Air flow through cracks

L P Hopkins BSc
B Hansford

SUMMARY

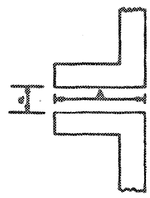
This paper contains a description of the experimental method used and the results obtained in a series of experiments aimed at investigating the characteristics of air flow through domestic cracks, including the "straight through", "L-shaped and multi-cornered" forms found in the construction of a dwelling.

NOMENCLATURE

A	Area (m^2)
C_A	Apparent coefficient
C_d	Discharge coefficient
d	Crack thickness (width) (m)
D_h	Hydraulic diameter (m)
K_1	Empirical constant
l	Crack length (m)
p	Static pressure of fluid (Nm^{-2})
Δ_p	Pressure difference (Nm^{-2})
Q	Volume flow of fluid through a crack (m^3s^{-1})
Q_{AD}	Adventitious volume flow (m^3s^{-1})
Q_t	Total flow ($Q_1 = Q + Q_{AD}$) (m^3s^{-1})
Re_h	Reynolds Number based on hydraulic diameter
U_c	Centre line velocity through a crack (ms^{-1})
u	Average velocity over area A (ms^{-1})
Z	Centre line distance through a crack (m)
ρ	Density (Kg m^{-3})
ν	Kinematic viscosity (m^2s^{-1})
∇^2	Laplacian operator

1 INTRODUCTION

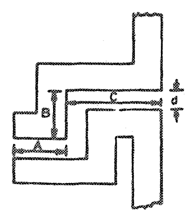
The work being carried out on the ventilation of dwellings necessitates an accurate knowledge of the values of open area that are associated with typical room components such as doors and windows. Any computer programme written to simulate ventilation effects in a room would require accurate knowledge concerning the flow characteristics of cracks associated with these room components.
The computer method used at present relies on balancing flow rates through a number of openings using a simple law normally applied to flow through thin plate orifices. Because the flows normally associated with adventitious ventilation are rather different from the turbulent conditions of orifice plate flow it was considered useful to investigate the Reynolds Number dependence of such flows. This would enable a semi-empirical result to be used in the computer method which was more representative of the types of flow experienced.



CRACK	A	d
1	25 (1")	
2	19 (¾")	1 2 3 5,
3	50 (2")	8 10.
4	6 (¼")	

DIMENSIONS IN mm

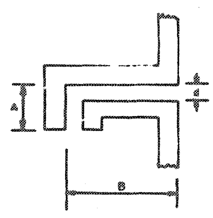
Fig 1a: Straight through cracks.



CRACK	A	B	C	d
11	20	29	24	3 5
12	25	29	32	5 0

DIMENSIONS IN mm

Fig 1b: L-shaped cracks.



CRACK	A	B	d
5	24	32	0 5.3 7
6	12	19	1 0.3 7
7	12	50	0 5.3 5 7
8	24	50	0 5 3 7
9	24	19	0 5 3 5 7
10	12	32	0 5.3 5.7 5

DIMENSIONS IN mm

Fig 1c: Multi-cornered cracks.

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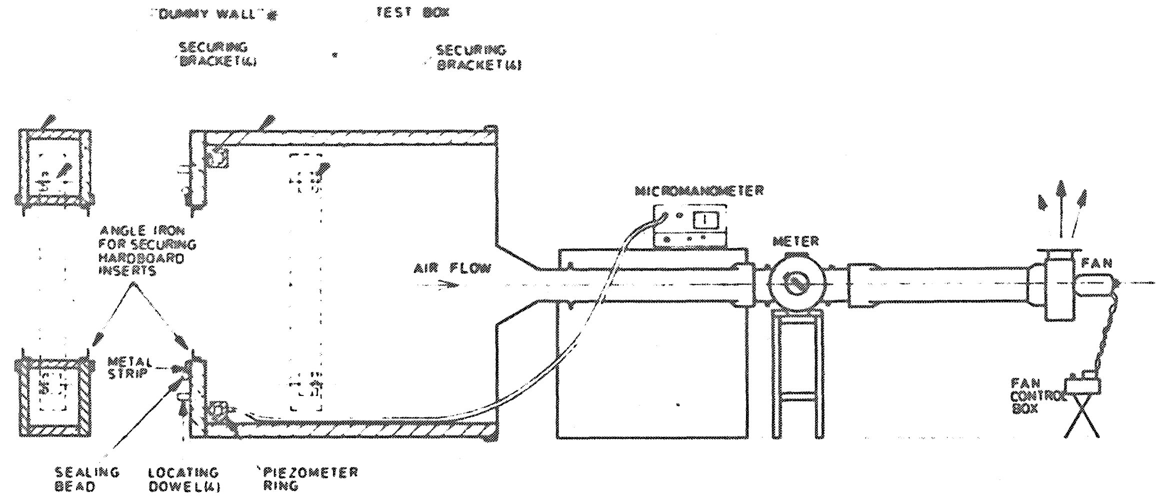

Fig 2: Arrangement of test box.

Three main crack forms are normally found in a dwelling (see Fig. 1). The first is a "straight through" crack where air passes directly through an opening; for example the gap between a door and the floor. The second is an "L-shaped" crack where the air has to pass round a right-angle bend, an example being a casement window shut against the frame. The third is a "multi-cornered" crack where there are two right-angled bends, such as those in the groove of a sash window.

Various crack geometries were tested with crack thicknesses varying from 0·5 mm to 7·5 mm, these limits being the ones likely to be found in a dwelling. A ventilator test box, shown in Fig. 2, normally used for finding the open area of proprietary air vents, was utilized to draw air through the cracks.

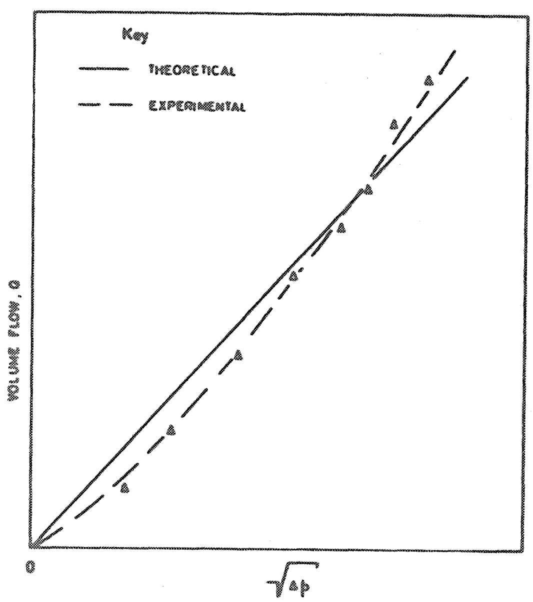

Fig 3: Graph of volume flow against $\sqrt{\Delta p}$ for a typical room.

2 THEORY

It was found in laboratory tests[1] that the rate of air flow through such openings as ventilators and the cracks around windows and doors is approximately proportional to the square root of the pressure difference acting across the component. This simple law also applies to the flow through a thin plate orifice which for a coefficient of discharge of 0·65 is given by:

$$\Delta p = \frac{1{\cdot}4\, Q^2}{A^2} \qquad \ldots.(1)$$

So if the rate of flow Q through a component is known for a given pressure Δp across it, the area A of the thin plate orifice to which the component can be regarded as being equivalent may be calculated.

If this relationship is true in practice there will be a straight line relationship between Q and $\sqrt{\Delta p}$. However, this is not the case, as shown in Fig. 3.

There can be a number of reasons for this deviation from theory:

1. The open area A increases, as the pressure difference Δp increases, due to distortion of the crack or cracks being investigated.
2. In equation 1 the numerical constant contains a discharge coefficient equal to 0·65 as mentioned earlier; if there is any variation in the discharge coefficient then this constant will vary, giving rise to a deviation from the theory.
3. The square law approximation is not strictly true for all types of crack, crack geometries and pressure differences.

Work was carried out in 1953[2] in which the flow-pressure curves were fitted to quadratic equations. In 1970[3] a study of natural ventilation by the HVRA produced an equation of the form:

$$\Delta p = \left(\frac{Q}{l.C.}\right)^n$$

l being the total length of the crack and n an exponent equal to 1·6 but which might take on values anywhere

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between 1 and 3. C is an air leakage coefficient.

Considering the above results, experiments performed by British Gas in 1972 showed that equation 1 with an exponent of 1·65 would give satisfactory results for on-site determination of adventitious open areas. This was not, however, sufficiently accurate for insertion into a computer prediction technique for ventilation rates within dwellings.

To further clarify the situation an investigation has been undertaken into the variation of discharge coefficient with Reynolds Number for the types of crack likely to be found in a dwelling.

The equation of motion for the centre-line velocity in a rectangular crack is given by:

$$Uo \frac{\partial Uo}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \nu(\nabla^2 Uo) \qquad \ldots (2)$$

From this equation, the pressure drop across the crack may be given by:

$$\frac{Po - Pz}{\frac{1}{2}\rho\bar{u}^2} = \left[\left(\frac{Uo}{\bar{u}}\right)^2 - 1\right] + \frac{2\nu}{\bar{u}^2}\int_0^z -(\nabla^2 Uo)dz \qquad \ldots (3)$$

Where $(p_o - p_z)$ is the pressure drop across the crack. This equation has been integrated by Han[4] and the pressure drops have been related to a non-dimensional parameter

$$\frac{Z}{Re_h \cdot D_h}$$

where Re_h is Reynolds Number based on hydraulic diameter D_h and Z is the centre-line distance.

For engineering purposes equation 3 can be written as:

$$\frac{p_o - p_z}{\frac{1}{2}\rho\,\bar{u}^2} = \frac{C_A Z}{Re_h D_h}$$

Where C_A is an apparent coefficient which varies with aspect ratio and Reynolds Number.

The losses for a rectangular crack with abrupt entrance and exit may be expressed in terms of kinetic energy as:

$$p_e = K_1 \tfrac{1}{2}\rho\bar{u}^2$$

where K_t is an empirical constant.

The total pressure drop across the rectangular crack is therefore given by:

$$\frac{\Delta p}{\frac{1}{2}\rho\bar{u}^2} = \frac{C_A Z}{Re_h D_h} + K_1$$

where

$$\Delta p = (p_o - p_z - p_e)$$

Also

$$\frac{\Delta p}{\frac{1}{2}\rho\bar{u}^2} = \frac{1}{C_d^2}$$

where C_d is the discharge coefficient of the crack.

So

$$\frac{1}{C_d^2} = \frac{C_A Z}{Re_h D_h} + K_1 \qquad \ldots (4)$$

Equation 4 relates the discharge coefficient to the dimensions of the crack for a given Reynolds Number. If this relationship holds in practice it can be usefully employed in a mathematical model to calculate the correct value of the constant in equation 1.

It has not been possible to test this equation in field studies due to the complexity of cracks found in a typical room. It was therefore considered necessary to study the validity of the equation for given crack types under simulated natural conditions.

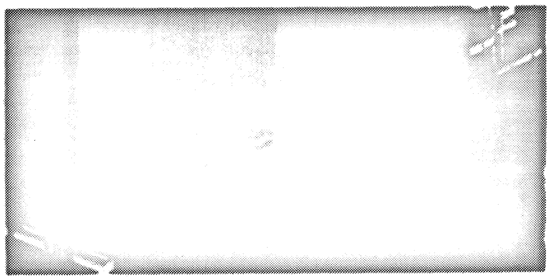

Fig 4: Perspective view of 'L-shaped' crack.

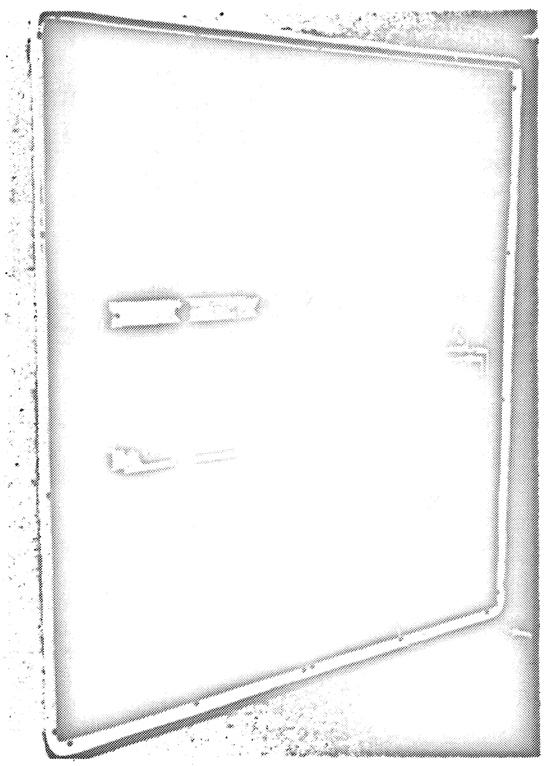

Fig 5: Front view of box.

3 EXPERIMENTAL INVESTIGATION

Twelve forms of crack were used, four of these being of the simple "straight through" type, six being "L-shaped" and two "multi-cornered". In order to

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obtain three representative variations in crack thickness for each of the "L-shaped" cracks it was necessary to have a "female" portion and three "male" portions.

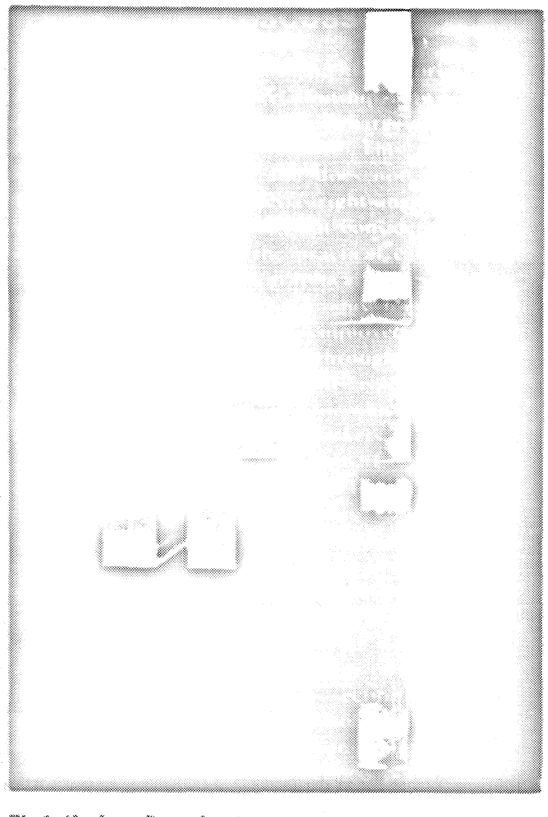

Fig 6: 'L-shaped' crack.

For accuracy and ease of handling the portions were made from 6 mm Perspex as shown in Figs. 4 and 6. The portions were fixed to the front of the ventilator test box as shown in Fig. 5.

For flow rates below 3 m^3/h (0·00083 m^3/s), air was drawn into the box and through a rotameter, for flow rates in excess of 3 m^3/h the flow rate was measured by a Roots meter. The pressure difference across the crack was measured using a micromanometer measuring up to 100 N/m^2 and a sloping gauge measuring up to 500 N/m^2 using a piezometer ring situated in the internal frame of the test box and a tapping on a shielded extension point of the box.

To obtain a good degree of accuracy in the experiments, a method of subtracted adventitious flows was adopted. The adventitious flows were obtained by sealing up the crack and setting up the required pressure differences between the inside and outside of the box, and measuring the flow. Then the flow through the crack was obtained by drawing air from the box at a known rate ~~and~~ subtracting from it the adventitious flow at that particular pressure difference. This method was used for the twelve crack geometries with a new adventitious volume flow test being made for each new set of readings. From the results of these experiments the discharge coefficient, C_d, and the Reynolds Number, Re_h, were obtained as described in the Appendix.

4 RESULTS AND DISCUSSION

The theoretical considerations of this work have produced, in equation 4, a relationship between the dimensions of the crack and the discharge coefficient in terms of the Reynolds Number. This is for an ordinary rectangular orifice and does not take into consideration such peculiarities as right-angled bends. This relationship therefore was not considered to be an exact representation of the practical case. Using this as a base for obtaining a graphical representation of the empirical data, curves are shown which are typical of the three types of crack employed.

Fig. 7A gives results for a 'straight-through' crack such as that found beneath a door. This is essentially a long rectangular orifice the results for which are in fair agreement with those of previous workers.

Fig. 7B gives a typical result for an "L-shaped" or right-angled bend crack such as that found around a door. The curve is not smooth as suggested by equation 4: this deviation from a smooth curve can be explained in the following way. At low Reynolds Numbers the flow is laminar along the whole length of the crack, i.e. in the entrance length before the bend and in the exit length after the bend with laminar separation occurring at the sharp edge of the corner, the flow emerges as a jet (in cross-section) from the inside of the crack. As the Reynolds Number is increased, laminar separation remains as above, but laminar reattachment at a well-defined point occurs (provided the exit length is sufficiently long) and subsequent development of a laminar flow profile

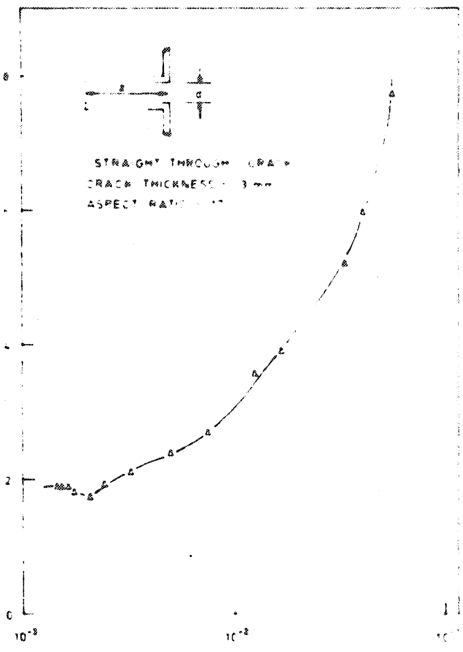

Fig 7a: Graph of $1/c_d2$ against Log ν/Reh Dh for crack 3.

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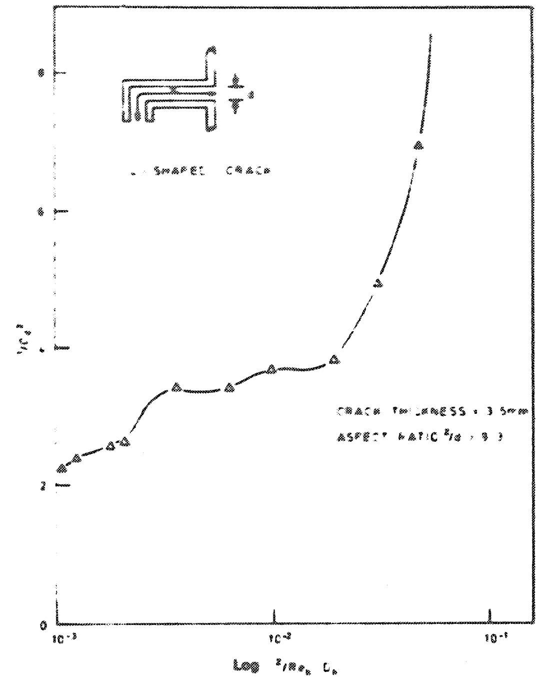

Fig 7b: Graph of $1/C_d2$ against Log z/Reh Dh for crack 9.

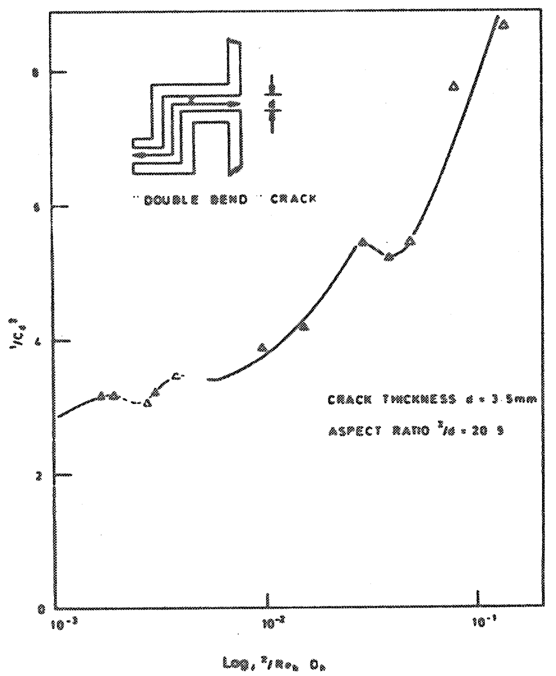

Fig 7c: Graph of $1/C_d2$ against Log z/Reh Dh for crack 11. ('Double bend' is referred to in text as 'multi-cornered.')

along the rest of the crack. Further increase in Reynolds Number causes the flow after the bend to become unstable and gives rise to a wavering motion. This wavering causes a rise in the hydraulic resistance of the crack and a lowering of the discharge coefficient resulting in a rise in $1/C_d^2$ so forming a hump in the curve. Further increase in Reynolds Number brings about the deterioration of the flow pattern after the bend. A circulating flow is set up in the separation region and the separated flow becomes turbulent, this transition resulting in reattachment being distributed over an area rather than being concentrated at a clearly defined point. The transition raises the hydraulic resistance once more, resulting in another hump corresponding to a relevant Reynolds Number. This explanation was arrived at by the observation of flow patterns, in a cross-section of the crack, using flow visualization by means of smoke. Fig. 7C gives a typical curve for a 'multi-cornered' crack and shows the same characteristics as the 'L-shaped' crack except for the extra hump. The explanation for two of these humps is the same as above, the transitions taking place in the exit length beyond the second bend. The third hump is caused by some effect which occurs in the middle length of the crack. The above analysis is purely on a qualitative basis, for a quantitative analysis it was necessary to obtain values of C_A and K_1 of equation 4 for each family of cracks. These values were obtained for each crack from graphs of $1/C_d^2$ against log Z/Re_hD_h, each slope gave a value of C_A and each intercept a value of K_1. Fig. 8 shows curves of C_A against aspect ratio for each type of crack from which the relevant value of C_A may be obtained. Fig. 9 shows the spread and trend of the values of K_1, obtained for each type of crack.

Taking an average value of aspect ratio for each family of cracks and using the values of C_A and K_1 obtained from Figs. 8 and 9, for given values of Z/Re_hD_h the corresponding values of $1/C_d^2$ can be obtained. Figs. 10A, 10B and 10C show semi-empirical curves obtained in this way compared with the experimental points for "straight-through", "L-shaped" and 'multi-cornered' cracks respectively.

The values of C_A and K_1 obtained in this way give close enough agreement to enable the equation to be used in obtaining an independent value of the discharge coefficient for each type of crack for a given Reynolds Number and may be incorporated into the computer technique for predicting the effect of combinations of room components on the ventilation of a building.

It is necessary to use an iterative method to arrive at the correct value of discharge coefficient using equation 1 in the new form:

$$\Delta p + \frac{K}{A^2} Q^{1.65}$$

where

$$K = \frac{\rho}{2C_d^2}$$

5 CONCLUSIONS

1. A Square Law Flow relationship is not valid for small openings, but a 1·65 power law gives satisfactory results for the purpose of obtaining adventitious open areas.
2. A variation in discharge coefficient was obtained which did not conform to any available rectangular duct theory, but which could be explained from changes in the flow pattern that was observed.

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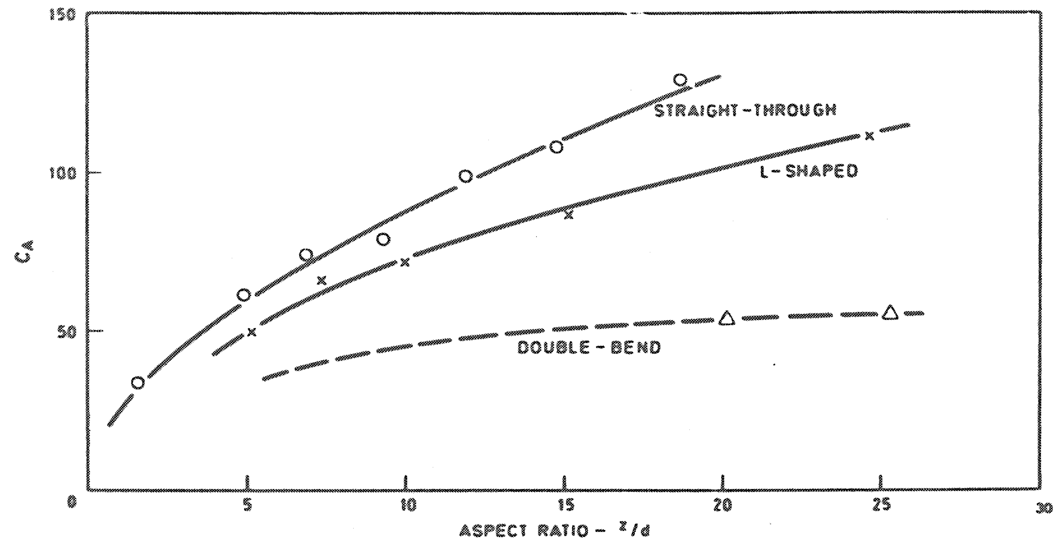

Fig 8: Curves for obtaining the relevant value of Ca.

3. The experimental and theoretical study has given semi-empirical results for three types of crack found in dwellings. This semi-empirical result will be written into the mathematical prediction technique for ventilation rates within dwellings.

ACKNOWLEDGEMENTS

The authors would like to thank their colleagues at Watson House for their assistance in the preparation of this paper and British Gas Corporation for permission to publish it.

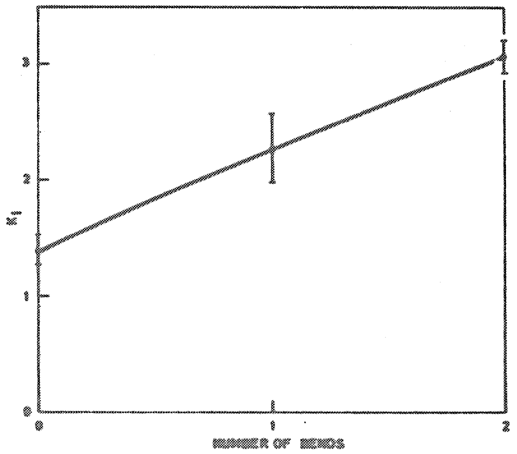

Fig 9: Trend of values of K1.

REFERENCES

1. J. B. Dick: The fundamentals of natural ventilation in houses, *JIHVE*, June 1950.
2. D. A. Thomas and J. B. Dick: Air infiltration through gaps around windows, *JIHVE*, June 1953.
3. P. J. Jackman: A study of the natural ventilation of tall office buildings, *JIHVE*, August 1970.
4. L. S. Han: Hydrodynamic entrance lengths for incompressible, lamina flow in rectangular ducts, *J. of Applied Mechanics*, A.S.M.E., September 1960.

APPENDIX

EVALUATION OF Re$_h$ and D$_h$

$$D_h = 4R_h$$

where

$$R_h = \text{hydraulic radius} = \frac{\text{Flow Area}}{\text{Wetted Perimeter}}$$

$$Re_h = \frac{\bar{u}D_h}{\nu}$$

$$Re_h = \frac{Q}{A}\frac{D_h}{\nu}$$

where

$$Q = Q_1 - Q_{AD}$$

Q_1 is the flow measured directly and Q_{AD} is the adventitious flow for that particular crack and pressure difference.

For a crack with length l width d:

$$R_h = \frac{1 . d}{2(1 + d)}$$

which reduces to:

$$R_h = \frac{d}{2}$$

So

$$D_h = 2d$$

Values of C_a were obtained from the experimental results using:

$$C_a = \frac{Q}{A}\sqrt{\frac{\rho}{2\Delta p}}$$

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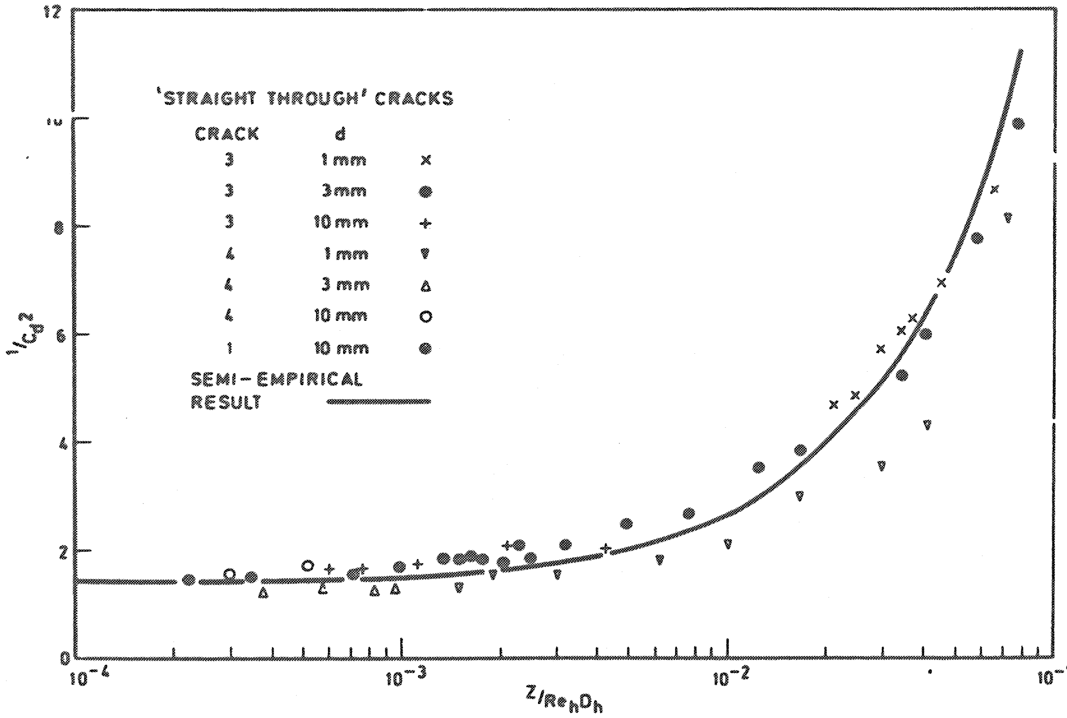

Fig 10a: Comparison between the semi-empirical curve and experimental results.

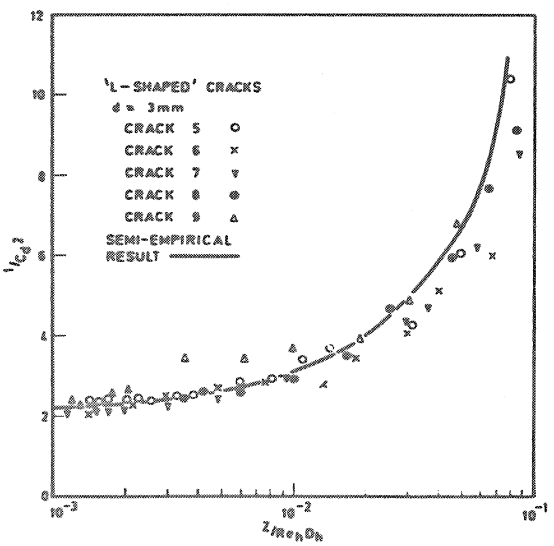

Fig 10b: Comparison between the semi-empirical curve and experimental results.

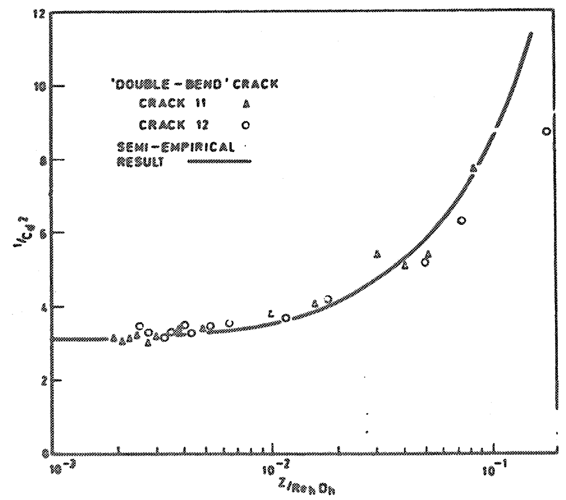

Fig 10c: Comparison between the semi-empirical curve and experimental results. ('Double-bend' is referred to in text as 'multi-cornered'.)

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DISCUSSION

Afternoon Session

Chairman: Mr K W Dale

Mr J Shannon (Fabers): (You said that you are aiming to look at J and K). In your first equations you showed the equation $AQ + BQ^2$. These two terms are really each describing the proportions of the laminar and turbular parts of the flow, for a particplar type of crack. As you showed, the two terms can be compounded into a single power law $K.Q^n$ and 'n' will vary for different cracks. However, you have chosen to hold 'n' constant for all cracks. The 'n' really is what tells you about the split. Why have you elected to do it in this round-about way, as it seems to me?

Mr Hopkins: Firstly, we wanted to have a simple equation for the types of crack that we are dealing with. These cracks are quite small and for the field-work we have obtained some good agreement between the equations and results by keeping K constant and nominating the value of 1.65 to n. For our computer prediction technique, however, we wanted to look at various flow rates through different cracks. This problem becomes rather complex in its simulation in the program and we thought that this equation approach was the best way to go about it.

Mr Surtees (North Thames Gas): In about 1965 Watson House did some work on the same lines on adventitious ventilation and published two special booklets which gave nomagrams for calculating the effect of adventitious ventilation when assessing requirements for rooms. Was any reference made to this former work when this study was undertaken, and, if so, what is the basic difference between what you are doing now and the results achieved then?

Dr Harris-Bass: We are aware of the earlier work at Watson House. However, we considered that the original work did not really delve into the flow mechanics of the problem, and we endeavoured to take a different slant by looking at the Reynolds Number dependence of the flow. I am not saying that the earlier work is now useless. What we are trying to do is to get a better insight into what is happening and therefore to update the data already available to people like yourself in North Thames Gas.

Dr P R Warren (BRE): The authors are to be congratulated on producing a large quantity of data and experiments. Do they intend to publish their results? This document only contains the results for three particular cracks. It would be very interesting if they would do so. I believe that Han's equations referred to laminar flow, in which case when you were plotting C_A against $\frac{Z}{D}$ for the straight through opening one would perhaps expect it, as Z goes to infiinity, to approach of value of 96, which would be the value expected for the very long plane crack with laminar flow. Your values seem to be well above this.

Dr Harris-Bass: The answer to your first question is: Yes, we will be publishing the results of this and also future work that we hope to carry out in this particular field. One of the conditions that we have not yet loked at is the flow through a crack which has foam-backed weather stripping in it. This presents a rather more advanced flow pattern.

With regard to the value of C_A, this was a point that worried me, quite honestly. I agree that our results are higher. I think there is a possibility that Han's results are liberal for laminar flow. We would hope that at this particular point we are dealing with pure laminar flow. Perhaps we are not. I would be interested to hear afterwards your comments on that facet of the research. I do not think we have talked about it yet.

Dr P R Warren (BRE): I believe you said in your introduction that you were intending to use the derived equations for a programme. One of the problems in using such an equation is that the Reynolds Number involves the volume flow rate. Do you envisage any difficulties with a large number of different cracks?

Mr L Hopkins: This work is still at the experimental stage and this is a problem that we are still thinking about. However, we hope that an interative technique, within the program, will overcome any foreseeable difficulties.

Mr Wood: Is N a variable, or is this the figure 1.6, and, if so, on what basis have you surmised that that should be the figure?

Secondly, can you amplify in your appendix the formula $Q = Q_1 - Q_{AD}$, with Q_A as the flow measured directly and Q_{AD} as the adventitious flow? Is that the total flow or the adventitious flow, to which some other calculating amount has to be added?

Mr L Hopkins: As was said before, the n can vary anywhere between 1 and 2, but we performed some tests in the field on adventitious open areas, extracting air from rooms and measuring the pressure differences across all the components in the room. By plotting a graph we obtained an exponent of 1.65 which we intended to use for the sizes of cracks that we were investigating.

With regard to the formula $Q = Q_1 - Q_{AD}$, this was a method we used for finding the volume flow rates through the cracks in the actual laboratory experiments.

The crack was tightly closed and then air was drawn from the box and the adventitious volume flow measured. The box obviously contained some small perforations and cracks which could not be sealed up with paint and tape. Having taken many flow and pressure drop measurements we drew a graph relating the adventitious flow to the pressure drop. We opened the crack and did our test, then in order to get the correct flow through the crack at a particular pressure drop we substracted the adventitious flow, obtained from the graph, from the measured flow. This ensured

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that we were not taking a part of the flow through the crack as the flow through the adventitious areas in the box although these were very small.

Mr A F Whitbread (North Thames Gas Board): I am trying to relate this to the previous paper. I think I am right in supposing that this means that an adventitious area of say 10 in^2 at a wind speed of 10 mph would not be 10 in^2 at a wind speed of 5 mph. If that is correct, can you say what is the order of difference?

Mr. L. Hopkins: If you had an open area concentrated in the form of a circular hole in the wall then I would agree that the area would not change, no matter what strength of wind blew on it. But you must appreciate that the cracks that we are dealing with are not concentrated into one place, they are distributed over the whole wall. Up to now, many people have tried to get over the problem of using various flow pressure equations. What we have tried to do is to use our own flow pressure equation to find out how this open area varies. If we have a very small crack then for a small pressure across it we shall only get a small flow through it. But as the pressure builds up the flow will go up until from the equation we can see that the open area will appear to open up. Although we cannot measure it, it does have an apparently large open area when there is a large pressure difference across it. With regard to the question, the answer will depend on the nature of the crack.

Mr Whitbread: I am only talking about the order of things.

Mr Hopkins: We would have to look into the question.

Dr J Moorhouse (British Gas Corporation, Midlands Research Station): If we are assuming that the aim is to reduce adventitious ventilation, is it better to have a series of L-shaped cracks or would it be better to have one long thin crack around windows and doors?

Mr L Hopkins: That is a very good point! With a series of long thin cracks we are back to the draught problem. With an L-shaped crack, although there is no apparent restriction to the flow, there is a possibility of the flow being broken up, depending on the geometry of the crack. We have noticed that the flow becomes turbulent in the exit length of the crack and it can be quite unstable over a range of Reynolds numbers. On the whole I think it would be better from the question of reducing the adventitious ventilation to have a series of L-shaped cracks.

A speaker (? Housing Department): I have never yet seen a crack with uniform polished sides. Surely with any irregularities your experimentation technique would be completely irrelevant?

Mr L Hopkins: No. You will appreciate that this is based on a theoretical approach and to be able to repeat tests we had to use a consistent form of crack. We hope in the future to test irregularly finished cracks to see what sort of error is induced with roughness etc.

* **A speaker:** I am not at all sure that I fully understand what the experiments have been about. We have on the board an expression relating pressure drop and the volume, and exponent n.

Mr. Hopkins: I am using n equal to 1.65 as mentioned in the text.

The speaker: I would suspect that on the whole you could have related your results by variation of n.

Mr. Hopkins: As I said, we would do that for our field measurements. The agreement is quite close when assessing the open area in a room using n = 1.65. For our computer program we decided that we needed more accuracy and so we required more detail about each individual crack.

The speaker: I think you are aiming at pseudo-accuracy. A speaker in the discussion said that the crack may close up or increase in size, and you are supposed to take that into account.

Mr J P Cockroft (Building Services Research Unit, University of Glasgow): Do you have any ideas as to how you would measure the width of these cracks as they occur in practice?

Mr Hopkins: You might be wondering how we arrived at these thicknesses. We went round a number of houses with feeler gauges, measuring cracks to get typical values.

* *Name not given*

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