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EVALUATION OF HEAT AND MASS TRANSFER THROUGH A LARGE HORIZONTAL OPENING

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Summary

The work was concerned with measuring natural convection through a large horizontal opening between two rooms in a building. Airflow rates between the two rooms were measured using a tracer-gas decay technique. Room 1 was heated to various temperatures in the range 18°C to 33°C using thermostatically-controlled heaters. Room 2 was unheated. A multi-point sampling unit was used to collect tracer-gas samples from each room. The concentration of SF_6 tracer was measured using an infra-red gas analyser. The heat and mass flow rates between the two rooms were calculated from the tracer-gas concentrations and temperature differences. The coefficient of discharge of the opening was found to be function of the temperature difference between the two rooms.

List of symbols

A	= Cross-sectional area of the opening, (m^2)
a	= Width of the opening, (m)
b	= Length of the opening, (m)
C_1	= Concentration of the tracer at time t in room 1, (ppm)
C_2	= Concentration of the tracer at time t in room 2, (ppm)
C_p	= Specific heat of air, (J/kgK)
D_h	= Hydraulic diameter of the opening, (m)
F	= Volumetric flow rate, (m^3/s)
g	= Acceleration due to gravity, (m/s^2)
H	= Thickness of the partition containing the opening, (m)
h	= Heat transfer coefficient, (W/m^2K)
k	= Thermal conductivity, (W/mK)

L_1 = Friction and entrance pressure losses in the opening, airflow from room 1 to 2, (bar)
L_2 = Friction and entrance pressure losses in the opening, airflow from room 2 to 1, (bar)
M = Mass flow rate, (kg/s)
P_1 = Pressure at room 1, (bar)
P_2 = Pressure at room 2, (bar)
q = Heat transfer rate, (W)
T = Mean absolute temperature of the two rooms, (°C or K)
T_1 = Average air temperature in room 1, (°C or K)
T_2 = Average air temperature in room 2, (°C or K)
ΔT = Average temperature difference between the two rooms, (°C or K)
U = Mean velocity, (m/s)
U_1 = Upward velocity at the opening of room 1, (m/s)
U_2 = Downward velocity at the opening of room 2, (m/s)
V_1 = Interior volume in room 1, (m^3)
V_2 = Interior volume in room 2, (m^3)
β = Coefficient of the thermal expansion, (K^{-1})
μ = Dynamic viscosity, (kg/ms)
ρ_1 = Air density of room 1, (kg/m^3)
ρ_2 = Air density of room 2, (kg/m^3)
ρ = Average air density, (kg/m^3)
$\Delta\rho$ = Air density difference between the two rooms, (kg/m^3)
υ = Kinematic viscosity, (m^2/s)

Dimensionless Parameters

Gr = Grashof number

K = Coefficient of discharge

Nu = Nusselt number

Re = Reynolds number

Pr = Prandtl number

α = Velocity pressure loss-factor of opening

1. Introduction

In recent years use of natural ventilation has become more widespread in order to minimise air conditioning and resulting emissions of greenhouse gases. Building services designers and architects require design tools for accurate prediction of air movement in buildings. Several advanced computer models such as ESP (1), BREEZE (2) and COMIS (3) have been developed for prediction of ventilation and interzone air movement in buildings. However, these models lack suitable algorithms for estimation of airflow through large horizontal openings, such as ventilation shafts, stairwells and lifts. Airflow through this type of opening has serious implications on energy saving, moisture and pollutant transfer, thermal comfort and control of fire and smoke.

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A review of airflow through large openings carried out by Riffat (4) showed that little work has been published on interzonal convection through large horizontal openings. Brown and Solvason (5) have investigated airflow through small square openings in horizontal partitions. Riffat (6) has studied buoyancy-driven flow through a staircase in a house and Reynolds et. al (7) have developed a model for buoyancy driven flow in a stairwell. Advancements in tracer-gas technology allow scope for conducting extensive measurements to investigate airflow through horizontal openings of various sizes in partitions of different thickness. The results could be used to develop accurate algorithms for inclusion in existing mathematical models. The present paper provides the foundations for development of such algorithms.

2. Theory

2.1. Interzone airflows

Airflows in a two-zone system are shown in Figure 1. Air can infiltrate from outside the building into each room (F_{01} and F_{02}) and exfiltrate from each room to the outside (F_{10} and F_{20}). In addition, air can exchange between the rooms through a large horizontal opening (communication opening) in both directions (F_{12} and F_{21}). If one applies the tracer-gas material balances in each room, assuming that a steady state exists, the rate of change of tracer concentration in room 1 at time t is given by:

$$V_1 \, dC_1 / dt = - C_1 (F_{10} + F_{12}) + C_2 F_{21} \qquad (1)$$

Similarly, the rate of change of tracer concentration in room 2 at time t is given by:

$$V_2 \, dC_2 / dt = C_1 F_{12} - C_2 (F_{21} + F_{20}) \qquad (2)$$

The other flow rates can be then determined using the continuity equation as follows:

$$F_{01} = F_{12} + F_{10} - F_{21} \qquad (3)$$

$$F_{02} = F_{20} + F_{21} - F_{12} \qquad (4)$$

The volumetric-balance equations can be solved using the theoretical technique based on the Sinden method (8). The method assumes that a multizone system may be represented by a series of cells of known and constant volume which are all connected to a cell of infinitely large volume, i.e., the outside space. The volumetric balance for each room can be expressed by a series of equations which can then be solved using matrices.

The tracer-gas technique used in this work has been validated in the laboratory by measuring airflow between two small chambers equipped with a calibrated flowmeter. The airflow determined using SF_6 tracer-gas and that measured with the flowmeter agreed to within ± 5%.

2.2 Interzone heat and mass transfer

Figure 2 shows airflow through a horizontal opening separating two zones. (see Appendix). Applying Bernoulli's equation, the mass flow rate through the opening is:

$$M = \rho \; A \; K \sqrt{\frac{\Delta T \; gH}{T}} \qquad (5)$$

Substituting equation (A10) into (A11), the heat transfer flow between zone 1 and zone 2 through the opening is:

$$q = \rho \; A \; K \; C_p \sqrt{\frac{(\Delta T)^3 \; gH}{T}} \qquad (6)$$

Substituting equation (A12) into (A13), heat-transfer coefficient h is:

$$h = \rho \; K \; C_p \sqrt{\frac{\Delta T \; gH}{T}} \qquad (7)$$

Equation (8) describes convection through an opening in terms of the Nusselt number, Grashof number and Prandtl number :

$$N_u = K \; G_r^{0.5} \; P_r \qquad (8)$$

3. Material and method

Experiments were carried out using two rooms as shown in Figure 3. Room 1 is located downstairs and has dimensions 3.6m × 6m × 3.2m, (Volume = $69m^3$), Room 2 is located upstairs and has dimensions 3.6m × 11.7m × 3.2m, (Volume = $135m^3$). The two rooms are connected via a horizontal opening of dimensions, 1.3m × 1.3m through partition of thickness 0.3m. Room 1 was heated to various temperatures using thermostatically-controlled heaters. Room 2 was unheated. The temperature was measured at three different heights in each room using grids situated at the centre of the opening.

Airflow measurements were carried out using a single tracer-gas technique . Several tracer gases are available, but sulphur hexafluoride was chosen for this work since it has desirable characteristics in terms of detectability, safety, and cost and it has been used successfully in previous air movement studies. To estimate the airflow between the two rooms, two multi-point sampling systems were used. The first system was used to collect tracer-gas samples from room 1, while the second was used to collect samples from room 2. At the beginning of each test the communication door between the two rooms was closed and gaps between the door and its frame were sealed. This prevented heat and tracer-gas leakage prior to starting the test. The tracer-gas was released in room 1, where it was mixed with air using an oscillating fan. To ensure that a uniform concentration had been achieved in room 1, samples were taken at ten sampling points in each room. After a mixing period of about 15 minutes, the communication door was opened. Samples were taken every 30 seconds for a total duration of 60 minutes. The concentration of SF_6 was measured using a BINOS 1000 analyser made by Rosemount Ltd, U.K. The temperature at various locations in each room was measured using thermocouples. The wind speed and direction were recorded during the test.

4. Results and discussion

The airflows between the two rooms were estimated from the tracer-gas concentration data using the method described in section 2.1. Several experiments were carried out for various temperature differences between rooms; only room 1 was heated to temperatures in the range 18°C to 33°C. Following this, the communication door was opened and temperature and tracer-gas concentration were monitored. The temperature in room 1 fell rapidly during the first 10 minutes and then decreased at a much slower rate. The temperature in room 2 increased during the first 10 minutes and then gradually stabilized at an almost constant value.

Figures 4 and 5 show tracer-gas concentration against time for two temperature differences. To evaluate the coefficient of discharge, K for the horizontal opening, the airflow measured using the tracer-gas technique was divided by the theoretical airflow given by equation 5 (see section 2.2). Figure 6 shows the variation of K with ΔT. The results were correlated well with :

$$K = 0.57\, e^{-0.23\, \Delta T} \qquad (9)$$

The coefficient of the discharge was found to be in the range 0.24 to 0.52 (α between 0.81 and 0.89) depending on the temperature difference between the two zones. The decrease in the coefficient of discharge may be due to an increase in interfacial mixing as a result of the direct transfer of cold air from the upper floor to the lower floor. In addition, the increase in density difference could cause an increase in turbulence in the two zones affecting the coefficient of discharge.

The Reynolds numbers based on the hydraulic diameter D_h of the opening were found to be in the range 657 to 892. For H = 0.3m, a = b = 1.3m and T ≈ 300K, the mass flow rate between the two rooms can be given in the form :

$$M = 0.114\, e^{-0.23\, \Delta T} (\Delta T)^{0.5} \qquad (10)$$

Similarly the heat flow rate between the two rooms through the opening is given by:

$$q = 114.5\, e^{-0.23\, \Delta T} (\Delta T)^{1.5} \qquad (11)$$

Equation (12) describes convection through the opening in terms of the Nusselt number, Grashof number and Prandtl number:

$$Nu = 0.57\, e^{-0.23\, \Delta T}\, Gr^{0.5}\, Pr \qquad (12)$$

The mean interzone heat transfer coefficient can be calculated using the following equation :

$$h = 67.75\, e^{-0.23\, \Delta T}\, (\Delta T)^{0.5} \qquad (13)$$

5. Conclusions and recommendations

i) The experimental study shows that the coefficient K for the horizontal opening is between 0.24 and 0.52 depending on the interzonal temperature difference. Further work is required to examine the effect on coefficient of discharge of the geometries of the zone and size and shape of the opening.

ii) The heat and mass transfer through the opening was found to increase significantly with increasing temperature difference. However, further investigation is necessary to study the effect of temperature stratification and wall temperature on interzonal heat and mass transfer.

iii) The use of the single-tracer gas technique was found to a simple and convenient method for measuring interzonal airflows. Measurement accuracy could be improved by employing a multiple-tracer gas technique.

iv) Further work is required to study heat and mass transfer through large horizontal openings under combined natural and forced convection.

Appendix

The theoretical analysis was carried out following Brown and Solvason (5). Figure 2 shows airflow through a horizontal opening separating two zones. The temperature and density in zone 1 and 2 are assumed to be T_1 , T_2 and ρ_1 , ρ_2 respectively. The density ρ_2 is assumed to be higher than density ρ_1.

Airflow from zone 1 to zone 2:

$$P_1 - P_2 = \rho_1 \frac{U_1^2}{2} + L_1 + \rho_1 gH \qquad (A1)$$

Airflow from zone 2 to zone 1:

$$P_1 - P_2 = - \rho_2 \frac{U_2^2}{2} - L_2 + \rho_2 gH \qquad (A2)$$

Applying the continuity equation for airflow across the opening:

$$\rho_1 U_1 A_1 = \rho_2 U_2 A_2 \qquad (A3)$$

Assuming that :

$$\rho_1 \approx \rho_2 \approx \rho \qquad U_1 \approx U_2 \approx U \qquad L_1 \approx L_2$$

Therefore from equation A1 and A2:

$$(\rho_1 - \rho_2) gH + \rho U^2 + 2L = 0 \qquad (A4)$$

For a opening through a thin partition the fluid friction loss can be assumed negligible, the pressure loss in the opening is:

$$L = \frac{1}{2} \alpha \rho U^2 \qquad (A5)$$

Substituting equation (A5) into (A4) and rearranging we have :

$$U = \sqrt{\frac{(\rho_2 - \rho_1)\ gH}{\rho\ (1+\alpha)}} \qquad (A6)$$

Since the coefficient of thermal expansion $\beta = 1/T = -\Delta\rho / (\rho\Delta T)$, Equation A6 can be rewritten as follows:

$$U = \sqrt{\frac{\Delta T\ gH}{T\ (1+\alpha)}} \qquad (A7)$$

Mass flow rate between the zones is:

$$M = \rho\ A\ U \qquad (A8)$$

Substituting equation (A7)and (A8),

$$M = \rho\ A \sqrt{\frac{\Delta T\ gH}{T\ (1+\alpha)}} \qquad (A9)$$

Since the coefficient discharge is:

$$K = \frac{1}{\sqrt{1+\alpha}}$$

Therefore, mass flow rate between the two zone is:

$$M = \rho\ A\ K \sqrt{\frac{\Delta T}{T}\ gH} \qquad (A10)$$

The heat flow rate between zone 1 and zone 2 is:

$$q = M\ C_p\ \Delta T \qquad (A11)$$

Substituting equation (A10) into (A11) , we have:

$$q = \rho\ A\ K\ C_p \sqrt{\frac{(\Delta T)^3\ gH}{T}} \qquad (A12)$$

The heat-transfer coefficient h is defined as:

$$h = \frac{q}{A \, \Delta T} \qquad (A13)$$

$$h = \rho \; K \; C_p \sqrt{\frac{\Delta T \; gH}{T}} \qquad (A14)$$

The Nusselt number is given by:

$$N_u = \frac{h \; H}{k} \qquad (A15)$$

Substituting equation (A14) into (A15) , we have:

$$N_u = K \; G_r^{0.5} \; P_r \qquad (A16)$$

The Grashof number based on H is defined as:

$$G_r = \frac{\Delta T \; gH^3}{T \; \upsilon^2} \qquad (A17)$$

Where, Prandtl number is:

$$P_r = \frac{C_P \; \mu}{k} \qquad (A18)$$

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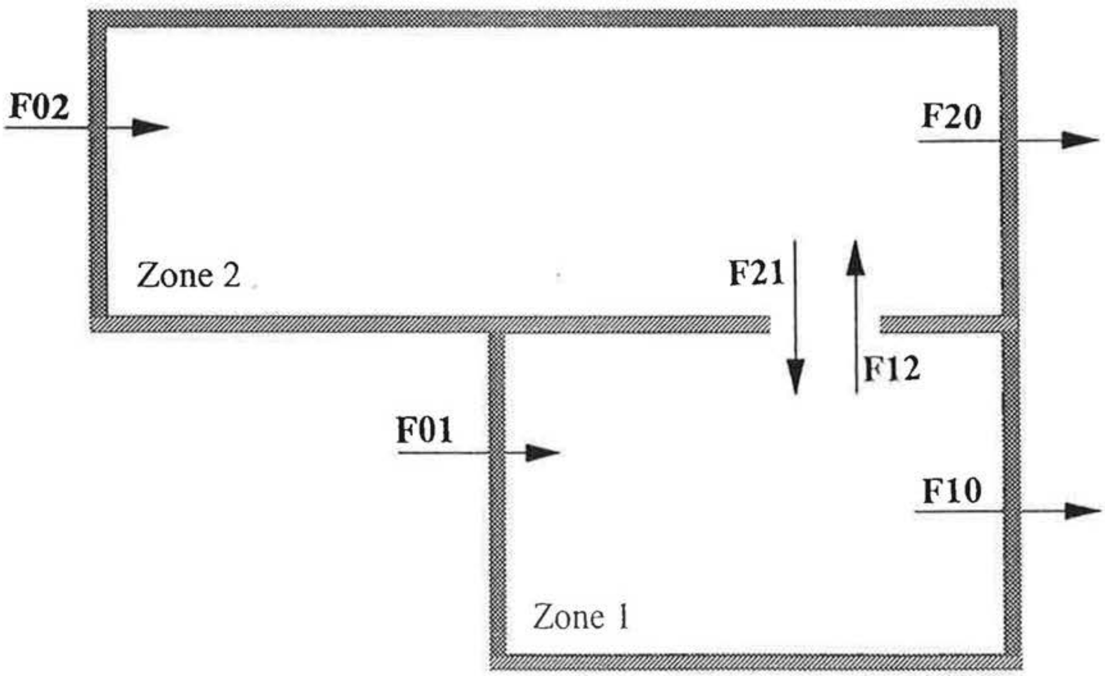
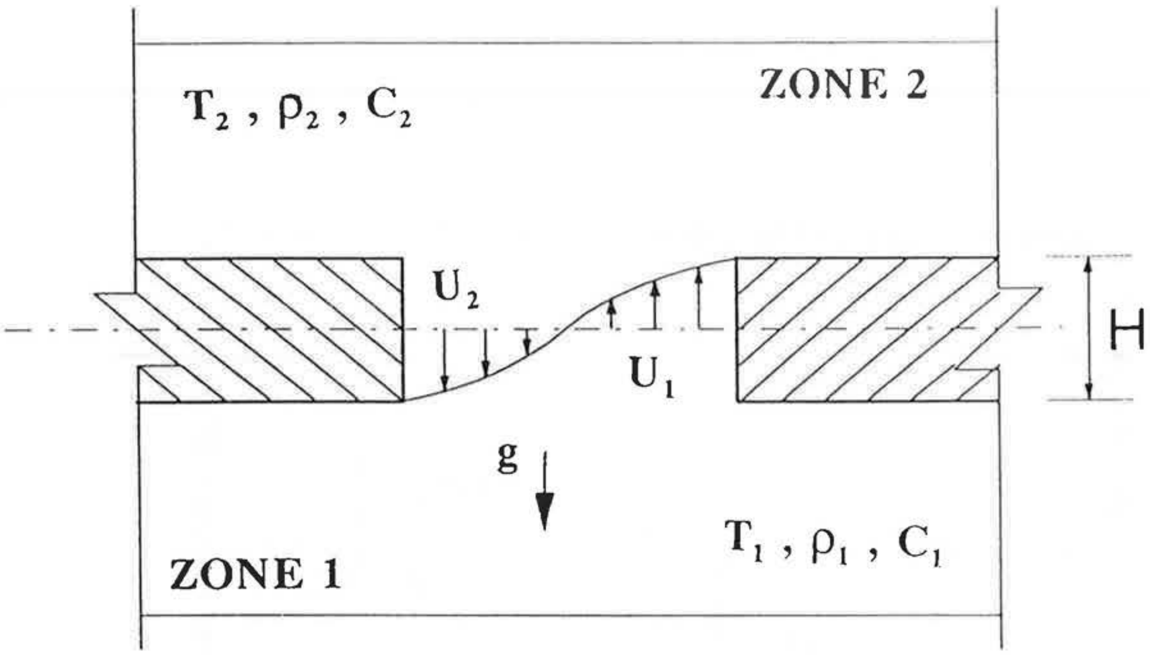
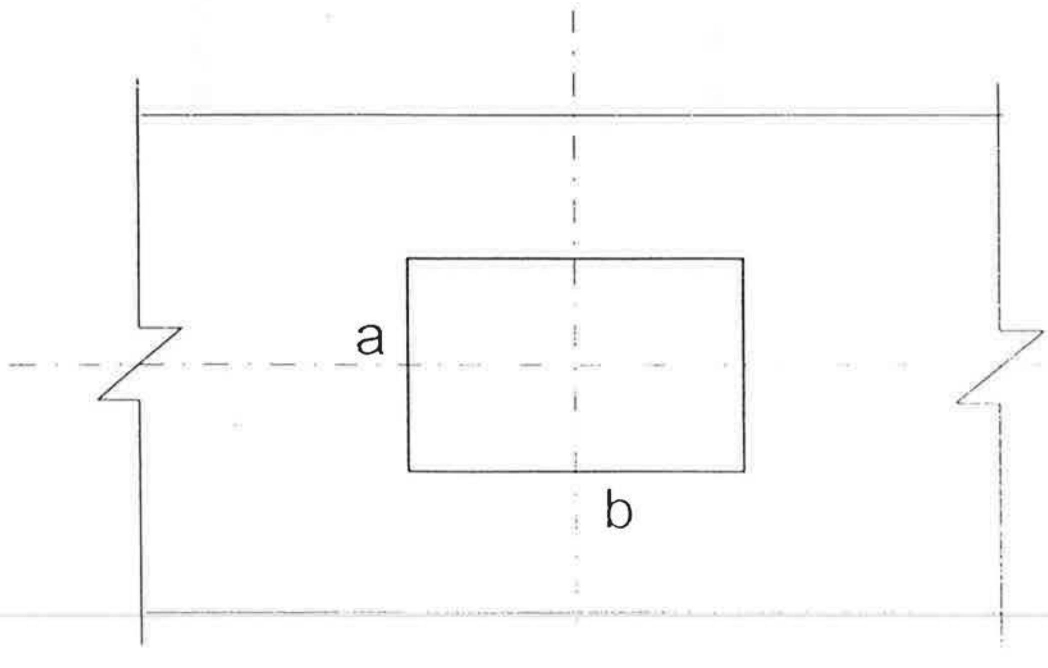
Figures

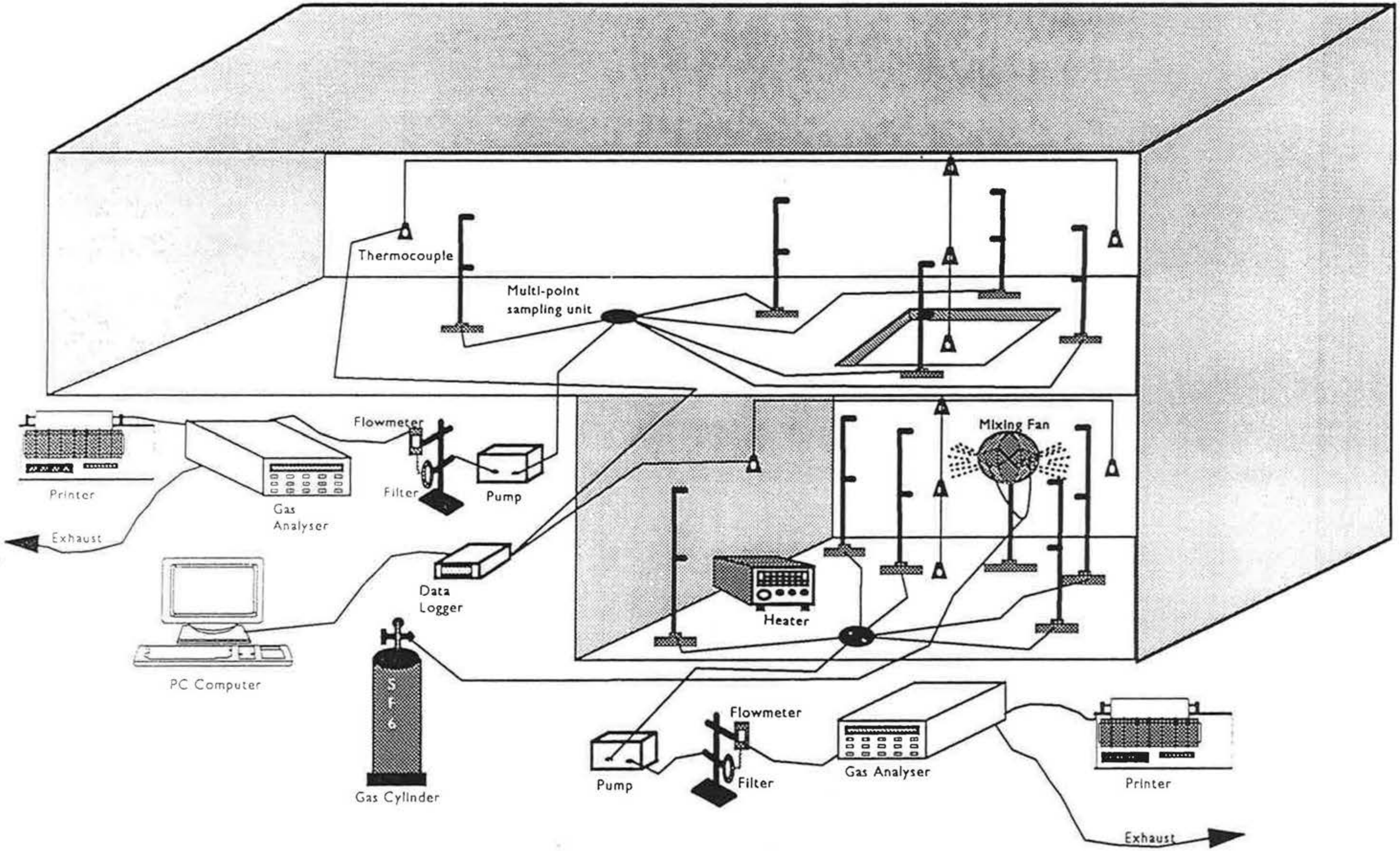

F02
F20
Zone 2
F21
F12
F01
F10
Zone 1



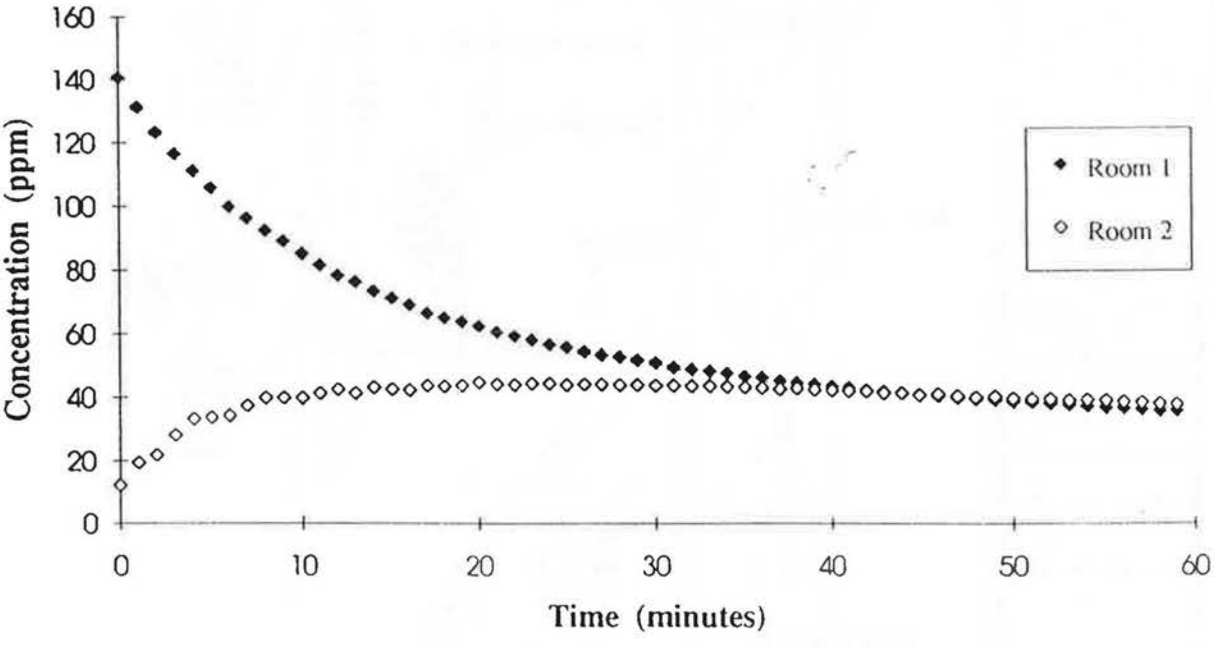
T_2 , ρ_2 , C_2
ZONE 2
U_2
U_1
H
g
T_1 , ρ_1 , C_1
ZONE 1



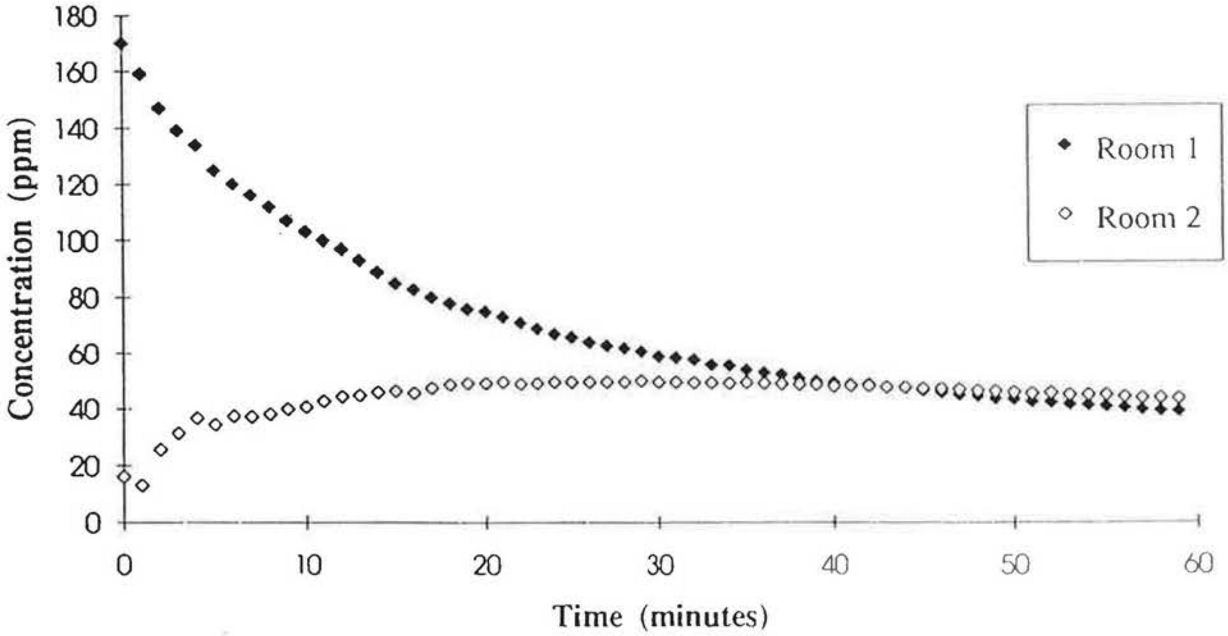
a
b



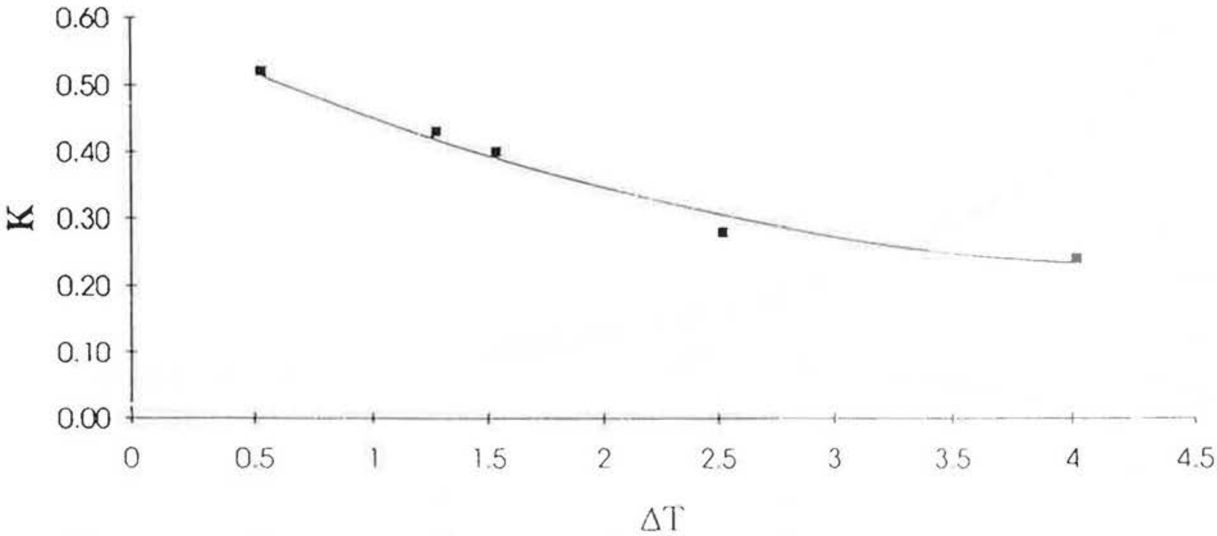
Thermocouple
Multi-point sampling unit
Flowmeter
Printer
Gas Analyser
Filter
Pump
Exhaust
Mixing Fan
Data Logger
Heater
PC Computer
SF 6
Gas Cylinder
Flowmeter
Pump
Filter
Gas Analyser
Printer
Exhaust



Concentration (ppm)
160
140
120
100
80
60
40
20
0
Room 1
Room 2
0
10
20
30
40
50
60
Time (minutes)



180
160
140
120
100
80
60
40
20
0
Concentration (ppm)
0
10
20
30
40
50
60
Time (minutes)
Room 1
Room 2



0.60
0.50
0.40
0.30
0.20
0.10
0.00
K
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
ΔT