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Algorithm for Interzonal Particle Flow Through Openings

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SYNOPSIS

Measurements of interzone airflow and movement of aerosol particles were carried out in an environmental chamber. SF_6 tracer gas and oil-smoke particles were used for this work. A series of measurements were conducted to investigate the effect of parameters such as interzone temperature difference and size of opening on the flow of aerosol particles. The particle deposition rate on the surfaces of the chamber together with algorithms for interzonal particle flow through the openings were determined. Results were compared with those obtained using the tracer-gas.

LIST OF SYMBOLS

A	surface area of zone, (m^2)
A_x	cross-sectional area of opening, (m^2)
A_m	maximum area of opening, $H = 0.5$m and $W = 0.7$m, (m^2)
A_r	ratio of A_x to A_m, (dimensionless)
d	diameter of particle, (μm)
C_1	concentration of tracer-gas at time t in zone 1, (μg/m^{3}h or ppm)
C_2	concentration of tracer-gas at time t in zone 2, (μg/m^{3}h or ppm)
C_d	coefficient of discharge, (dimensionless)
F	volumetric flow rate, (m^3/s)
g	acceleration due to gravity, (m/s^2)
H	height of opening, (m)
I	tracer-gas exchange rate, (μg/m^{3}h or h^{-1})
P	particle-exchange rate, (μg/m^{3}h or h^{-1})
T	mean absolute temperature of the two zones, (K)
ΔT	average temperature difference between the two zones, ($^\circ$C or K)
V	volume of zone, (m^3)
W	width of opening, (m)
α	particle deposition rate, (μg/m^{2}h)

1. INTRODUCTION

Investigation of particulate pollutants in the indoor environment of residential and commercial buildings is important because of the potentially harmful effects on the health of the occupants. Indoor aerosol particles are not only associated with outdoor sources (e.g., automobile exhaust emissions, coal and oil combustion, road dust, etc.) but also arise from a number of indoor sources (e.g., cigarette smoke, building materials, personal products, etc.). Particulate pollutants in buildings can have harmful effects on the health of the occupants and studies have shown that indoor aerosol particles influence the incidence of sick building syndrome (1). Aerosol particles can deposit on surfaces of rooms or be transported between zones; this can have serious effects in hospitals and buildings used by pharmaceutical industries (2). Contamination of electronic equipment by particulate pollutants can significantly affect the reliability of equipment used by the micro-electronic industries (3,4). Soiling of collections in museum and galleries caused by the deposition of airborne particles is a topic under investigation by other researchers and studies have been carried out to establish means to reduce the soiling rate (5).

The concentration of indoor aerosol particles can be reduced by mechanical or natural ventilation. The ventilation rate is usually estimated using tracer-gas techniques. However, measurements based on these techniques are not sufficient to describe the removal of particles as particle deposition rate, particle type, source and concentration must be included to estimate the accurate exchange rate.

In this paper, a series of experiments were carried out based on buoyancy-driven air and particle flow through vertical openings in a two-zone chamber. The deposition of particles in the chamber was studied and algorithms for interzonal air and particle flow were established.

2. THEORY

Figure 1 shows a schematic diagram of a two-zone system. F_{01} and F_{02} show the infiltration from outside the chamber into each zone while F_{10} and F_{20} show the exfiltration of tracer-gas (e.g. SF_6) and particles (e.g. oil-smoke) from each zone to the outside. In addition, tracer gas and particles can exchange between the two zones through a doorway (communication opening) in the direction, F_{12} and F_{21}. If one applies the material balance in each zone, assuming that a steady state exists and that the concentration of tracer gas (or particles) is negligible, then the rate of change of tracer-gas (or particle) concentration in zone 1 at time t is given by:

$$V_1 \frac{dC_1}{dt} = -C_1(F_{10} + F_{12}) + C_2F_{21} \tag{1}$$

Similarly, the rate of change of tracer (or particle) concentration in zone 2 at time t is given by:

$$V_2 \frac{dC_2}{dt} = C_1F_{12} - C_2(F_{21} + F_{20}) \tag{2}$$

The other two flow rates can then determined using the continuity equations as follows:

$$F_{01} = F_{12} + F_{10} - F_{21} \tag{3}$$

$$F_{02} = F_{20} + F_{21} - F_{12} \tag{4}$$

Equations 1 - 4 may be solved using the theoretical technique described by Sinden (6). This 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 zone can be expressed by a series of equations which can then be solved using matrices.

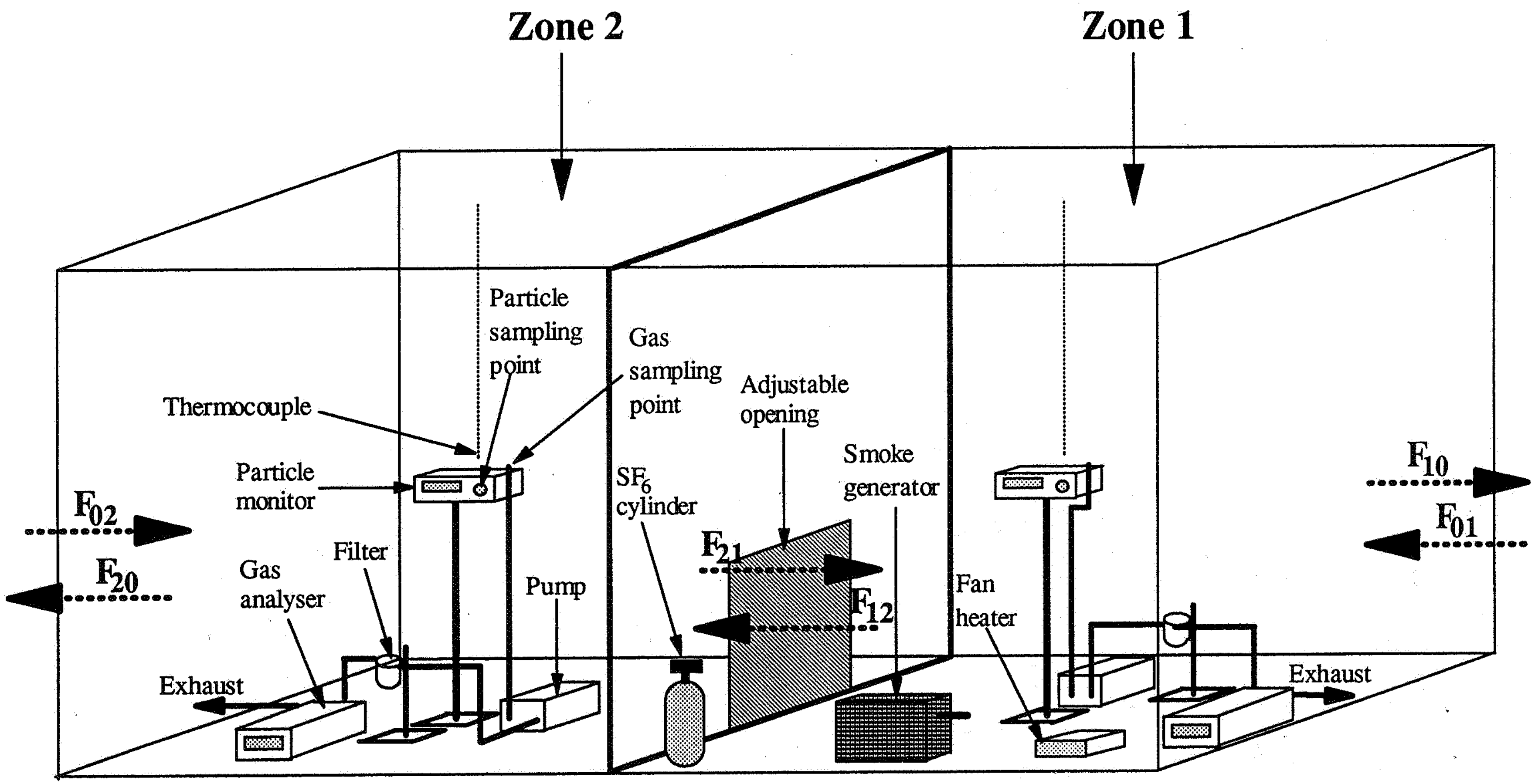

Figure 1 Schematic diagram of two-zone environmental chamber and its instrumentation

Shaw and Whyte (7) have given the volumetric discharge through an opening as:

$$F = C_d \frac{W}{3} \left[g H^3 \left(\frac{\Delta T}{T} \right) \right]^{0.5} \tag{5}$$

3. EXPERIMENTAL WORK

An environmental chamber consisting of two tightly-sealed zones was used for the experimental work (see Figure 1). The dimensions of each zone were 2.5m x 3m x 2.4m, (volume = $18m^3$) and these were connected by an opening with a sliding door. The height of the opening (H) could be adjusted by a pulley arrangement while the width (W) was fixed at 0.7m. The chamber was constructed from plywood sheet with a cavity insulated using polystyrene. Zone 1 was heated using a convector electric-heater; zone 2 was unheated. Temperatures were measured at the centre of the zone at mid-height locations using Ni/Cr/Al thermocouples.

Each experiment started with an initial release of SF_6 tracer-gas and oil-smoke particles into zone 1 with the sliding door between the two zones closed and gaps between the door and its frame sealed. This prevented leakage of tracer-gas and oil-smoke particles prior to the start of the test. An oscillating desk fan was used to assist mixing. After a mixing period of 1 hour, the desk fan was switched off and the sliding door was raised to a predetermined height. This was followed by simultaneous measurements of tracer-gas and oil-smoke particle concentration for both zones using an infra-red gas analyser type BINOS 1000 made by Rosemount Ltd., U.K. and an infra-red particle monitor type Grimm 1.100 manufactured by Grimm Ltd., Germany, respectively. Tracer-gas and oil-smoke samples were collected at the same locations as the thermocouples.

4. RESULTS AND DISCUSSION

4.1 Tracer-gas

The air flows between the zones were estimated using the concentration-decay technique. Several experiments were carried out for various temperature differences between the zones; only zone 1 was heated to temperatures in the range 18°C to 45°C. Following this, the sliding door was opened and both temperature and tracer-gas concentration were monitored. The sliding door was raised between 0.1m - 0.5m. The coefficient of discharge was found to correlate well with the area of the opening:

$$C_d = 1.36\, e^{-2.24A_r} \tag{6}$$

For W = 0.7m, g = $9.81m/s^2$ and T = 300K and substituting equation (6) into equation (5) yields:

$$F = 0.057\, e^{-2.24A_r} \left[H^3 \Delta T \right]^{0.5} \tag{7}$$

4.2 Aerosol particles

SF_6 tracer-gas and oil-smoke particles were injected into zone 1. After a mixing period of 1 hour, simultaneous measurements of tracer-gas and oil-smoke particle concentration were performed using the infra-red gas analyser and particle monitor, respectively. Figure 3a and 3b show the variation of concentration of tracer-gas and smoke particles ($0.5\mu m < d < 5\mu m$) respectively with time for $A_x = 0.1m \times 0.7m$ and $\Delta T = 12.8K$. The tracer-gas and particle curves were found to be simple exponential functions for all conditions.

The correlation between discharge coefficient and area of opening based on particle flow was determined:

$$C_d = 1.23\, e^{-1.42A_r} \tag{8}$$

The volumetric flow rate through opening was established by substituting equation (8) into equation (5) with W = 0.7m, $g = 9.81 m/s^2$ and T = 300K:

$$F = 0.074\, e^{-1.42A_r}\, [H^3 \Delta T]^{0.5} \tag{9}$$

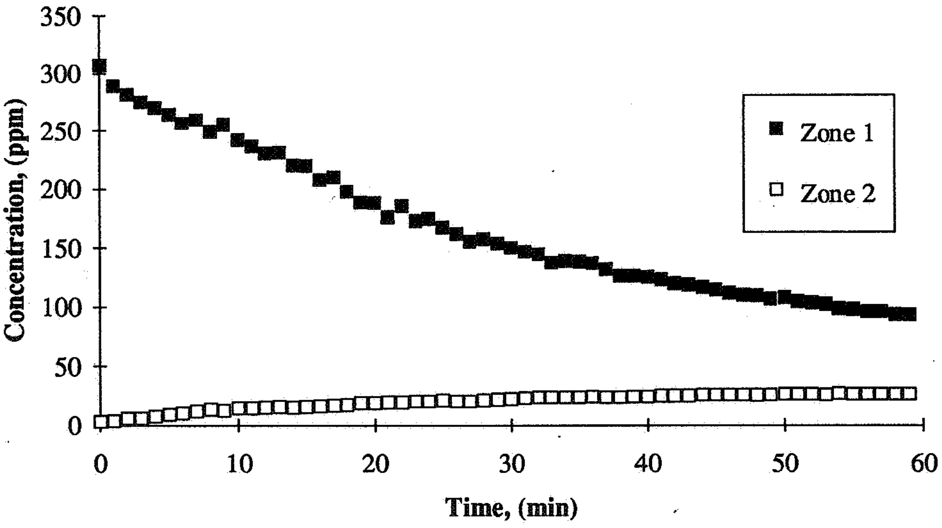

Figure 3a Variation of tracer-gas concentration with time in zone 1 and zone 2, H = 0.1m, ΔT = 12.8K

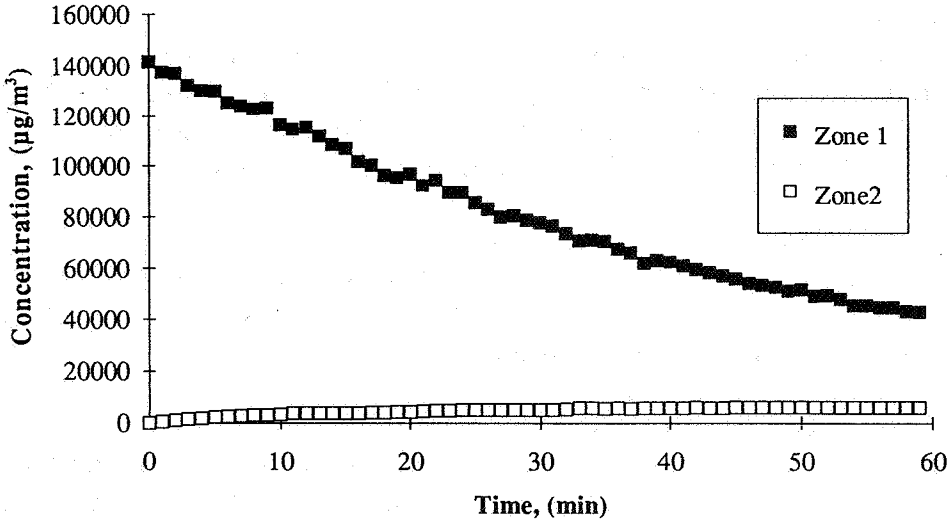

Figure 3b Variation of particle concentration with time in zone 1 and zone 2, $0.5\mu m < d < 5\mu m$, H = 0.1 m, $\Delta T = 12.8K$

For $A_r = 1$, H = 0.5m and $\Delta T = 10K$, the interzone airflow rates based on tracer-gas and particles were 24.4 m^3/h and 72 m^3/h, respectively. The particle exchange rates were found to be higher than tracer-gas exchange rates. The difference in tracer-gas and particle exchange rate is due to deposition (or adsorption effect) of particles on the surfaces of the environmental chamber. This was estimated using the following equation:

$$\alpha = (P-I) \times \frac{V}{A} \tag{10}$$

Deposition of particles was found to be negligible in zone 1, (heated) and high in zone 2, (unheated). Thermophoresis might be partly responsible for deposition of particles as the warm particle came into contact with the cooler wall in the unheated zone. The deposition rates for particles ($0.5\mu m < d < 5\mu m$) in zone 2 for openings with areas $0.07m^2$, $0.21m^2$, $0.28m^2$ and $0.35m^2$ were in the range 2.77 - $9.78\mu g/m^2h$, 4.30 - $64.64\mu g/m^2h$, 12.48 - $32.07\mu g/m^2h$ and 5.21 - $23.77\mu g/m^2h$, respectively. This showed that the deposition of particles was random and independent of the area of opening. The coefficients of discharge based on tracer-gas and particles for openings with areas $0.07m^2$, $0.21m^2$, $0.28m^2$ and $0.35m^2$ were found to be 0.87, 0.35, 0.23 and 0.14, and 0.93, 0.52, 0.39 and 0.30, respectively. The coefficients of discharge based on particles were generally higher than those determined from tracer-gas measurements.

5. CONCLUSIONS

(i) The correlation between coefficient of discharge and cross-sectional area of opening was determined for tracer-gas and particles. Coefficient of discharge was found to vary with the area of opening and the coefficients of discharge based on particles were generally higher than those based on tracer-gas measurements.

(ii) Algorithms for interzonal particle and tracer-gas flow in a two-zone environmental chamber were established. The results showed that particle exchange rates were generally higher than tracer-gas exchange rates. This was due to the deposition effect of particles on the surfaces of the chamber.

(iii) The deposition rate in the heated zone is low compared with that in the unheated zone. This may be due to thermophoresis as warm particles were deposited on the cooler wall. In addition, the deposition rates of particles were found to be random.

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REFERENCES

1. Turiel, I.
"Indoor air quality and human health"
Standford University Press, Standford, California, 1985.
2. Farrance, K. and Wilkinson, J.
"Dusting down suspended particles"
Building Services, Vol. 12, 1990, pp45-46.
3. Reagor B.T.
"Dust: What, Where, Why and How"
Proceedings National Communications Forum, Vol. 42, 1988, pp981-982.
4. Reagor B.T. and Russell C.A.
"A survey of problems in telecommunications equipment resulting from chemical contamination"
IEEE Trans Comp, Hybrids, Manuf Technol, Vol. 9, 1986, pp209-214.
5. Nazaroff W.W. and Cass G.R.
"Protecting museum collections from soiling due to the deposition of airborne particles"
Atmospheric Environment, Vol. 25A, No. 5/6, 1991, pp841-852.
6. Sinden F.W.
"Multi-chamber theory of air infiltration"
Building and Environment, Vol. 13, 1978, pp21-28.
7. Shaw B.H. and Whyte W.
"Air movement through doorways: the influence of temperature and its control by forced air flow"
Bldg Serv. Engrg, Vol 42, 1974, pp210-218.