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Measurements of air change rates and air flow patterns in large single-cell buildings

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Abstract

This paper describes the measurements of the air change rates and air flow patterns in two large single-cell aircraft hangar buildings. The decay of the tracer gas sulfur hexafluoride was used to measure the air change rates. It was possible to achieve a uniform mixture of indoor air and the tracer gas in the hangars using the air circulation fans of the heating system. Stratified air layers characterized the air flow patterns within the hangars. For the test conditions, measured air change rates for the two hangars are in the range 0.32 to 0.47 air changes per hour. Results also suggest that five sampling locations at about 1.8 m (6 ft) height are sufficient to obtain a representative air change rate for large single-cell buildings. Crown Copyright © 1997 Published by Elsevier Science S.A.

Keywords: Field measurement; Air change rate; Air flow pattern; Large space industrial buildings; Aircraft hangars

1. Introduction

Air leakage characteristics of large buildings are essential to accurately assess their ventilation and energy requirements. Misjudging the air infiltration rate can lead to under- or oversized heating and ventilation systems. In addition to excessive energy loss, air infiltration can cause occupants discomfort. Better understanding of the air flow patterns within a building can help maintain a comfortable and healthy working environment and reduce the building's energy requirements.

Few air leakage measurements in large single-cell buildings have been reported in the literature. Ashley and Lagus [1] reported air leakage measurements of five military aircraft hangar buildings ranging in volume from 24 000 to 96 000 m^3 and are located in various climatic zones in the USA. Measured air leakage rates were in the range 0.6 to 2.0 air changes per hour (ach). They used the tracer gas decay technique using sulfur hexafluoride (SF_6) which was dispersed at five locations in the building. The tracer gas decay was subsequently sampled from the same locations. Lawrance and Waters [2] reported measurements in five buildings that included a hangar building (31 300 m^3 volume) in the UK. The objective of their study was to develop equipment and a method for measuring the air infiltration rate of large industrial buildings. The tracer gas, SF_6, was dispersed in an arbitrary zone on the windward side of the building and the decay of the tracer gas was sampled at six locations in the building. The measured air change rates for the hangar were in the range 2.92 to 5.74 ach. They noted that the hangar was considered very leaky. Roulet and Van der Maas [3] used the decay of a locally generated tracer gas, CO_2, to measure the air change rate as well as the air flow pattern in an industrial building (60 000 m^3 volume). The tracer gas, CO_2, was a combustion byproduct of the building's heating system (several propane burners). They measured the decay of CO_2 (after the propane burners had been shut off) at 1.5 m height at the centre of the building, and at three heights (1, 6 and 12 m) at another location in the building. The measured air leakage rate of the building was very low (0.08 ach). Jones et al. [4] used the constant concentration as well as the tracer decay methods (using N_2O) to measure the air infiltration rates of three factory buildings (4320 m^3 volume each) that were built to minimize air infiltration rate. The objective of their measurements was to check a ventilation zonal model. The measured average infiltration rate for each building was 0.16 ach (outdoor condition 16.2°C and low wind speed).

Walker and Perera [5] described a simplified technique to measure air infiltration rates of large buildings. The method, which relies on long-term decay rate measurements of SF_6, is intended to be tolerant of a non-uniform dispersal of the tracer gas. Using the simplified method, they measured a mean rate of 0.75 ach in a hangar (4690 m^3 volume). Also

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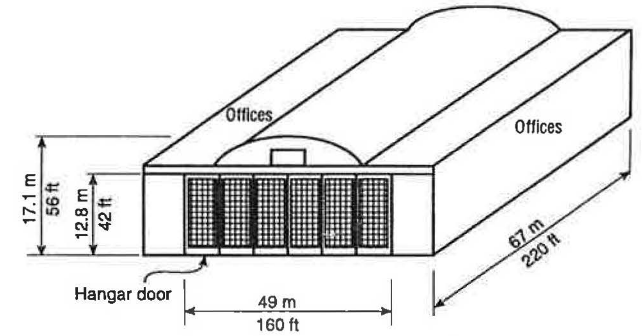
relevant is the study of Freeman et al. [6] in which they compared various tracer gas methods for measuring air infiltration rates of large volume buildings. They performed the measurements in three buildings ranging in volume from 33 to 650 m^3. The difficulties in achieving a good mixing of the tracer gas in large single zone buildings were also discussed.

Perera and Tull [7] measured the airtightness of four large single-cell buildings (a hangar and three industrial buildings) ranging in volume from 4690 to 15 000 m^3. They used a multi-fan pressurization system to pressurize the whole building. This method only gives the building's air infiltration rate indirectly. Perera et al. [8] describe how this is done.

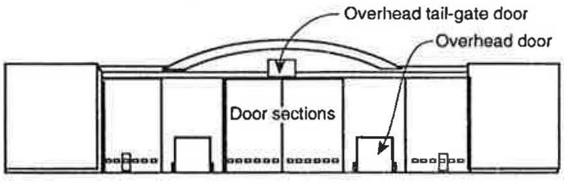
This paper describes the measurements of the air change rates of two aircraft hangar buildings (48 000 m^3 volume each) using the tracer gas decay method. Air flow patterns were also measured. The measurements were conducted during the heating season as part of a project to determine the extent of thermal stratification in aircraft hangar buildings [9].

2. Hangar buildings

The aircraft hangar buildings, of similar construction, are located in Ottawa, Ontario (4634 degree-days base 18°C). The ceiling of both hangars, Fig. 1, is semicircular (Quonset) starting at 12.8 m (42 ft) at the sides, and gently arching to a maximum height of 17.1 m (56 ft). Office space borders the entire 67 m (220 ft) length of the hangar-bay area on both sides of the hangar. Large horizontal-sliding folding doors span the entire 49 m (160 ft) width in both ends of the hangar. Each door consists of 6 panels, each 8.5 m (28 ft) wide and 12.5 m (41 ft) high. There is also an overhead tail-gate door, 2.44×2.44 m (8×8 ft), at the centre (Fig. 1). The doors in Hangar #1 are mostly single-pane glass while the doors in Hangar #2 are fully insulated except for a row of single pane glass view ports at eye level (1.5 m (5 ft) height). The north-end door in Hangar #2 includes 2 overhead doors with automatic door openers for transport vehicles (Fig. 1(b)). The hangar doors are weather sealed with rubber boot seals.



a) Schematic view of hangars



b) View of hangar # 2 north side overhead doors

Fig. 1. Schematic view of hangars.

A vertical discharge forced warm air heating system (3500 cfm, 120 500 Btu/h) is used in both hangars. This system is also known as the 'Door Pocket system' because its main function is to prevent the mechanisms of the doors from freezing. The system consists of two floor mounted steam heating coils (mounted at 0.91 m (3 ft) height from the floor), one at each end of the hangar. Indoor air is drawn through the steam heating coil, ducted under ground, and discharged through a floor grille in front of each hangar door. The average supply air temperature was about 41°C (106°F), and the length of throw was about 12.5 m (41 ft). The heaters are each controlled by a thermostat mounted on the wall beside the air intake of each heater at a height of 1.72 m (5.67 ft) and is about 6.7 m (22 ft) from the hangar door.

The office spaces bordering the hangar-bay area have their own heating (steam radiators) and ventilating systems. The offices are usually slightly pressurized, typically 1 Pa (0.004 in water) with respect to the hangar-bay area. The steam is supplied to all buildings from a central heating plant.

3. Measurement methods

3.1. Air change rate

The decay of the tracer gas sulfur hexafluoride (SF_6) was used to measure the air change rate. SF_6 (100 ppb) was injected at the air intake of the two air circulation fans of the forced warm air heating system (a total of 200 ppb for each building). In Test #1 (Hangar #2) the 200 ppb was injected at the intake of the north-end fan because the south-end fan was not working due to a faulty thermostat. The SF_6 was released from two hand-held portable cylinders positioned directly into the intake of the air circulation fans. The release of SF_6 into both fans was synchronized. Once the gas had been dispersed, the fans were allowed to run for 10 min before collecting the first sample in order to allow for the mixing of the tracer gas with indoor air. Samples of indoor air were collected manually at 10 min intervals in 20 ml sampling glass tubes using a 60 ml sampling syringe. The sampling tubes prior to their use were evacuated and were fitted with a rubber septum stopper. The background concentration was sampled prior to the release of the tracer gas.

All doors to the hangar-bay area were kept closed during the two-hour test duration. No attempt was made to seal around the doors. In Tests #2 to #4, the air circulation fans of the heating system were set into manual operating mode for the 2 h test duration. In Test #1, the north-end circulation

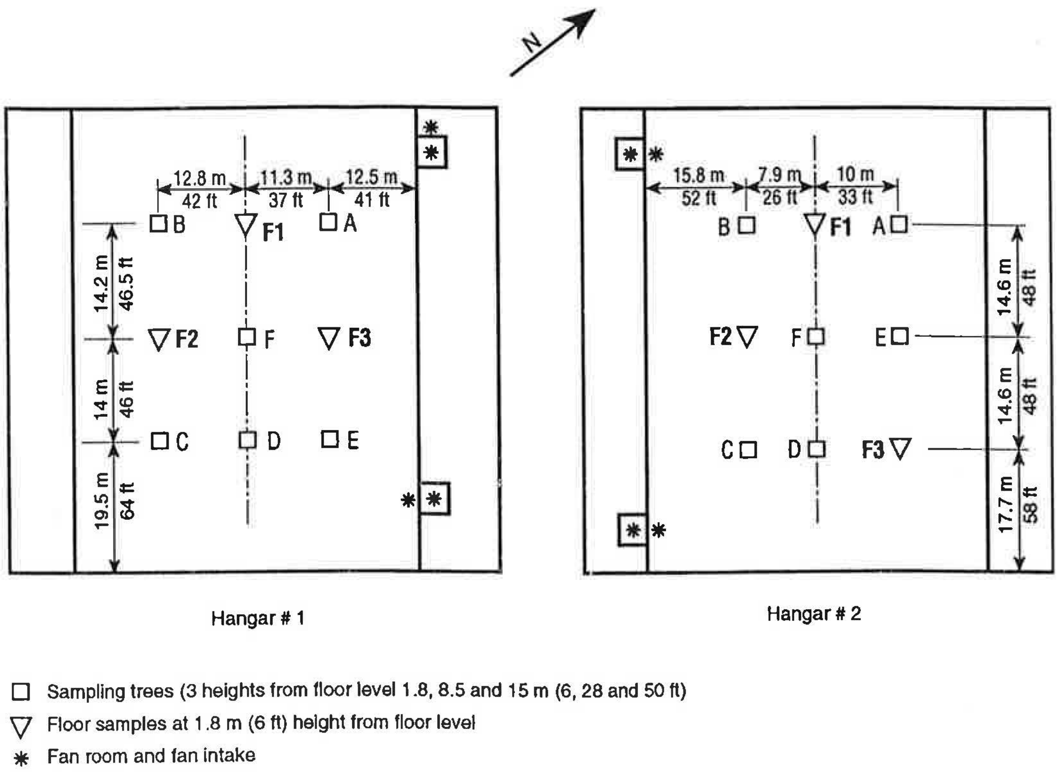


Fig. 2. Tracer gas sampling locations.

fan (the south-end fan was not operating) was set into the automatic operating mode. The fan was automatically started three times during the two-hour test period (51 to 59 min, 75 to 80 min, and 100 to 106 min from the start of the test).

Samples were collected at 21 locations in the hangar-bay area. In addition, samples were collected from each of the fan rooms and at the inlet to each fan room in the hangar. The sampling locations, Fig. 2, were distributed throughout the hangar-bay area, and were drawn at three heights, 1.8, 8.5, and 15 m (6, 28, and 50 ft)). The samples at 8.5 m (28 ft) and 15 m (50 ft) heights were drawn through nylon tubing (3 mm (1/8″) i.d.) using diaphragm-type sampling pumps.

3.2. Air flow patterns

Chemical smoke from smoke-bombs was used to visualize the overall air flow patterns in the hangar-bay area. The smoke-bombs, 3 min duration each, generate a cool, white, and non-toxic smoke. They are commonly used in testing smoke control systems in buildings.

The smoke-bombs were placed in a metal wastebasket and were ignited one at a time (a total of 4 smoke-bombs were used in each test). A wastebasket was located near the air intakes of the air circulation fans of the heating system. The release of the smoke into the intake of both fans was synchronized. The smoke drawn into the air stream of the intake was discharged through the floor grille in front of the hangar doors. The air flow patterns in the hangar were recorded using video cameras supplemented by freehand sketches.

4. Results and discussion

Two air change rate and two air flow visualization tests were conducted in each hangar. The flow visualization tests were conducted following the tracer gas tests. Tables 1 and 2 list measured air change rates, ambient weather conditions, and average indoor air temperatures. The weather data was obtained from the weather station at the nearby airport.

Fig. 3 shows measured vertical temperature profiles at the centre of the hangars during the tests. As noted earlier, in Tests #2 to #4, the two air circulation fans operated for the two hour test duration. As a result, during these tests, indoor air temperatures were higher than usual because the heating coils are energized by steam all the time. The thermostat mainly controls the operation of the air circulation fans. Higher indoor air temperatures would lead to higher stack effects and hence higher air infiltration rates for the same

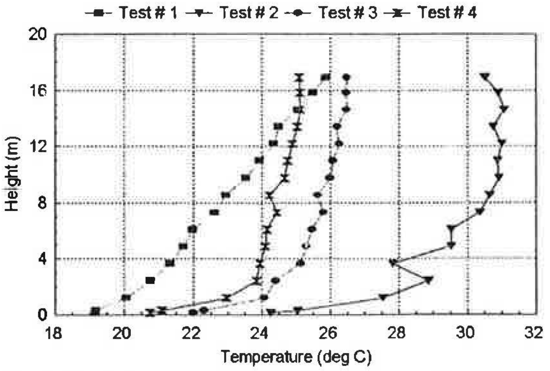


Fig. 3. Vertical temperature profiles at the centre of the hangars.

Table 1
Measured air change rates (ach) of Hangar #2 (mean ach: 0.45)

Sampling tree	Sampling height (m (ft))	Test #1		Test #2	
		(ach)	(r^2)	(ach)	(r^2)
A	15 (50)	0.46	0.980	0.44	1.000
B	15 (50)	0.50	0.996	0.44	0.999
C	15 (50)	0.46	0.994	0.43	0.999
D	15 (50)	0.47	0.994	0.41	1.000
E	15 (50)	0.46	0.997	0.42	1.000
F	15 (50)	0.46	0.993	0.42	1.000
Mean	15 (50)	0.47		0.43	
A	8.5 (28)	0.47	0.853	0.44	0.999
B	8.5 (28)	0.47	0.970	0.45	0.999
C	8.5 (28)	0.47	0.971	0.44	0.998
D	8.5 (28)	0.45	0.855	0.44	0.997
E	8.5 (28)	0.50	0.833	0.44	0.996
F	8.5 (28)	0.49	0.730	0.43	0.999
Mean	8.5 (28)	0.48		0.44	
A	1.8 (6)	0.50	0.778	0.44	0.997
B	1.8 (6)	0.53	0.919	0.43	0.993
C	1.8 (6)	0.44	0.843	0.41	0.990
D	1.8 (6)	0.42	0.785	0.42	0.992
E	1.8 (6)	0.47	0.932	0.43	0.992
F	1.8 (6)	0.47	0.881	0.43	0.999
Mean	1.8 (6)	0.47		0.43	
F1	1.8 (6)	0.48	0.801	0.43	0.998
F2	1.8 (6)	0.53	0.903	0.43	0.997
F3	1.8 (6)	0.42	0.680	0.43	0.999
Mean ach		0.47		0.43	
Standard deviation (% of mean ach)		2.7		1.0	
Indoor temp. (°C)		22.7		29.4	
Ambient weather		air temperature: −2.6°C, wind: WNW 19 to 22 km/h		air temperature: −4°C, wind: ENE 8 km/h	
Indoor-to-outdoor temp difference (°C)		25.3		25.4	
Notes		one fan (north-end) operating in automatic mode (operated 3 times during the test), south-end fan not operating		both fans operating (manual mode) for the 2 h duration of test	

outdoor air temperatures. The temperature profiles indicated that two air layers existed in the hangar-bay area, a warm upper layer and a cooler lower layer. The lower layer (up to 3 m (10 ft) from the floor) is characterized by a steep vertical temperature gradient, whereas in the upper air layer (above 3 m) the gradient reduces dramatically. The air temperature in the upper layer was almost uniform during Tests #2 to #4. These characteristics of the temperature profiles are typical of aircraft hangars [9].

4.1. Air flow patterns

The observed air flow patterns in the two hangars are sketched in Fig. 4. Stratified air layers characterized the air flow patterns which is consistent with the measured temperature profiles (Fig. 3). In Hangar #1, two visible stratified air layers were observed in the zone between the top of the hangar door (about 12 m (40 ft) height) and the ceiling. In the top layer, the smoke travelled along the ceiling from the south end towards the north end of the hangar, and below it the smoke travelled in the opposite direction from the north end to the south end. The vertical warm air jets out of the floor grilles by the hangar doors reached the top of the hangar doors (12.5 m (41 ft) height) in the north end, and reached the top of the tail-gate door (14.4 m (48 ft) height) in the south end. The south-end jet appeared to be stronger than the north-end jet. The south-end jet, after travelling north-bound along the ceiling, dropped down near the north door. After the smoke filled the ceiling zone, it started to drop down to the floor in stratified layers. The bay area became smoke logged in about 10 min.

When the hangar doors were fully opened to clear the smoke after the test, the smoke was observed to exit the hangar at the tail-gate. This indicates that, under the test conditions, the neutral pressure level [1] of the fully open hangar door at the south end was about 12 m (40 ft) above the floor.

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[1] Neutral pressure level (NPL) is the height at which the interior and exterior pressures are equal. Above this height, during heating season, the air flows from inside to outside; below NPL, the air flows from outside to inside.

Table 2
Measured air change rates (ach) of Hangar #1 (mean ach: 0.36)

Sampling tree	Sampling height (m (ft))	Test #3		Test #4	
		(ach)	(r^2)	(ach)	(r^2)
A	15 (50)	0.31	0.999	0.39	0.999
B	15 (50)	0.32	0.999	0.40	0.998
C	15 (50)	0.31	0.999	0.42	0.997
D	15 (50)	0.31	0.998	0.41	0.997
E	15 (50)	0.31	0.999	0.40	0.997
F	15 (50)	0.30	0.999	0.41	0.999
Mean	15 (50)	0.31		0.41	
A	8.5 (28)	0.32	0.999	0.39	0.999
B	8.5 (28)	0.32	0.999	0.39	0.998
C	8.5 (28)	0.31	0.999	0.40	0.999
D	8.5 (28)	0.32	0.998	0.40	0.998
E	8.5 (28)	0.31	0.999	0.40	0.997
F	8.5 (28)	0.31	0.999	0.40	0.999
Mean	8.5 (28)	0.32		0.4	
A	1.8 (6)	0.36	0.974	0.39	0.989
B	1.8 (6)	0.35	0.996	0.40	0.999
C	1.8 (6)	0.33	0.995	0.40	0.999
D	1.8 (6)	0.32	0.987	0.38	0.989
E	1.8 (6)	0.32	0.999	0.40	0.998
F	1.8 (6)	0.33	0.990	0.37	0.966
Mean	1.8 (6)	0.34		0.39	
F1	1.8 (6)	0.33	0.995	0.40	0.989
F2	1.8 (6)	0.37	0.973	0.38	0.984
F3	1.8 (6)	0.31	0.999	0.40	0.997
Mean ach		0.32		0.4	
Standard deviation (% of mean ach)		1.8		1.1	
Indoor temp. (°C)		25.3		24	
Ambient weather		air temperature: 8°C, wind: E 11 km/h		air temperature: 2°C, wind: E 22 km/h	
Indoor-to-outdoor temp. difference (°C)		17.3		22	
Notes		both fans operating (manual mode) for the 2 h duration of test		both fans operating (manual mode) for the 2 h duration of test	

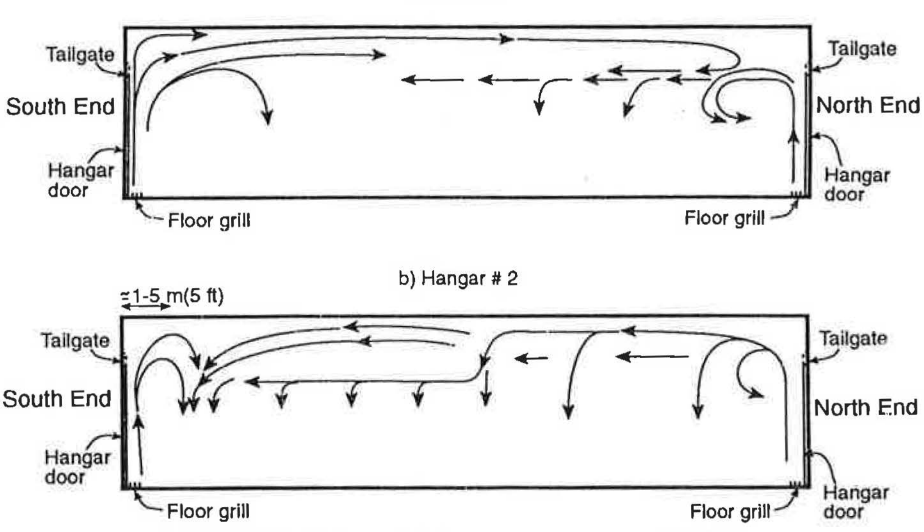

Fig. 4. Sketch of observed air flow patterns in Hangars #1 and #2.

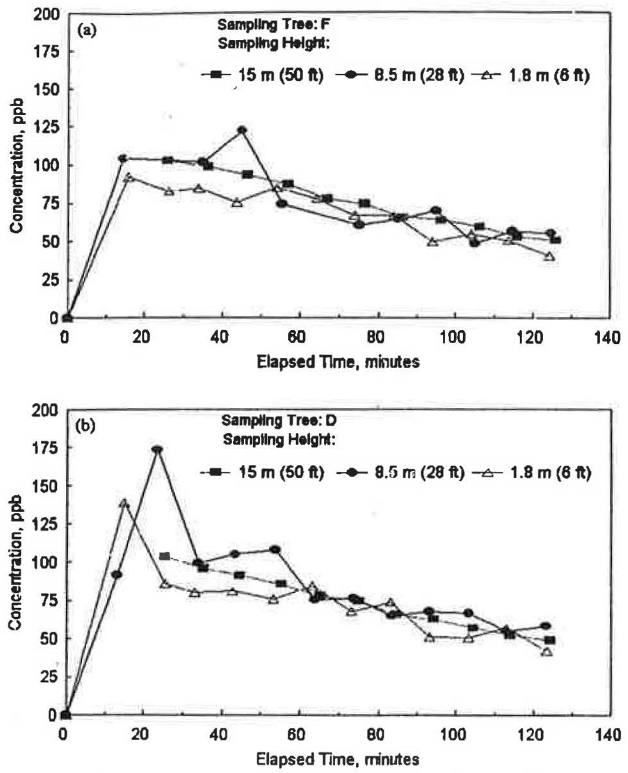

Fig. 5. Tracer gas concentration decay, Test #1 (Hangar #2), one air circulation fan (north-end) operating.

Similar air flow patterns were observed in Hangar #2 (Fig. 4(b)) but in this case the north-end jet appeared to be stronger than the south-end jet. The south-bound air flow stream along the ceiling dropped downwards at about half way, then continued travelling south-bound. It intersected the north-bound air stream near the south end and both streams were deflected downwards toward the floor. Similar to Hangar #1, the hangar-bay area became smoke logged in about 10 min. Under the test conditions, the neutral pressure level of the fully-open hangar door at the south end was about 2/3 of the door height (about 8 m or 27 ft).

4.2. *Air change rate*

The tracer concentrations in the samples were analyzed using an electron capture detector gas chromatograph at the laboratory. Figs. 5–10 show typical measured decay curves of the tracer gas in the hangar buildings for Tests #1 to #3 (the decay curves for Test #4 are similar to those for Test #3). The hourly air change rate (ach) was determined by:

$$\text{ach} = -(1/\Delta t)\ \ln(C_f/C_i) = Q/V \qquad (1)$$

where Δt = time interval between measurements of C_i and C_f (usually $\Delta t = 1$ h), C_i = concentration of tracer at the beginning of time interval, C_f = concentration of tracer at the end of the time interval, Q = air infiltration rate, in volume per unit time, between the hangar-bay area and its surroundings, and V = volume of the hangar-bay area.

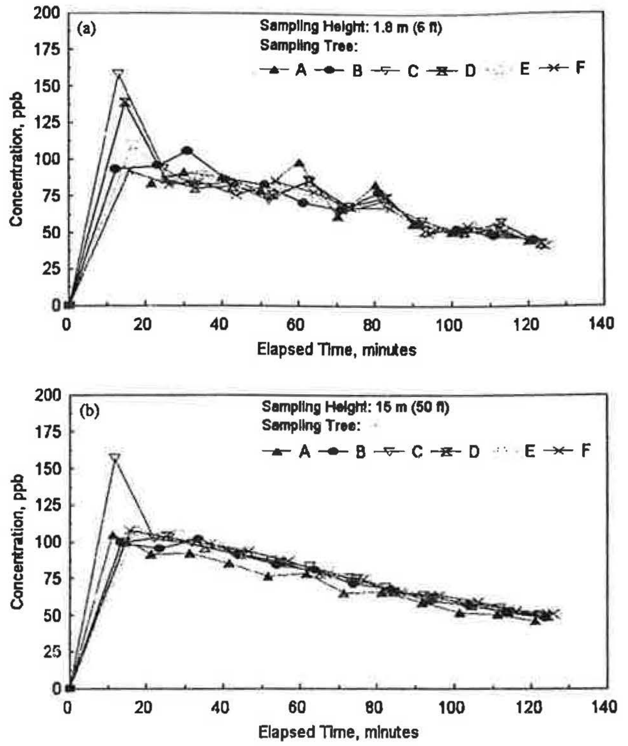

Fig. 6. Tracer gas concentration decay, Test #1 (Hangar #2), one air circulation fan (north-end) operating.

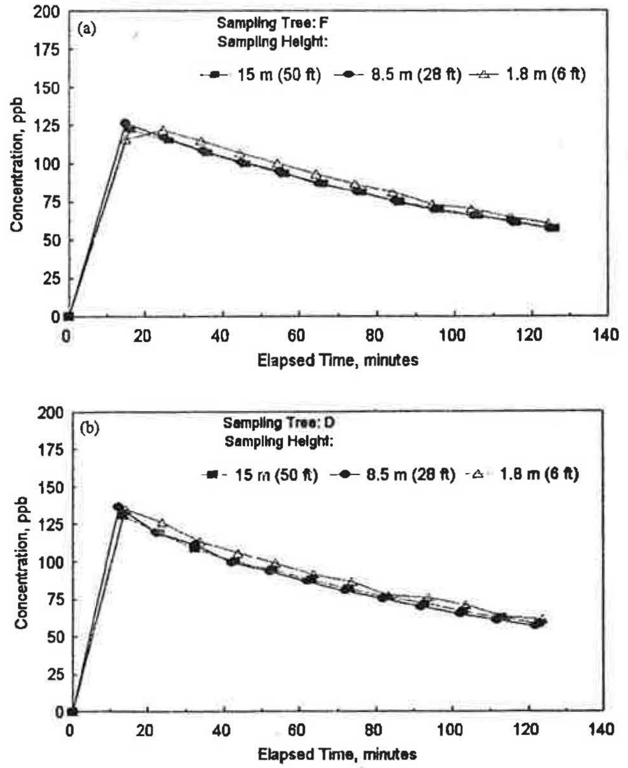

Fig. 7. Tracer gas concentration decay, Test #2 (Hangar #2), both air circulation fans operating.

Local variations of measured air change rates, r^2 values, and standard deviations (expressed as a percentage of the mean air change rates) are listed in Tables 1 and 2. The mean air change rate ranged from 0.32 to 0.4 ach for Hangar #1

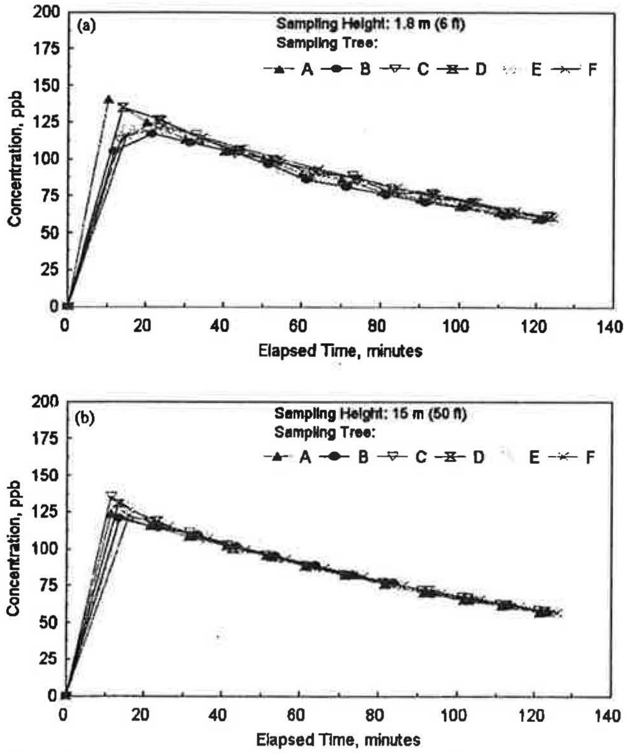

Fig. 8. Tracer gas concentration decay, Test #2 (Hangar #2), both air circulation fans operating.

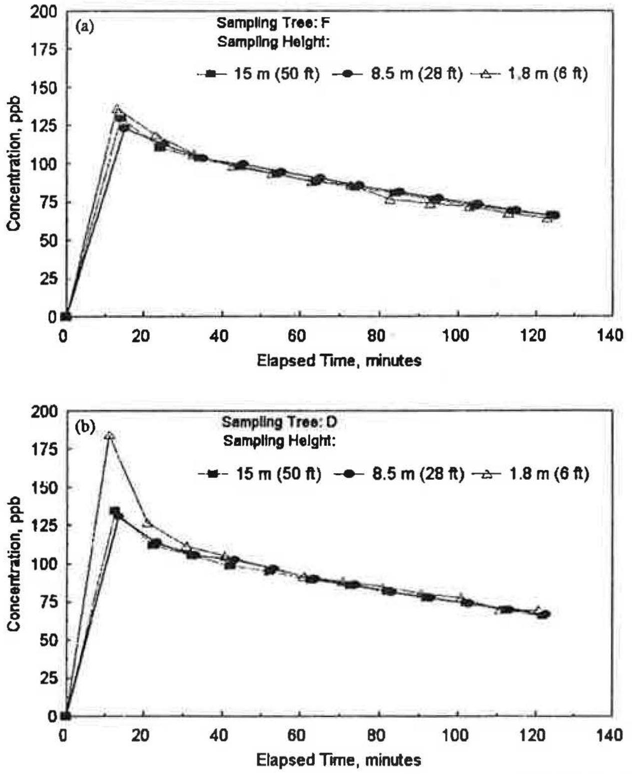

Fig. 9. Tracer gas concentration decay, Test #3 (Hangar #1), both air circulation fans operating.

(Table 2) and 0.43 to 0.47 ach for Hangar #2 (Table 1). For the latter, the range between the two tests is less because the indoor-to-outdoor temperature difference is almost the same in both tests (see Table 1). The higher air change rate in Test #4 (Table 2) compared to Test #3 was due to the large temperature indoor-to-outdoor difference (22°C versus 17.3°C).

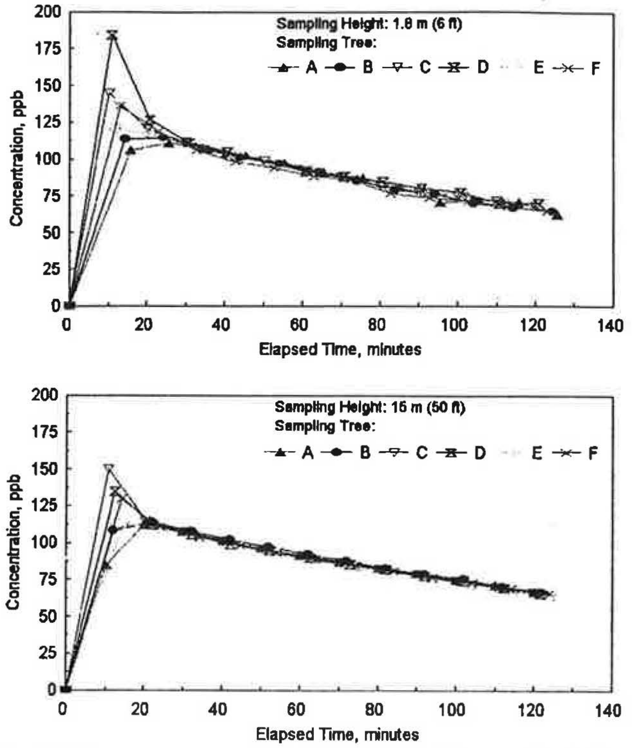

Fig. 10. Tracer gas concentration decay, Test #3 (Hangar #1), both air circulation fans operating.

Eq. (1) is based on the assumption that the tracer gas concentration within the building is uniform. Thus, it is important that the tracer gas is well mixed with the indoor air, otherwise the determination of the air change rate will be subjected to errors. The mixing is usually achieved by using the ventilation system, multiple gas injections throughout the building, portable blowers, or all three. In large single-cell buildings, using equipment such as portable blowers to induce a large amount of mixing may destroy normal air flow patterns in the building and may cause interpretation errors when analyzing measured local air change rates. In this study, the air circulation fans of the hangar's heating system were used. Figs. 5 to 10 demonstrate the degree of uniformity achieved within these large volume single-cell buildings using the air circulation fans of the buildings. The figures show the mixing of the tracer gas is quite good particularly when both air circulation fans are operating. In Test #1, where only the north-end circulation fan was operating, the mixing was not as good as in Tests #2 to #4. However, this did not seem to have a significant effect on measured air change rates (see Table 1). The standard deviation of measured air change rates in this test is 2.7% of the mean air change rate.

Tables 1 and 2 further demonstrate the degree of mixing in the hangars. The variation in measured air change rates in each hangar is small. The standard deviation of measured air change rates is less than 3% of the mean value. This suggests that the mixing level achieved in the hangars was sufficient to obtain representative air change rates in such large single-cell buildings even when only one circulation fan was operating (Table 1, Test #1). The measured data also suggests that it is possible to measure the air change rates of large single-cell buildings using the tracer gas decay technique without the necessity for a large number of sampling positions at various heights and various spatial locations throughout the volume. For instance, the mean air change rate of the samples at 1.8 m (6 ft) height is a good representative value of the mean air change rate of all samples. Therefore, it is sufficient to sample the tracer gas at a practical height, such as 1.8 m, at five spatial locations in the hangar. This appears to be the practical approach commonly used in the literature. For example, Ashley and Lagus [1] sampled the tracer gas SF_6 in five locations, Lawrance and Waters [2] sampled SF_6 in six locations, and Roulet and Van der Maas [3] sampled CO_2 in four locations.

5. Conclusions

Measurements of air change rates and air flow patterns in two large single-cell aircraft hangar buildings are described.

Stratified air layers characterized the air flow patterns within the hangars. Under test conditions, the measured mean air change rates for the two hangars were in the range 0.32 to 0.47 ach. In spite of the physical characteristics of the aircraft hangars (high ceiling large volume single-cell buildings), it was possible to achieve a uniform mixture of the air and the tracer gas using the air circulation fans of the heating system. Results also suggest that five sampling locations at about 1.8 m (6 ft) height are sufficient to obtain a representative air change rate for large single-cell buildings.

Acknowledgements

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References

[1] J.L. Ashley and P.L. Lagus, Air infiltration measurements in large military aircraft hangars, *ASTM Special Tech. Pub. 904, ASTM Symp. on Measured Air Leakage of Buildings, Philadelphia, PA, 2–3 April, 1984*, pp. 120–134.

[2] G.V. Lawrance and J.R. Waters, Measurements of infiltration and air movement in five large single-cell buildings, *8th AIVC conference, Uberlingen, Germany, 21–24 September, 1987*, pp. 2.1–2.18.

[3] C.-A. Roulet and J. Van der Maas, Measurements of air flow patterns and temperatures in a 60 000 m^3 industrial hall, *Proc. 4th Int. Conf. on Air Distribution in Rooms, Krakow, Poland, 15–17 June 1994*, Vol. 2, pp. 439–453.

[4] P.J. Jones, G. Powell and D.K. Alexander, The energy impact of ventilation on industrial buildings, *14th AIVC Conference, Copenhagen, Denmark, September 21–23, 1993.*

[5] R.R. Walker and M.D.A.E.S. Perera, The BRESIM technique for measuring air infiltration rates in large buildings, *BRE Information Paper No. IP 11/90*, Building Research Establishment, Garston, Watford, UK, 1990.

[6] J. Freeman, R. Galle and J.P. Lilly, Ventilation measurements in large buildings, *4th AIVC Conference, Elm, Switzerland, September 26–28, 1983.*

[7] M.D.A.E.S. Perera and R.G. Tull, Envelope leakiness of large, naturally ventilated buildings, *10th AIVC Conference on Progress and Trends in Air Infiltration and Ventilation Research, Espoo, Finland, September 25–28, 1989.*

[8] M.D.A.E.S. Perera, G. Powell, R.R. Walker and P.J. Jones, Ventilation performance of large buildings: prediction using pressurization measurements, *Building Serv. Eng. Res. Technol., 12* (1991) 95.

[9] M.N.A. Saïd, R.A. MacDonald and G.C. Durrant, Measurement of thermal stratification in large single-cell buildings, *Energy Build., 24* (1996) 105.