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DEVELOPMENT OF A MICROPROCESSOR-CONTROLLED TRACER GAS SYSTEM AND MEASUREMENT OF VENTILATION IN A SCALE MODEL

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SYNOPSIS

This paper describes the development of a microprocessor-controlled tracer gas system which is capable of collecting a large number of tracer gas samples at short or long intervals. The system can be used for accurate measurement of air flow through openings, e.g. cracks, windows and doorways.

The sampling speed of the system can be adjusted so that a larger number of tracer gas samples can be collected during the transient period of an experiment and smaller number of samples during the dominant period. This technique minimises the error in the term dC/dt (where C is the concentration of tracer gas and t is time) and hence allows an accurate estimation of air flow rate to be made.

Measurements of window ventilation and interzone air movement have been made in a scale-model. The model, which represents a two-storey house, was built from perspex and had the dimensions 0.85m x 0.85m x 0.85m. The model was provided with a number of windows. In order to carry out measurements of pressure distribution in a wind tunnel, the model was provided with a large number of external and internal pressure tappings. Pressure measurements were used to calculate air flow through openings and the results were compared with tracer gas measurements. Results are presented on ventilation rate, interzone air movement, pressure and discharge coefficients.

NOMENCLATURE

F	Volumetric air flow rate, m^3/s
A	Free area of an opening, m^2
U_{ref}	Reference wind tunnel speed, m/s
P_o	External pressure measurement at the pressure tappings, Pa
P_i	Internal pressure measurement at the pressure tappings, Pa
P_{ref}	Reference static pressure, measured at the free stream, Pa
ΔP	Pressure difference across the opening, Pa
Cd	Coefficient of discharge of an opening (dimensionless)
C_{po}	External pressure coefficient (dimensionless)
C_{pi}	Internal pressure coefficient (dimensionless)
C_1	Concentration of tracer gas at time t in zone 1, ppm
C_2	Concentration of tracer gas at time t in zone 2, ppm
V1	Interior volume of zone 1, m^3
V2	Interior volume of zone 2, m^3
ρ	Air density, kg/m^3

1. INTRODUCTION

Natural ventilation in buildings is an important area of investigation, as it has a significant effect on energy conservation, air quality and thermal comfort. The characteristics of natural ventilation in buildings are dependent on the wind environment around the structure and the thermal gradient across the building envelope. Prediction of natural ventilation in buildings is difficult because of the large number of variables involved and the interaction between these parameters. Measurements on scale-models in wind tunnels can provide useful data for the design of buildings prior to their construction. The use of scale models to study natural ventilation has been carried out previously by several authors[1,2,3,4], however little work on the accuracy of quantification of air flow through openings caused by wind-driven force appears in the literature. Some researchers[5] have reported a considerable discrepancy between the measured air flow through openings in buildings and that calculated using engineering Handbooks such as ASHRAE[6] and CIBSE[7]. To date most studies of natural ventilation have been carried out on open areas occupying more than 10% of the surface area of a wall. To author's knowledge the only published data available on small openings (occupying 1% or less of the wall area) are due to Dick[8], Bilsborrow and Fricke[9] and Etheridge and Nolan[10]. Natural ventilation through openings occupying less than 1% of the wall area is typically the situation encountered in buildings in cold climates when all windows are closed[9].

Natural wind-ventilation in a building can be determined from a knowledge of wind speed, pressure coefficient and area of the opening. Pressure coefficients can be obtained using full-scale buildings[11] or by scale-model experiments in a wind-tunnel[12,13,14]. In addition, wind tunnel testing provides a simple means of examining the effect of various factors such as, opening sizes and location, wind speed and direction, on the ventilation rate. Ventilation through a single opening (single-sided ventilation) has been investigated by De Gids and Phaff[15], Warren[16] and Crommelin and Vrins[17]. The scale-model described in this paper is used to verify cross ventilation prediction through openings. We have implemented the use of a new tracer gas system to determine the ventilation rate and interzone air movement in a simplified scale-model of a building.

2. DESCRIPTION OF THE SCALE-MODEL

Measurements of air flow were made in a scale-model, Figure 1. The simple model, which represents a two-storey house, had the external dimensions 0.85m x 0.85m x 0.85m. The interior of the model was divided into two floors; each had the dimensions 0.686m x 0.686m x 0.302m. The exterior and interior walls of the model were separated by a cavity wall construction. The model was built from clear acrylic sheet (perspex) in order that air flow patterns could be investigated using smoke.

The scale-model was provided with a large number of pressure tappings on both the internal and external walls. These tappings were made from brass tubes with an external diameter of 3.3mm and an internal diameter of 1mm. Plastic tubes were then extended from the pressure tappings, down the inside of the cavity wall and exited from the base of the model. The plastic tubes were subsequently connected to a multi-tube manometer.

On the walls of each floor of the model, one inlet and one outlet opening each of an area of $256mm^2$ were made for ventilation. One additional large opening (area $= 0.011m^2$) was made between the two floors of the scale-model to represent the stairway. This opening was used to simulate the interzonal air flow between the two floors of the house.

The Loughborough University wind-tunnel was used for testing the scale-model. Free stream velocities of up to 10m/s could be generated in the test section using a blower and a variable speed motor. The test section was fabricated from perspex sheet and had two access doors located on the side walls of the tunnel. A grid was installed on the upstream side of the tunnel floor to simulate atmospheric boundary layer flow.

Pitot-static tubes and hot-wire anemometers were used in conjunction with precision manometers for measurement of static and velocity pressures in the wind tunnel.

3. MICROPROCESSOR-CONTROLLED TRACER GAS SYSTEM

Air flow measurements were carried out using a variable speed microprocessor tracer gas system, Figure 2. The system which is in its first stage of development, is capable of taking samples at intervals as frequent as every 5 seconds. In essence, the tracer gas system incorporates solenoid valves, tracer gas sample bags, a pulse pump, a microprocessor-based controller, a manifold and a by-pass valve. The short sampling period was achieved using a specially designed microprocessor controller. The tracer gas system was designed to take up to 40 samples from each zone at short or long intervals. In a typical experiment the system would collect up to 30 samples during the transient period of the experiment (at 5-10 second intervals depending on the size of the opening and the temperature difference) and up to 10 samples (at intervals greater than 10 seconds) during the dominant period. The large number of data points taken during the transient period minimised the error in the term dC/dt (see equations 6 and 7) and hence allowed an accurate estimation of infiltration and interzone air movement to be made.

As it was possible to adjust the sampling period of the tracer gas system within a wide range (seconds, hours, weeks or months), the system could also be used to measure long term averages of infiltration rate.

The sampling system could be used with different types of tracer gases. Nitrous oxide, N_2O, was used in this work has it has desirable characteristics in terms of detectability and cost. N_2O gas has been used successfully in previous air movement studies[18].

The tracer gas injection unit was designed so that it would allow either the decay or constant emission methods to be used. The decay method requires the use of only a small quantity of tracer gas to carry out air flow measurements, but a continuous flow of tracer gas at a fixed rate is necessary if the constant injection method is to be used.

After tracer gas release and mixing, samples were collected and injected automatically into a portable gas chromatograph or analyser. This allowed the concentration of tracer gas in each sample to be determined.

4. RESULTS AND DISCUSSION

4.1 Cross Ventilation in Each Floor

Following the installation of the scale-model in the test section of the wind tunnel, measurements of pressure distribution and window ventilation were carried out at different wind speeds. In the first set of experiments, cross ventilation in lower floor of the model was investigated. The tracer gas decay method was used in these measurements. A small amount of tracer gas was injected in the lower floor of the model and the dilution of tracer gas was monitored using the microprocessor-controlled tracer gas system.

Figure 3, 4 and 5 show tracer gas concentration against time for air flow parallel to the window (i.e. $\alpha = 0^{o}$) for three different wind speeds. The decay of tracer gas in the zone was found to be fast at higher wind speeds. The smoothness of the decay curves indicates that the mixing of tracer gas with air in the zone was uniform. The volumetric flow rates through the window were found to be $2.1 m^3/h$ and $5.5 m^3/h$ at wind speeds of 2.9m/s and 6.2 m/s.

The experiments were then repeated to investigate air flow through the window in the upper floor of the scale-model. The same wind speeds as used previously were used in these experiments. For low wind speeds, the air flow rate through the upper window was found to be slightly larger than the flow rate through the window in the lower floor. The reason for this could be the difference in turbulence level in the two floors. Figure 6 shows the variation of air flow rate through the lower and upper windows as a function of wind speed. The results correlated with:

$$F = 2.084 \times 10^{-4} \times U^{1.15}_{ref} \qquad (1)$$

Figure 6 also shows this correlation compared with a previous correlation, or 'rule of thumb', describing flow through windows[19]. The two correlations were found to be in close agreement.

4.2 Estimation of Ventilation Rate using Pressure Coefficients

The ventilation rate through an opening in a building may be estimated from:

$$F = C_d A (2\Delta P/\rho)^{0.5} \qquad (2)$$

Pressure measurements were used to estimate the internal and external pressure coefficients of the model. The external wind pressure coefficient, is defined as:

$$C_{po} = (P_o - P_{ref})/0.5 \rho U^2_{ref} \qquad (3)$$

The internal wind pressure coefficient is defined as:

$$C_{pi} = (P_i - P_{ref})/0.5 \rho U^2_{ref} \qquad (4)$$

Combination of equation 2, 3 and 4 gives:

$$F = C_d \; A \; U_{ref} \, (C_{po} - C_{pi}) \, |C_{po} - C_{pi}|^{-0.5} \qquad (5)$$

Pressure coefficients were determined for the internal and external pressure tappings. Figure 7 shows the variation of average pressure coefficient with the reference wind speed for the surfaces A, B, C and D. The formation of vortices around the sharp corners of the scale-model causes large negative pressure coefficients on the surfaces B and D.

Figure 8 shows a plot of local pressure coefficient with reference wind tunnel speed for three different locations on the surfaces B of the scale-model. The local pressure coefficient for B1, B2 and B3 (which represent the average pressure coefficient for each column of pressure tappings) is different for various wind speeds. The largest negative pressure coefficients were observed for B1 which is close to the sharp edge of the model (in direction of air flow) and the smallest negative pressure coefficient were observed for B3.

The discharge coefficients, C_d, for the lower and upper openings were calculated using equation 5. Figure 9 shows the variation of the discharge coefficient with the reference wind tunnel speed. The average value of the coefficient of discharge for the lower window was found to be approximately 0.56 and that for the upper window was found to be approximately 0.62. These results are similar to those obtained by Dick[8] for openings in houses. The analysis showed that the opening in the upper floor has a higher coefficient of discharge than that for the opening in the lower floor. The cause for this behaviour could be partly attributed to the difference in the pressure distributions over lower and upper surface walls of the model surfaces and partly to the difference in the fluctuation of the pressure acting across the openings.

4.3 Interzone Air Flow Measurements

Measurements of interzone air movement in the model were carried out using a single tracer gas technique. The experimental procedure involved the injection of a certain quantity of tracer gas in the lower floor (zone 1) while the opening between the lower and upper floor (zone 2) was closed (see Figure 10). Following tracer gas mixing under natural conditions, the communication opening between the two zones was opened and the decay of tracer gas was then monitored. If one applies the material balances for tracer gas in each zone, assuming that a steady state exists and the concentration of tracer gas in the outside air is negligible, then the rate of decrease of tracer gas concentration in zone 1 at time t is given by:

$$V_1 \, dC_1/dt = - \, C_1 \, (F_{10} + F_{12}) + C_2 \, F_{21} \qquad (6)$$

Similarly, the rate of decrease of tracer gas concentration in zone 2 at time t is given by:

$$V_2 \, dC_2/dt = - \, C_2 \, (F_{21} + F_{20}) + C_1 \, F_{12} \qquad (7)$$

The remaining flow rates can then be determined using the continuity equations as follows:

$$F_{01} = F_{12} + F_{10} - F_{21} \qquad (8)$$

$$F_{02} = F_{20} + F_{21} - F_{12} \qquad (9)$$

The tracer gas volumetric-balance equations can be solved using one of the analysis methods described by Riffat[20].

Air flow measurements were carried out using two microprocessor-controlled tracer gas systems. The first system was used to collect samples from zone 1 while the second was used to collect samples from zone 2. A known volume of tracer gas was released in zone 1 using a mass flow controller. After a mixing period of about 15 minutes, the communication opening between the two zones was opened and samples were taken at 25 seconds intervals. This sampling period was found to be adequate to provide a sufficiently large number of samples during both the transient and dominant periods.

Several experiments were carried out on the scale-model using different wind speeds. Figures 11, 12 and 13 show tracer gas concentration against time for three different wind speeds. The concentrations of tracer gas in the two zones were found to reach equilibrium in a shorter period when the wind speed was high. The smoothness of the tracer gas curves indicates that good mixing was achieved in the two zones. Tracer gas concentrations were used to estimate interzone air flow. Figures 14, 15 and 16 display schematics of interzonal air flows. The flow rates through the lower and upper windows were found to be greater for higher wind speeds. The flow rate through the window in the upper floor was found to be greater than the flow rate through the window in the lower floor in all experiments. This could be a result of the shape of velocity distribution of air at different heights from the wind tunnel floor. When the air velocity was 2.9 m/s, flow from the lower floor to the upper floor was 0.96 m^3/h and that from the upper floor to the lower floor was 0.72 m^3/h. At wind speeds of 4.5 m/s and 5.3 m/s, the air flow rate from the lower floor to the upper floor was negligible.

5. CONCLUSIONS

The experimental results show that cross ventilation in the scale-model is directly proportional to the reference wind tunnel speed. The ventilation rate through the window in upper floor of the model was slightly higher than that through the window in the lower floor. The ventilation rate through the windows depends upon the turbulence level.

The average coefficients of discharge for the lower and upper windows were approximately 0.56 and 0.62, respectively. The largest negative pressure coefficients were observed near the corners of the scale-model.

The air flow rate from the lower floor to the upper floor was negligible at wind speeds above 3.5 m/s.

The use of the variable speed sampling system has proved to be a reliable and simple approach for measuring air flow ventilation rate and interzone air movement.

6. ACKNOWLEDGEMENTS

The author wishes to thank the workshop staff at Loughborough University for constructing the scale-model and the tracer gas systems.

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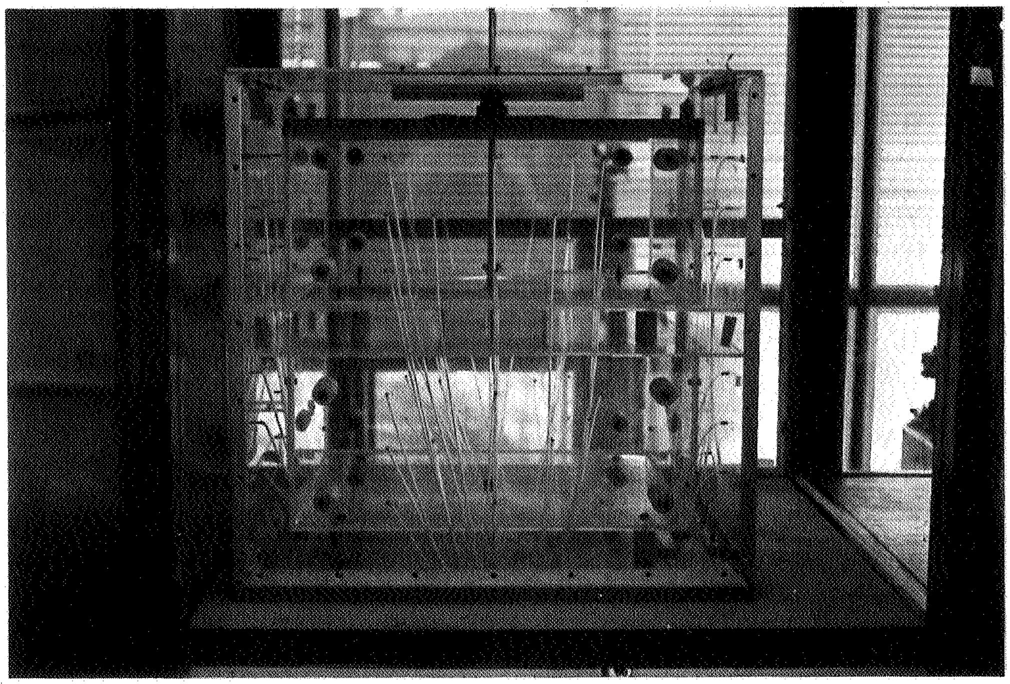

Figure 1 Photograph of the scale-model

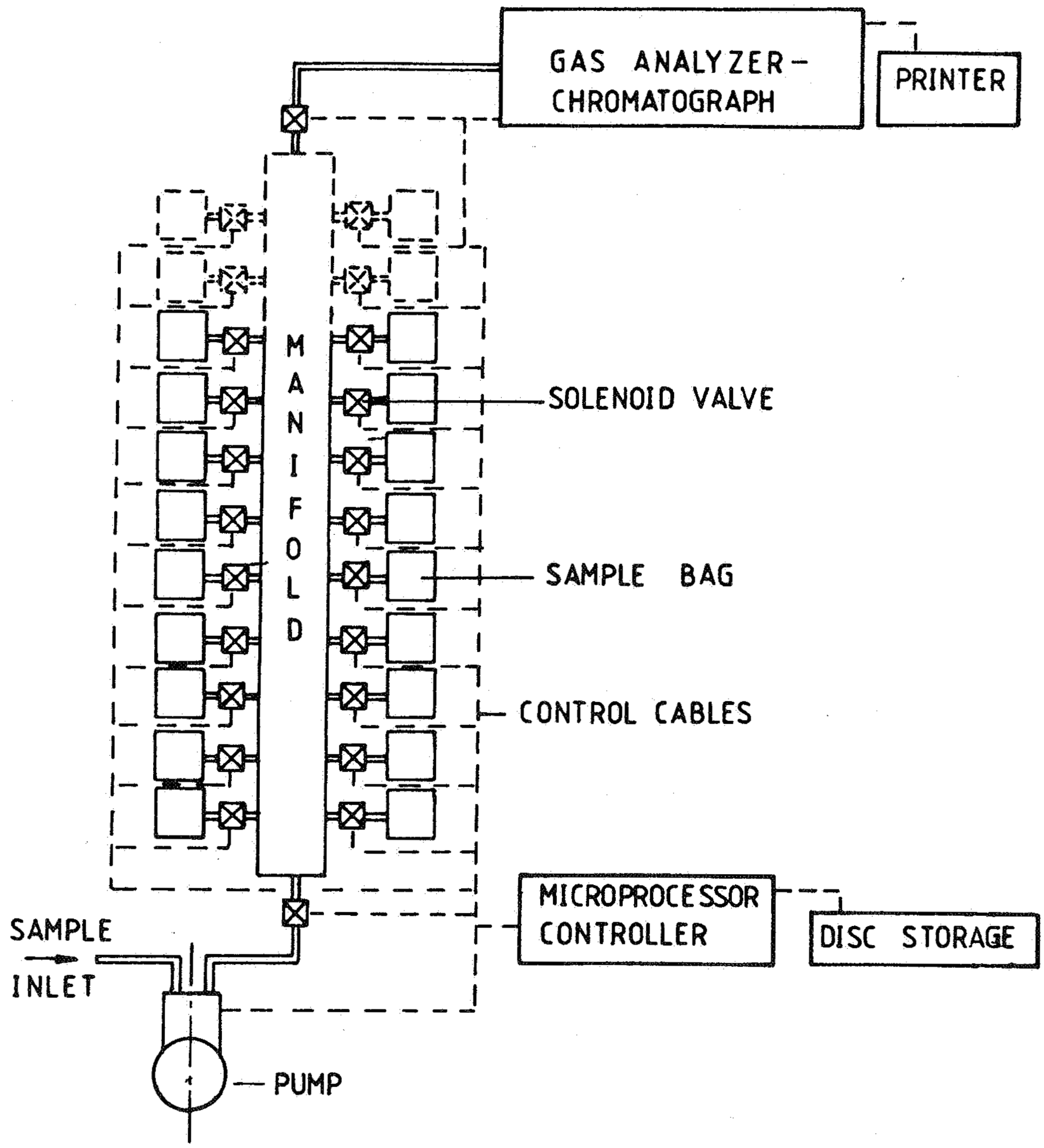

Figure 2 **Microprocessor-controlled tracer gas system**

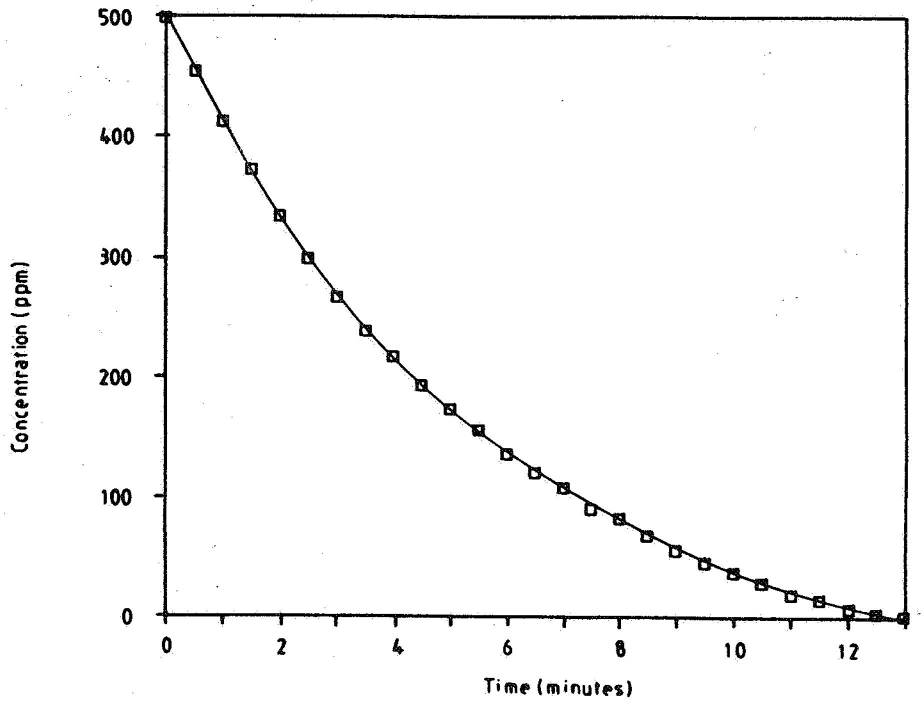

Figure 3 Variation of tracer gas concentration with time, U_{ref} = 2.9 m/s

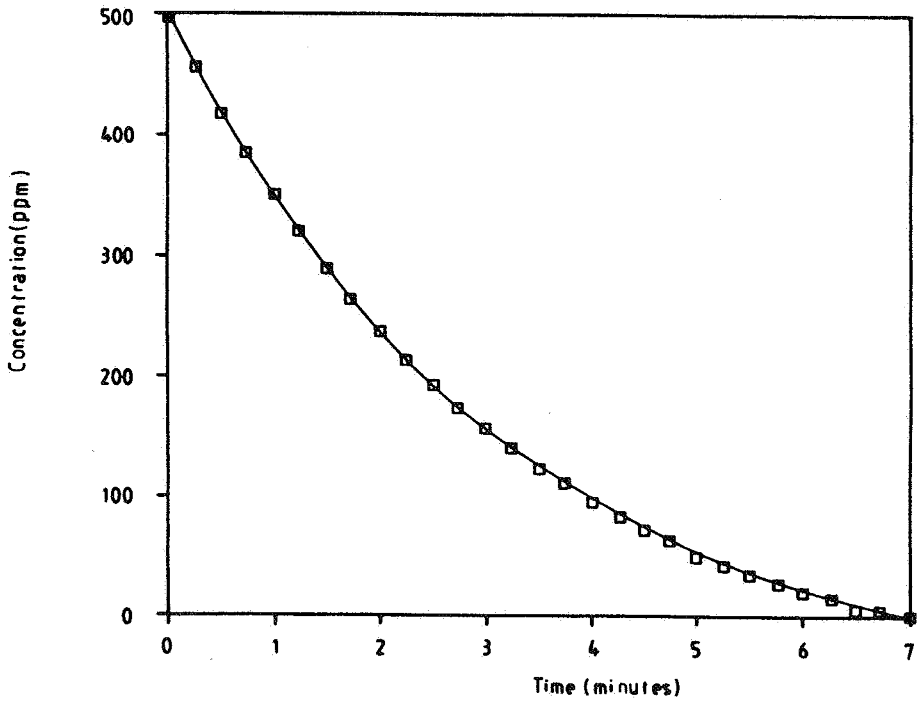

Figure 4 Variation of tracer gas concentration with time, U_{ref} = 4.4 m/s

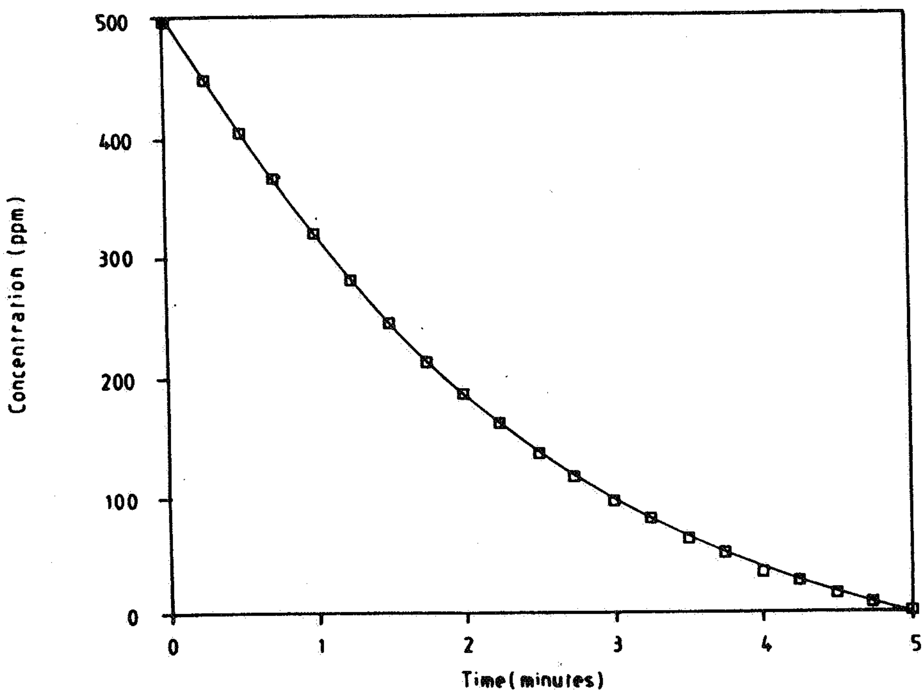

Figure 5 Variation of tracer gas concentration with time, U_{ref} = 6.2 m/s

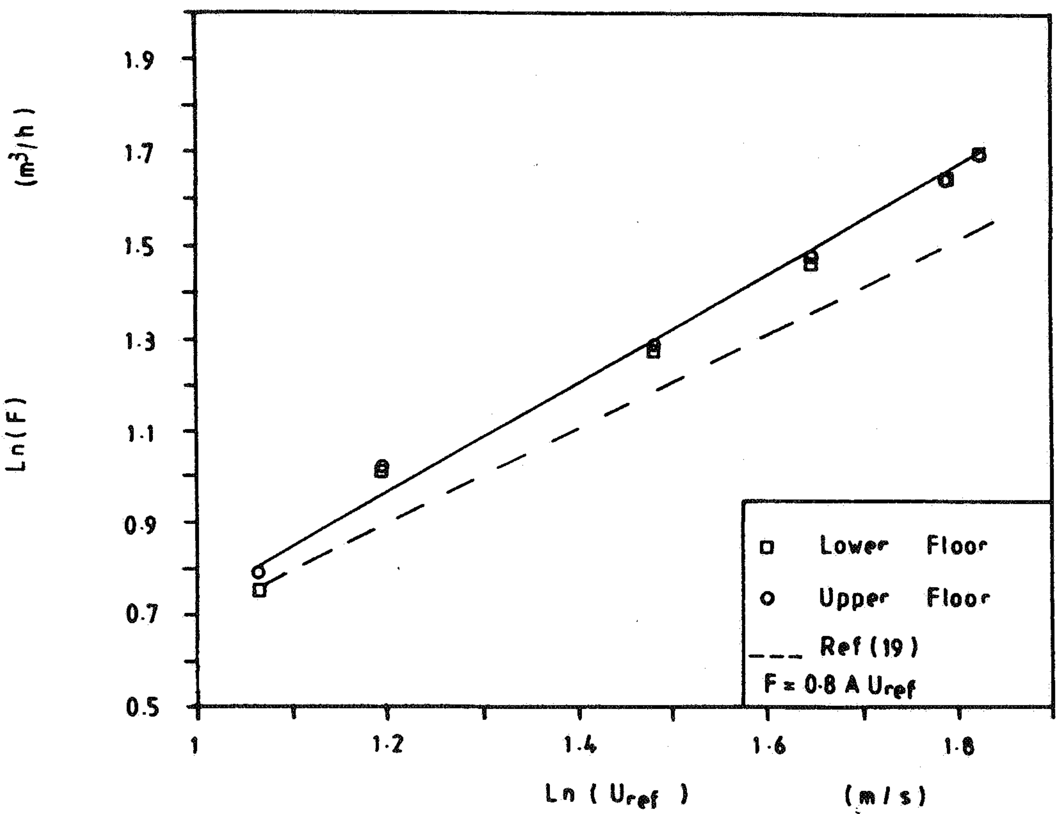

Figure 6 Variation of flow rate through the windows in the lower and upper floors as a function of wind tunnel speed

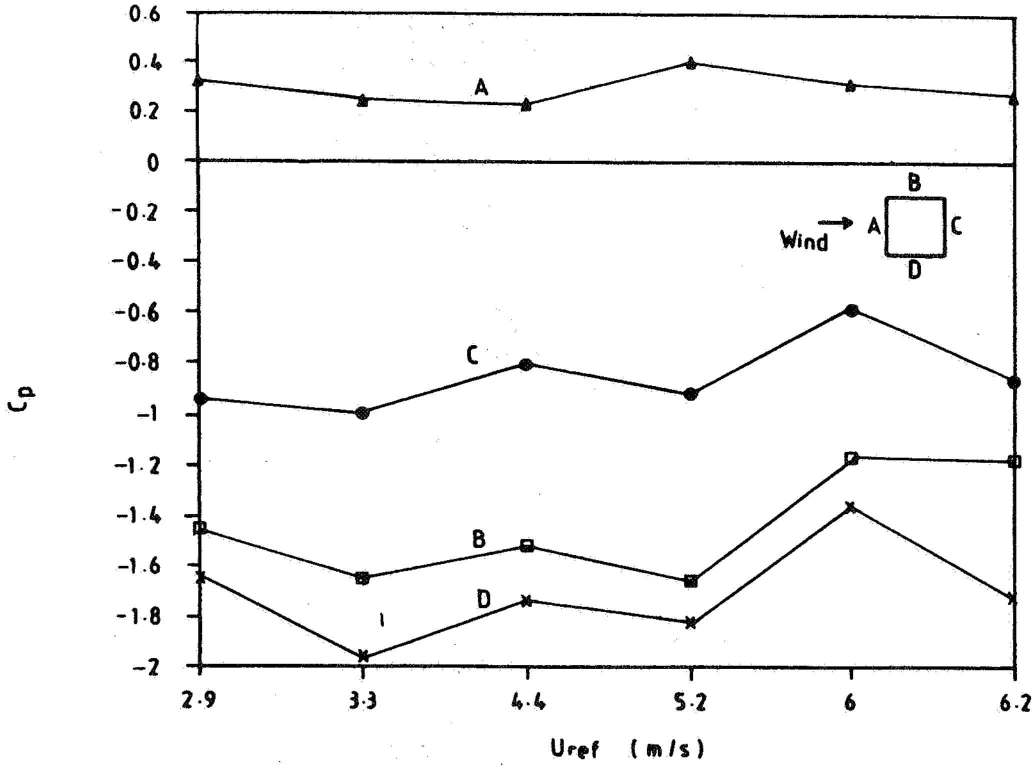

Figure 7 Variation of the average pressure coefficient for the surfaces A, B, C and D with wind tunnel speed

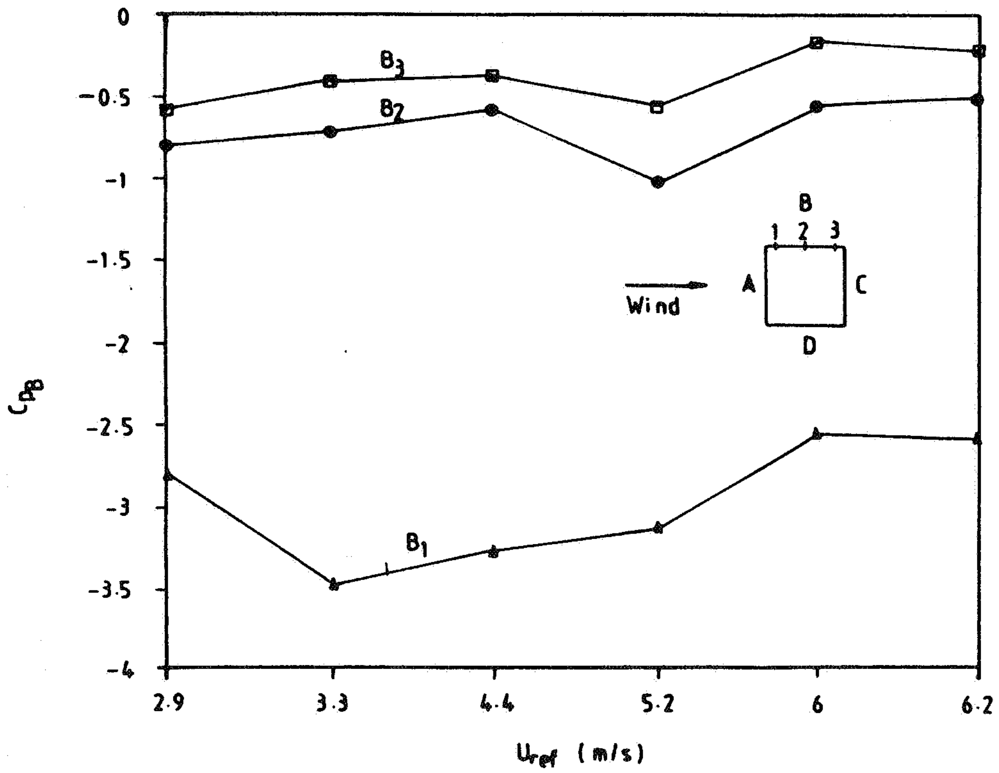

Figure 8 Variation of local pressure coefficient for the surface B with wind tunnel speed

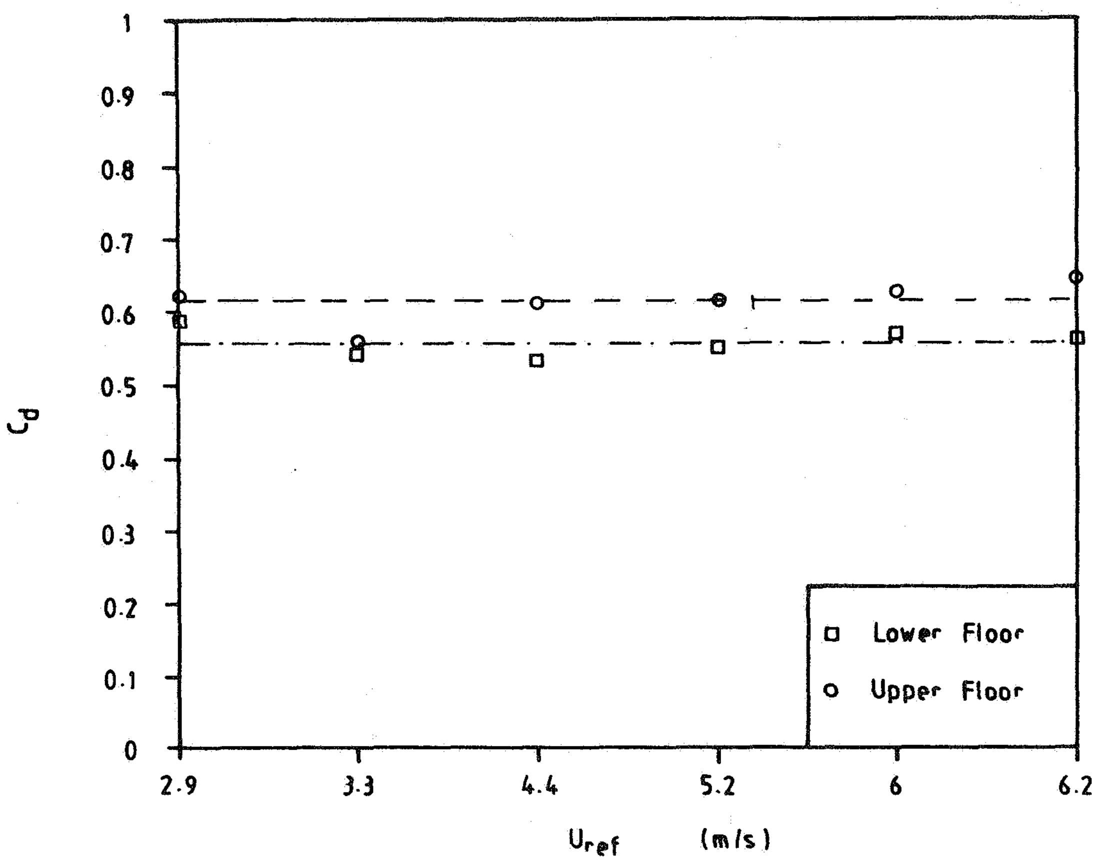

Figure 9 **Discharge coefficient versus wind tunnel speed**

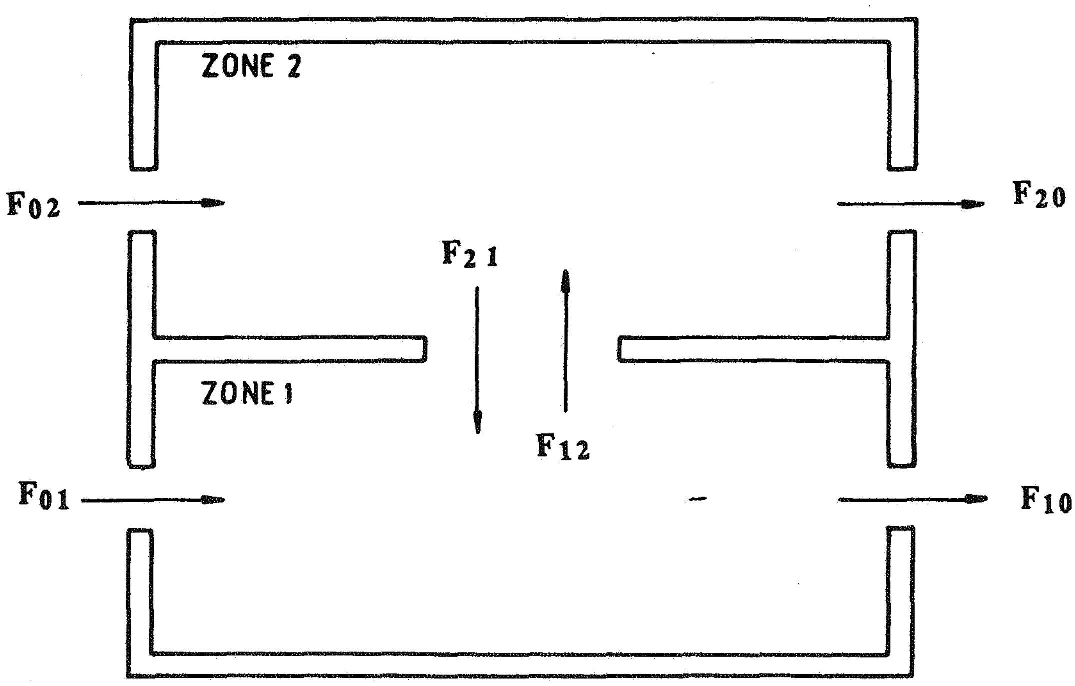

Figure 10 **Air movement between two zones**

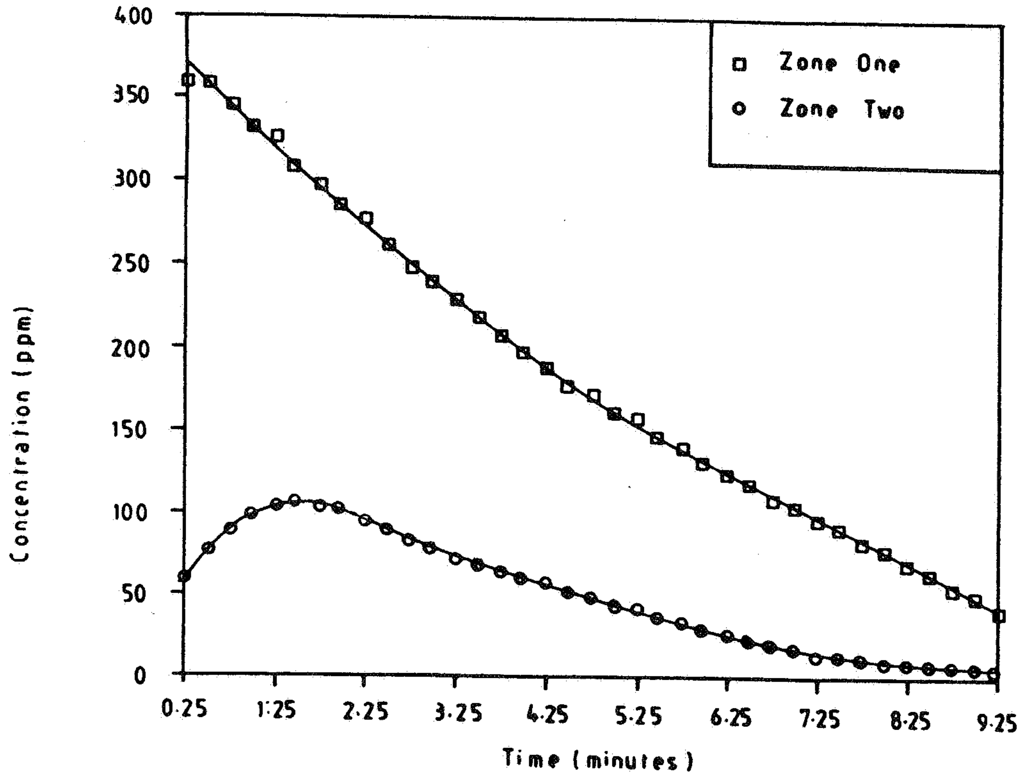

Figure 11 Variation of tracer gas concentration in the two zones with time, U_{ref} = 2.9 m/s

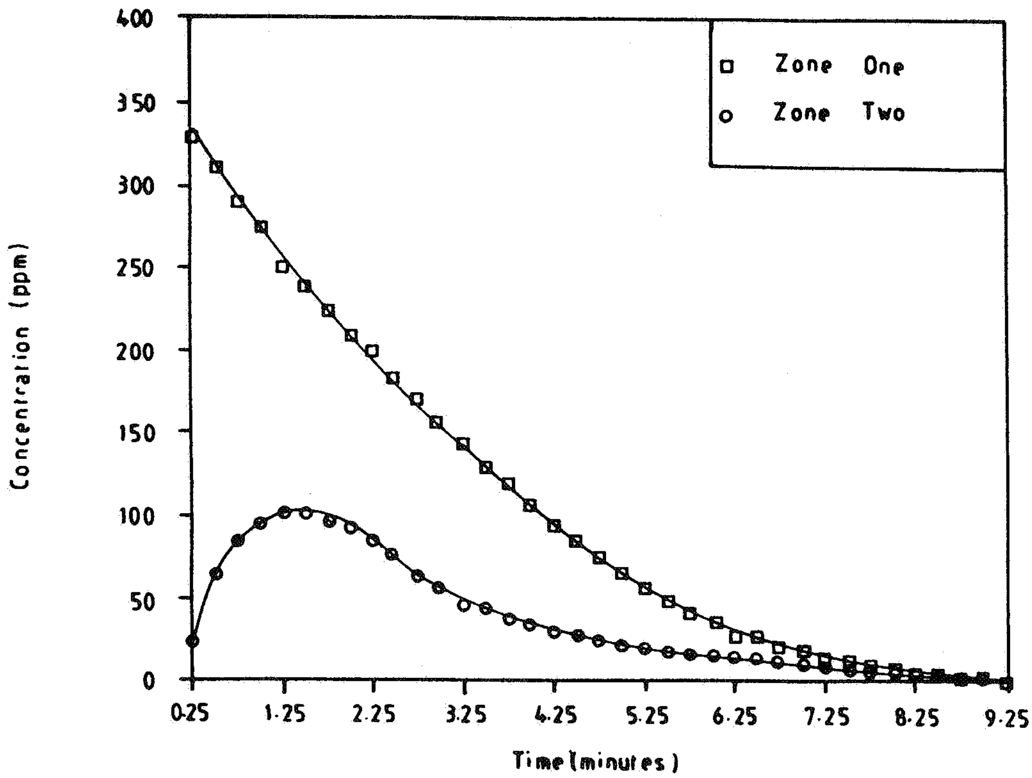

Figure 12 Variation of tracer gas concentration in the two zones with time, U_{ref} = 4.5 m/s

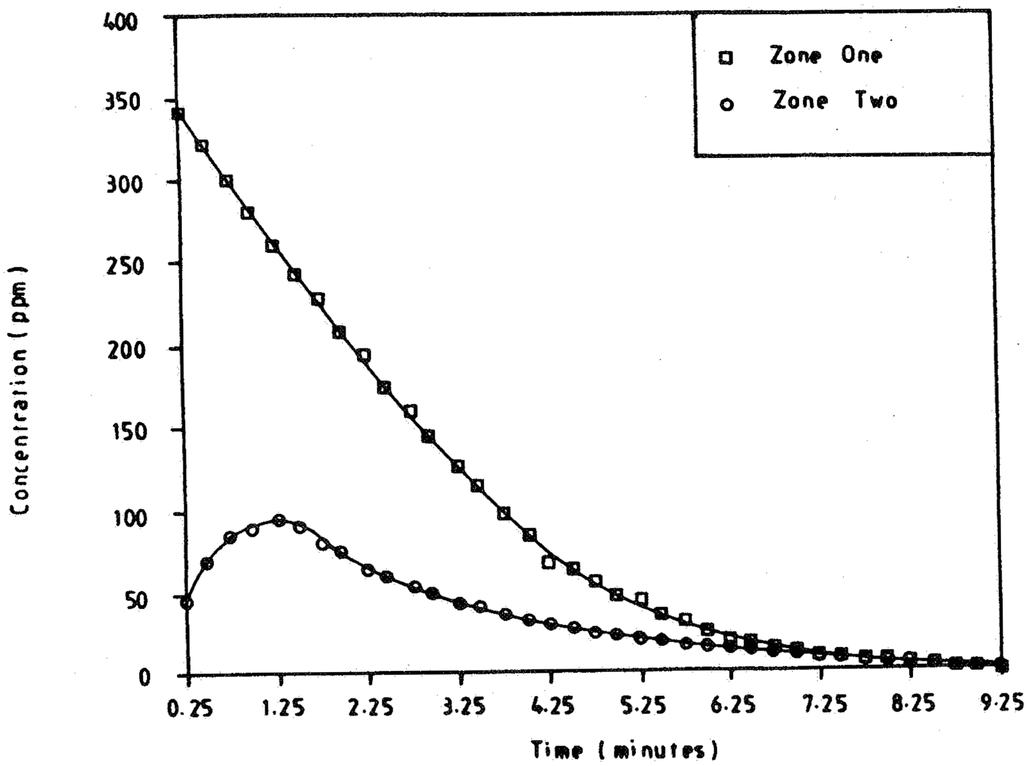

Figure 13 Variation of tracer gas concentration in the two zones with time, U_{ref} = 5.3 m/s

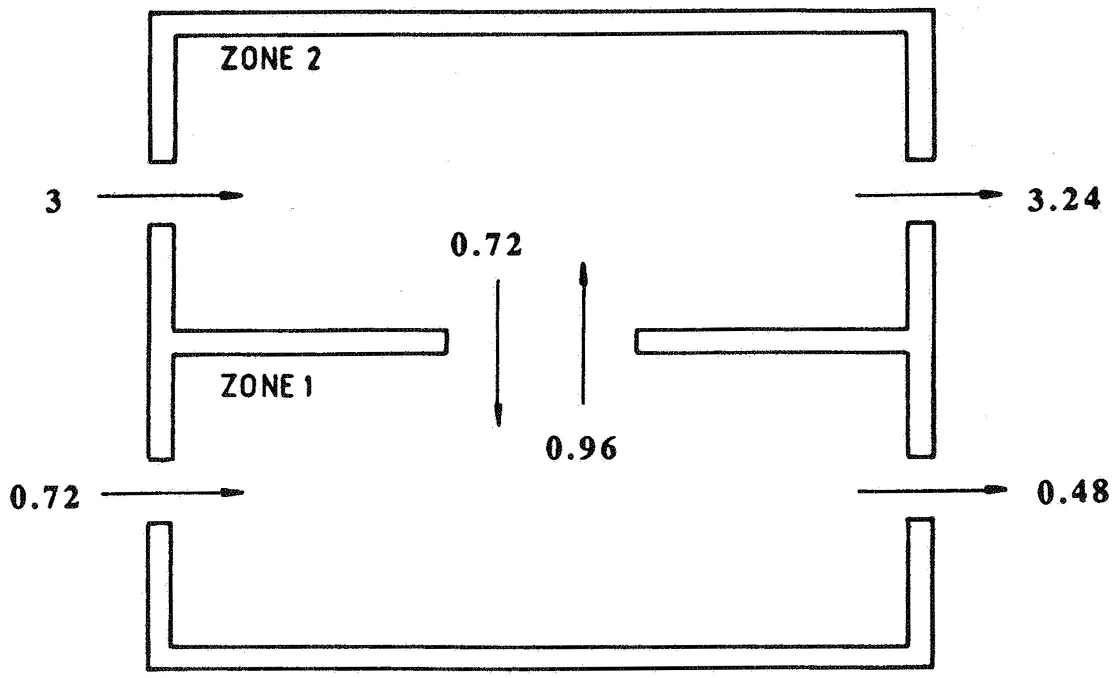

Figure 14 Calculated interzonal flow rates in m^3/h, U_{ref} = 2.9 m/s

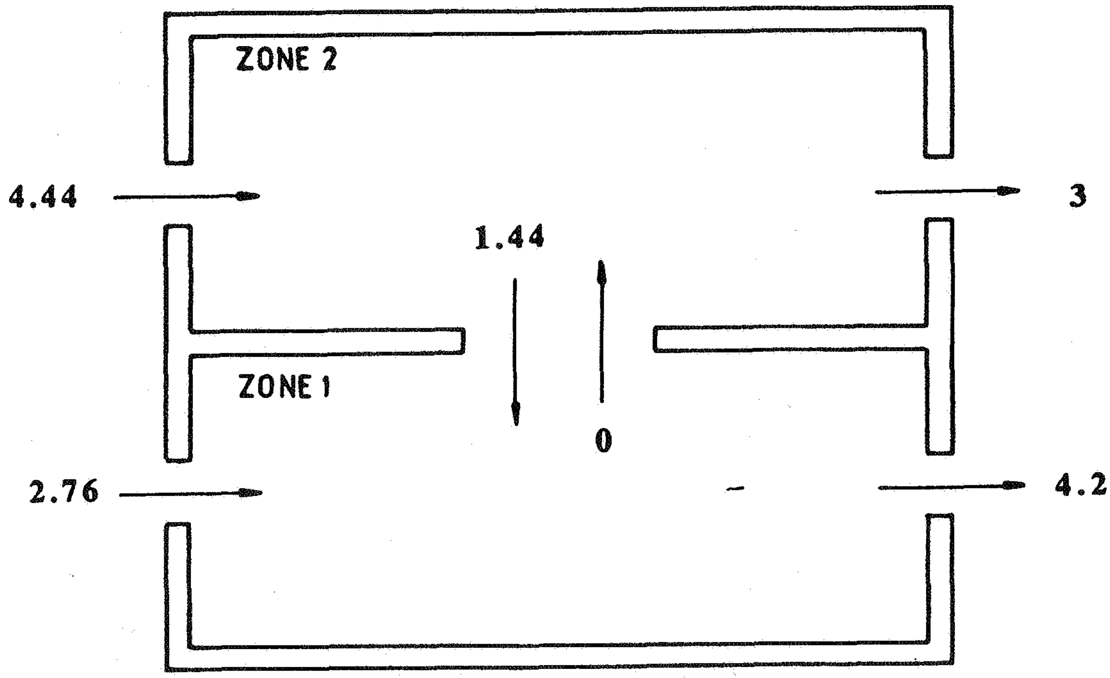

Figure 15 Calculated interzonal flow rates in m^3/h, U_{ref} = 4.5 m/s

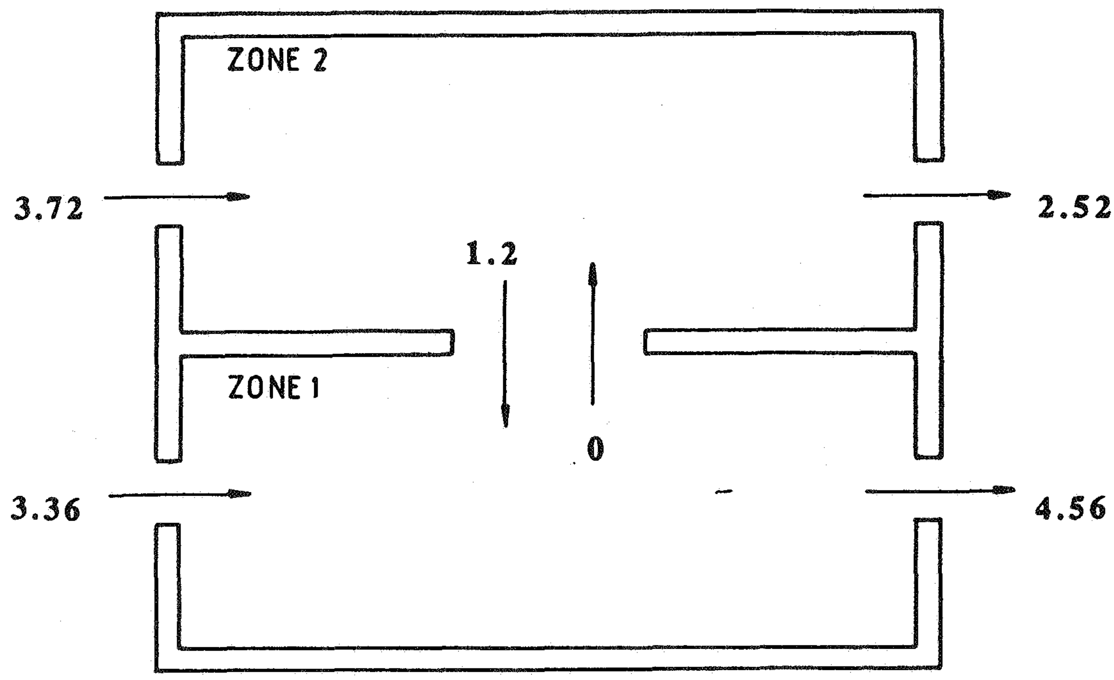

Figure 16 Calculated interzonal flow rates in m^3/h, U_{ref} = 5.3 m/s