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Summary Despite its practical importance, there has been a general lack of information on air infiltration through building background cracks, especially when induced by temperature differences. This paper describes experimental work in which it was found that the rate of air infiltration due to temperature differences through cracks is proportional to the temperature difference between two adjoining rooms (or a building and the atmosphere) which the cracks connect. This finding agrees with theoretical predictions. The experimental results also confirm that the infiltration rate increases with increasing vertical distance between cracks.

Air infiltration through background cracks due to temperature difference

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1 Introduction

Information on building air infiltration and ventilation forms an important part of investigations of the building thermal performance, energy efficiency and indoor air quality. It is realised that, although background leakage through cracks represents 25–50% of the total building leakage area(1), data on such air infiltration are scarce.

Infiltration through background cracks can be classified into two categories: (*a*) infiltration due to pressure difference (between two rooms or a room and the atmosphere, which the crack connects), e.g. that caused by wind, and (*b*) infiltration due to temperature difference (or stack effect), e.g. that between a heated and an unheated room or a heated house and the atmosphere. Although temperature difference as a driving force manifests itself as pressure difference, the infiltration due to temperature difference (*b*) is distinguished from the infiltration due to pressure difference (*a*) because in case (*b*) the pressure difference would disappear if the temperature difference were absent.

There has been significant progress in the area of pressure-driven background crack air infiltration studies(2). Information on crack infiltration due to temperature difference, however, is not yet available.

In this work, the effects of the two most important factors affecting the infiltration rate through cracks due to temperature differences, namely those of the temperature difference across the crack and the distance between the cracks, were investigated experimentally.

2 Theoretical formula for the rate of infiltration through cracks due to the existence of temperature difference

The pressure in a room varies with height and the rate of the variation depends on the temperature in the room. Therefore, if the temperatures in two adjoining rooms (Figure 1) are different, then a pressure difference exists across the common wall at any particular height (except the neutral height, which will be discussed later). This pressure difference causes air flow if cracks exist in the wall.

The pressure variation with height is described by

$$P_h = P_r - \int_{h_r}^{h} g\rho \mathrm{d}h \tag{1}$$

where P_r is the pressure at a reference height h_r along the wall; g is the gravitational acceleration and ρ is the density. The density is related to temperature by

$$\rho = \frac{P}{RT} \tag{2}$$

where R is the gas constant for air. From the above two equations, we can derive

$$P_h = P_r - \int_{h_r}^{h} \frac{gP}{RT}\mathrm{d}h \tag{3}$$

Suppose the temperature is uniform with height, then equation 3 becomes

$$P_h = P_r - \frac{g}{RT}\int_{h_r}^{h} P\mathrm{d}h \tag{4}$$

Since variation of P along h is in the order of 10 Pa, the magnitude of the relative variation of P is 10^{-4}, which is negligible. Therefore, the P in the integral term can be regarded as constant and given the value of the local atmospheric pressure (P_{atm}). So we have

$$P_h = P_r - \frac{gP_{\mathrm{atm}}}{RT}(h - h_r) \tag{5}$$

In the case of adjoining rooms, if we take the neutral height (defined as the height at which the pressure difference across the common wall is zero) as the reference height and let $h = 0$ at that height, then the pressure difference across the common wall is evaluated by

$$\Delta P_h = P_{1h} - P_{2h} = \left(P_n - \frac{gP_{\mathrm{atm}}}{RT_1}h\right) - \left(P_n - \frac{gP_{\mathrm{atm}}}{RT_2}h\right) = \frac{gP_{\mathrm{atm}}h}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \tag{6}$$

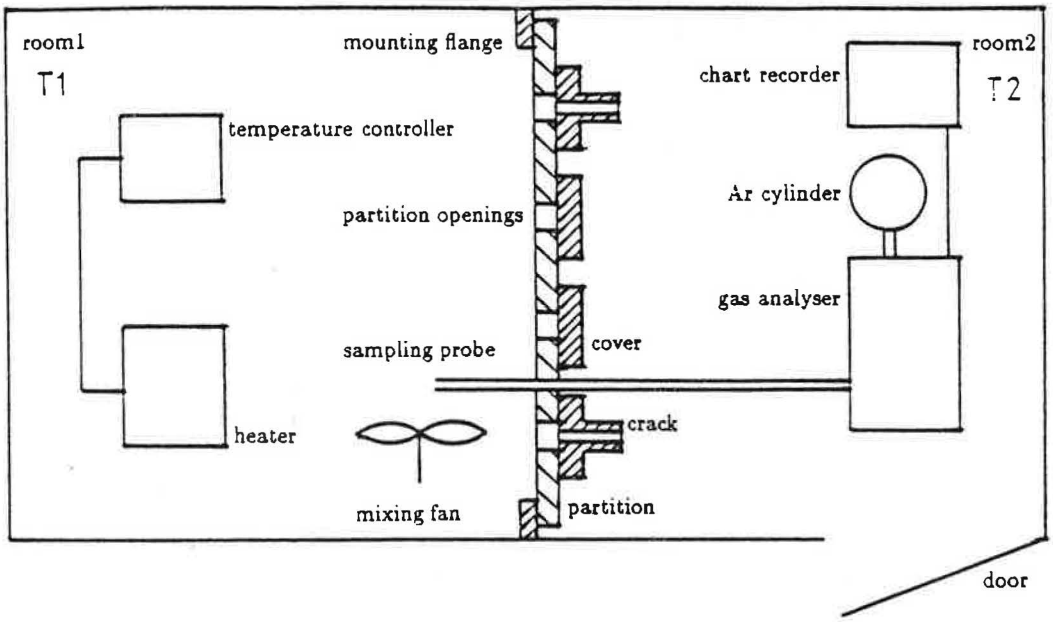

Figure 1 The two adjoining rooms and the test facility

where Δ indicates difference and subscripts 1, 2 and n denote room 1, room 2 and neutral height, respectively.

Suppose a horizontally positioned crack of rectangular cross-section exists at height h, then according to the pressure drop formula for viscous duct flow[3] and equation 6, the air infiltration rate is

$$Q = \frac{Ld^3}{12\mu z}\Delta P_h = \frac{Ld^3}{12\mu z}\frac{gP_{\text{atm}}h}{R}\left(\frac{1}{T_2}-\frac{1}{T_1}\right) \tag{7}$$

where z, L and d are the length, width and height of the crack duct and μ is the air dynamic viscosity. The viscous duct flow formula is selected here because first, results from this and other experiments[2] showed that crack-flow Reynolds numbers are around several hundred, therefore the flow is laminar and second, among the crack-flow equations for Q versus ΔP it is so far the physically most sound. (Detailed discussion of the latter issue is beyond the scope of this paper.)

In the above derivation of equation 7, an assumption is made that a neutral height exists along the height of common wall. This is always true as long as the two rooms are connected (via crack openings) and the air conditions in the rooms are in a steady state. This is obvious for mass-flow balance reasons. In other words, if there were no such neutral height, pressure in one room would be higher than in the other room along the full height of the common wall. As a consequence, air infiltration across the common wall would be a one-way process and air condition in neither room can be steady, which contradicts the precondition.

The exact position of the neutral height is dictated by the requirement of the balance of air flow across the common wall. Therefore, it depends not only on the number of cracks and their individual positions, but also on the geometry (and surface condition) of each of the cracks, as can be seen from equation 7. Locating the neutral height can thus be a complicated matter. However, for certain simple crack arrangements, the neutral height can be located easily. For example, if there is only one horizontal crack in the common wall between the two otherwise airtight rooms, the neutral height is actually the height of the crack. In addition, if only two identical horizontal cracks exist in the wall between the two rooms, the neutral height is the average of the heights of the two cracks. In the latter case, the air infiltration rate through each of the cracks is

$$\begin{aligned} Q &= \frac{Ld^3}{12\mu z}\Delta P_h = \frac{Ld^3}{12\mu z}\frac{gP_{\text{atm}}}{R}\frac{H}{2}\left(\frac{1}{T_2}-\frac{1}{T_1}\right) \\ &= \frac{Ld^3}{12\mu z}\frac{gP_{\text{atm}}}{R}\frac{H}{2}\left(\frac{\Delta T}{T_1T_2}\right) \end{aligned} \tag{8}$$

where H is the vertical distance between the two cracks and ΔT is $T_1 - T_2$.

3 Test facilities and test procedures

The test facilities include two adjoining rooms, separated by a partition with purposely constructed cracks, temperature control equipment and equipment for tracer concentration measurements, as shown in Figure 1.

In accordance with the objective of this experimental study, the two rooms must be free of the influence of wind. Therefore, two window-less rooms built in the centre of a large building were used. In addition, one of the rooms (the one without a door) was sealed using polythene sheets. This method reduced the background leakage of the room to (under a typical temperature difference) a mere 0.29 $m^3 h^{-1}$. Having the room unsealed not only makes the measurement of infiltration through the purposely made cracks less accurate, but also makes the theoretical prediction (used to compare with test results) of the infiltration rates impossible, since the neutral height cannot be determined due to the lack of information on the position and geometry of the background cracks. Both rooms measure 2.970 m × 1.533 m × 2.072 m.

The two rooms are separated by a removable partition made of a single sheet of plywood. The partition is mounted onto a flange, and airtight sealing tape was applied between the partition and the flange. In order to study the effect of the distance between the cracks, four identical rectangular

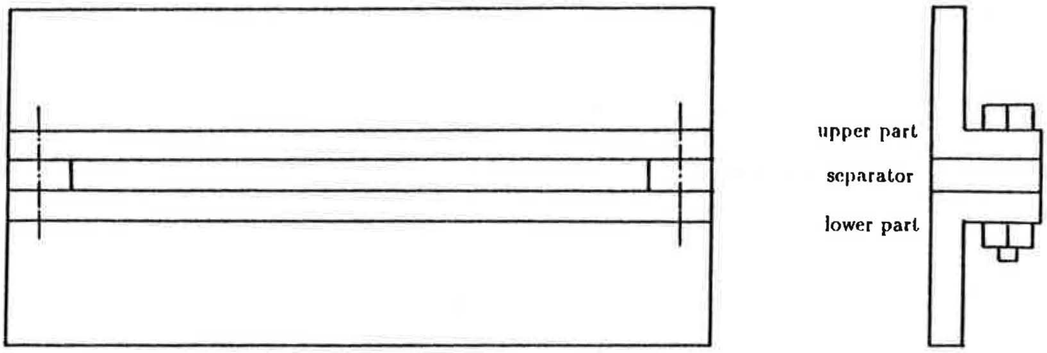

Figure 2 Schematic of the crack used in the tests

shaped openings (with the longer sides horizontal), vertically evenly spaced at 0.42 m, were built into the partition. Either the purpose-built cracks or plywood covers can be mounted onto or removed from any of the openings, depending on the test requirement.

The removable, purpose-built cracks consist of aluminium angle lower and upper parts and steel separators (Figure 2). The height of the cracks can be changed by using separators of varying thickness. Since the centre of interest in this experiment is the effect of the temperature difference or stack effect and not the effect of crack geometry, only straight-through cracks were used and their height, length and width were fixed. At least two cracks should be mounted onto the partition in order to achieve steady crack flows (section 2). For simplicity, two identical cracks were mounted onto the partition for all the tests.

To study the effect of temperature difference, various values of temperature difference have to be created. This was achieved, in this experiment, by fixing the temperature in one room (letting it be the same as the ambient building temperature; 23°C) and controlling only the temperature in the other (sealed) room. There are three objectives in controlling temperature. First, altering the temperature to whatever is needed in the test; second, keeping the temperature constant during a test; third, maintaining a uniform temperature distribution in the room. The first and the second objectives were achieved by using a conventional 2 kW fan heater and a proportional temperature control unit. A specific temperature could be preset on the control unit, which controls the heater and maintains a constant temperature until the setting is changed. The proportional control mechanism overcomes the shortcoming of temperature fluctuation associated with the conventional on/off temperature control devices. Moreover, results from calibration tests showed that the miniature heater fan hardly affects the flow through the cracks. For the third objective, prolonged heating was employed on the heavyweight walls so as to achieve a state almost at thermal equilibrium. In addition, the wooden partition was thermally sealed using polystyrene boards and polythene sheets trapping air beneath. Using the two techniques together significantly improves the temperature distribution uniformity. The sensor for the temperature control unit was located close to the fan. Calibration tests show that the temperature variation across the space in the heated room is within ±1°C and the temperature was held very steady throughout the test duration.

The air infiltration rate is measured using a tracer gas decay method, which can be briefly described as follows: if fresh air enters a confined space of volume V filled with a gaseous mixture of a tracer gas and air, it dilutes the mixture. Suppose the entering fresh air mixes uniformly and instantly with the gas mixture inside, then the flow rate of the fresh air can be evaluated as a simple exponential decay[(4)]:

$$Q = \frac{V}{\Delta t} \ln \frac{C_0}{C_t} \qquad (9)$$

where Δt is the duration of the test; C_0 and C_t are the tracer concentration at the beginning and end of the test, respectively.

SF_6 is used as the tracer gas, and equipment used in the tracer decay measurement includes an AI gas analyser (together with the cylinder of carrier gas and the gas sampling probe), a chart recorder and a mixing fan (Figure 1). An intermittent sampling method with short sampling duration and long periods between samples was used. The sampling flow is two orders of magnitude weaker than the flow through the cracks.

Tracer gas was injected only into room 1 (Figure 1). However, during a test, as fresh air enters room 1, the tracer–air mixture in it flows into room 2. In order to prevent the re-entry of the tracer gas into room 1, the door of room 2 was left open during the test. This proved to be very effective, as no noticeable tracer gas concentration was detected in room 2, and thus the re-entry of tracer gas from room 2 into room 1 is zero or negligible.

Before a test started, the sealed room would be heated for 24 hours. Tracer gas was then injected into the room and thoroughly mixed with the air using the mixing fan. Before the cracks were opened and the test started, the mixing fan would be turned off. Calibration test results show that the distribution of tracer gas remained uniform throughout the test duration, which is confirmed by the tracer decay results presented in the next section. During a test, gas mixture samples were taken at regular time intervals from the sealed room and their tracer concentration measured and recorded using the AI gas analyser and the chart recorder. Samples were always taken three at a time and the average of their concentrations taken as the tracer concentration at that moment, to improve the measurement accuracy. After a test, the tracer concentration decay curve was plotted and the air infiltration rate calculated using equation 9.

4 Results and discussion

Effects of temperature difference and the distance between the cracks on the rate of infiltration due to temperature

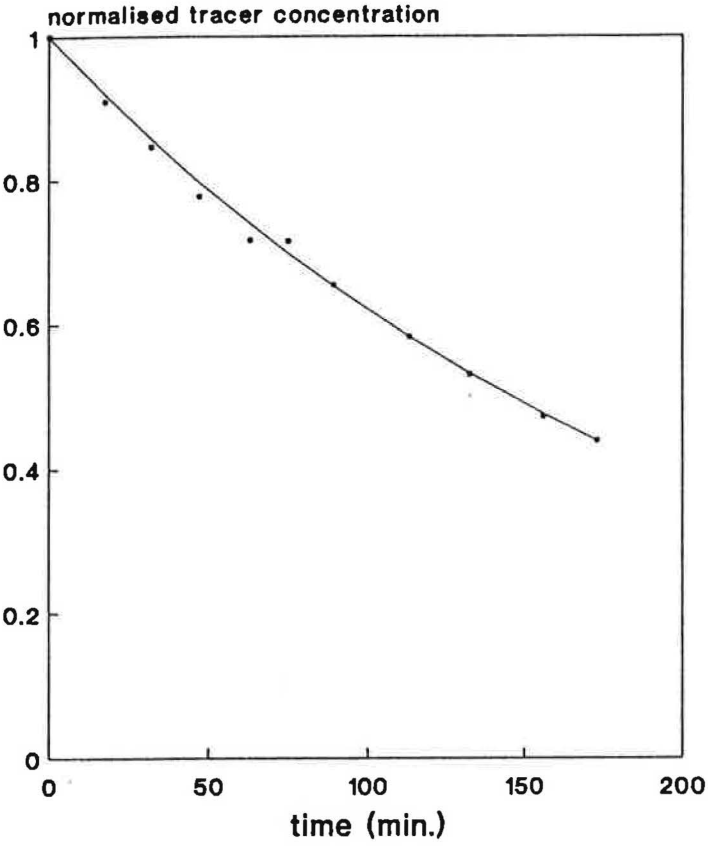

Figure 3 Decay of tracer concentration at the temperature difference of 22°C

difference were studied. In the experiment testing the effect of temperature difference, the distance between the cracks was maintained constant at 1.26 m and three temperature differences, 22°, 17° and 13.5°C were used, respectively.

Figure 3 shows the tracer concentration decay curve obtained from the test in which the temperature difference was 22°C. To facilitate comparison with results corresponding to other temperature differences, the concentration figures are normalised ones (obtained by dividing the concentration readings by the reading taken at the beginning of the test). The points shown are from the experiment, and the full curve represents the theoretical decay curve between the concentrations at the beginning and the end of the test. The good fit between the measured results and the theoretical prediction means that the assumption of uniform tracer concentration made in the tracer gas concentration decay method is practically correct in this test situation, and thus that equation 9 can be used with confidence to calculate infiltration rate figures. The good fit was repeated when the temperature differences were 17 and 13.5°C. The decay curves for all three temperature differences are plotted together in Figure 4 (for clarity, the experimental points are omitted). The faster decay and hence higher infiltration rate related to a higher temperature difference is evident. Translating the curves into infiltration rates using equation 9 and plotting them against temperature difference produces the points in Figure 5. The full curve represents the theoretical prediction obtained from equation 8. Here again, normalised figures are obtained by dividing the flow rates by that corresponding to the temperature difference of 22°C. As can be seen from Figure 5, the experimental results agree with the theory in that the correlation between the temperature difference and the infiltration rate is linear. It is true that equation 8 indicates that infiltration rate Q is proportional to $\Delta T/T_1T_2$ rather than the simple ΔT. However, since T_2 is constant and the variation of T_1 is small (30 K in 300 K), the variation of T_1T_2 is orders of magnitude smaller than that of ΔT, and thus T_1T_2 can practically be regarded as constant.

In the experiment testing the effect of the distance between the cracks, the temperature difference was kept constant at 22°C and three distances between the cracks were used: 0.42 m, 0.84 m and 1.26 m.

Results showed, as in the case of the temperature effect tests, that the experimental tracer decay curves corresponding to the three distances between cracks are very close to the theoretical curves. The three decay curves are compared in Figure 6, which shows that the larger the distance between cracks the faster the tracer concentration decay, and thus the greater the infiltration rate. Figure 7 shows this relation quantitatively. The curve showing the theoretical prediction, again derived from equation 8, points to a linear correlation, which is, however, not borne out by the present test results. It is very likely that this discrepancy is due to the difficulties related to measuring the rate of infiltration due to temperature difference through closely positioned cracks. To explain this, two facts must be recalled. First, pressure differences caused by temperature differences are small (typically an order of magnitude smaller than those generated by wind), and are even smaller when the cracks are close together, as can be seen from the analysis in section 2. Second, the effects of disturbances from the test environment (such as the random movement of passers-by) always enhance the gas exchange across the partition. Thus, when the cracks are close together and the driving force of the

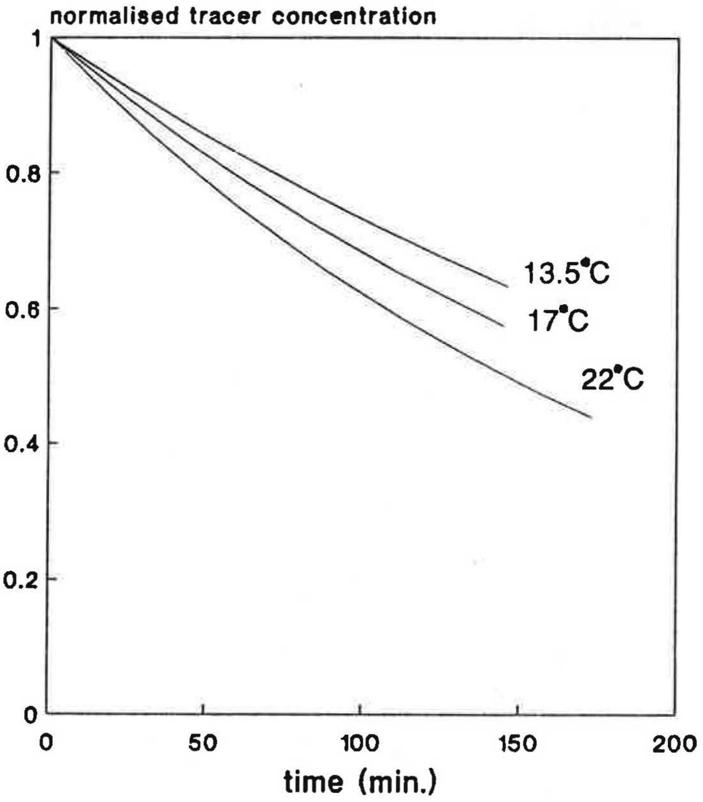

Figure 4 Decay of tracer concentrations

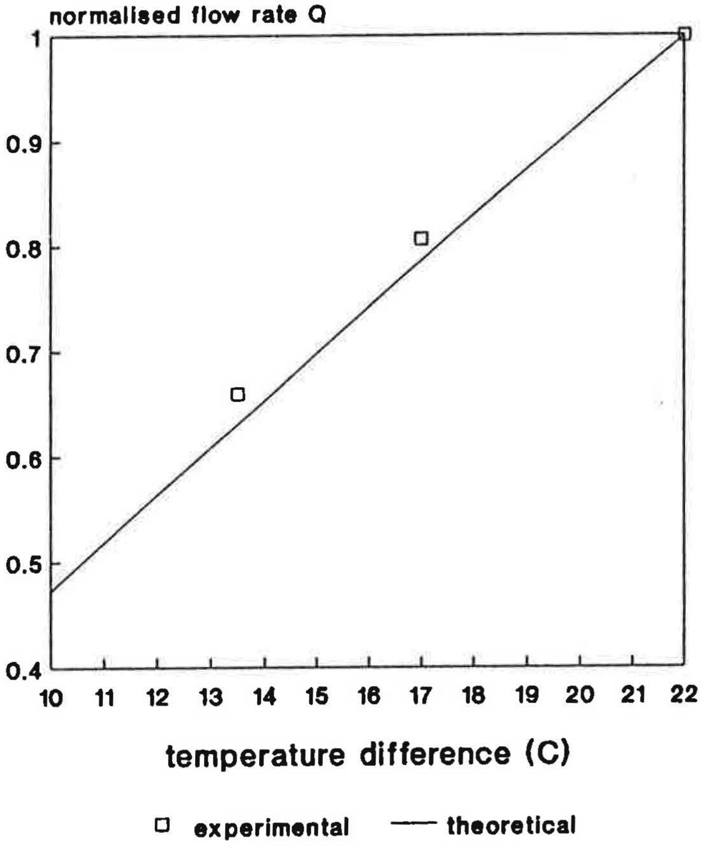

Figure 5 Effect of temperature difference on air flow rate

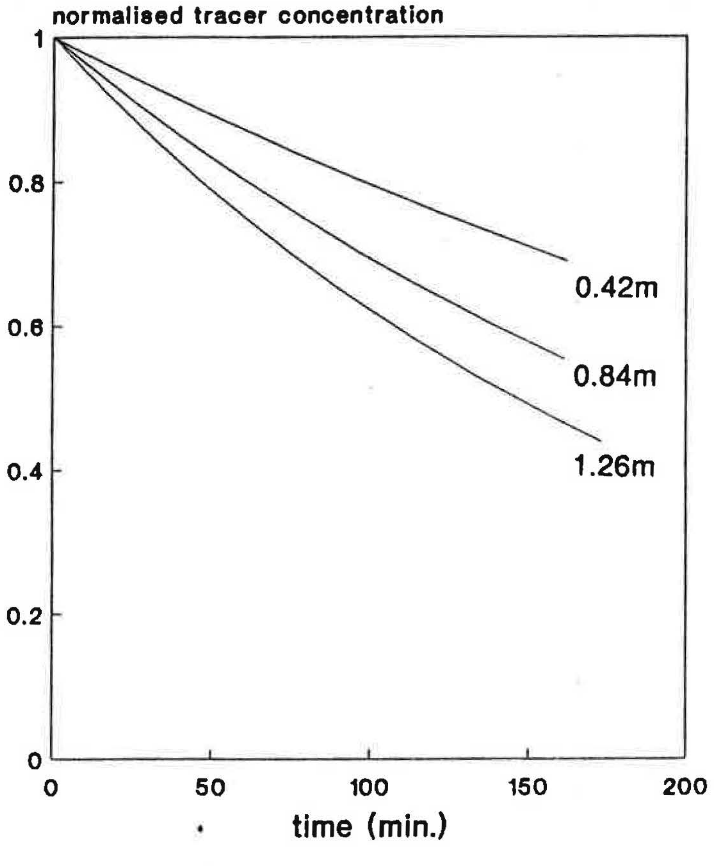

Figure 6 Decay of tracer concentrations

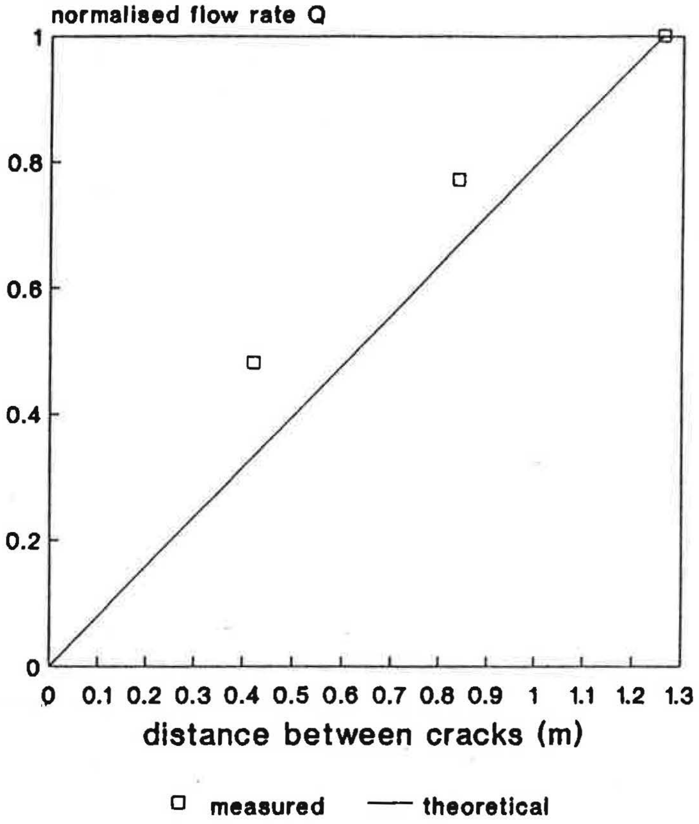

Figure 7 Effect of distance between cracks on air flow rate

air infiltration—the pressure difference—is reduced, these effects become increasingly significant and cause the observed deviation. The increasing discrepancy with decreasing distance between the cracks shown in Figure 7 lends support to this view.

5 Conclusions and suggestions

The experiment shows that the inter-zonal air flow rates due to temperature difference are proportional to the temperature difference between the two adjoining rooms (or a room and the atmosphere) which the cracks connect. This finding is in agreement with the theoretical prediction.

It is also predicted by the theory that the rate of infiltration due to the temperature difference increases with the vertical distance between cracks, and that the correlation between them is proportional. The former point is supported by the results from the present experiment. However, the latter can not yet be confirmed due to limitations imposed by the present test environment and test facilities.

There are two ways of improving the experiment testing the proportionality of the correlation between the infiltration rate and the distance between cracks. One is by reducing the level of disturbance, e.g. by restricting activity around the test facilities. The other is by increasing the driving force ΔP, thereby keeping the effect of the disturbances insignificant. This can be done either by increasing the temperature difference (by about 2–3 times) or by using taller rooms for the tests (2–3 times higher) so that the distance between the cracks can be increased.

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