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Summary Flows around doors in partly open positions are measured in full-scale laboratory chambers and in site tests. Flows which are primarily temperature driven are measured using tracer gas techniques. Also investigated are the superimposed effects of mechanical ventilation in the laboratory tests and of wind and stack effects in the site tests. At small door opening positions, conventional buoyancy theory can be applied to estimate the two-way flow generated by temperature difference. Combined temperature and pressure driven flows can be analysed within ±20% by superimposing the respective theories. Room air movement plays an important part, giving rise to relatively high superimposed flows. For this reason, back-flow is almost inevitable when the door is not properly closed.

Air flows between predominantly naturally ventilated rooms through partly open doors

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List of symbols

A, A_1, A_2	Areas of openings (m^2)
C_d	Discharge coefficient
E	Ratio of areas A_1/A_2
g	Acceleration due to gravity (m s^{-2})
h	Height of single opening or vertical distance between two openings (m)
p	Pressure (Pa)
Δp	Pressure difference between rooms
Q	Volume flow rate (m^3 s^{-1})
Q_p	Volume flow rate (specifically pressure driven) (m^3 s^{-1})
Q_T	Volume flow rate (specifically temperature driven) (m^3 s^{-1})
T	Absolute temperature (K)
ΔT	Temperature difference between rooms (K)

1 Introduction

The degree of mobility of air between rooms of dwellings is strongly dependent on the positions of the internal doors. When the doors are closed, zones are badly connected and the interzonal air flows occur through cracks between the door and its casing. When the doors are wide open, the temperature and pressure differences tend to collapse and the zones become well connected; the building then resembles a large single zone. Hence the main controller of interzonal air movement is the internal door. This paper describes measurements of the two-way flows which occur between rooms when the doors are partly open and follows a previous Technical Note[1] concerning pressure-driven flows through such openings.

Part of the work has taken place in laboratory conditions where the complexities of fluctuating weather parameters could be avoided. The remaining part of the work was carried out in a dwelling so that the effects of superimposition of inside–outside pressure and temperature variations could be assessed.

Some of the site measurements have compared the ventilation and internal air movements with and without a well sealed external window. These results can be interpreted as revealing the effects of including trickle ventilators.

The effects of extract fans have fallen within the scope of this work. Measurements of combined temperature- and pressure-driven flows through partly open doors have been included.

2 Theoretical basis

Brown and Solvason[2] and Shaw[3] have developed the theory of flow generation between two spaces at different temperatures through openings in the dividing partition. When there is a continuous vertical opening (Figure 1), the total volumetric discharge through one half of the opening is given by:

$$Q = C_d \frac{A}{3} \left(\frac{g \Delta T}{T} \right)^{0.5} h^{1.5} \tag{1}$$

this being matched by an equal and opposite flow in the other half of the opening.

Warren[4] has developed a corresponding theory for the flows through pairs of openings (Figure 2), vertically separated in the partition. The flow rate is given by:

$$Q = \frac{C_d (A_1 + A_2) \sqrt{2E}}{(1 + E)(1 + E^2)^{1/2}} \left(\frac{g \Delta T h}{T} \right)^{1/2} \tag{2}$$

where E is the ratio of the areas A_1/A_2.

Both these theories are well known and form the basis of most of the predictive techniques in common use (e.g. the *CIBSE Guide*[5]). For the present investigation involving an array of cracks and orifices in juxtaposition around the partly open doors, it is proposed that equation 2 be applied to the opening at the top of the door, forming a driving 'moment' with the opening at the bottom of the door, while equation 1 is used for the vertical openings.

The major uncertainties in applying these equations concern

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§ This work was carried out when Prof. Howarth was at the School of Construction, Sheffield City Polytechnic.

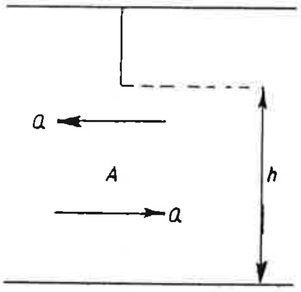

Figure 1 Temperature-driven flows through high single opening

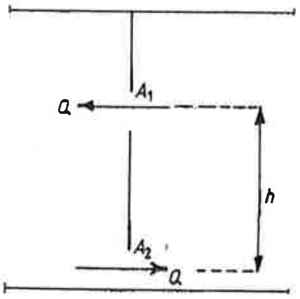

Figure 2 Temperature-driven flows through two openings

the values of the discharge coefficient C_d and the effects of turbulence.

2.1 *Discharge coefficients*

In respect of the discharge coefficient, a range of factors have been considered by previous workers. Riffat(6) observed coefficients of discharge between 0.22 and 0.61 at temperature differences between 13°C and 0.5°C respectively; the suggested implication being the increasing interference of more vigorous adjacent and opposite flows at the higher temperatures. A similar phenomenon has been observed by Kiel and Wilson(7) but is not anticipated in the present work which concentrates on small door openings providing a tall thin orifice.

Shaw(3) found a range of discharge coefficients based on temperature difference; from 1.8 to 0.65 as the temperature difference increased from 0.25°C to 10°C, and Etheridge(8) found that there are different flow regimes through different types of openings. Gaps around closed doors and windows take the form of 'cracks' whereas larger openings are more akin to orifices. Effectively, the exponent of the driving pressure difference (0.5 for orifice flows implied by equations 1 and 2 above) increases at the lower flow rates and this would apply to the temperature-driven flows currently under consideration. A discharge coefficient which is higher at lower temperature difference (and hence lower velocity of flow through the opening) is consistent with the findings of Baker, Sharples and Ward(9) who found a dependence of C_d on Reynolds number—with the higher values of C_d at the lower Reynolds number.

The previous measurements(1) of pressure-driven flows through the door openings described here showed that a discharge coefficient of 0.6 was appropriate at the range of pressure differences employed and when applied to all the open areas lumped together. This result is not necessarily directly applicable to the temperature-driven flows described in this paper; firstly, the velocity through the opening was higher than in the present work so there may be differe
(perhaps higher) values of C_d applicable here and secondl
the areas of opening totalled around the door consisted of
blend of cracks (down the hinge side) and orifices (part
the top and down the latch side). However, even with t
door only slightly ajar, the flows through the larger openin
swamped the flows through the cracks, so it is not surprisi
that a discharge coefficient of value normally associated wi
orifice flows was appropriate.

2.2 *Background air movement*

The problem of specifying a discharge coefficient at the lo
velocities anticipated in flows driven by normal room-t
room temperature differences is linked to the problem
dealing with turbulence. It will be seen that there is stron
evidence of flow fluctuation which has a significant effect o
the interzonal flows in the form of scatter and of a flow a
zero temperature difference.

Since the object of this work is to acquire a deeper understanding of the air movements within multi-zone building
such as dwellings, the driving temperature differences ar
small. The interzonal bulk air movements are then of simila
order of magnitude to the background room air movement
generated by convective sources (e.g. cold walls an
radiators). Variable results at these low temperature differences have been observed by workers such as Kiel an
Wilson(7) and Hendrix, Henderson and Jackson(10). Thes
variations cannot be avoided in the full-scale tests describe
here and their existence is regarded as a significant findin
of this work. Thus the results are intended to provide simpl
algorithms for mean flows to be used in ventilation model
and also to indicate the expected variations from such mean
flow predictions.

2.3 *Simultaneous pressure- and temperature-driven flows*

Pressure- and temperature-driven flows were assumed to be superimposed in the manner shown in Figure 3. Here Q_T is assumed to be the equal temperature-driven flow in and out, while Q_p is the total unidirectional pressure-driven flow. Thus where the two flow regimes occur simultaneously, the difference between the inflow and the outflow is the pressure-driven component and the average of the two flows is the temperature-driven component.

3 Method

3.1 *Laboratory facility*

A full-scale double chamber was employed. The two zones, each of volume 30.4 m^3, were separated by a partition of timber studding with plasterboard on each side and a standard internal door (1.98 m × 0.76 m). The areas of opening around the door in its three positions are shown in Table 1. Each side of the chamber had an independent air supply and exhaust system.

Temperature control was by use of ventilation of the 'cool' side and by a thermostatically controlled convector heater on the 'warm' side of the partition.

3.2 *Site facility*

The dwelling was of stone construction with walls 0.36 m thick, a slate pitched roof and sash windows. The size of the dwelling was such that internal seals were required to reduce the volume to a size more representative of common UK

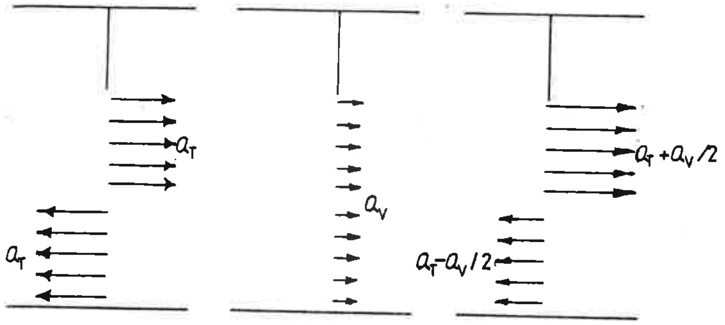

Figure 3 Simplified approach to analysis of combined temperature- and pressure-driven flows

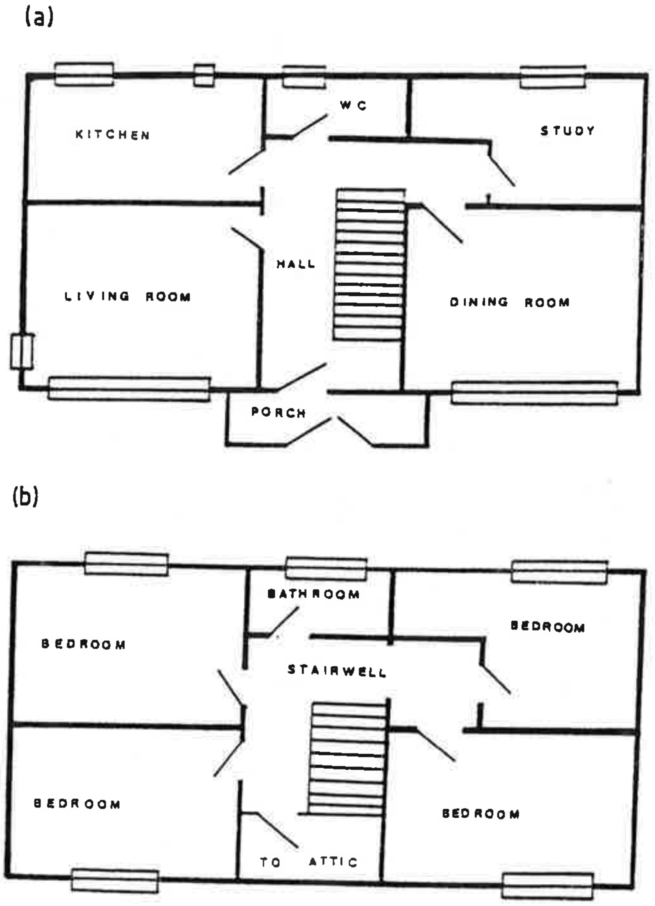

Figure 4 Plans of (a) ground and (b) first floors of test dwelling

family accommodation. An indication of the layout is shown in the plans of Figure 4. Most of the measurements were concentrated on the living room/stairwell/bedroom 2 flow path. Both the rooms faced a south-easterly direction and, while little influence could be expected from neighbouring detached houses, there were several mature trees within 10 m.

3.3 *Air flow measurement*

Table 1 Crack and gap areas (m^2) around the door used in the laboratory tests

Position no.	Gap at open (latch) edge of door (mm)	Location: Latch	Hinge	Top	Bottom	Total
1	2.4	0.0048	0.0045	0.0022	0.0055	0.0170
2	6.3	0.0126	0.0055	0.0023	0.0055	0.0259
3	24.5	0.0490	0.0059	0.0195	0.0055	0.0799

Flows in the laboratory chambers were measured using single tracer gas decay in the warm side where the temperature was maintained by a thermostatically controlled convector. The 'cold' side was provided with a constant ventilation rate to remove the heat transferred in the air stream at the door opening.

For the site tests, a multiple tracer gas technique (using freon gases 114, 12 and BCF) was employed for the measurement of interzonal air flows. This method, previously described by Irwin, Edwards and Howarth⁽¹¹⁾ had the advantages of relatively low cost, portability of the equipment and simplicity of analysis of the results. The method has been previously validated in a controlled three-zone laboratory test where errors of less than 8% were reported. The gas analyser is an AI Model 50.500.

The tracer gases were released in the zones by bursting balloons containing the gases. The balloons were exploded remotely by electrical heating elements.

To provide a uniform tracer gas concentration within the space, oscillating mixing fans were operated for 5 min with closed doors between the test zones. After the mixing period, a further 3 min was allowed to enable pre-mixing equilibrium conditions to return. In most of the tests other air movement generators in the form of heaters and/or mechanical extract were in use, so providing a form of passive mixing while the tests were in progress. Scrutiny of the results would occasionally reveal signs of bad mixing—such as variations of concentration in different parts of the same zone. Such results were rejected.

4 Temperature-driven flows around partly open doors

4.1 *Laboratory measurements*

Using the door openings of Table 1, the following theoretical equations have been derived for the two-way temperature driven flows using the method described in section 2:

Position 1:

$$Q = 3.5\Delta T^{1/2}$$

Position 2:

$$Q = 5.4\Delta T^{1/2}$$

Position 3:

$$Q = 19.6\Delta T^{1/2}$$

where Q is the volume flow rate (m^3h^{-1}). A coefficient of discharge of 0.61, consistent with the findings of the pressure-driven flows(1), is used in these derivations. Temperatures varied with time and with height in the chambers. Temperature were averaged in both dimensions.

The experimental results are shown in Figure 5. The empiri-

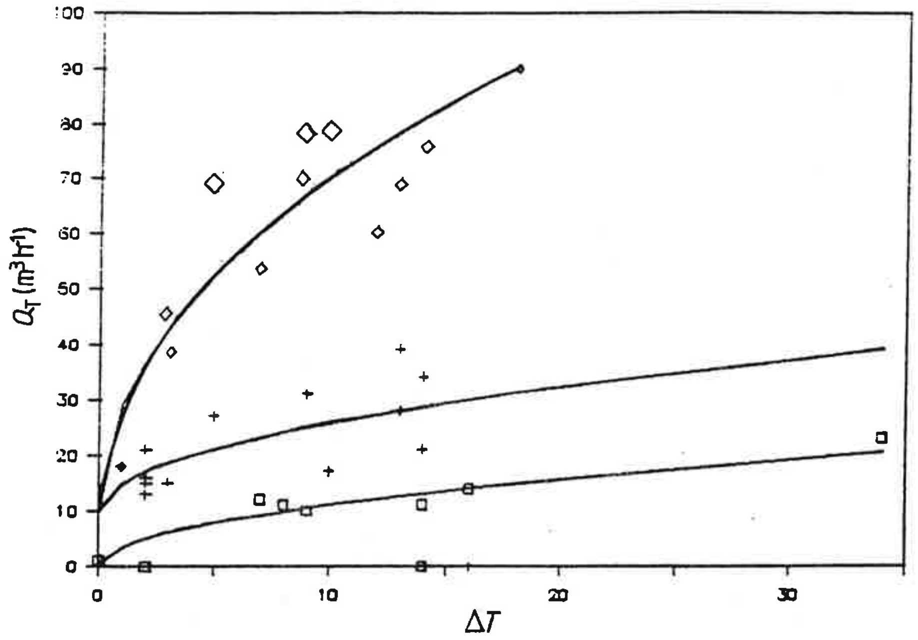

Figure 5 Temperature-driv flows through partly open door laboratory tests: □ position 1, position 2, ◇ position 3, — empi cal

Table 2 Open areas around doors used in site tests

Location around door	Area (m²)
Sneck	0.1010
Hinge	0.0078
Top	0.0203
Bottom	0.0014
Total	0.1305

cal lines of best fit are as follows:

Position 1:

$$Q = 3.5\Delta T^{1/2} + 0.02$$

Position 2:

$$Q = 5.0\Delta T^{1/2} + 10$$

Position 3:

$$Q = 19\Delta T^{1/2} + 10$$

4.2 Site measurements

The doors of the dwelling were larger than the door used in the laboratory tests. The corresponding open areas around the doors in the position tested are shown in Table 2.

The two-zone tests were carried out using the stairwell exchanging air with a bedroom and/or the lounge. Other internal doors not involved with the tests were closed but unsealed. The main leakage path, other than the tested room door itself, was the crackage of the front door which opened onto the stairwell zone.

The results of the temperature-driven flow tests are shown in Figure 6. The results shown are the average of the measured outflows and inflows. Most of the measurements were carried out with the windows sealed. The few resul with the window in the bedroom unsealed are also shown.

The line of best fit is as follows:

$$Q = 23\Delta T^{1/2} + 11$$

The theoretical relationship based on Shaw and the abo areas is:

$$Q = 21.8\Delta T^{1/2}$$

Thus the theoretical result is shown to provide a satisfactor approximation if turbulence is superimposed. The nature the turbulence is unknown, but a constant flow rate $11\ \mathrm{m^3 s^{-1}}$ is implied.

The difference between the outflows and inflows effectivel indicates any superimposed unidirectional flow and wa generally less than 0.8 airchanges per hour for the bedroom Although the results were not sufficiently well condition to relate these effects to wind speed/direction or overal stack effect, it was possible to draw the following conclusion when larger superimposed flow was implied:

(*a*) Extra large stack effects, equivalent to more than 25° inside–outside temperature difference, forced more ai into the bedroom at a throughput equivalent t 0.8 ac h^{-1}. It was believed that the continuity of flo through the room with sealed windows was maintaine by an outflow of air through the background leakag path—a background leakage similar to the flow throug the unsealed window was observed in pressurisatio tests on the bedroom.

(*b*) In all cases when the bedroom window was sealed th superimposed throughput into the bedroom was in th landing–bedroom direction, suggesting a prevalent stac effect. With the window sealed, the effect of win pressure and its direction did not succeed in reversin this direction.

(*c*) When the bedroom window was unsealed, the super imposed throughput was greater, again usually in th landing–bedroom direction. However, when the win

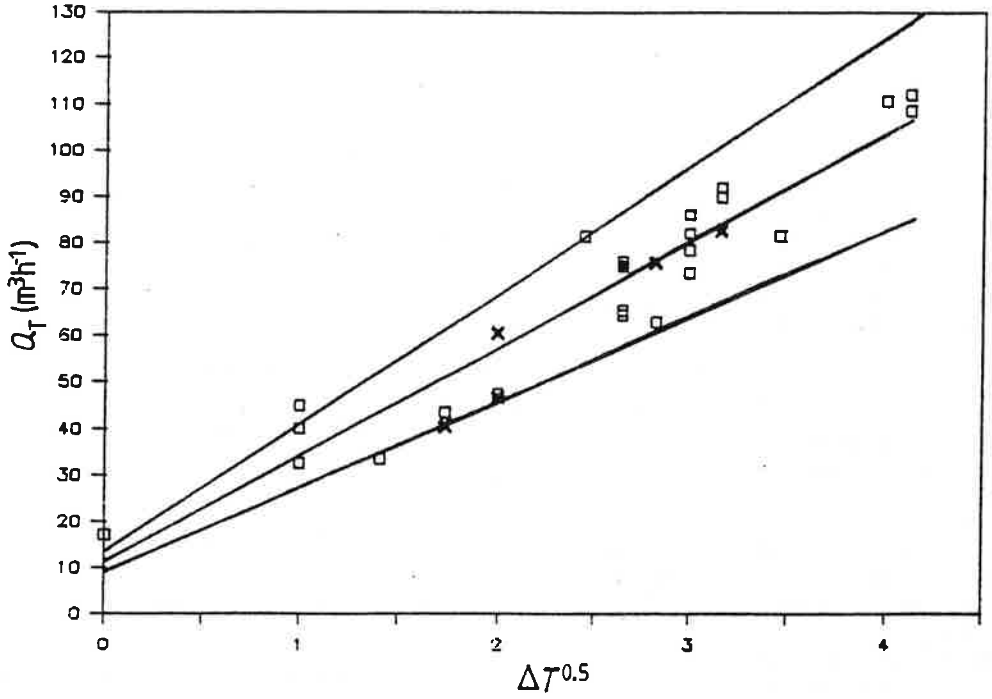

Figure 6 Temperature-driven flows through partly open door (position 4A) in site tests: □, × two-way flow, — $23\Delta T^{0.5} + 11$

was blowing onto the bedroom window, the flow direction was reversed and there was a net influx of outside air.

Examples of the input–output flow distributions for the bedroom are shown in Table 3.

4.3 Combined pressure- and temperature-driven flows around partly open doors (laboratory)

Figure 7 shows the arrangement of the chambers used in the measurements of combined temperature- and pressure-driven flows.

The average of the two interzonal flows was plotted in Figure 8. This represents the temperature-driven component and, although there is some scatter, reasonable agreement with the previous theoretical and empirical results is found.

The line of best fit is given by:

$$Q = 18\Delta T^{1/2} + 19$$

The constant term representing turbulence is higher than in the case of pure temperature-driven flow, as would be expected with the additional mixing produced by the mechanically induced airflow.

The pressure induced component is shown in Figure 9. Again there is some scatter (±20%). In this case, the equation for pressure-driven flow found in the earlier tests is superimposed. The results fit in the +18%, −22% scatter around this line.

It is argued from these results that it is reasonable to apply the theoretical equations of pressure- and temperature-driven flows, algebraically superimposed, in order to predict the effects of extractor fans. However, it must be emphasised that the effect of turbulence is uncertain since it depends again on the nature of the background room air movements, this time generated by both the heat source and the mechanically induced flow.

It should be noted that in *all* cases tracer gas from the low-

Table 3 Interzonal air flows (m^{3}h^{-1})

Window state	Location				Comments
	Landing–bed	Bed–landing	Bed–outside	Outside–bed	
Sealed	83	74	21	12	Wind → Window
	66	60	6	0	
	56	39	17	0	High stack
	55	32	21	0	High stack
	38	43	0	5	Wind → Window
	62	69	15	22	Wind → Window
Unsealed	98	67	34	3	
	106	43	86	23	
	102	51	51	0	
	31	63	43	75	Wind → Window

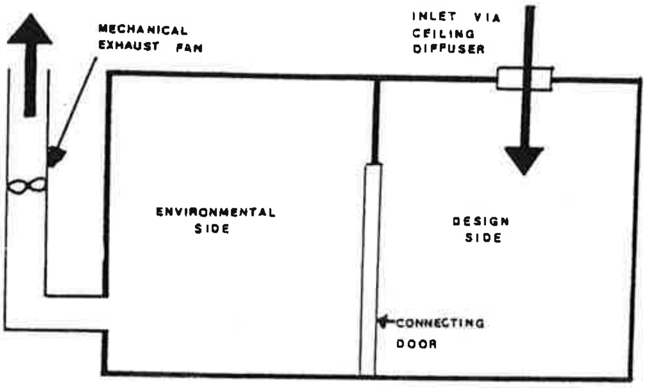

Figure 7 Air supply and extract system for chambers in combined pressure- and temperature-driven flows

pressure zone travelled 'back' into the high-pressure one, even when the pressure dominated the buoyancy forces. The lowest back flow was 6 m^3h^{-1}. Local room air movement effects are thought to be responsible.

5 Overall conclusions

5.1

At small door opening positions, conventional buoyancy theory can be applied to estimate the two-way flow generated by temperature difference. However, an additional constant term should be included in the flow rate estimation. With convective heating the constant term has been found to be approximately 10 m^3h^{-1} (but lower values were implied with the door resting on the latch). It is suggested that the room air movement causes scatter among the results and dictates the size of the constant term. In a dwelling, conventional buoyancy theory can also be applied to estimate the two-way temperature-driven flows. Here, higher constant terms were implied (20 m^3h^{-1}).

5.2

The superimposed flows generated by stack and wind in the dwelling were much in evidence, though they were too variable to display any correlation. A strong stack effect implied by a high inside–outside temperature difference increased the flow into the bedroom from the landing. Rarely was there a net flow into the bedroom from elsewhere. However, trickle ventilators increase the amount of fresh air input even though it may still be exceeded by the outflow. Wind blowing towards the window inevitably increases the rate of input of outside air and may also produce a net outflow onto the landing.

5.3

Combined temperature and pressure driven flows can be analysed by superimposing the respective theories found above. Room air movement plays an important part, giving rise to relatively high constant terms, especially when the fan creates vigorous momentum flows. Back-flow is almost inevitable when the door is not properly closed even when superimposition suggests that the pressure-driven flow should be swamping the temperature-driven flow. Local room air movement and turbulence may again explain this phenomenon.

5.4

The factor which the occupant can operate (consciously or otherwise) to control internal air movements to greatest effect is the internal door. Even small openings increase dramatically the movement of air from zone to zone within the dwelling, especially upwards in the case of two-storey houses. Trickle ventilators increase the probability of input of fresh air, even on the leeward side of the building. Extractor fans greatly reduce the outflow of air from the depressurised room, but cannot guarantee zero outflow if the door is not properly closed.

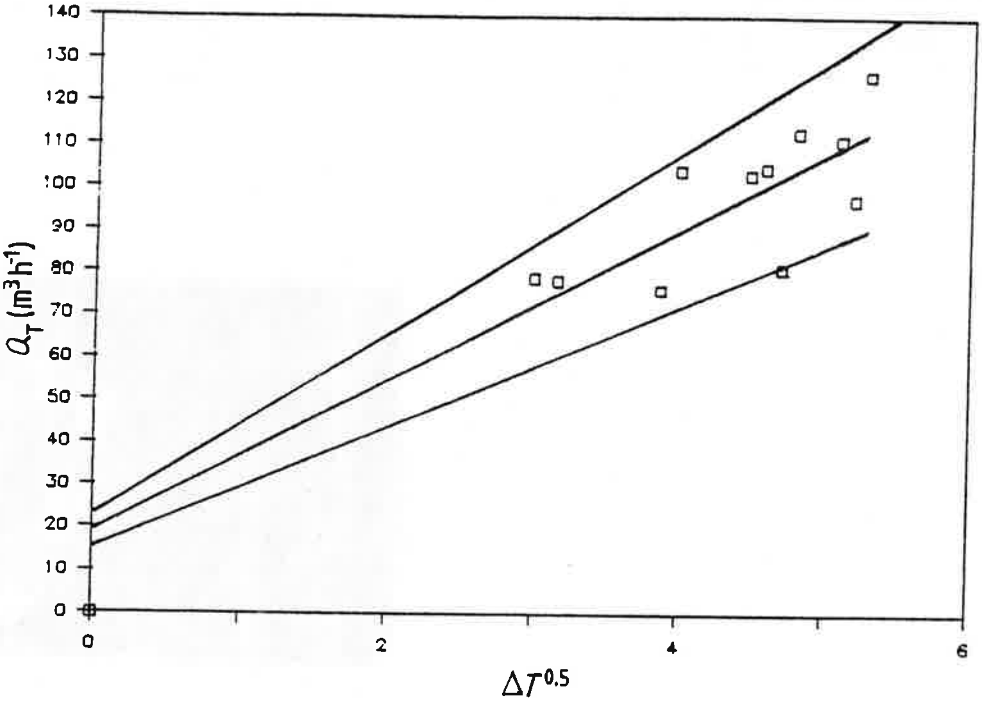

Figure 8 Temperature-driven component of combined pressure- and temperature-driven flows: □ measured flow, — $18\Delta T^{0.5} + 19$

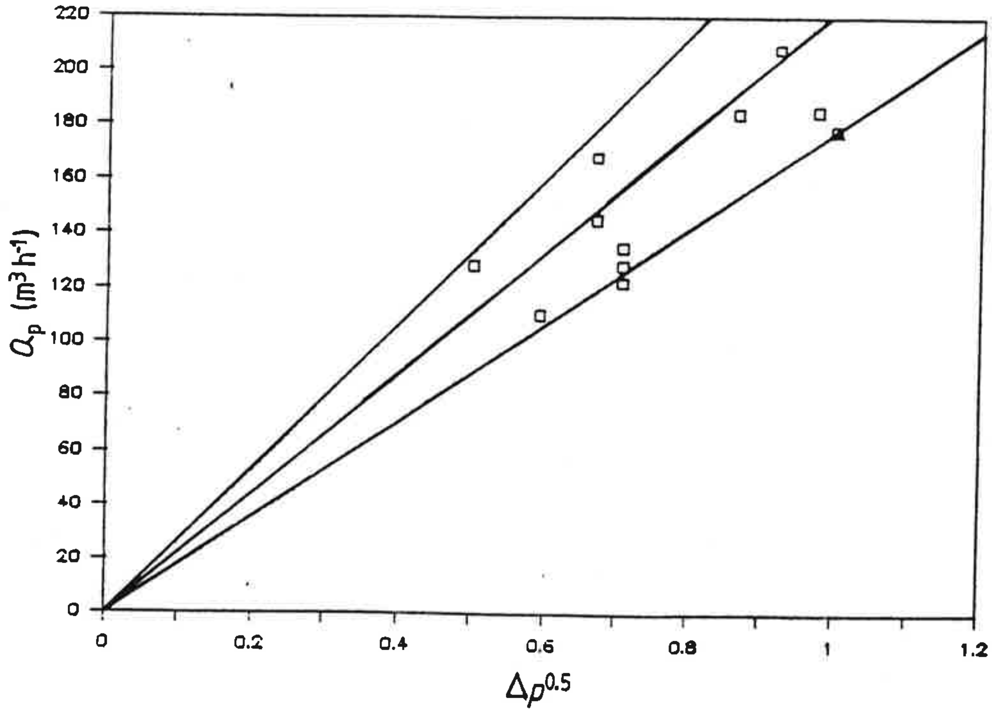

Figure 9 Pressure-driven component of combined pressure- and temperature-driven flows: ☐ measured flow, — $222\Delta p^{0.5}$

Acknowledgement

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