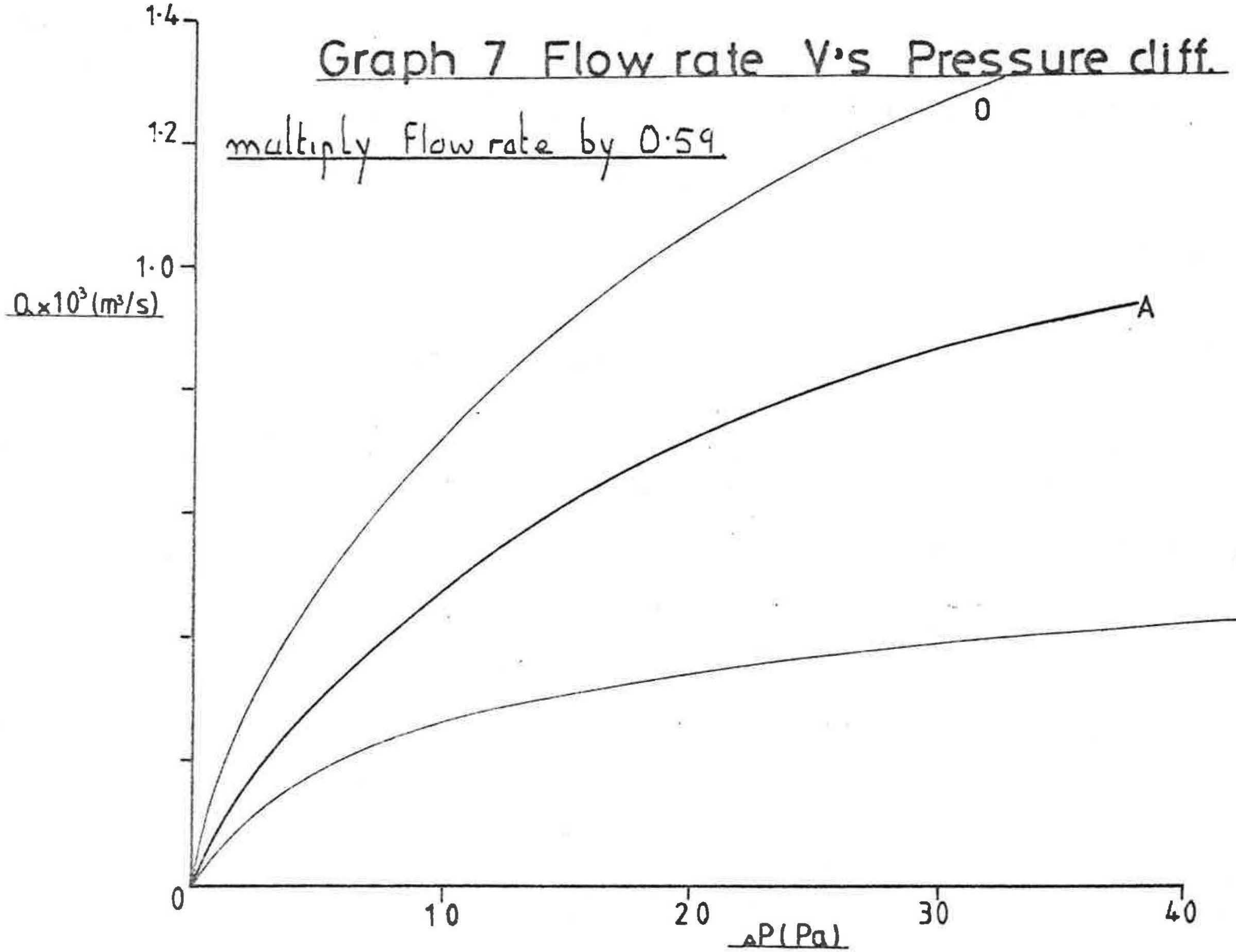


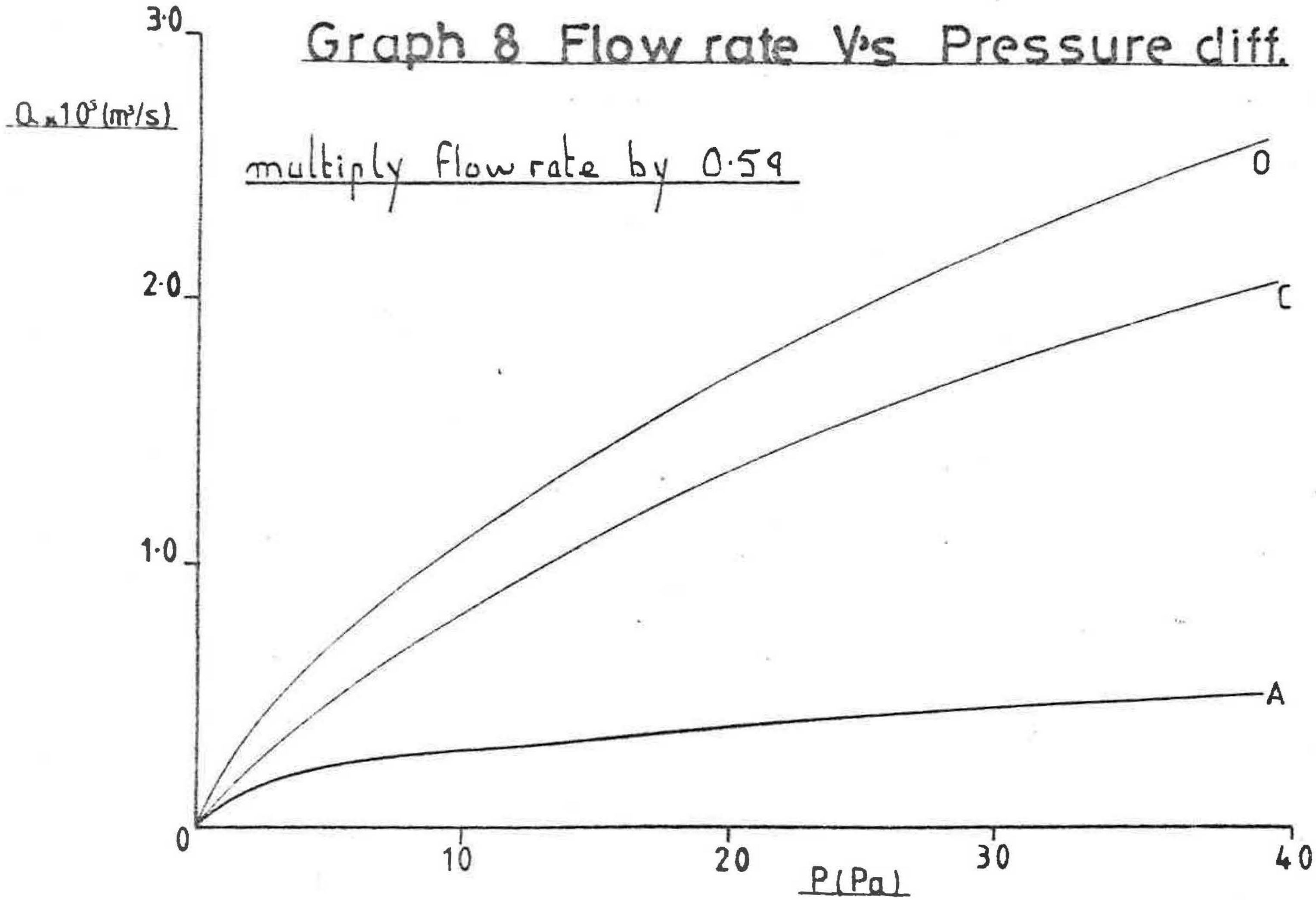
Graph 4 Flow rate V's Pressure diff.



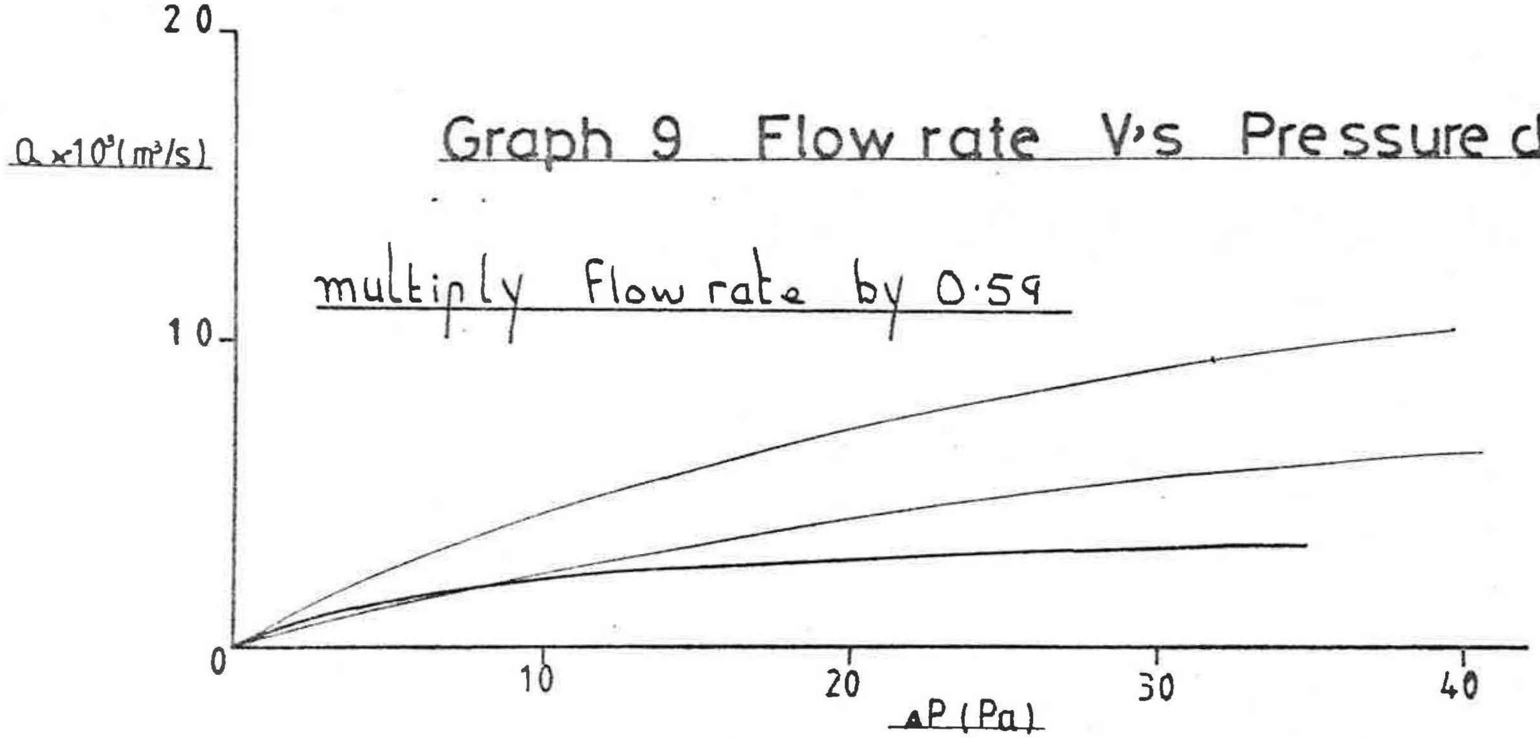

Graph 5 Flow rate V's Pressure diff.
multiply Flow rate by 0.59
Q × 10³ (m³/s)
5.0
4.0
3.0
2.0
1.0
0
10
20
30
40
P (Pa)
O
A
C


Graph 6 Flow rate V's Pressure diff.
multiply flow rate by 0·59
Q×10³ (m³/s)
2·0
1·0
0
10
20
30
40
ΔP (Pa.)
O
A
C


Graph 7 Flow rate V's Pressure diff.
multiply Flow rate by 0·59
1·4
1·2
1·0
Q×10³ (m³/s)
0
10
20
30
40
ΔP (Pa)
O
A
C

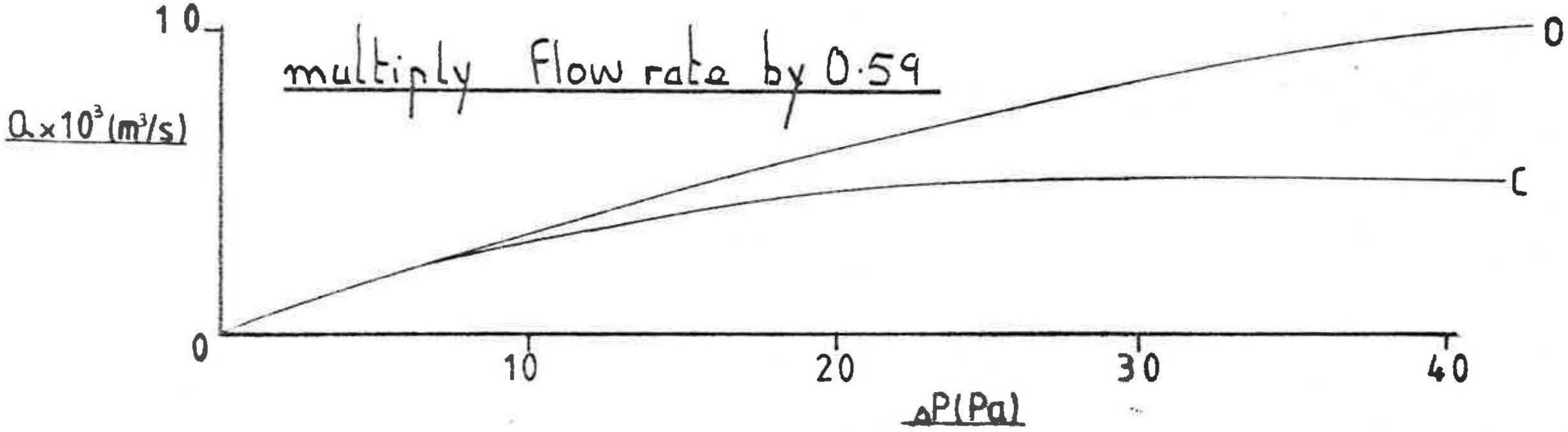


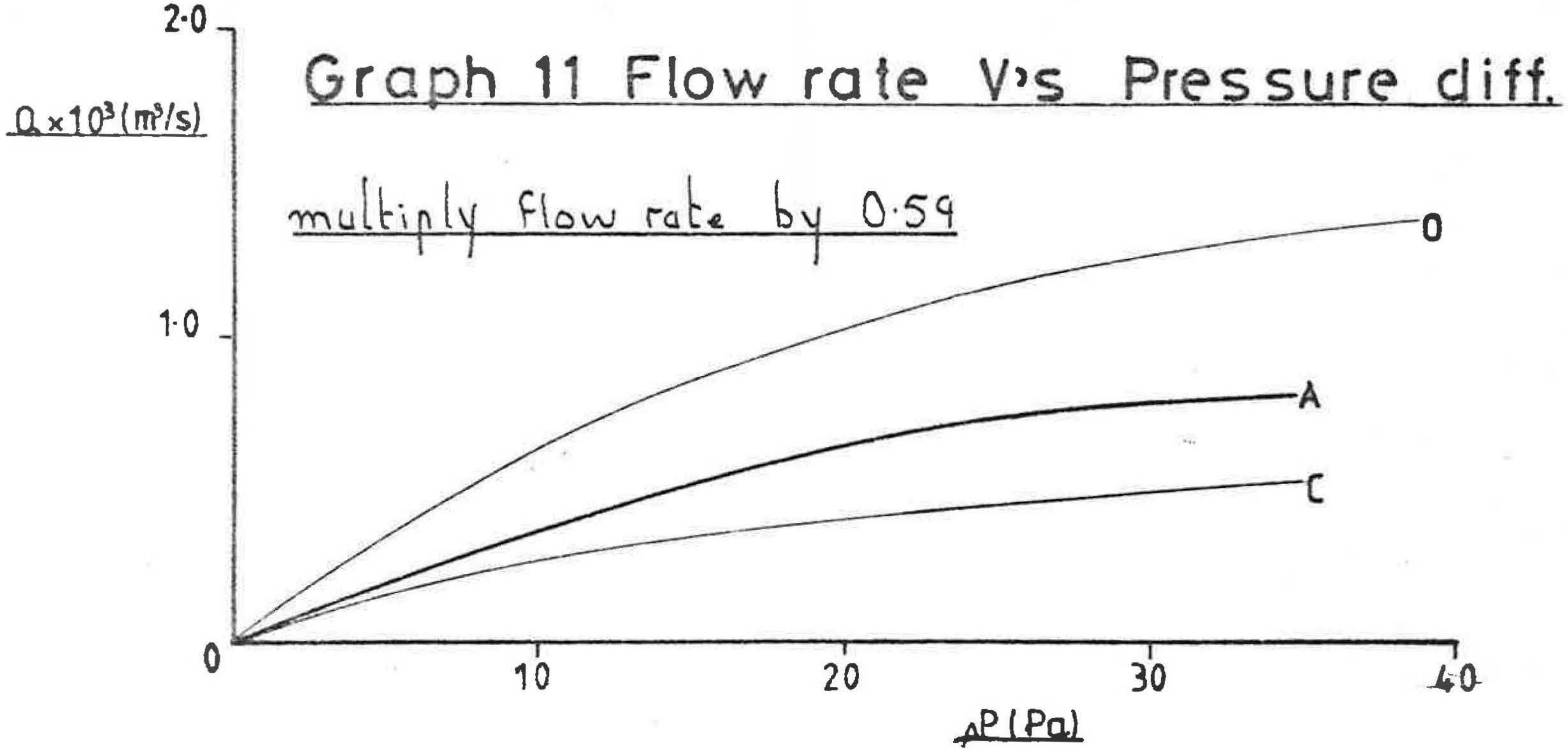
Graph 8 Flow rate V's Pressure diff.

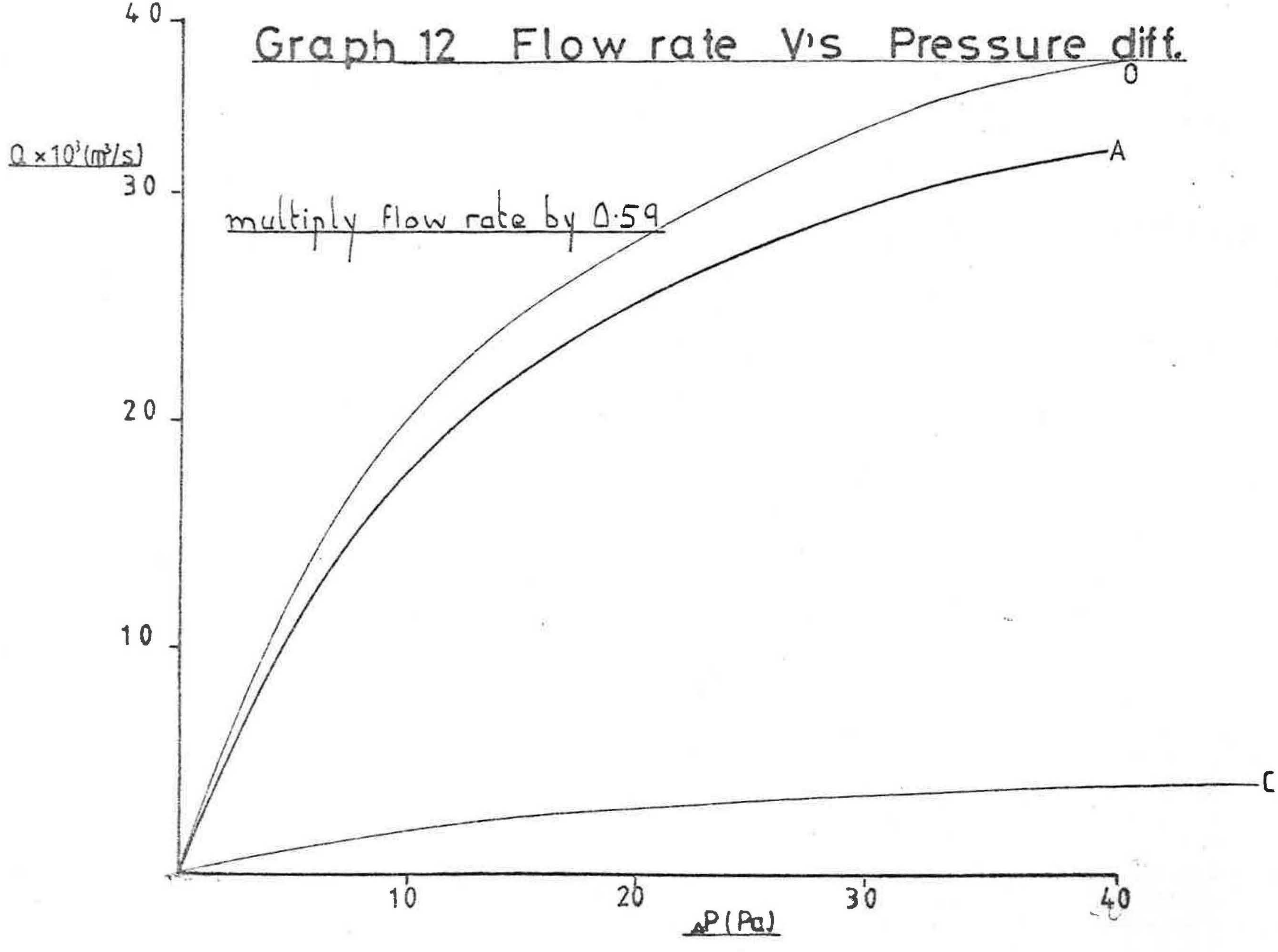


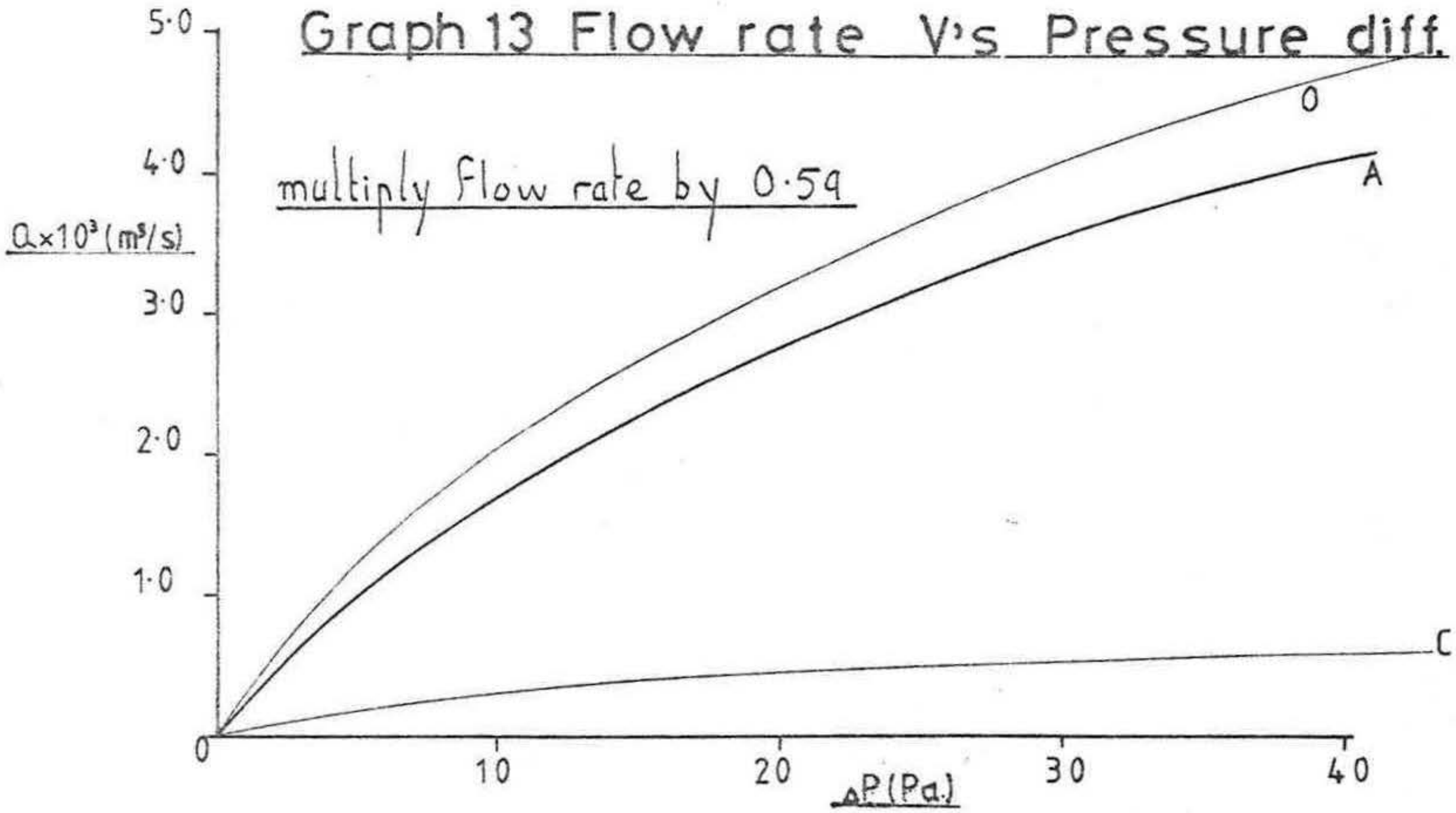
Graph 9 Flow rate V's Pressure diff.

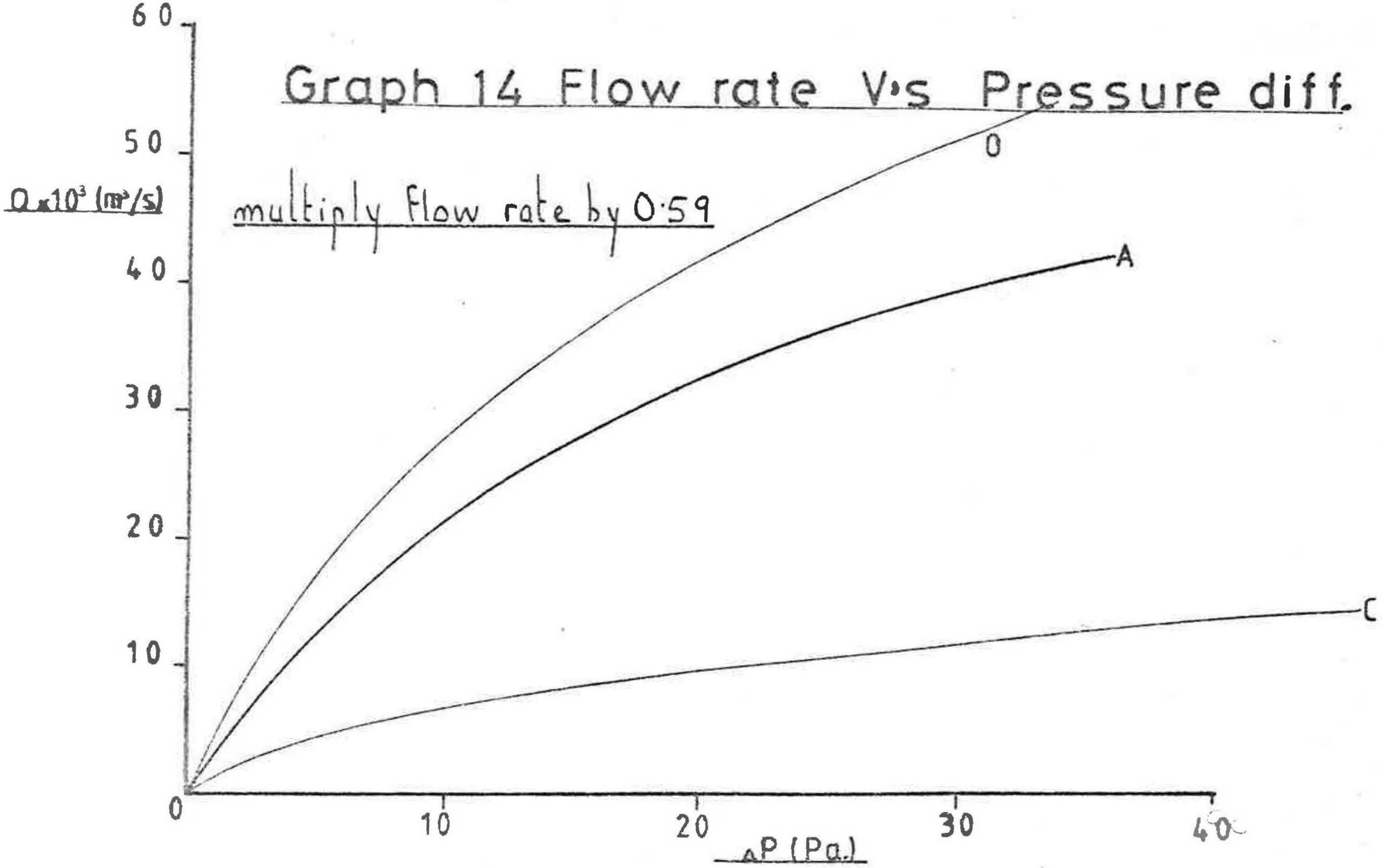
Graph 10 Flow rate V's Pressure diff.



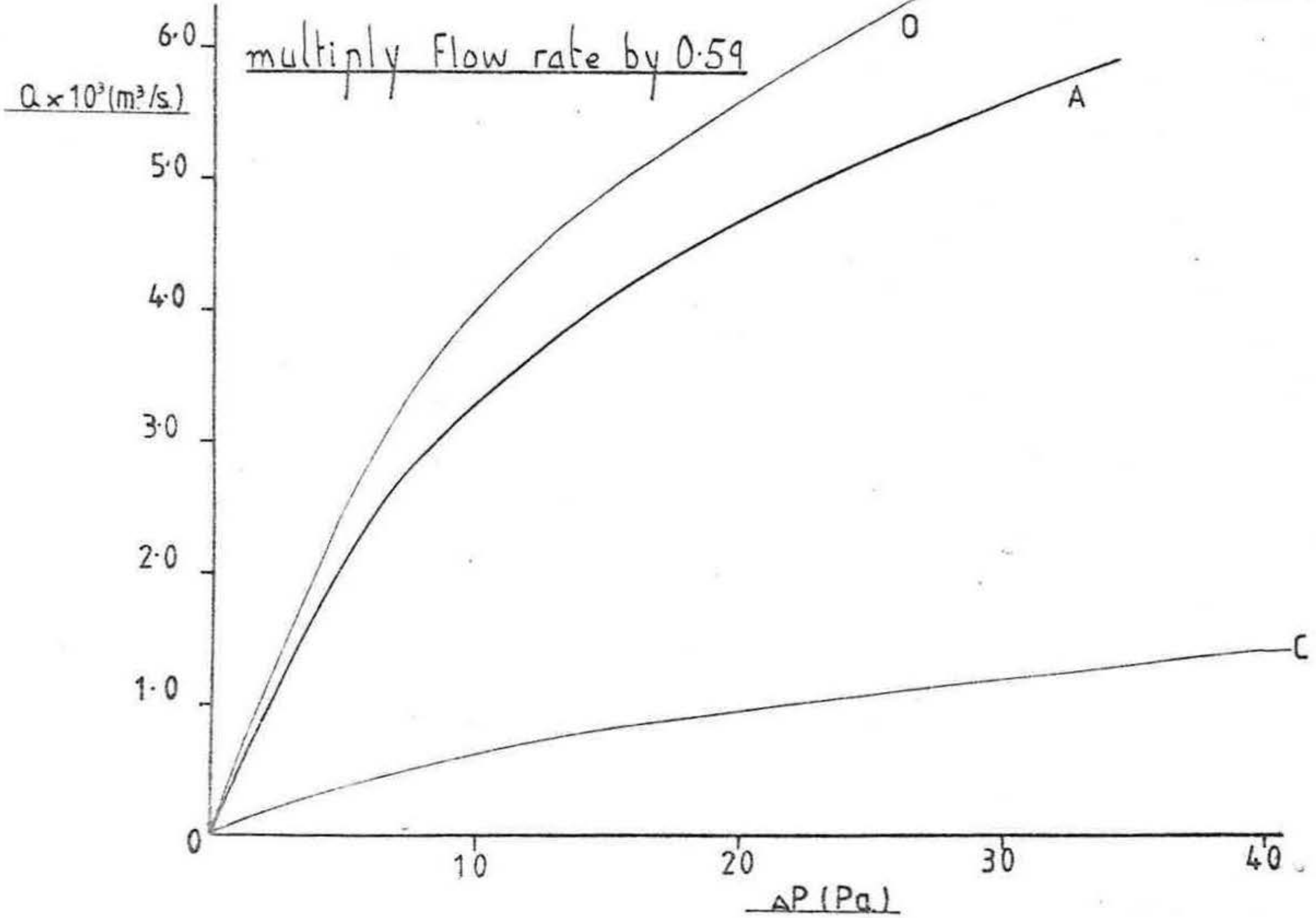

Graph 11 Flow rate V's Pressure diff.
multiply flow rate by 0.59
Q x 10³ (m³/s)
2·0
1·0
0
10
20
30
40
ΔP (Pa)
O
A
C


Graph 12 Flow rate V's Pressure diff.
Q × 10³ (m³/s)
multiply flow rate by 0·59
40
30
20
10
0
A
C
10
20
30
40
ΔP (Pa)

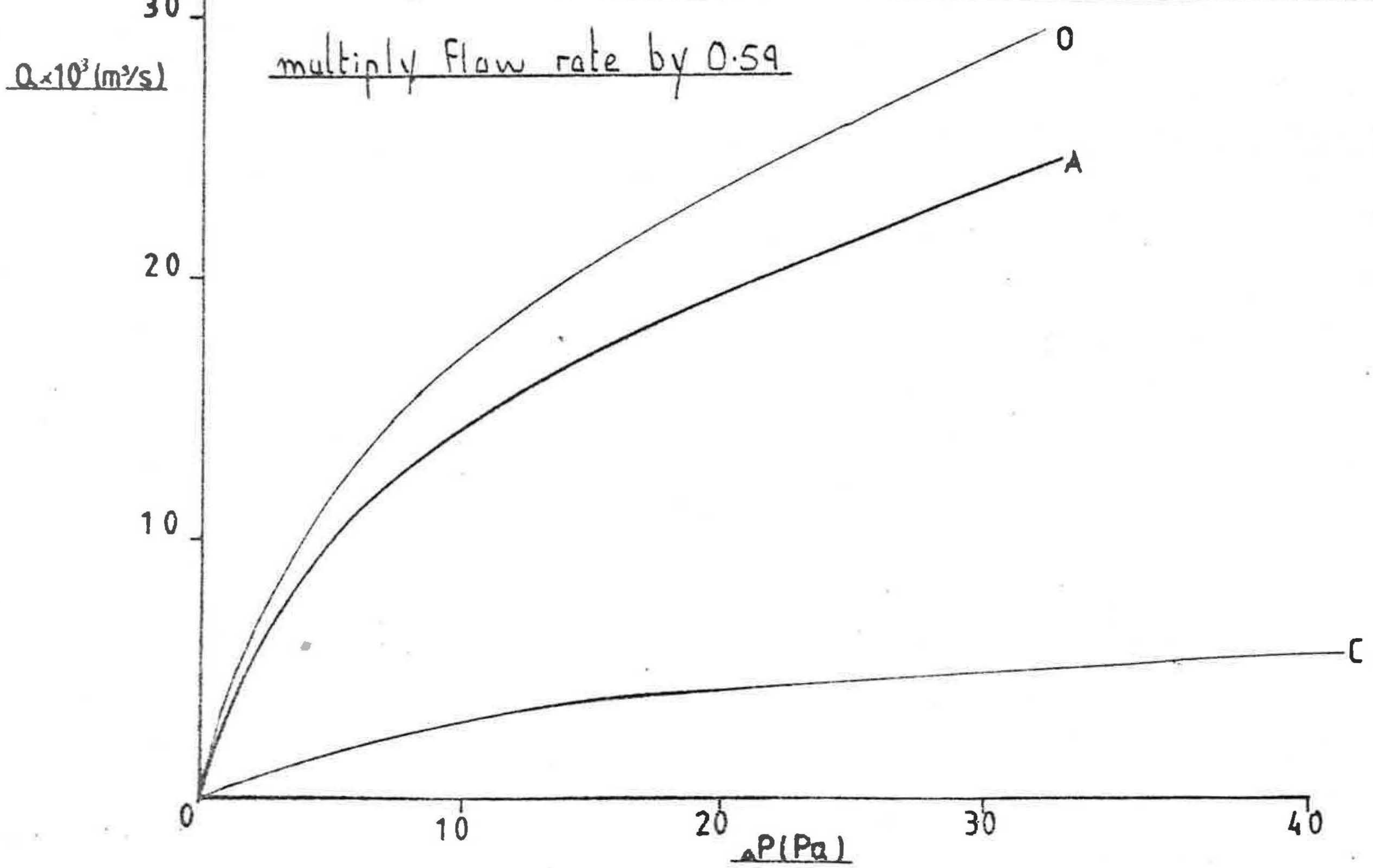

Graph 13 Flow rate V's Pressure diff.
multiply Flow rate by 0.59
Q×10³ (m³/s)
5·0
4·0
3·0
2·0
1·0
0
10
20
30
40
ΔP (Pa.)
O
A
C

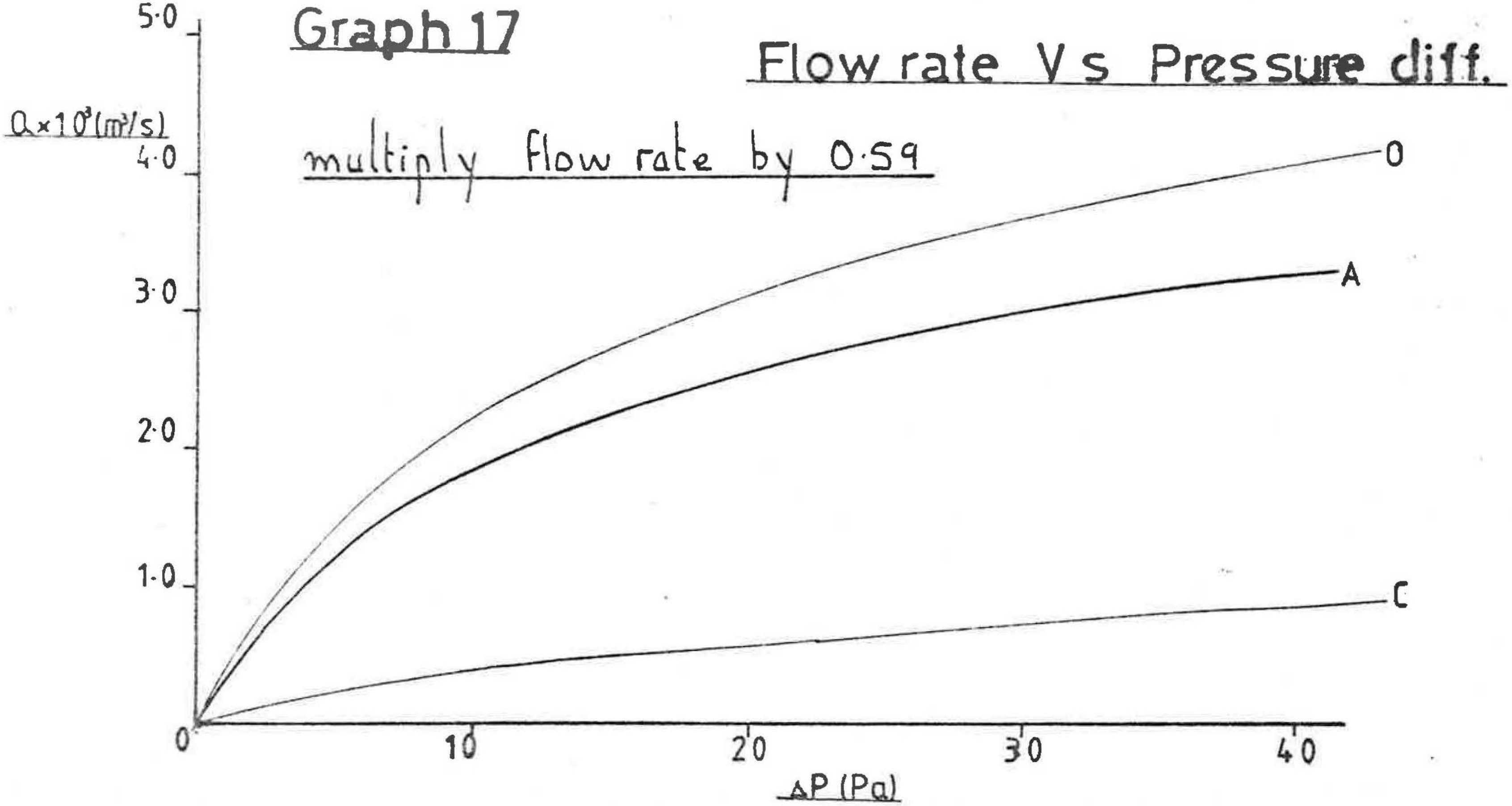

Graph 14 Flow rate V's Pressure diff.
multiply flow rate by 0·59
Q x10³ (m³/s)
60
50
40
30
20
10
0
10
20
30
40
ΔP (Pa.)
0
A
C

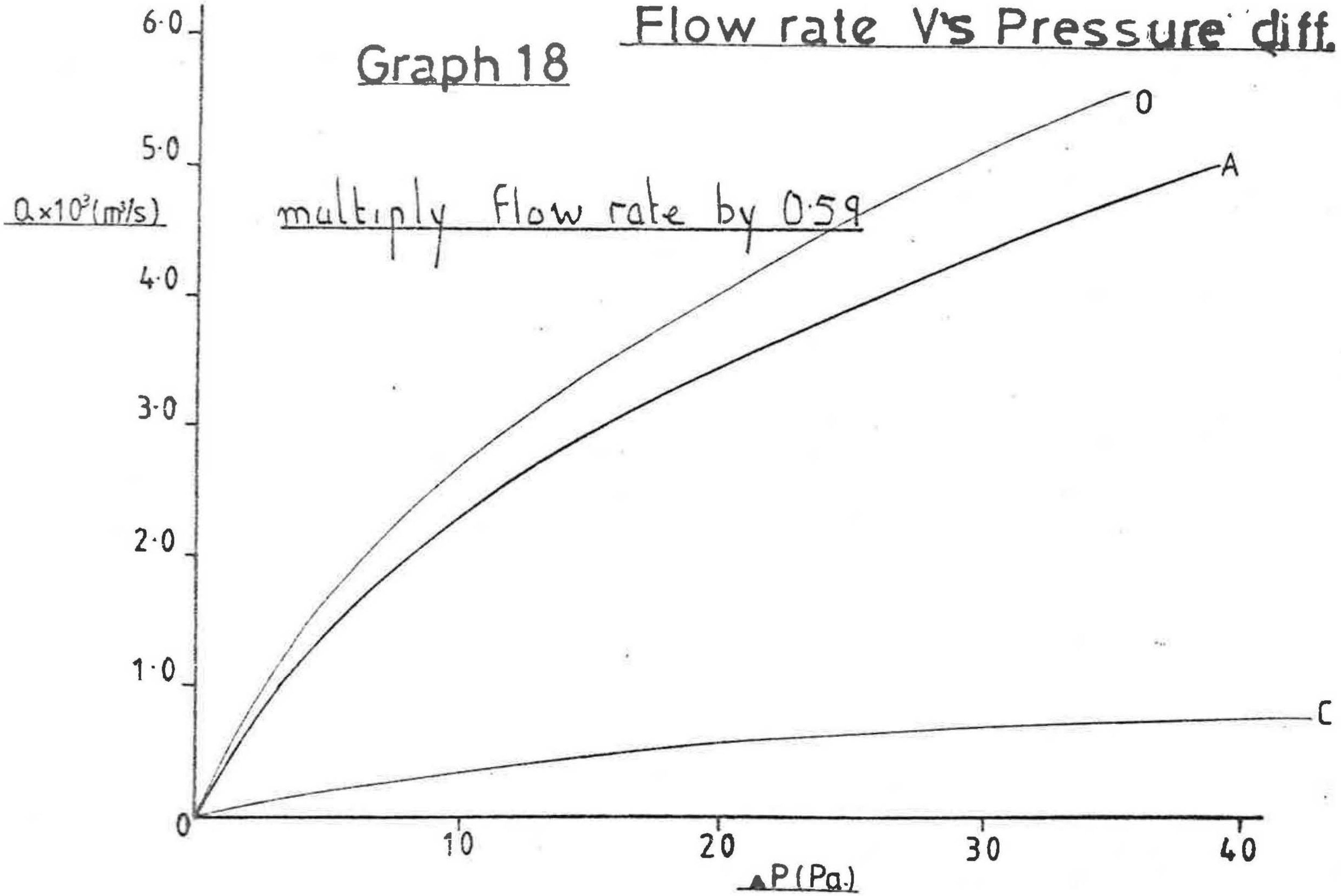
Graph 15 Flow rate V's Pressure diff.



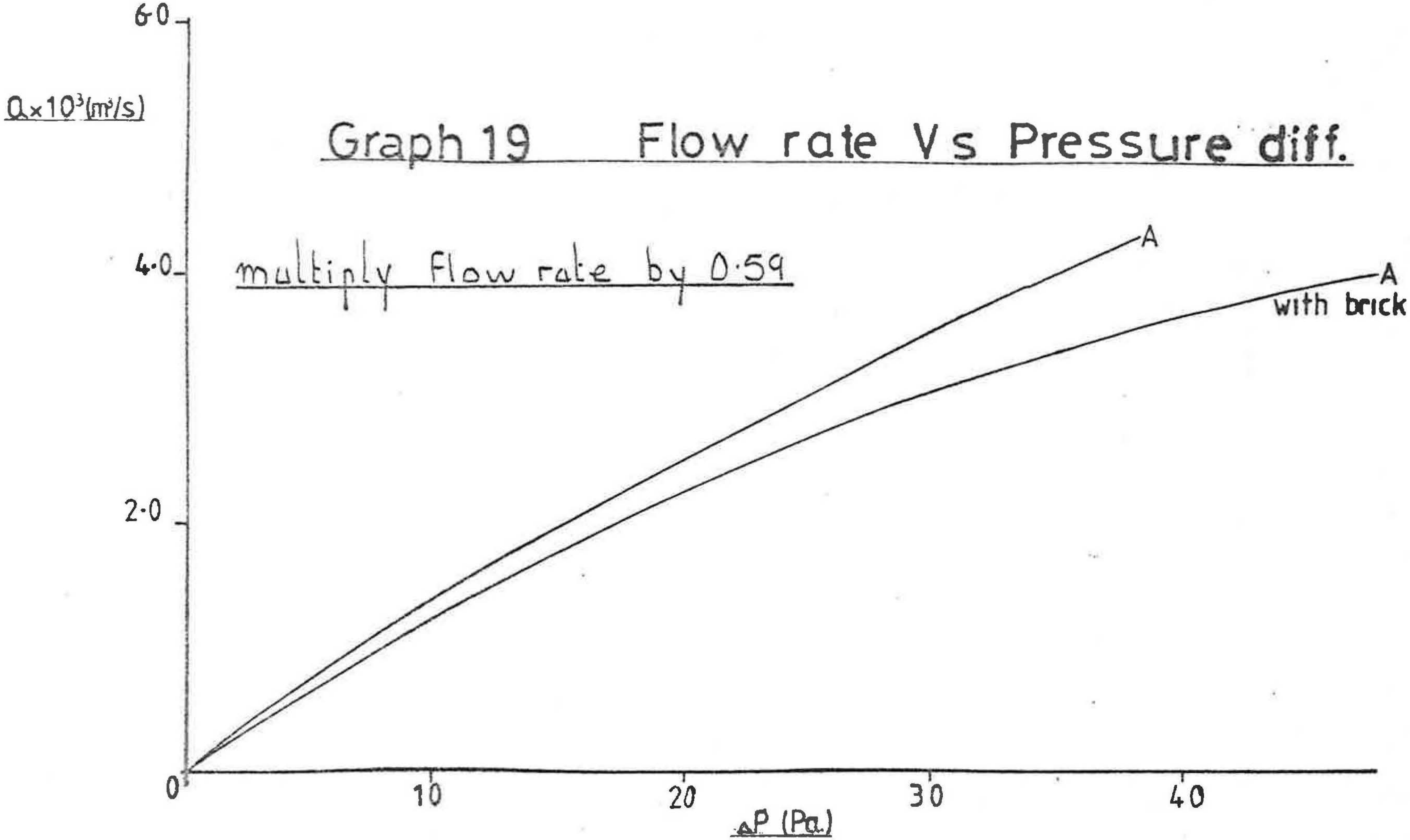
Graph 16 Flow rate V's Pressure diff.



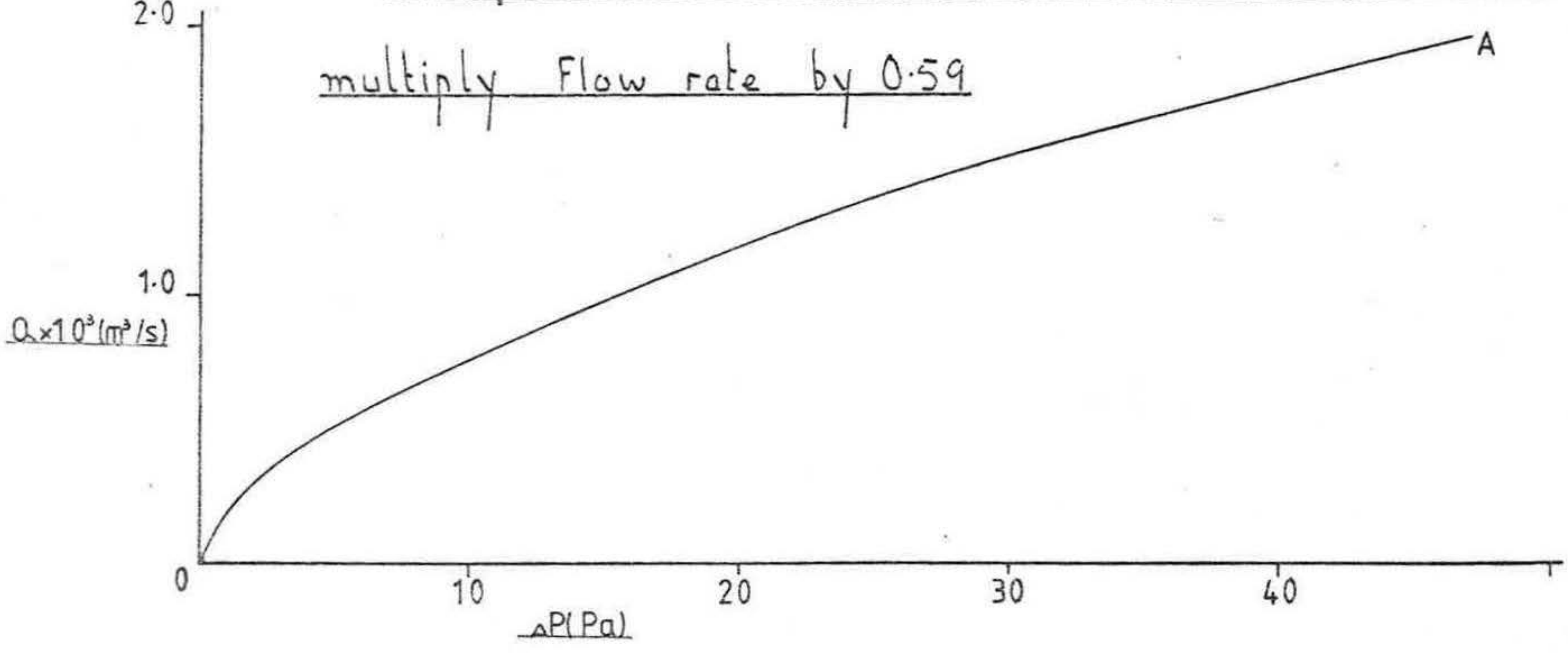

Graph 17
Flow rate Vs Pressure diff.
multiply flow rate by 0·59
Q×10³(m³/s)
5·0
4·0
3·0
2·0
1·0
0
10
20
30
40
ΔP (Pa)
O
A
C


Graph 18
Flow rate V's Pressure diff.
multiply flow rate by 0·59
Q×10³ (m³/s)
6·0
5·0
4·0
3·0
2·0
1·0
0
10
20
30
40
ΔP (Pa)
O
A
C

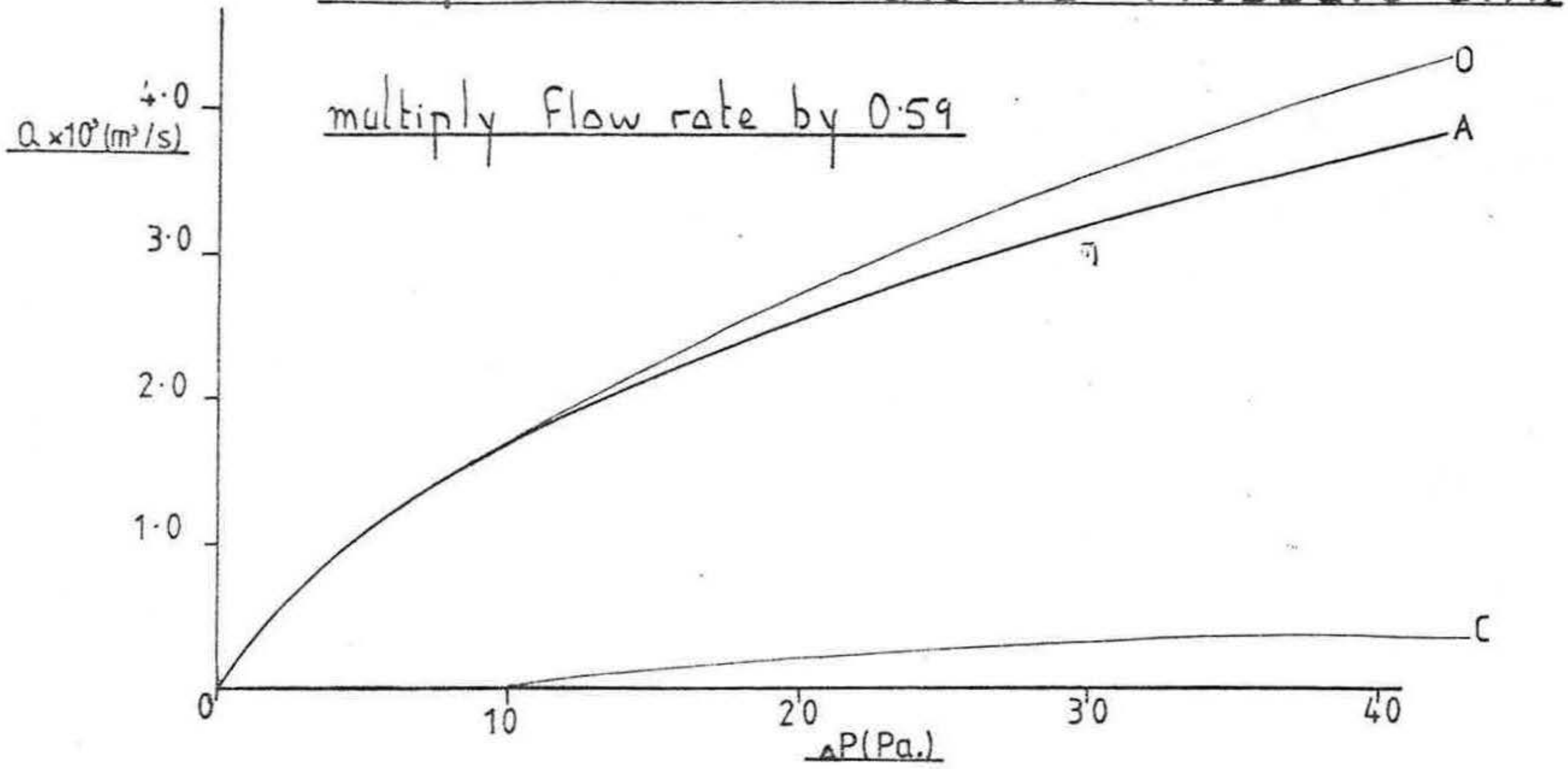
Graph 19 Flow rate Vs Pressure diff.



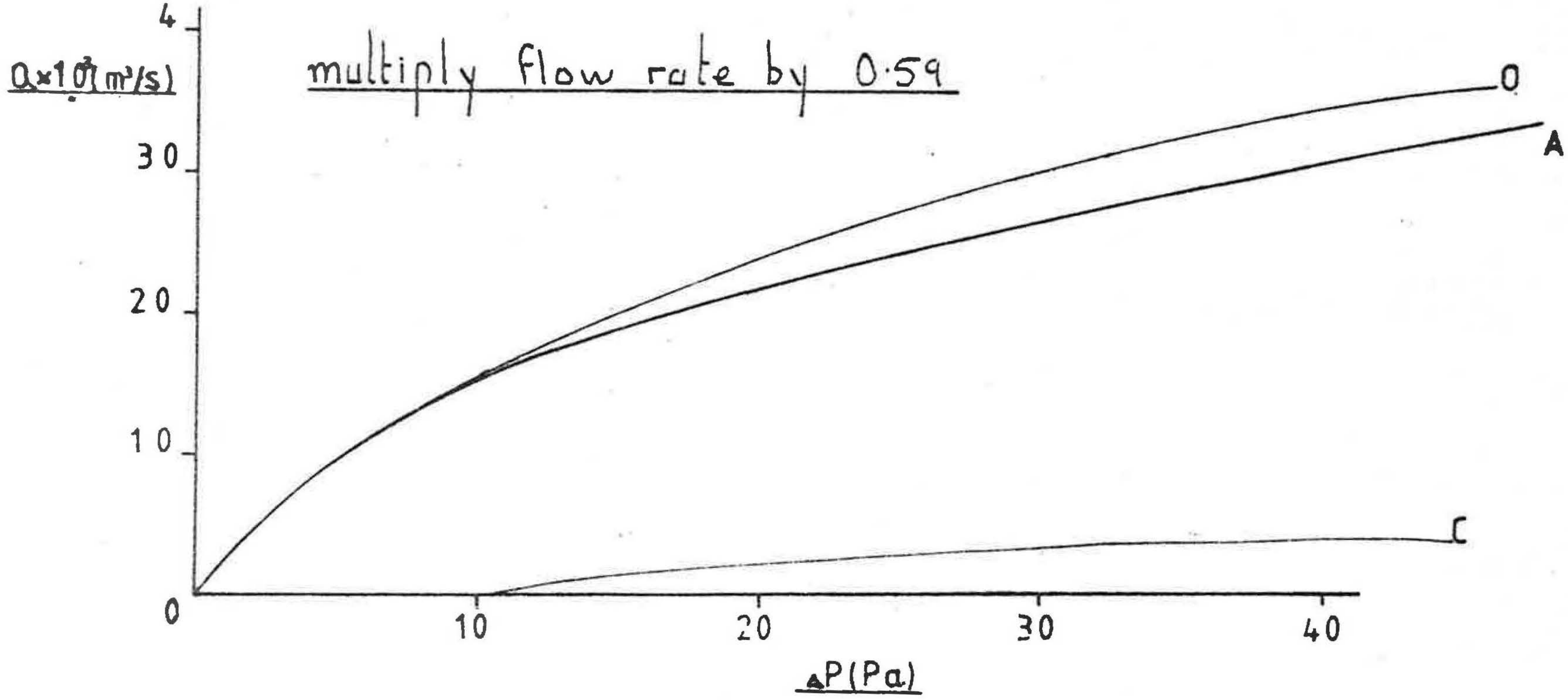
Graph 20 Flow rate Vs Pressure diff.

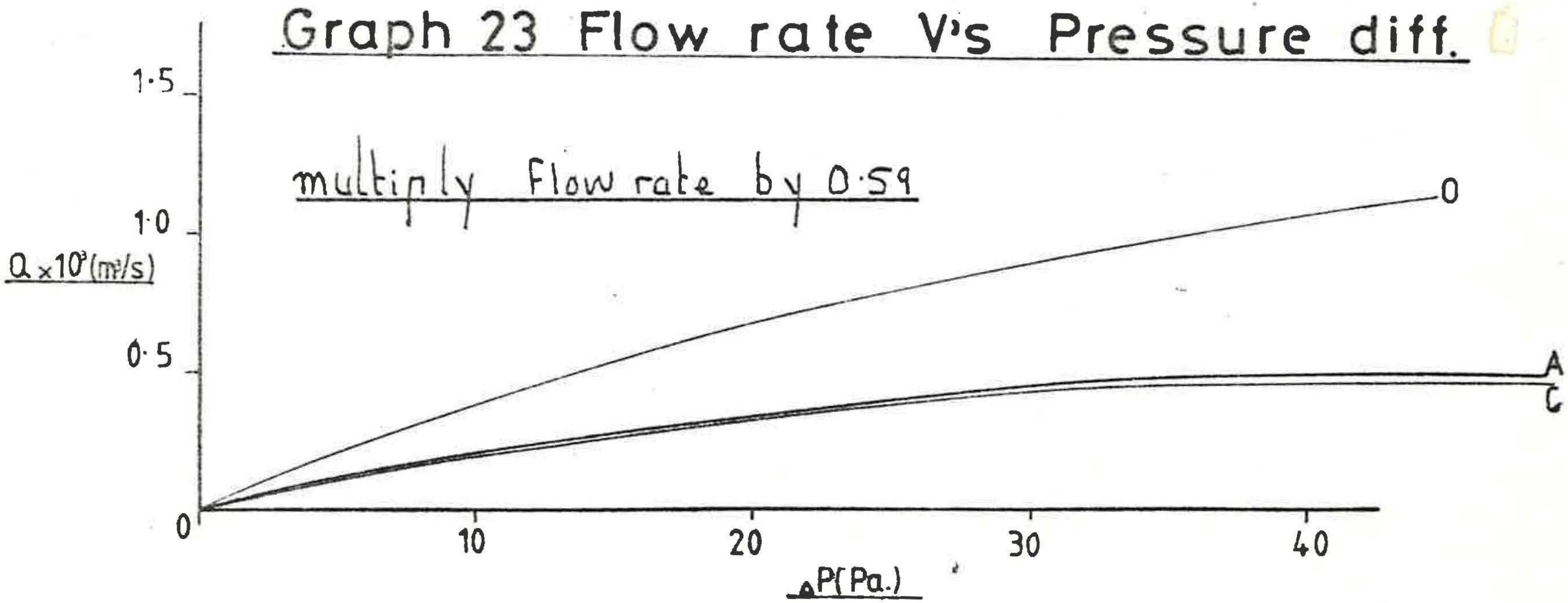


Graph 21 Flow rate V's Pressure diff.



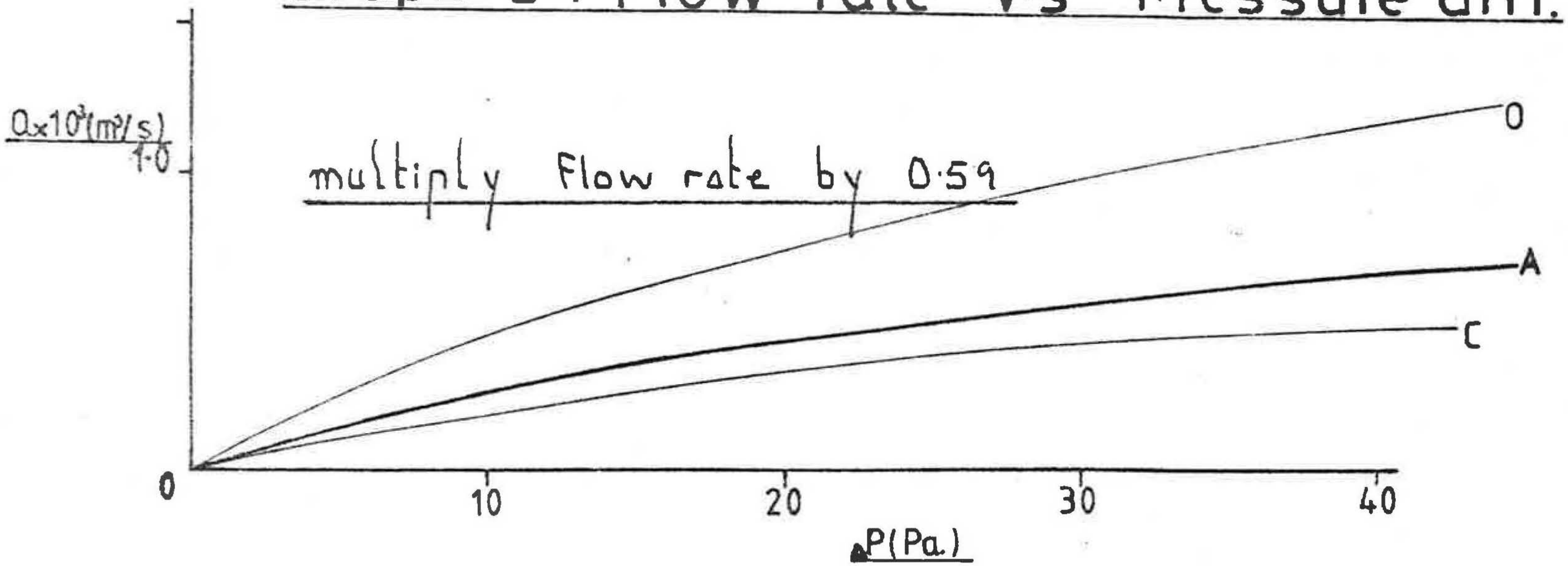
Graph 22 Flow rate V's Pressure diff.





Graph 23 Flow rate V's Pressure diff.

Graph 24 Flow rate V's Pressure diff.



Graph 25. Flow rate V's Pressure diff.

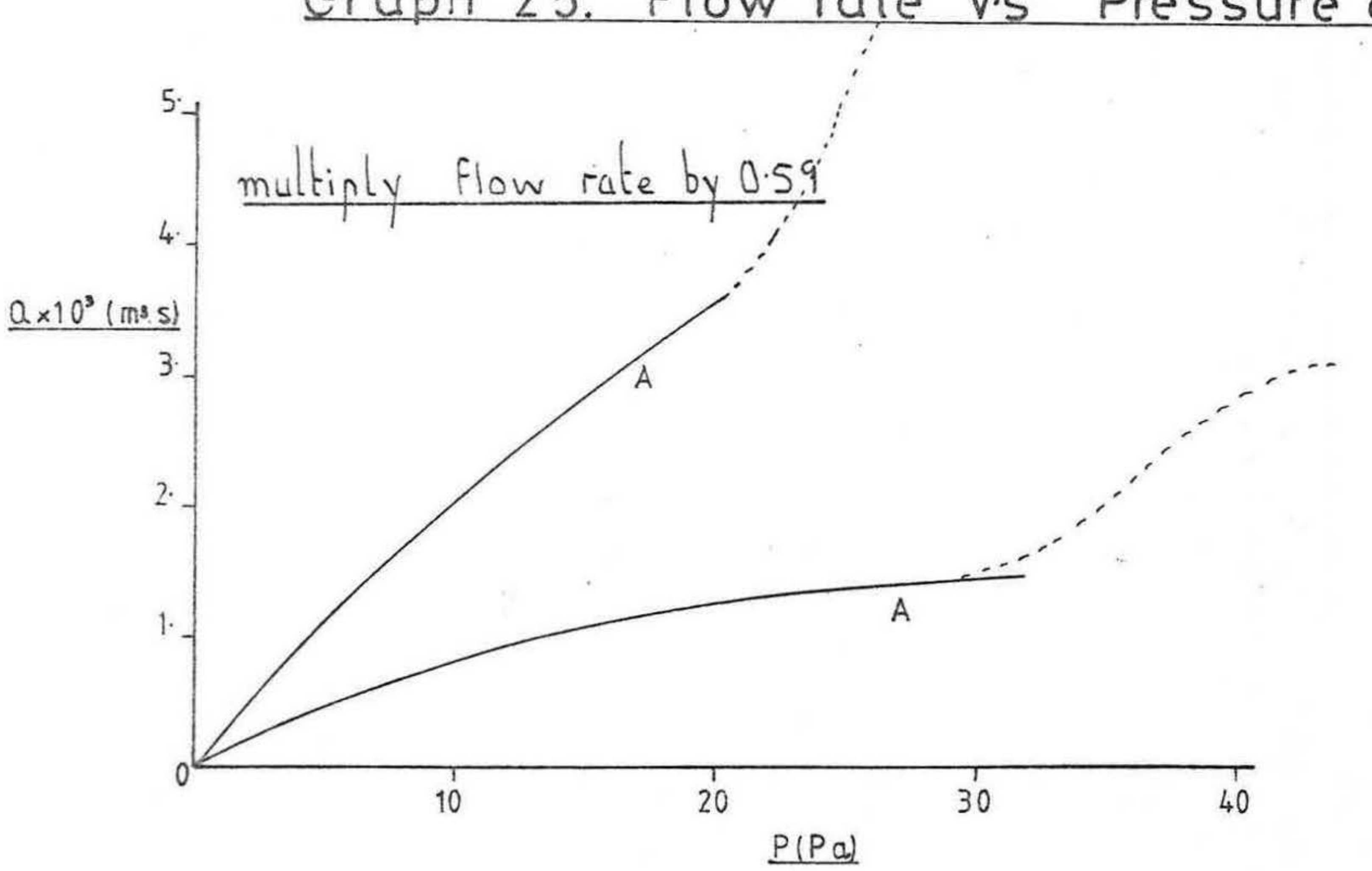


Table I

Results of ventilation rate test on test chamber using tracer gas

Run	t(mins)	C(t)	ln C(t)	gradient
1	0.25	5.6	1.72	
	1.0	3.9	1.36	
	2.0	2.6	0.95	
	3.5	1.6	0.47	
	5.0	1.0	0.0	
				-0.37
2	0.25	10.4	2.34	
	1.0	7.75	2.05	
	2.0	4.9	1.59	
	3.5	2.55	0.94	
	5.0	1.55	0.44	
				-0.41
3	0.75	13.4	2.59	
	1.0	11.3	2.43	
	2.0	7.75	2.05	
	3.0	4.9	1.59	
	5.0	2.2	0.79	
	7.0	1.0	0.0	
				-0.42
4	0.25	9.6	2.26	
	0.75	7.8	2.05	
	2.0	4.6	1.53	
	3.0	3.0	1.1	
	5.0	1.6	0.47	
	6.0	1.2	0.18	
				-0.36

Table I - continued ...

Table I - continued

5	0.29	10.0	2.30	
	1.0	7.5	2.01	
	2.0	4.8	1.57	
	3.5	2.7	0.79	
	5.0	1.65	0.50	
	6.5	1.0	0.0	
				-0.37
6	0.25	6.8	1.92	
	1.0	4.9	1.59	
	2.0	3.0	1.10	
	3.5	1.8	0.59	
	5.0	1.0	0.0	
				-0.4
7	1.6	13.5	2.6	
	2.0	11.6	2.45	
	3.0	7.9	2.07	
	4.0	4.1	1.41	
	5.0	3.2	1.16	
	6.0	1.9	0.64	
	8.0	1.0	0.0	
				-0.42

mean ventilation rate = 0.39 min^{-1} (gradient)
standard deviation = 0.02 min^{-1}

N.B.

In the above analysis the coefficient of determination and coefficient of correlation were both very close to equalling one. The standard error of estimate less than 0.075.

Table II

Measurement of ventilation of test chamber using a flowmeter

Diameter of flowmeter	=	0.112 m.
Area of flowmeter	=	$9.8520.10^{-3}$ m^2
Velocity through flowmeter	=	0.41 $m.s^{-1}$
Volume flowrate	=	0.2423 m^3. min^{-1}
Dimensions of test chamber	=	0.722 x 0.819 x 0.917
Volume of test chamber	=	0.5422 m^3
Ventilation rate	=	0.44 hr^{-1}

Table IV Joints Open, +ve. pressure

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
4	6.0	0.7	7.89×10^{-3}
	12.0	1.1	10.84 "
	22.0	1.4	14.28 "
	36.0	1.8	17.73 "
	42.5	1.9	19.21 "
	51.0	2.1	20.69 "
5	58.0	2.3	22.66×10^{-3}
	41.5	2.0	19.70 "
	32.5	1.7	16.75 "
	22.5	1.5	14.78 "
	15.0	1.1	11.33 "
	10.0	0.9	8.87 "
	7.5	0.7	7.78 "
	4.5	0.5	4.93 "
6	3.5	0.5	5.22×10^{-3}
	7.5	0.8	8.18 "
	10.0	0.9	9.06 "
	14.5	1.2	11.82 "
	22.0	1.4	14.28 "
	31.5	1.7	17.24 "
	42.0	2.0	19.70 "
	55.0	2.3	22.66 "
7	46.0	2.1	20.69×10^{-3}
	35.0	1.8	18.23 "
	24.0	1.5	14.78 "
	14.0	1.2	11.82 "
	10.0	0.9	9.36 "
	5.0	0.6	6.40 "
	2.5	0.5	5.02 "

Results of Test 2

Description; Doorway to room H.6, Pariser building, U.M.I.S.T.

Table V Joints Closed, +ve pressure

multiply Flow rate by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	7.0	0.3	3.74×10^{-3}
	12.5	0.3	3.84 "
	21.0	0.4	4.43 "
	30.5	0.5	4.63 "
	40.0	0.5	4.63 "
	58.5	0.5	4.63 "
2	62.0	0.5	4.63×10^{-3}
	52.5	0.5	4.43 "
	39.5	0.4	4.43 "
	29.0	0.4	4.43 "
	17.5	0.4	4.43 "
	10.0	0.3	3.45 "
	8.0	0.3	3.15 "
3	7.0	0.3	3.45×10^{-3}
	13.5	0.4	4.33 "
	20.5	0.5	4.93 "
	33.0	0.5	4.93 "
	44.0	0.5	4.73 "
	52.5	0.4	4.43 "
	34.0	0.4	4.43 "
	25.0	0.4	4.43 "
	15.0	0.4	3.95 "
	10.5	0.3	3.64 "
	7.0	0.3	3.45 "

Table V Continued ...

Table V Continued

4	7.5	0.4	3.64×10^{-3}
	10.0	0.4	4.14 "
	17.0	0.5	4.93 "
	22.0	0.5	4.83 "
	26.0	0.5	4.83 "
	37.5	0.5	4.93 "
	52.0	0.4	4.33 "

multiply flow rates by 0·59

Table VI Joints Open, +ve. pressure

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3 s^{-1}$)
1	0.5	0.5	5.12×10^{-3}
	2.0	1.2	11.82 "
	4.0	1.7	17.24 "
	8.0	2.4	23.64 "
	12.0	2.7	27.09 "
	19.0	3.4	33.50 "
	27.5	4.5	44.33 "
	38.5	4.5	44.33 "
	48.0	5.0	49.26 "
2	47.0	4.9	48.27×10^{-3}
	40.5	4.5	44.33 "
	30.0	4.0	39.41 "
	21.5	3.5	34.48 "
	14.5	2.8	27.58 "
	9.0	2.4	23.64 "
	4.0	1.6	15.76 "
	1.5	0.9	9.36 "
	0.5	0.6	5.91 "

Table VI Continued ....

Table VI Continued

3	0.0	0.4	4.43 x 10^{-3}
	2.0	1.3	12.81 "
	5.0	2.0	19.70 "
	7.5	2.3	22.66 "
	12.5	2.8	27.59 "
	20.0	3.5	34.48 "
	31.0	4.2	41.38 "
	39.0	4.5	44.33 "
	48.0	5.0	49.26
4	47.5	4.9	48.27 x 10^{-3}
	38.5	4.5	44.33 "
	31.5	4.0	39.41 "
	24.5	3.7	36.45 "
	19.5	3.2	32.02 "
	11.0	2.5	24.63 "
	6.5	2.2	21.67 "
	2.5	1.5	14.78 "
	1.0	0.8	7.88 "

Results of Test 1

Description: Fifth window from right, looking West, Room H8.

Table III. Joints Closed, +ve. pressure

multiply Flow rate by 0.59

RunΔ	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	7.5	0.6	5.96×10^{-3}
	11.5	0.7	7.83 "
	17.5	1.0	9.85 "
	26.0	1.3	13.30 "
	35.0	1.6	16.26 "
	43.0	1.9	19.21 "
	55.0	2.3	22.66 "
2	52.0	2.2	21.67×10^{-3}
	38.0	1.9	18.72 "
	27.5	1.4	13.79 "
	19.5	1.0	10.34 "
	10.0	0.7	7.39 "
	5.5	0.5	5.42 "
3	5.5	0.5	5.42×10^{-3}
	9.0	0.7	7.14 "
	17.5	1.0	10.34 "
	23.5	1.2	12.31 "
	37.5	1.6	16.26 "
	52.5	2.1	20.69 "

Results of Test 3

Description: Front door, Fairfield.

Table VII Joints sealed, +ve. pressure

multiply Flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	29.0	1.9	18.72×10^{-3}
	24.5	1.8	17.73 "
	19.0	1.5	14.78 "
	14.0	1.2	11.82 "
	9.5	1.0	9.85 "
	5.0	0.7	6.90 "
	4.0	0.6	5.91 "
2	6.5	0.8	7.8 "
	11.0	1.1	10.84 "
	16.0	1.3	12.81 "
	21.0	1.6	15.76 "
	26.0	2.0	19.70 "
	35.0	2.3	22.66 "
3	32.5	2.3	22.66×10^{-3}
	27.5	2.1	20.69 "
	21.5	1.8	17.73 "
	15.5	1.4	13.79 "
	10.0	1.1	10.84 "
	6.5	0.8	7.88 "
	4.0	0.7	6.90 "

Table VIII Continued ....

Table VII Continued

4	4.0	0.6	5.91×10^{-3}
	10.0	1.1	10.84 "
	16.5	1.4	13.79 "
	22.5	1.8	17.73 "
	27.5	2.1	20.69 "
	36.0	2.4	23.64 "

Table VIII Joints Open, +ve. pressure

multiply Flow rates by 0·59

Run	Pressure difference (Pa)	Velocity (m.s^{-1})	Flow rate (m^3.s^{-1})
1	21.0	6.5	64.04 x 10^{-3}
	17.0	5.6	55.17 "
	11.5	4.5	44.33 "
	8.5	3.7	36.45 "
	4.0	2.2	21.67 "
	2.0	1.2	11.82 "
2	2.0	1.2	11.82 x 10^{-3}
	5.0	2.6	25.61 "
	8.5	3.8	37.43 "
	12.5	4.6	45.32 "
	15.5	5.1	50.24 "
	17.5	5.6	55.17 "
	20.0	6.4	63.05 "
3	2.0	0.9	8.87 x 10^{-3}
	4.0	2.1	20.69 "
	8.5	3.1	30.54 "
	14.0	5.0	49.26 "
	17.5	5.5	54.19 "
	20.0	6.5	64.04 "
4	20.0	6.5	64.04 x 10^{-3}
	16.0	5.6	55.17 "
	11.0	4.4	43.35 "
	7.0	3.8	37.44 "
	5.0	2.5	24.63 "
	2.0	1.1	10.84 "

Results of Test 4

Description: Front window, back room: Fairfield

Table IX Joints Sealed, +ve. pressure

multiply flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	3.0	0.2	1.97×10^{-3}
	6.0	0.3	2.96 "
	12.0	0.5	4.93 "
	16.5	0.6	5.91 "
	26.5	0.8	7.88 "
	32.5	0.9	8.87 "
	36.0	1.0	9.85 "
2	36.0	1.0	9.85×10^{-3}
	33.3	0.9	8.87 "
	27.0	0.8	7.88 "
	20.0	0.7	6.90 "
	16.0	0.6	5.91 "
	11.0	0.4	3.94 "
	5.0	0.2	1.97 "
3	5.0	0.2	1.97×10^{-3}
	10.0	0.4	3.94 "
	19.0	0.6	5.91 "
	20.0	0.8	7.88 "
	35.0	0.9	8.87 "

Table X Joints Open, +ve pressure

multiply flow rate by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	39.0	1.2	11.82×10^{-3}
	31.0	1.1	10.84 "
	24.5	0.9	8.87 "
	17.5	0.8	7.88 "
	12.0	0.6	5.91 "
	6.0	0.4	3.94 "
	4.5	0.3	2.96 "
2	5.0	0.3	2.96×10^{-3}
	10.5	0.5	4.93 "
	15.5	0.7	6.90 "
	23.0	0.9	8.87 "
	27.5	1.0	9.85 "
	36.0	1.2	11.82 "
3	50.0	1.4	13.79×10^{-3}
	39.5	1.2	11.82 "
	26.0	1.0	9.85 "
	17.0	0.8	7.88 "
	10.5	0.5	4.93 "
	5.0	0.3	2.96 "

Results of Test 5

Description: Back kitchen window, Fairfield

Table XI. Joints Sealed + ve. pressure

multiply Flow rates by 0·59

Run	Pressure difference (Pa)	Velocity (m.s^{-1})	Flow rate (m^3.s^{-1})
1	43.0	1.2	11.82×10^{-3}
	37.5	1.1	10.84 "
	28.0	1.0	9.85 "
	17.5	0.7	6.90 "
	5.0	0.3	2.96 "
2	5.5	0.3	2.96×10^{-3}
	7.5	0.4	3.94 "
	13.0	0.6	5.91 "
	22.0	0.9	8.87 "
	32.0	1.1	10.84 "
	41.5	1.2	11.82 "
3	40.0	1.2	11.82×10^{-3}
	35.0	1.1	10.84 "
	27.0	1.0	9.85 "
	20.0	0.8	7.88 "
	14.0	0.7	6.90 "
	9.0	0.5	4.93 "
	3.0	0.3	2.96 "

Table XII Joints Open

multiply Flow rates by 0·59.

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	3.5	1.3	12.81×10^{-3}
	9.0	1.7	16.75 "
	10.0	2.5	24.63 "
	19.5	3.5	34.48 "
	25.5	4.0	39.41 "
	34.4	4.7	46.30 "
2	39.5	5.0	49.26×10^{-3}
	29.0	4.5	44.33 "
	19.0	3.5	34.48 "
	9.5	2.5	24.63 "
	5.0	1.8	17.73 "
	3.0	1.2	11.82 "
3	2.0	0.3	2.96×10^{-3}
	5.0	1.8	17.73 "
	7.5	2.2	21.87 "
	10.0	2.6	25.61 "
	17.5	3.5	34.48 "
	26.5	4.2	41.38 "
	32.5	4.5	44.33 "
	39.0	5.0	49.26 "

Results of Test 6

Description: Rear window, back-room, Fairfield

Table XIII Joints Sealed

multiply Flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	10.0	0.3	2.96×10^{-3}
	14.0	0.4	3.94 "
	20.0	0.4	3.94 "
	26.5	0.5	4.93 "
	34.5	0.6	5.91 "
	39.0	0.6	5.91 "
2	41.0	0.7	6.90×10^{-3}
	37.0	0.6	5.91 "
	31.0	0.5	4.93 "
	25.0	0.5	4.93 "
	18.5	0.4	3.94 "
	12.0	0.3	2.96 "
3	12.0	0.3	2.96 "
	17.0	0.4	3.94 "
	21.5	0.5	4.93 "
	27.0	0.6	5.91 "
	31.0	0.6	5.91 "
	42.0	0.7	6.90 "

Table XIV Joints Open

multiply Flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	2.0	0.4	3.94×10^{-3}
	8.0	0.9	8.87 "
	16.5	1.3	12.81 "
	22.0	1.5	14.78 "
	28.0	1.9	18.72 "
	34.0	2.0	19.70 "
2	41.0	2.2	21.67×10^{-3}
	32.0	2.0	19.70 "
	27.0	1.8	17.73 "
	19.0	1.4	13.79 "
	11.0	1.0	9.89 "
	4.5	0.5	4.93 "
	2.5	0.4	3.94 "
3	3.0	0.4	3.94×10^{-3}
	6.0	0.7	6.90 "
	10.0	1.0	9.85 "
	17.5	1.3	12.81 "
	26.0	1.7	16.75 "
	30.5	1.9	18.72 "
	35.0	2.1	20.69 "

Results of Test 7

Description: Parlour window, Fairfield

Table XV Joints Sealed

multiply flow rates by 0.59

Run	Pressure difference (Pa)	Velocity $(m.s^{-1})$	Flow rate $(m^3.s^{-1})$
1	57.0	0.9	8.87×10^{-3}
	40.0	0.9	8.87 "
	31.0	0.8	7.88 "
	20.0	0.7	6.90 "
	12.5	0.5	4.93 "
	8.0	0.4	3.94 "
	5.5	0.3	2.96 "
2	4.0	0.3	2.96×10^{-3}
	10.5	0.5	4.93 "
	15.5	0.6	5.91 "
	26.5	0.8	7.88 "
	32.5	0.9	8.87 "
	43.0	0.9	8.87 "
3	48.5	0.9	8.87×10^{-3}
	35.5	0.9	8.87 "
	24.5	0.8	7.88 "
	15.0	0.6	5.91 "
	12.5	0.5	4.93 "
	7.5	0.4	3.94 "
	6.0	0.3	2.96 "

Table XVI Joints Open

multiply Flow rates by 0.59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	3.0	0.3	2.96×10^{-3}
	8.0	0.7	6.90 "
	16.5	1.0	9.85 "
	22.5	1.1	10.84 "
	31.0	1.3	12.81 "
	44.5	1.4	13.79 "
2	44.0	1.4	13.79×10^{-3}
	28.5	1.2	11.82 "
	20.0	1.0	9.85 "
	13.5	0.9	8.87 "
	10.0	0.8	7.88 "
	6.5	0.5	4.93 "
	3.5	0.4	3.94 "
3	4.0	0.4	3.94×10^{-3}
	8.5	0.6	5.91 "
	11.5	0.8	7.88 "
	22.5	1.1	10.84 "
	30.0	1.3	12.81 "
	36.0	1.3	12.81 "

Results of Test 8

Description: R.h. window to room G.10, Pariser Building

Table XVII Joints Sealed

multiply Flow rates by 0.59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	3.0	0.3	2.96×10^{-3}
	10.0	0.9	8.87 "
	16.5	1.1	10.84 "
	26.5	1.5	14.78 "
	32.5	1.8	17.73 "
	42.0	2.1	20.69 "
2	40.0	2.0	19.70×10^{-3}
	35.5	1.9	18.72 "
	22.5	1.5	14.78 "
	18.5	1.3	12.81 "
	14.0	1.0	9.85 "
	4.0	0.5	4.93 "
3	2.5	0.4	3.94×10^{-3}
	9.0	0.8	7.88 "
	18.0	1.2	11.82 "
	21.0	1.3	12.81 "
	29.0	1.6	15.76 "
	38.0	1.9	18.72 "

Table XVIII Joints Open

multiply flow rates by 0.59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	1.0	0.3	2.96 x 10^{-3}
	5.0	0.6	5.91 "
	13.5	1.1	10.84 "
	18.0	1.6	15.76 "
	22.5	1.7	16.75 "
	30.0	2.2	21.67 "
	39.0	2.6	25.61 "
2	51.0	3.0	29.56 x 10^{-3}
	39.0	2.5	24.63 "
	34.0	2.3	22.66 "
	26.0	2.0	19.70 "
	22.0	1.7	16.75 "
	16.5	1.4	13.79 "
	11.0	1.0	9.85 "
	3.5	0.5	4.93 "
3	2.0	0.4	3.94 x 10^{-3}
	5.0	0.6	5.91 "
	13.5	1.3	12.81 "
	20.0	1.2	11.82 "
	27.0	1.9	18.72 "
	30.0	2.2	21.67 "
	40.5	2.5	24.63 "

Results of Test 9

Description: Downstairs toilet window, Peel Av.

Table XIX Joints Closed, -ve. pressure
multiply flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	40.0	0.5	4.93×10^{-3}
	27.5	0.5	4.93 "
	19.0	0.5	4.93 "
	14.0	0.4	3.94 "
	7.5	0.2	1.97 "
2	42.0	0.5	4.93×10^{-3}
	22.0	0.4	3.94 "
	15.5	0.4	3.94 "
	9.5	0.3	2.96 "
	6.5	0.2	1.97 "
3	5.5	0.2	1.97×10^{-3}
	8.5	0.3	2.96 "
	17.5	0.4	0.9 "
	27.0	0.5	4.93 "
	36.5	0.6	5.91 "

Table XX Joints Open, -ve. pressure

multiply Flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	44.0	1.1	10.84 x 10^{-3}
	32.0	0.8	9.87 "
	23.5	0.7	6.90 "
	13.5	0.4	3.94 "
	7.0	0.2	1.96 "
2	7.5	0.2	1.97 x 10^{-3}
	12.5	0.3	2.96 "
	21.5	0.6	5.91 "
	29.5	0.7	6.90 "
	33.0	0.9	8.87 "
	41.0	1.0	9.85 "
3	42.5	1.0	9.85 x 10^{-3}
	33.5	0.9	8.87 "
	25.0	0.7	6.90 "
	17.5	0.5	4.93 "
	10.0	0.2	1.97 "
	6.0	0.2	1.97 "

Results of Test 10

Description: Door to G 10, Pariser Building

Table XXI Joints Closed, -ve. pressure

multiply flow rates by 0.59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	38.0	0.6	5.91×10^{-3}
	30.0	0.5	4.93 "
	22.5	0.4	3.94 "
	16.5	0.3	2.96 "
	10.0	0.2	1.97 "
	8.0	0.2	1.97 "
	5.0	0.0	0.0 "
2	12.5	0.2	1.97×10^{-3}
	14.5	0.3	2.96 "
	20.0	0.4	3.94 "
	25.0	0.4	3.94 "
	32.0	0.5	4.93 "
	40.0	0.6	5.91 "
3	39.5	0.6	5.91×10^{-3}
	32.0	0.5	4.93 "
	27.5	0.5	4.93 "
	19.5	0.4	3.94 "
	14.5	0.3	2.96 "
	11.5	0.2	1.97 "
	8.5	0.2	1.97 "

Table XXII. Joints Open, -ve. pressure

multiply Flow rates by 0.59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	4.8	0.2	1.97×10^{-3}
	6.5	0.4	3.94 "
	10.0	0.5	4.93 "
	16.0	0.6	5.91 "
	9.0	0.7	6.90 "
	2.5	0.8	7.88 "
	34.0	1.0	9.85 "
	43.0	1.1	10.84 "
2	40.0	1.0	9.85 "
	31.0	0.9	8.87 "
	21.5	0.6	5.91 "
	16.5	0.7	6.90 "
	10.5	0.4	3.94 "
	3.5	0.2	1.97 "
3	5.0	0.2	1.97×10^{-3}
	0.5	0.4	3.94 "
	15.0	0.6	5.91 "
	22.5	0.7	6.90 "
	28.5	0.8	7.88 "
	37.0	0.9	8.87 "

Results of Test 11

Description: Door to G.10, Pariser Building

Table XXIII Joints Closed, +ve. pressure

multiply flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	39.5	0.6	5.91×10^{-3}
	30.5	0.5	4.94 "
	19.5	0.3	2.96 "
	13.0	0.3	2.96 "
	8.0	0.2	1.97 "
2	2.5	0.0	0.00×10^{-3}
	11.0	0.2	1.97 "
	16.0	0.3	2.96 "
	23.5	0.4	3.94 "
	32.0	0.5	4.93 "
	34.5	0.5	4.93 "
3	33.5	0.5	4.93×10^{-3}
	25.5	0.4	3.97 "
	18.5	0.3	2.96 "
	12.0	0.2	1.97 "
	7.5	0.2	1.97 "

Table XXIV Joints Open; +ve. pressure
multiply Flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	45.5	1.3	12.81×10^{-3}
	32.5	1.2	11.82 "
	25.5	1.1	10.84 "
	18.0	1.0	9.85 "
	16.5	0.8	7.88 "
	11.0	0.7	6.90 "
	7.5	0.5	4.93 "
	3.5	0.3	2.96 "
2	3.0	0.2	1.9×10^{-3}
	4.0	0.4	3.94 "
	9.5	0.5	4.93 "
	19.5	0.8	7.88 "
	27.5	1.1	10.84 "
	39.0	1.3	12.81 "
3	2.0	0.2	1.97×10^{-3}
	7.0	0.6	5.91 "
	10.5	0.7	6.90 "
	16.0	1.0	9.85 "
	22.0	1.1	10.84 "
	35.0	1.5	14.78 "

Results of Test 12

Description: Attic bedroom door, Peel Ave.

Table XXV. Joints Closed, -ve. pressure
multiply flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	45.5	0.4	3.94×10^{-3}
	33.0	0.3	2.96 "
	23.5	0.3	2.96 "
	17.0	0.2	1.97 "
	8.5	0.2	1.97 "
2	13.5	0.2	1.97×10^{-3}
	20.0	0.3	2.96 "
	27.5	0.3	2.96 "
	38.5	0.4	3.97 "
	42.5	0.4	3.97 "
3	41.5	0.4	3.97×10^{-3}
	33.5	0.3	2.96 "
	21.5	0.3	2.96 "
	14.0	0.2	1.97 "
	8.5	0.2	1.97 "

Table XXV1. Joints Open, -ve. pressure

multiply flow rates by 0.59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	39.0	3.5	34.48×10^{-3}
	32.0	3.2	31.53 "
	23.0	2.8	27.59 "
	13.0	2.5	24.63 "
	9.0	2.0	19.70 "
	4.0	0.9	8.87 "
2	3.5	0.8	7.88×10^{-3}
	7.5	1.7	16.75 "
	13.5	2.7	26.60 "
	22.0	3.1	30.54 "
	31.5	3.5	34.48 "
	41.5	3.5	34.48 "
3	42.0	3.6	35.47×10^{-3}
	31.0	3.3	32.51 "
	23.0	3.0	29.56 "
	13.0	2.5	24.63 "
	6.0	1.3	12.81 "
	5.0	0.6	5.91 "

Test 13

Description: Attic door, Peel Av.

Table XXVII Joints Closed, +ve, pressure
multiply flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	5.5	0.2	1.97×10^{-3}
	10.5	0.3	2.96 "
	19.5	0.4	3.94 "
	30.0	0.5	4.93 "
	38.5	0.6	5.91 "
	48.0	0.6	5.91 '
2	41.0	0.6	5.91×10^{-3}
	33.5	0.5	4.93 "
	25.0	0.4	3.97 "
	16.0	0.3	2.96 "
	10.0	0.2	1.97 "
	5.0	0.1	0.98 "
3	9.5	0.2	1.97×10^{-3}
	18.5	0.4	3.94 "
	24.0	0.5	4.93 "
	28.0	0.5	4.93 "
	42.5	0.6	5.91 "

Table XXVIII Joints Open, +ve. pressure

multiply Flow rates by 0.59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	2.5	0.9	8.87×10^{-3}
	7.5	1.7	10.75 "
	15.0	2.7	26.60 "
	23.5	3.5	34.48 "
	29.0	4.1	40.39 "
	34.0	4.4	43.35 "
	40.0	4.7	46.30 "
2	38.5	4.6	45.32×10^{-3}
	28.5	4.0	39.41 "
	21.5	3.1	30.54 "
	15.0	2.7	26.60 "
	10.5	2.6	25.61 "
	5.0	1.3	12.81 "
	2.5	0.9	8.87 "
3	7.0	1.6	15.76×10^{-3}
	17.5	2.8	27.59 "
	27.0	3.7	"
	35.0	4.3	42.36 "
	37.5	4.5	44.33 "

Results of Test 14

Description: Front Attic window, Peel Av.,

Table XXIX Joints Closed, -ve. pressure

multiply Flow rates by 0·59

Run	Pressure difference (Pa)	Velocity $(m.s^{-1})$	Flow rate $(m^3.s^{-1})$
1	45.0	1.5	14.78×10^{-3}
	38.5	1.3	12.81 "
	25.5	1.1	10.84 "
	18.0	1.0	9.85 "
	12.5	0.8	7.88 "
	8.0	0.6	5.91 "
	2.5	0.3	2.96 "
2	2.5	0.4	3.97×10^{-3}
	5.5	0.5	4.93 "
	8.0	0.7	6.90 "
	14.0	0.8	7.88 "
	20.5	1.1	10.84 "
	32.5	1.2	11.82 "
	42.0	1.4	13.79 "
3	37.5	1.3	11.82×10^{-3}
	30.5	1.1	10.84 "
	24.5	1.0	9.85 "
	17.5	0.9	8.87 "
	9.5	0.7	6.90 "
	2.0	0.3	2.96 "

Table XXX Joints Open, -ve. pressure

multiply flow rates by 0.59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	1.0	0.7	6.90×10^{-3}
	2.5	1.2	11.82 "
	6.0	2.6	26.61 "
	12.0	3.5	34.48 "
	18.5	4.0	39.41 "
	25.5	4.6	45.32 "
	31.5	6.2	61.08 "
2	32.5	5.4	53.20×10^{-3}
	28.5	4.6	45.32 "
	18.0	4.0	39.41 "
	10.0	2.8	27.59 "
	6.0	2.1	20.69 "
	3.5	1.4	13.79 "
3	5.0	1.8	17.73×10^{-3}
	8.0	2.6	25.61 "
	11.0	2.9	28.57 "
	16.5	3.6	35.47 "
	21.5	4.4	43.35 "
	26.5	4.8	47.29 "
	32.0	5.3	52.22 "

Results of Test 15

Description: Front Attic window, Peel Av.

Table XXXI Joints Closed, +ve. pressure
multiply flow rates by 0.59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	35.5	1.3	12.81×10^{-3}
	27.5	1.1	10.84 "
	20.0	0.9	8.87 "
	13.0	0.7	6.90 "
	7.5	0.5	4.93 "
	2.5	0.3	2.96 "
2	5.0	0.4	3.94×10^{-3}
	10.0	0.6	5.91 "
	15.5	0.8	7.88 "
	19.0	0.9	8.87 "
	26.0	1.1	10.84 "
	32.0	1.2	11.82 "
	40.0	1.4	13.79 "
3	41.0	1.4	13.79×10^{-3}
	34.5	1.3	12.81 "
	30.5	1.2	11.82 "
	21.5	0.9	9.85 "
	13.0	0.7	6.90 "
	6.5	0.4	3.94 "
	4.0	0.3	2.96 "

Table XXXII Joints Open, +ve. pressure

multiply flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	29.5	7.0	68.96 x 10^{-3}
	24.5	6.0	59.11 "
	18.5	4.9	48.27 "
	7.5	3.5	34.48 "
	4.0	2.0	19.70 "
	2.5	1.0	9.85 "
	1.5	0.7	6.90 "
2	1.5	0.7	6.90 x 10^{-3}
	2.5	1.4	13.79 "
	4.0	2.5	24.63 "
	10.5	4.4	43.35 "
	15.0	4.9	48.27 "
	17.5	4.9	48.27 "
	20.0	5.4	53.20 "
	26.0	6.1	60.10 "
	29.5	6.5	64.04 "
3	29.5	6.8	67.00 x 10^{-3}
	28.0	6.3	62.07 "
	25.0	6.2	61.08 "
	16.0	4.6	45.32 "
	9.5	3.6	35.47 "
	5.5	2.4	23.64 "
	3.5	1.3	12.81 "
	1.5	0.7	6.90 "

Results of Test 16

Description: Re-test of door to H6, Pariser Building.

Table XXXIII Joints Closed

multiply flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	7.0	0.2	1.97×10^{-3}
	12.0	0.3	2.96 "
	19.5	0.4	3.94 "
	21.0	0.4	3.94 "
	35.5	0.5	4.93 "
	42.0	0.5	4.93 "
2	47.0	0.6	5.91×10^{-3}
	39.0	0.5	4.93 "
	29.0	0.4	3.94 "
	21.5	0.4	3.94 "
	16.0	0.3	2.96 "
	13.0	0.3	2.96 "
	9.0	0.2	1.97 "
	7.0	0.2	1.97 "
3	6.5	0.2	1.97×10^{-3}
	10.0	0.3	2.96 "
	18.0	0.4	3.94 "
	28.5	0.5	4.93 "
	34.0	0.5	4.93 "
	45.0	0.7	6.90 "

Table XXXIV Joints Open

multiply flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	1.5	0.7	6.90×10^{-3}
	5.5	1.3	12.81 "
	12.0	1.9	18.72 "
	17.0	2.2	21.67 "
	20.0	2.3	22.66 "
	27.0	-	
	35.0	3.0	29.56 "
2	37.5	3.1	30.54×10^{-3}
	27.0	2.3	22.66 "
	21.0	2.2	21.67 "
	13.0	1.8	17.73 "
	7.0	1.4	13.79 "
	2.5	0.8	7.88
3	1.0	0.5	4.93×10^{-3}
	6.5	1.5	14.78 "
	10.0	1.7	16.75 "
	16.0	2.1	20.69 "
	22.0	2.4	23.64 "
	26.0	3.0	29.56 "
	32.0	3.1	30.54 "

Results of Test 17

Description: Front bedroom window, Peel Av.,

Table XXXV Joints Closed, -ve. pressure

multiply flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	5.0	0.2	1.97×10^{-3}
	11.0	0.4	3.94 "
	20.0	0.5	4.94 "
	27.5	0.7	6.90 "
	36.0	0.8	7.88 "
	42.5	0.8	7.88 "
2	40.0	0.8	7.88×10^{-3}
	29.0	0.7	6.90 "
	22.0	0.6	5.91 "
	14.0	0.4	3.94 "
	8.0	0.3	2.96 "
	5.0	0.2	1.97 "
3	6.5	0.3	2.96×10^{-3}
	17.0	0.5	4.93 "
	24.5	0.6	5.91 "
	34.5	0.8	7.88 "
	41.5	0.8	7.88 "

Table XXXVI Joints Open, -ve. pressure

multiply Flow rate by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	42.5	4.1	39.41×10^{-3}
	34.5	3.9	38.42 "
	29.0	3.6	35.47 "
	21.5	3.1	30.54 "
	11.5	2.4	23.64 "
	6.0	1.7	16.75 "
	2.0	0.8	7.88 "
2	2.0	0.7	6.90×10^{-3}
	5.0	1.6	15.76 "
	12.5	2.4	23.64 "
	22.5	-	-
	32.0	3.8	37.44 "
	39.0	4.0	39.41 "
3	36.0	4.0	39.41×10^{-3}
	27.0	3.6	45.32 "
	18.0	2.9	28.59 "
	9.0	2.1	20.69 "
	4.0	1.2	11.82 "

Results of Test 18

Description: Front bedroom window, Peel Av.

Table XXXVII Joints Closed, +ve. pressure
multiply Flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	3.5	0.2	1.97×10^{-3}
	5.0	0.2	1.97 "
	10.0	0.3	2.96 "
	17.5	0.5	4.93 "
	27.5	0.7	6.90 "
	35.0	0.8	7.88 "
	42.0	0.8	7.88 "
2	39.0	0.7	6.90×10^{-3}
	32.0	0.6	5.91 "
	22.5	0.5	4.93 "
	15.0	0.4	3.94 "
	9.5	0.3	2.96 "
	5.0	0.2	1.97 "
3	6.5	0.2	1.97×10^{-3}
	12.5	0.4	3.94 "
	20.0	0.5	4.93 "
	25.5	0.6	5.91 "
	30.5	0.6	5.91 "
	40.0	0.7	6.90 "

Table XXXVIII Joints Open, +ve. pressure

multiply flow rates by 0.59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	41.5	5.9	58.13 x 10^{-3}
	34.5	5.6	55.17 "
	29.0	4.8	47.29 "
	20.5	4.0	39.41 "
	12.0	3.0	29.56 "
	6.5	1.9	18.72 "
	3.0	1.3	12.81 "
2	4.0	1.6	14.78 x 10^{-3}
	7.5	2.3	22.66 "
	15.0	3.4	33.50 "
	24.0	4.3	42.36 "
	35.0	5.4	53.20 "
	40.0	5.7	56.16 "
3	41.0	5.7	56.16 x 10^{-3}
	33.0	5.0	49.26 "
	21.5	4.0	39.41 "
	11.5	2.8	27.59 "
	4.0	1.7	16.75 "

Results of Test 19

Description: A four square section of false ceiling at Prototype Nucleus Ward, Pinderfield Hosp.

Table XXXIX. Measurement of unrestricted flow, +ve. pressure

multiply flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	42.0	6.3	62.07×10^{-3}
	36.5	4.0	39.41 "
	26.5	3.1	30.54 "
	20.0	2.1	20.69 "
	10.0	1.3	12.81 "
	6.0	0.8	7.88 "
	1.0	0.2	1.97 "
2	4.0	0.6	5.91×10^{-3}
	8.5	1.3	12.81 "
	16.0	2.0	19.70 "
	22.0	2.7	26.60 "
	25.5	3.0	29.56 "
	34.5	3.7	36.45 "
	39.0	4.4	43.35 "
	42.0	6.4	63.05 "
3	37.5	4.3	42.36 "
	23.0	2.6	25.61 "
	16.0	2.0	19.70 "
	9.0	1.3	12.81 "
	4.0	0.8	7.88 "

Table XL Measurement of restricted flow, +ve. pressure

multiply flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	3.5	0.8	7.88×10^{-3}
	12.5	1.6	15.76 "
	22.5	2.4	23.64 "
	31.0	2.9	28.59 "
	42.0	3.6	35.47 "
	51.0	4.2	41.38 "
2	42.0	4.1	40.39×10^{-3}
	31.5	3.0	29.56 "
	20.5	2.2	21.67 "
	11.5	1.2	11.82 "
	5.0	0.7	6.90 "
	1.5	0.2	1.97 "
3	7.5	0.7	6.90×10^{-3}
	14.0	1.9	18.72 "
	26.0	2.6	25.61 "
	35.5	3.1	30.54 "
	47.0	3.9	38.42 "

Results of Test 20

Description: A false-ceiling section on Prototype Nucleus Ward, Pinderfield Hosp.

Table XLI Measurement of unrestricted flow, -ve. pressure

multiply flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	2.5	0.4	3.94×10^{-3}
	10.0	0.6	5.91 "
	19.5	0.9	8.87 "
	31.5	1.6	15.76 "
	37.5	1.7	16.76 "
	48.0	2.0	19.70 "
2	37.0	1.5	14.78×10^{-3}
	28.5	1.4	13.79 "
	19.0	1.1	10.84 "
	12.0	1.0	9.85 "
	6.5	0.6	5.91 "
	3.5	0.4	3.97 "
3	3.0	0.5	4.93×10^{-3}
	7.5	0.6	5.91 "
	16.5	1.1	10.84 "
	28.0	1.5	14.78 "
	35.0	1.7	16.75 "
	48.0	2.0	19.70 "

Results of Test 21

Description: Front, small-bedroom door, 4 Spur Walk.

Table XLII Joints marked, +ve. pressure
multiply flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	53.5	0.4	3.97×10^{-3}
	40.5	0.3	2.96 "
	30.0	0.2	1.97 "
	20.0	0.2	1.97 "
	10.0	0.0	0.0 "
2	21.0	0.2	1.97×10^{-3}
	29.5	0.2	1.97 "
	32.5	0.3	2.96 "
	42.0	0.3	2.96 "
3	42.5	0.3	2.96×10^{-3}
	31.5	0.2	1.97 "
	22.5	0.2	1.97 "

Table XLIII Joints Open, +ve. pressure

multiply Flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	39.0	3.8	37.44×10^{-3}
	32.0	3.5	34.48 "
	22.5	2.9	28.59 "
	16.5	2.3	22.66 "
	8.0	1.4	13.79 "
	3.5	0.8	7.88 "
2	4.0	0.9	8.87×10^{-3}
	9.0	1.5	14.78 "
	19.0	2.3	22.66 "
	26.5	3.1	30.54 "
	36.0	3.7	36.45 "
	29.5	3.9	38.42 "
3	40.0	4.3	42.36×10^{-3}
	36.0	3.7	36.45 "
	30.0	3.5	34.48 "
	18.5	2.5	24.63 "
	10.0	1.7	16.75 "
	3.0	0.7	7.88 "

Results of Test 22

Description: Front-bedroom door, 4 Spur Walk

Table XLIV Joints Closed, -ve. pressure

multiply flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	44.0	0.3	2.96×10^{-3}
	35.0	0.3	2.96 "
	29.0	0.2	1.97 "
	19.0	0.2	1.97 "
2	19.0	0.2	1.97×10^{-3}
	28.0	0.2	1.97 "
	37.0	0.3	2.96 "
	43.0	0.3	2.96 "

Table XLV Joints Open, -ve. pressure
multiply flow rates by 0·59

Run	Pressure difference (Pa)	Velocity $(m.s^{-1})$	Flow rate $(m^3.s^{-1})$
1	42.5	3.6	35.47×10^{-3}
	33.5	3.1	30.54 "
	26.0	2.7	26.60 "
	21.0	2.4	23.64 "
	10.0	1.6	15.76 "
	5.0	1.1	10.84 "
	3.0	0.8	7.88 "
2	5.0	1.0	9.85×10^{-3}
	10.5	1.6	15.76 "
	15.5	2.0	19.70 "
	25.0	2.7	26.60 "
	35.0	3.1	30.54 "
	42.5	3.5	34.48 "
3	38.5	3.4	33.50×10^{-3}
	32.0	3.0	29.56 "
	22.5	2.5	24.63 "
	12.0	1.7	16.75 "
	5.5	1.1	10.84 "
	2.0	0.5	4.93 "

Results of Test 23

Description: Front, small-bedroom window, 4 Spur Walk.

Table XLVI Joints Closed, +ve. pressure

multiply flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	46.5	0.5	4.93×10^{-3}
	36.0	0.4	3.94 "
	28.0	0.3	2.96 "
	17.5	0.2	1.97 "
	9.5	0.2	1.97 "
2	9.0	0.2	1.97×10^{-3}
	16.5	0.3	2.96 "
	24.0	0.4	3.94 "
	34 5	0.4	3.94 "
	41.5	0.5	4.93 "
3	42.0	0.5	4.93×10^{-3}
	34.0	0.4	3.94 "
	27.0	0.4	.94 "
	19.5	0.3	2.96 "
	12.5	0.2	1.97 "
	7.0	0.2	1.97 "

Table XLVII Joints Open, +ve. pressure

multiply flow rates by 0.59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	4.0	0.2	1.97×10^{-3}
	10.0	0.4	3.94 "
	20.0	0.7	6.90 "
	26.5	0.8	7.88 "
	37.5	1.0	9.85 "
	42.0	1.1	10.84 "
2	43.5	1.1	10.84×10^{-3}
	33.0	0.9	8.87 "
	22.5	0.7	6.90 "
	14.5	0.5	4.93 "
	7.5	0.3	2.96 "
3	7.0	0.3	2.96×10^{-3}
	11.0	0.4	3.94 "
	20.5	0.7	6.90 "
	29.0	0.8	7.88 "
	36.0	1.0	9.85 "

Results of Test 24

Description: as for test 23

Table XLVIII Joints Closed, -ve. pressure
multiply flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	40.0	0.5	4.93×10^{-3}
	32.5	0.4	3.97 "
	22.0	0.35	2.96 "
	18.0	0.32	2.96 "
	11.5	0.2	1.97 "
2	13.5	0.2	1.97×10^{-3}
	23.0	0.35	2.96 "
	30.0	0.4	3.94 "
	40.0	0.5	4.93 "
3	40.5	0.5	4.93×10^{-3}
	33.5	0.45	3.94 "
	27.0	0.35	2.96 "
	18.0	0.25	1.97 "
	13.0	0.2	1.97 "

Table XLIX Joints Open, -ve. pressure

multiply flow rates by 0.59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	5.5	0.3	2.96×10^{-3}
	11.0	0.4	3.94 "
	21.5	0.7	6.90 "
	31.5	0.9	8.87 "
	39.5	1.2	11.82 "
2	37.5	1.1	10.84×10^{-3}
	28.5	0.9	8.87 "
	21.0	0.7	6.90 "
	10.5	0.5	4.93 "
	7.5	0.4	3.94 "
3	5.0	0.25	1.97×10^{-3}
	12.0	0.5	4.93 "
	24.5	0.85	7.88 "
	33.0	1.1	10.84 "
	40.0	1.4	13.79 "

Results of Test 25

Description: Loft trap, 7 Maes-Y-Llan

Table L Flow restricted, +ve. pressure
multiply flow rates by 0·59

Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate ($m^3.s^{-1}$)
1	37.5	2.7	26.60 x 10^{-3}
	24.5	1.4	13.79 "
	19.0	1.2	11.82 "
	9.0	0.7	6.90 "
	5.5	0.4	3.94 "
	3.5	0.3	2.96 "
2	6.5	0.5	4.93 x 10^{-3}
	17.0	1.1	10.84 "
	28.0	1.9	18.72 "
	38.0	2.4	23.64 "
	41.5	3.0	29.56 "

Table L1 Flow unrestricted, +ve. pressure
multiply flow rates by 0·59

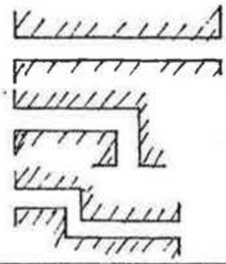
Run	Pressure difference (Pa)	Velocity ($m.s^{-1}$)	Flow rate (m^3 s^{-1})
1	27.5	6.3	62.07 x 10^{-3}
	19.0	3.4	33.50 "
	10.0	2.1	20.69 "
	4.5	1.0	9.85 "
	1.5	0.5	4.93 "
2	2.5	0.6	5.91 x 10^{-3}
	5.5	1.2	11.82 "
	13.5	2.2	21.67 "
	20.0	3.5	34.48 "
	27.5	6.2	61.08 "

Table LII

Measured dimensions of cracks around the test components

Crack type

1
2
3



Test	Crack type	ℓ(m)	w(m)	z(m)	Area(m^2)
1	3	7.084	1.6×10^{-3}	0.053	3.542×10^{-3}
				Tot =	3.542 "
2	2	1.27	1.0 "	0.037	1.27 "
"	"	1.96	0.5 "	0.056	1.96 "
"	1	1.27	6.0 "	0.044	7.62 "
"	2	1.96	1.0 "	0.056	0.98 "
"	3	1.96	2.5 "	0.032	4.9 "
				Tot =	16.46 "
3	2	1.96	1.6 "	0.063	3.13 "
"	"	1.96	0.8 "	"	1.56 "
"	"	0.838	4.8 "	"	3.98 "
"	1	0.838	9.5 "	0.050	7.96 "
				Tot =	16.63 "
4	1	0.78	1.6 "	0.017	1.26 "
				Tot =	1.26 "

Table LII Cont'd......

Table LII Continued

Test	Crack type	ℓ(m)	w(m)		z(m)	Area(m^2)	
5	2	0.83	11.1 x 10^{-3}		0.01	9.25 x 10^{-3}	
"	"	0.83	5	"	0.007	4.15	"
"	"	0.025	19	"	0.017	0.475	"
"	"	0.209	3.2	"	0.01	0.66	"
"	3	0.406	3.2	"	0.01	1.29	"
					Tot =	15.82	"
6	2	0.406	3.2	"	0.025	1.29	"
"	1	0.762	6.3	"	0.025	4.84	"
					Tot =	6.13	"
7	3	0.597	3.2	"	0.005	1.83	"
"	"	0.597	3.2	"	0.005	1.83	"
"	"	0.813	6.3	"	0.005	5.16	"
					Tot =	8.82	"
8	3	3.67	0.5	"	0.053	1.83	"
9	2	1.62	1.0	"	0.035		
"	"	0.78	0.5	"	0.042		
10	"	0.83	0.25	"	0.035	0.21	"
"	"	0.83	0.25	"	0.045	0.21	"
"	"	1.98	0.25	"	0.045	0.49	"
"	"	1.98	0.25	"	0.046	0.49	"
					Tot =	1.405	"
11			See test 10				
12	2	0.50	2.5 x 10^{-3}		0.030	1.25 x 10^{-3}	
"	"	1.67	0.75	"	0.030	1.52	"
"	"	1.95	0.25	"	0.023	0.49	"
"	1	0.66	1.5	"	0.009	0.99	"
					Tot =	4.25	"

Table LII Cont'd.....

Table LII Continued

Test	Crack type	ℓ(m)	w(m)	z(m)	Area(m^2)
13			See test 12		
14	2	0.73	1.0×10^{-3}	0.056	0.73×10^{-3}
"	"	0.73	1.5 "	0.060	1.09 "
"	1	0.73	3.5 "	0.014	2.55 "
"	3	0.76	2.0 "	0.065	1.52 "
"	"	0.79	0.75 "	0.075	0.59 "
"	"	0.76	1.5 "	0.065	1.14 "
"	"	0.79	1.0 "	0.075	0.79 "
					Tot = 8.41 "
15			See test 14		
16			See test 2		
17	3	0.82	0.25×10^{-3}	0.079	0.20×10^{-3}
"	"	0.82	0.25 "	0.076	0.20 "
"	"	0.89	0.5 "	0.081	0.44 "
"	"	0.89	1.5 "	0.076	1.33 "
"	"	0.83	0.5 "	0.072	0.41 "
"	1	0.83	5.0 "	0.012	4.15 "
"	"	0.83	0.5 "	0.041	0.41 "
					Tot = 7.17 "
18			See test 17		
19	2	9.44	1.75 "	0.023	16.52 "
					Tot = 16.52

Table LII Cont'd...

Table LII Continued

Test	Crack type	ℓ(m)	w(m)		z(m)	Area(m^2)	
20			See test 19				
21	2	0.70	2.0×10^{-3}		0.048	1.4×10^{-3}	
"	"	2.02	0.5	"	0.049	1.01	"
"	"	2.02	1.5	"	0.048	3.03	"
"	1	0.70	1.0	"	0.037	0.70	"
					Tot =	6.1	"
22			See test 21				
23		Cracks too small to estimate					
24			See test 24				
25i	2	1.4	0.25	"	0.041	0.35	"
					Tot =	0.35	"
25ii	2	1.4	2.0	"	0.041	2.8	"
					Tot =	2.8	"

Table LIII

Comparison of crackage area (m^2)

All values to be multiplied by 10^{-3} m^2

Test	A_m	A_e	A_1	σ_1	A_2	σ_2	A_3	σ_3
1	3.542	3.542	5.791	0.613	5.715	0.601	4.497	0.461
2	16.46	16.84	14.35	1.78	14.66	1.7	13.2	1.12
3	16.63	16.79	9.902	0.299	10.06	0.415	8.908	0.842
4	1.26	1.26	1.334	0.051	1.454	0.086	1.558	0.181
5	15.82	15.81	6.521	0.291	7.451	0.221	8.676	0.378
6	6.07	6.13	2.551	0.022	2.798	0.093	3.039	0.27
7	8.82	9.232	1.771	0.033	1.846	0.048	1.932	0.161
8	1.83	1.835	4.239	0.655	4.06	0.866	3.39	0.494
9								
10	1.405	1.405	4.512	0.470	4.456	0.46	3.518	0.347
11	1.405	1.405	4.735	0.264	4.682	0.258	3.719	0.201
12	4.250	4.01	7.190	0.235	7.55	0.448	7.411	1.018
13	4.25	4.01	6.961	0.151	6.698	0.448	7.052	0.872
14	8.41	8.46	10.34	0.127	10.63	0.261	9.79	0.859
15	8.41	8.46	12.85	0.532	13.21	0.836	13.52	1.969
16	16.46	16.84	11.94	1.581	12.00	1.524	10.21	1.08
17	7.17	7.09	10.96	0.339	11.15	0.255	9.918	0.461
18	7.17	7.09	12.05	0.37	12.37	0.184	11.33	0.532
19	16.52	16.52	9.008	0.256	9.051	0.195	7.684	0.273
20	16.52	16.52	8.442	0.801	8.438	0.765	7.017	0.542
21	6.14	5.98	9.048	0.132	9.239	0.106	8.330	0.544
22	6.14	5.98	8.810	0.221	8.97	0.120	8.001	0.384
23								
24								
25i	0.575	0.575	3.210	0.127	3.351	0.222	3.233	0.472
25ii	1.40	1.40	4.745	1.139	5.475	1.506	6.425	2.105

N.B. A - area; σ - standard deviation
subscripts; 1,2 & 3 - refer to crack type
m - measured; e - estimated

Table L1V

Comparison of Coefficients

Test		1	2	3	4	5	6	7	8	9
1	C_z	0.058	0.418	0.471	0.566	0.792	0.759	0.798	0.077	
	σ_z	0.016	0.079	0.112	0.083	0.012	0.031	0.011	0.019	
	C_a	0.092	0.367	0.324	0.583	0.703	0.602	0.553	0.173	
	σ_a	0.018	0.042	0.097	0.083	0.043	0.077	0.081	0.019	
2	C_z	0.059	0.396	0.437	0.505	0.659	0.637	0.663	0.080	
	σ_z	0.016	0.066	0.092	0.06	0.007	0.019	0.006	0.019	
	C_a	0.094	0.359	0.318	0.533	0.614	0.548	0.512	0.174	
	σ_a	0.018	0.038	0.092	0.062	0.026	0.057	0.062	0.019	
3	C_z	0.096	0.435	0.456	0.483	0.537	0.532	0.539	0.127	
	σ_z	0.026	0.039	0.049	0.025	0.002	0.004	0.001	0.028	
	C_a	0.118	0.396	0.354	0.497	0.528	0.504	0.487	0.215	
	σ_a	.023	0.031	0.086	0.028	0.008	0.024	0.031	0.022	
CP (all x 10^3)		0.96	4.75	2.58	0.16	5.4	1.66	0.64	1.06	0.335
n		0.37	0.69	0.85	0.95	0.51	0.63	0.61	0.48	0.95

Underlined values are used for comparison purposes.

Table L1V Cont'd.

Table L1V Continued

Test		10	11	12	13	14	15	16	17
1	C_z	0.034	0.037	0.297	0.293	0.327	0.358	0.377	0.234
	σ_z	0.009	0.013	0.080	0.079	0.088	0.09	0.077	0.066
	C_a	0.107	0.122	0.461	0.447	0.382	0.479	0.280	0.338
	σ_a	0.020	0.041	0.111	0.106	0.097	0.113	0.035	0.082
2	C_z	0.035	0.038	0.286	0.339	0.315	0.339	0.364	0.231
	σ_z	0.01	0.013	0.071	0.075	0.077	0.077	0.067	0.062
	C_a	0.108	0.124	0.437	0.461	0.370	0.451	0.279	0.331
	σ_a	0.021	0.041	0.095	0.091	0.088	0.096	0.033	0.076
3	C_z	0.057	0.062	0.346	0.345	0.376	0.388	0.419	0.305
	σ_z	0.016	0.021	0.058	0.057	0.060	0.054	0.044	0.062
	C_a	0.136	0.155	0.442	0.436	0.398	0.450	0.326	0.369
	σ_a	0.025	0.050	0.066	0.064	0.072	0.065	0.032	0.069
Cp (all x 10^3)		0.675	0.55	2.71	2.48	4.52	5.52	3.38	3.37
n		0.6	0.73	0.84	0.85	0.66	0.8	0.66	0.76

Table L1V Cont'd.

Table LIV Continued.

	Test	18	19	20	21	22	23	24	25i	ii
1	C_z	0.247	0.430	0.413	0.251	0.248			0.096	0.607
	σ_z	0.066	0.105	0.093	0.072	0.070			0.029	0.081
	C_a	0.381	0.266	0.251	0.355	0.342			0.437	0.691
	σ_a	0.084	0.074	0.077	0.090	0.084			0.114	0.109
2	C_z	0.243	0.406	0.393	0.247	0.244			0.095	0.532
	σ_z	0.061	0.087	0.079	0.066	0.065			0.028	0.056
	C_a	01370	0.264	0.235	0.346	0.335			0.417	0.602
	σ_a	0.076	0.071	0.052	0.083	0.078			0.100	0.072
3	C_z	0.314	0.442	0.437	0.319	0.317			0.136	0.492
	σ_z	0.059	0.051	0.046	0.062	0.062			0.034	0.022
	C_a	0.400	0.308	0.281	0.38	0.372			0.427	0.520
	σ_a	0.062	0.071	0.054	0.072	0.069			0.073	0.027
	Cp (all x 10^3)	4.3	1.4	2.48	2.68	2.6	0.22	0.29	1.07	2.13
	n	0.75	0.95	0.47	0.57	0.78	0.92	0.96	0.72	0.74

N.B. C_z - from equation 13; C_a - from equation 15: σ - standard deviation

REFERENCES

1. Dick, J.B., Fundamentals of natural ventilation in houses; J.I.H.V.E., June 50, Vol. 18, No. 179.

2. Tamura, G.T., The calculation of house infiltration rates; A.S.H.R.A.E. Transactions, Vol. 85, part 1, p.58, 1979.

3. Etheridge, D.W., and Alexander, D.K.; British Gas multi-cell model for calculating ventilation; A.S.H.R.A.E. Transactions; Vol. 86, part 2, 1980.

4. Kronvall, J.; Airtightness - measurements and measurement methods; Swedish Council for Building Research; Stockholm; 1980.

5. Grimsrudd, D.T., Sherman, M.H., Janssen, J.E.,Pearmen A.N., and Harje, D.T.; An intercomparison of tracer gases used for air infiltration measurement; A.S.H.R.A.E. Transactions; Vol. 86, part 1, p.258. 1980.

6. Tamura, G.T. Measurement of air leakage characteristics of house enclosures; A.S.H.R.A.E. Transactions, Vol. 8, part 1, p.202; 1975.

7. Dewsbury, J.; A. survey of research into some aspects of air infiltration; M.Sc. Dissertation, Dept. of Building, U.M.I.S.T., 1980.

8. I.H.V.E. Guide; part A.4.; C.I.B.S. (formerly I.H.V.E.), London; 1970.

9. Dick, J.B.,; Experimental studies in natural ventilation of houses; J.I.H.V.E., Dec. 49, Vol. 17, part 173.

10. Lee, B.S. Hussain, M. and Soliman, B.S.: natural ventilation forces acting on low rise buildings; Building Services Engineering Research and Technology; Vol. 1 No. 1, p.35; 1980.

11. Hopkins, L.P. and Hansford, B., ; Air flow through cracks; Building Services Engineer; Vol. 42, p.123

12. Etheridge, D.W.; Crack flow equations and scale effect; Building and Environment; Vol. 12, p. 181-189, 1977.

13. Potter, N.I.; Effect of fluctuating wind pressures on natural ventilation rates; A.S.H.R.A.E. Transactions, Vol. 85, part 2, p.445.

14. Reeves, G., McBride, M.F. and Sepsey, C.F., Air infiltration models for residences A.S.H.R.A.E. Transactions, Vol. 85, part 1, p.667; 1979.

15. A.S.H.R.A.E. Handbook and product directory; Fundamentals; A.S.H.R.A.E.; 1977; New York.

16. Dick, J.B., and Thomas, D.A.; Air infiltration through gaps around windows; J.I.H.V.E.; June 53.

17. Shaw, C.Y.; Methods for conducting small scale pressure tests and air leakage data of multi-storey apartment buildings; A.S.H.R.A.E. Transactions, Vol. 86, part 1, p.241, 1980.

18. Kronvall, J.; Air flow in building components; Report TUBH - 1002; Lund Institute of Technology, Sweden; 1980.

19. Hunt, C.M. and Burch, D.M.; Air infiltration measurements in a 4-bedroom townhouse using sulphur-hexafluoride as a tracer gas; A.S.H.R.A. Transactions: Vol. 81, part 1 p. 186; 1975.

20. C.P. 49/77; The repeatability and reproduceability on windows and walls spun elements and the unexpected results; Carruthers, J.F.S. and Newman, C.J.; H.M.S.O.; 1977.

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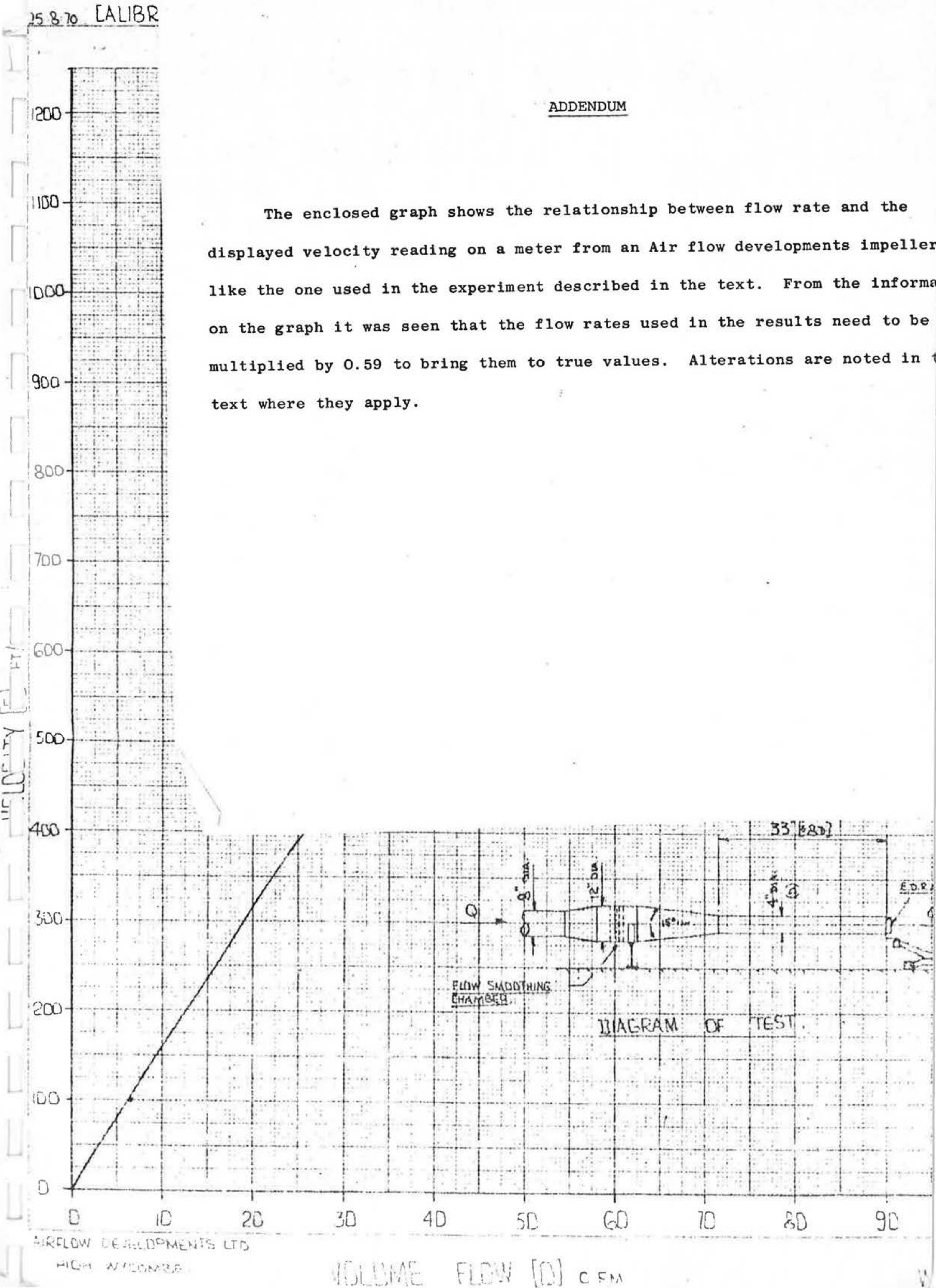
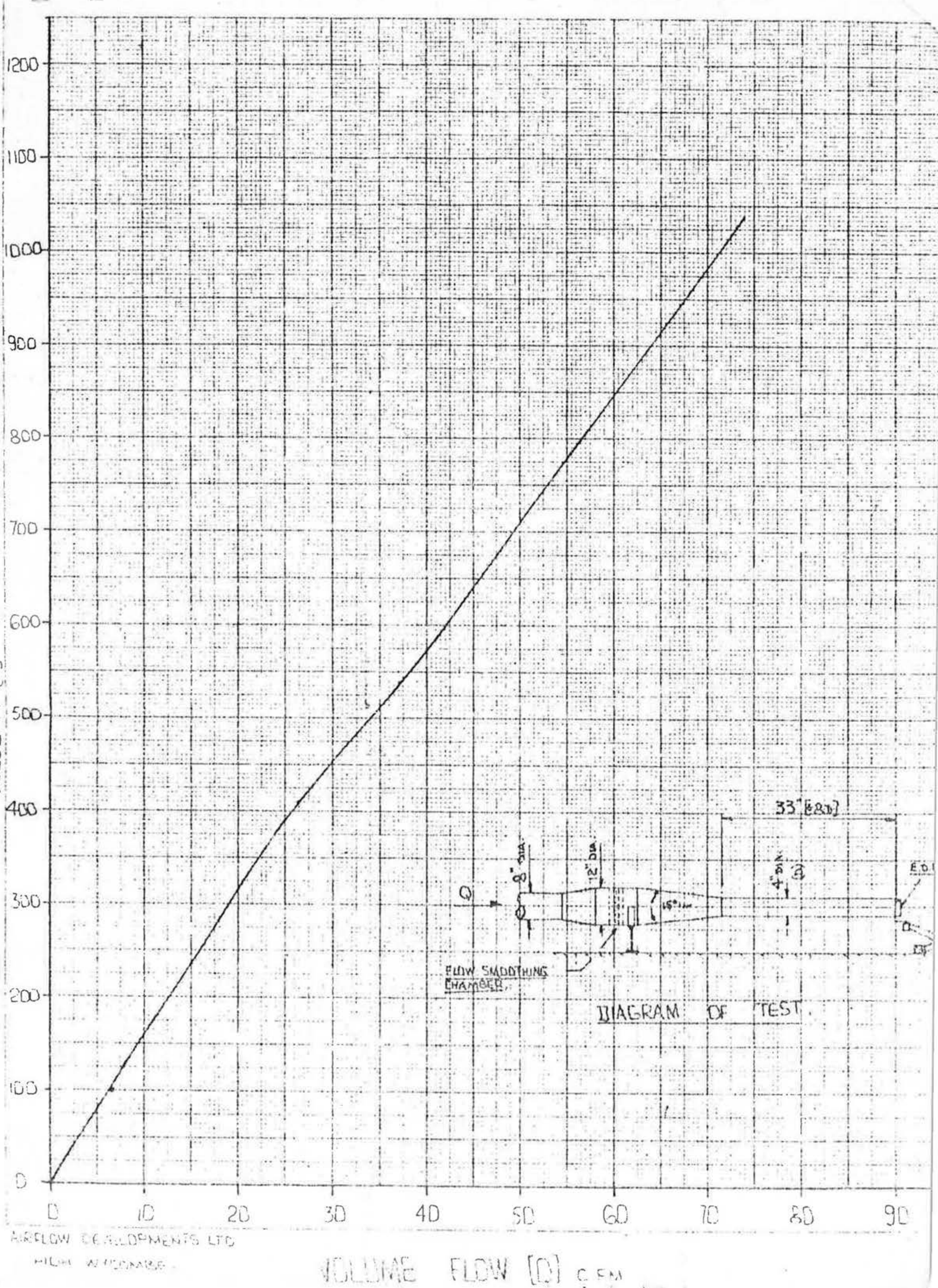
ADDENDUM

The enclosed graph shows the relationship between flow rate and the displayed velocity reading on a meter from an Air flow developments impeller like the one used in the experiment described in the text. From the informa on the graph it was seen that the flow rates used in the results need to be multiplied by 0.59 to bring them to true values. Alterations are noted in t text where they apply.



25.8.70 CALIBRATION OF E.D.R.A HEAD ATTACHED TO A 4" DIA PIPE OUTLET.



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