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VENTILATION STUDIES IN NINE AIR-CONDITIONED OFFICE BUILDINGS IN SINGAPORE

S.C.Sekhar, K.W.Tham, David Cheong and N.H.Wong

School of Building and Real Estate
National University of Singapore
Singapore, 117566

ABSTRACT

One of the significant factors affecting the quality of air in the built environment, particularly in the context of hot humid climates, is the design and implementation of the air-conditioning and mechanical ventilation system. While most building regulations would incorporate minimum ventilation requirements at design, it is often difficult to quantitatively measure the adequacy of such ventilation provision in in-situ buildings. A research initiative, aimed at obtaining status-quo measurements of the ventilation characteristics in air-conditioned office buildings in Singapore, has yielded a reasonably large database, which details are presented in this paper. Tracer gas techniques, employing the concentration decay method, were adopted to obtain the fundamental age of air values in nine buildings. Other ventilation characteristics such as the outside air change per hour, ventilation provision and air exchange effectiveness were subsequently computed. The measured air change per hour values in the building with the highest ventilation provision is almost eight times that of the building with the lowest ventilation provision. Apart from minor short-circuiting profiles in some zones, the air exchange effectiveness values have generally been observed to indicate well-mixed flow patterns.

KEYWORDS

Ventilation provision, Air Exchange Effectiveness, Air Change per Hour, Tracer gas techniques, Concentration Decay Method, Singapore, Office Building, Hot and Humid Climate, High-rise Air-conditioned Building

INTRODUCTION

The provision of fresh air to occupants in high-rise air-conditioned buildings is typically governed by building regulations and ventilation standards (ASHRAE, 1999; BCD, 1979). Whilst these provisions are generally regarded as design requirements, it often becomes difficult to ensure that they have been adequately met during the operation of a building. Tracer gas techniques become quite relevant in determining the ventilation characteristics of a building and provide a reasonable basis for evaluating the effectiveness with which the ventilation system in a building is able to dilute the various indoor pollutants

(Fisk, 1993; Sekhar and Tham, 1995). A comparison of status-quo measurements and analysis of the ventilation characteristics in nine air-conditioned office buildings in Singapore is presented in this paper.

METHODOLOGY

The various ages of air, air change rate (ACH) and air exchange effectiveness (AEE) are determined from tracer gas studies, using a multi gas monitor and a multiple doser and sampler, in which a tracer gas (Sulfur hexafluoride, SF_6) is dosed into the fresh air stream and its concentration at various sampling points in the occupied zones is monitored.

In the concentration decay process, the method adopted in the present study, the air change per hour (ACH) is defined as the slope of the tracer-gas concentration decay curve. The age of a sample of air is the average amount of time that has elapsed since molecules in this sample entered the zone and is measured using tracer-gas techniques (Fisk et al, 1993; Sekhar and Tham, 1995). The local age of air at a specific location within the occupied zone, the age in various air streams and the room average age of all air within the zone are some of the different types of age of air that are commonly used. The nominal time constant, t_N, is used in the definition of AEE parameters and is equal to the indoor air volume divided by the outside airflow rate. t_N is the reciprocal of the air exchange rate and is usually expressed in units of hours.

The three AEE parameters determined are defined by the following equations:

$$AEE_{GLOBAL} = AEE_G = t_N / \langle t \rangle \quad (1)$$
$$AEE_{OCCUPANT\ LEVEL} = AEE_{OL} = t_N / \langle t_{OL} \rangle \ldots \quad (2)$$
$$AEE_{LOCAL} = AEE_L = t_N / t_{OL} \ldots \quad (3)$$

Where t_N = the indoor air volume divided by the outside air flow rate and is the reciprocal of ACH, t_{OL} = local age of air measured at the occupant level, $\langle t \rangle$ = room average age of air within the entire zone and determined from measurements of tracer gas in the main return or exhaust air streams, $\langle t_{OL} \rangle$ = average of the measured local ages of air at occupant level.

AEE_G is representative of the entire zone as both the numerator and denominator of this parameter pertain to the entire building. It is, however, the range of AEE_L, which is useful for assessing the spatial variability of ventilation. AEE_{OL} is more relevant for human health as it is based on the average measured age of air at the occupant level $\langle t_{OL} \rangle$ instead of the room average age $\langle t \rangle$. But it is important to have multi point measurements to obtain a representative average value of t_{OL}.

DESCRIPTION OF BUILDINGS

A total of 9 buildings, the details of which are summarised in Table 1, were studied during the course of two research projects. The field measurements were typically conducted on the basis of a set-up in a given floor. Each set-up constitutes a study that consists of a dedicated Air Handling Unit(s) serving one or more occupied zones so that the concept of system-zone is employed in all the studies. The ventilation provision in A, B, C and CC is by means of fresh air openings at the respective AHUs in each floor while BB, DD, EE, D and E employs a centralised fresh air duct with branch ducts to the individual AHUs at each floor. All the 9 buildings employ chilled water based AHU systems and the return air path is through ceiling plenum.

TABLE 1
SUMMARY OF BUILDINGS INVESTIGATED

Building	Type of building	Number of floors investigated	Number of indoor sampling locations	Key building characteristics
A	7 Storey Institutional building	7	42	▪ Rectangular floor plan ▪ Floor by floor Air Handling Units ▪ Constant Air Volume system
B	47 Storey Office Building	3	18	▪ Square floor plan ▪ Floor by floor Air Handling Units ▪ Variable Air Volume system
C	23 Storey Office Building	3	30	Same as Building A
D	41 Storey Office Building	3	15	Same as Building B
E	52 Storey Office Building	3	15	Same as Building B except for a circular floor plan
BB	10 Storey office building	1	6	Same as Building B except for a rhombus floor plan
CC	63 Storey Office Building	3	18	▪ Rectangular floor plan ▪ 3 Central Air Handling Units ▪ Variable Air Volume system
DD	24 Storey Office Building	1	6	Same as Building B except for an odd-shaped floor plan (Half rectangular and half circular)
EE	4 Storey Office Building	1	6	Same as Building B except for a rectangular floor plan

RESULTS AND DISCUSSION

It is seen from Table 1 that the total number of indoor sampling locations is 156, which has resulted in a large database. The range involving the various ventilation characteristics for the 9 buildings investigated are presented in Figures 1 through 6. It is seen from Figure 1 that there are substantial variations in the ACH values among the 9 buildings and that the zone with the highest measured ACH (Building CC) is about 8.6 times that of the building with the lowest ventilation provision (Building E). A comparison of fresh air provision on the basis of design and actual occupancy rates is presented in Figures 2 and 3 respectively. It is to be noted that the actual occupancy, and consequently, the actual fresh air provision could not be determined for buildings D and E. in Figure 3. It is seen that the actual fresh air provisions are generally better than the design fresh air provisions and in most cases both provisions do conform to the local requirements of 3.6 lps/person (BCD, 1979). However, the ventilation provision of some zones in only 2 of the buildings based on design occupancy and 6 of the buildings based on actual occupancy would satisfy ASHRAE ventilation requirements of 10 lps/person (ASHRAE, 1999).

Figure 1 : Summary of Air Change per Hour (ACH) values

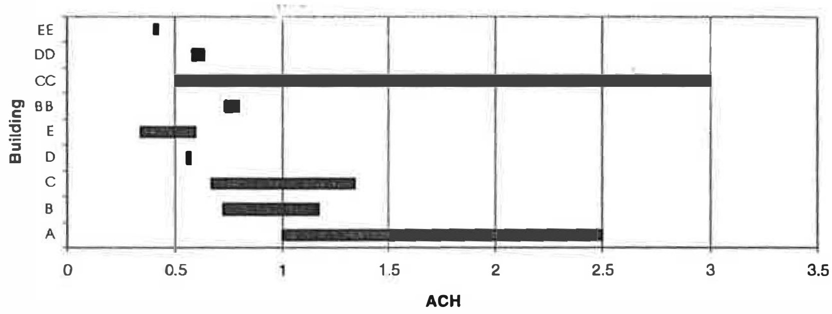


Figure 2 : Comparison of fresh air provision based on design occupancy

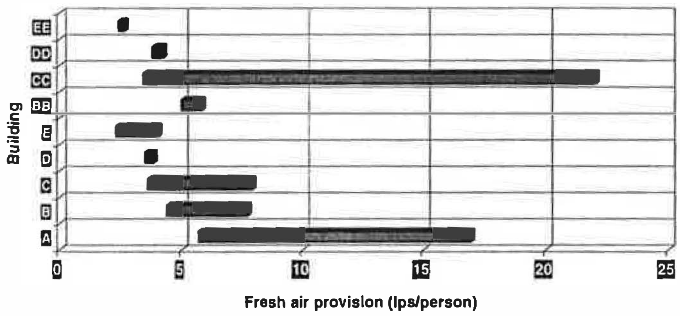


Figure 3 : Comparison of fresh air provision on the basis of actual occupancy

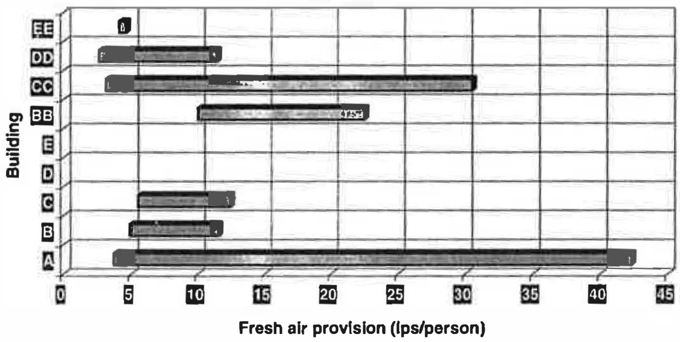


Figure 4 : Comparison of Global Air Exchange Effectiveness (AEEG) values

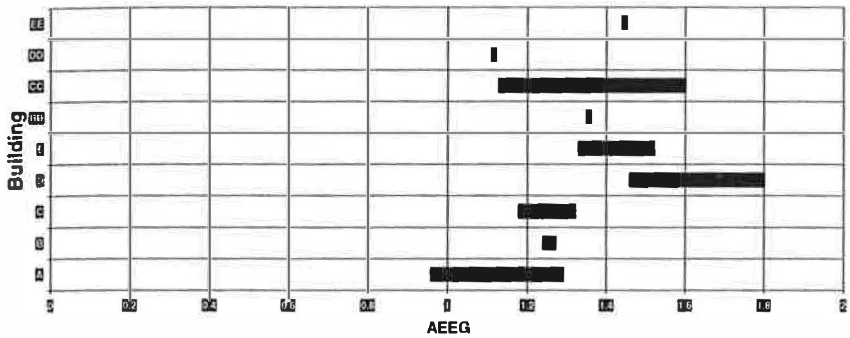


Figure 5 : Comparison of Localised Air Exchange Effectiveness (AEEL) Values

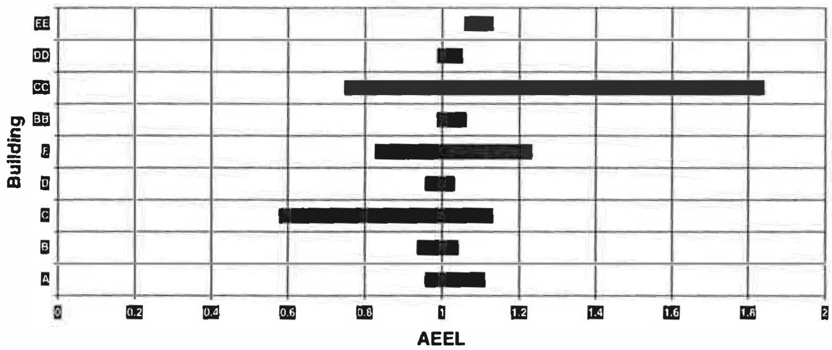
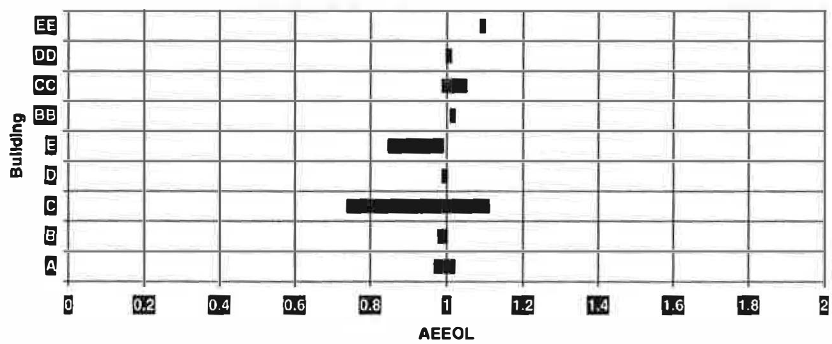


Figure 6 : Comparison of Occupant Level Air Exchange Effectiveness (AEEOL) values



The Global Air Exchange Effectiveness (AEE_G), Localised Air Exchange Effectiveness (AEE_L) and Occupant-level Air Exchange Effectiveness (AEE_{OL}) values are summarised and presented in Figures 4, 5 and 6 respectively. It is observed that the AEE_G values generally exceed 1, which is indicative of perfect mixing condition. When the zone is considered on a global scale, this is indicative of a piston-flow tendency in the airflow pattern. This may be attributed to "mixing" of the return air in the ceiling plenum and has no significant implication in our typical setup. While the AEE_L values are typically around 1, significant variations spanning both the short-circuiting and piston-flow regimes in the various zones are observed in, at least, 3 of the 9 buildings investigated (C, E and CC). AEE_L values are thus considered to be relatively important in providing a better insight into the spatial variation of the ventilation characteristics. AEE_{OL} values, representing an average of several localized air exchange effectiveness values in a zone, exhibit much less variation and provide an "average" indication of airflow pattern within the zone investigated. The measured AEE_{OL} values are usually around 1, implying a well-mixed air distribution pattern.

CONCLUSION

This paper deals with tracer gas analysis, employing the concentration decay method, which have been adopted for the ventilation studies in nine air-conditioned office buildings in Singapore. While the studies have revealed significant variations in the ACH values among the various zones of the nine buildings and minor short-circuiting profiles in some zones, the air exchange effectiveness values have generally been observed to indicate well-mixed flow patterns.

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