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Development and application of an indoor air quality audit to an air-conditioned building in Singapore

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Abstract

Good indoor air quality (IAQ) enhances occupant health, comfort and workplace productivity. This issue has become more critical in a country like Singapore that has no other natural resources except manpower. In addition, Singapore is located in the tropical region with a hot and humid climate and a large number of the buildings are served by air-conditioning and mechanical ventilation (ACMV) systems to maintain a thermally comfortable indoor environment. The provision of a thermally comfortable indoor environment for the occupants is only one aspect in achieving better indoor air quality. Chemical pollutants, dust particles and microbials are other factors that have impact on the quality of indoor air. Pollutant emissions from people, building materials, air handling units, etc. in the form of both living and dead material take place continuously in any type of buildings, i.e., residential, commercial, industrial, institutional, etc. An IAQ audit methodology developed is adopted to establish the IAQ profile of the building. In this paper, a case-study is used to demonstrate the application of the IAQ audit and evaluate its comprehensiveness and usefulness to the building owners or facility managers. This audit was conducted in the administration offices of a hospital building. The audit consists of examination of the air exchange rate, ventilation effectiveness and age of air. Thermal comfort parameters, microbial counts, dust particles and the concentrations of carbon dioxide (CO_2), carbon monoxide (CO), formaldehyde (HCHO) and total volatile organic compounds (TVOC) were also monitored. In addition, a questionnaire was completed by the staff in order to provide a subjective assessment of indoor air quality.

1. Introduction

An Arab oil embargo in 1973 triggered off an energy crisis worldwide, with the building industry implementing two types of measures to conserve energy. The first was to increase the efficiency of the equipment used in buildings. Thus, a modern refrigerator would consume considerably less power than before. In the effort to minimise heat loss and maximise the efficiency of air-conditioning, the building's interior is closed off to the outside as much as possible (i.e., more airtight), as an alternative to energy savings. The former leads to a better design of equipment, but the latter, saved a great amount of energy but at a cost. The air becomes stale as a result of the accumulation of pollutants such as excess dust, bacteria and chemicals. When the pollutants' concentration of the air in the building increases, the occupants' health will be jeopardised, and when a high frequency of complaints from the occupants occurs such building would be labelled as a "sick building".

In Singapore, there has been growing concern in the past decade over health complaints attributed to the so-called "sick building". The reasons could be related to an increase in public awareness of health implications, and people spending more time in air-conditioned environments. Indoor air quality has begun to surface as an important issue that affects the comfort, health and the productivity of office workers. Although the outdoor air quality is quite well established, this has little impact on the indoor air quality

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because the characteristics and sources of pollutants are quite different. Factors contributing to indoor air pollution include building location and air intake; building design, building materials and furnishings; and indoor activities. Some of the common causes of indoor air problems giving rise to poor air quality are the presence of indoor sources of pollution; poorly designed, maintained or operated air-conditioning and mechanical ventilation (ACMV) systems; and uses of the building that were unplanned for what the building was designed or renovated.

A ventilation system performs a vital role in the removal of pollutants originating in the air-space. In addition, the performance of the mechanical ventilation system influences thermal comfort; for example cold draughts can produce an unpleasant living or working environment for the occupants. Studies have shown that ventilation systems in buildings are largely responsible for Sick Building Syndrome [1,2]. These ventilation systems are either designed incorrectly or they are poorly maintained. Complaints of sickness among people in "tight buildings", especially those housing equipment and machines, have become a significant problem over recent years [3,4].

An IAQ audit methodology has been developed and this is applied to the offices in a hospital building. The development of this audit methodology was done in the last five years and has undergone refinements to establish a comprehensive and accurate IAQ profile of buildings. To date, this audit has been applied to more than 15 buildings locally. The IAQ Audit commences

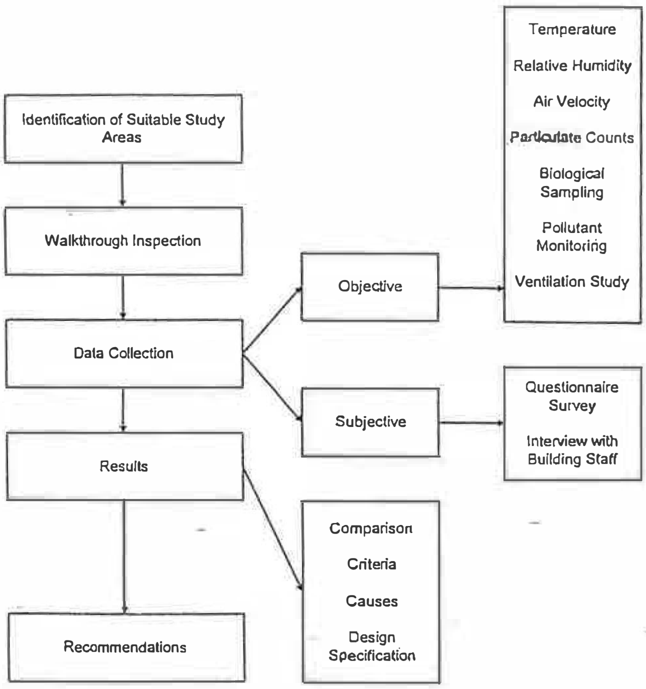

Fig. 1. IAQ audit methodology.

with a preliminary walkthrough of the premises followed by objective measurements and subjective assessment. Objective measurements involve the measurement of building ventilation rates, ventilation effectiveness of the ventilation system, and concentrations of selected indoor air pollutants. In the case of subjective assessment, a questionnaire was completed by the office staff to provide a subjective feeling on the environment. The results collated from this audit can be used to assess the air quality in the offices and recommendations can be made to the building owner or facility manager who has an overview of the organisation, sets policy and assigns staff responsibilities.

2. Indoor air quality (IAQ) audit

The IAQ audit follows a systematic approach as shown in Fig. 1. This audit is carried out in a hospital building. It was built in August 1994 and was first occupied in September 1996. It is a nine-storey building with a basement and roof level.

The basement level and first storey of the building are mainly the carpark areas while the second storey is where the Day Surgery Clinic, Operating Theatres and Recovery Area are located. The third and fourth storeys are the clinics and the fifth storey is designated for administration offices. The sixth to ninth storeys are for A1 wards and the roof level is used to house the majority of the plant rooms. The other major plant rooms are located at the second, fourth and fifth storeys.

The air-conditioning system for the whole building is a centralised chilled water system. The water-cooled chillers are located at roof level, the same level as the cooling towers. The chilled water is distributed to all the air handling units and fan coil units, located throughout the whole building.

The main area of interest for this indoor air quality audit is the administration offices on the fifth storey. The administration offices are served by a dedicated air-handling unit. This is mainly an open-concept office with low partitions with some rooms that have floor to ceiling brickwall partitions. There is a total of 51 administrative staff doing work such as managerial, secretarial and clerical in nature. The ratio of the male staff to female staff is about 1:1.

2.1. Walkthrough inspection

An initial visit to the hospital was done as soon as the building owner had given the approval for the study to be carried out. The objective of the visit is to identify the potential study areas and its monitoring locations within the area of interest. Once the area of interest was identified (i.e., the fifth storey Administration Office), available information and documentation such as floor plans and ACMV systems drawings are collected. Subsequently, a walkthrough inspection to the administration office was done. Identification of possible pollutant sources, potential problems, condition of the ACMV system and sampling points for the objective measurements are the main purposes of this walkthrough. Some of the main items to observe in terms of pollutant sources are odours, staining of the ceiling boards, excessive dust, fungal and mould growth, etc. Thermal comfort of the study areas is another important factor that needed more attention. In addition, complaints from the occupants can be very useful information in the assessment of the indoor air quality.

2.2. Objective measurements

Fig. 2 shows the locations of the sampling points for the fifth storey Administration Offices.

2.2.1. Chemical measurements (CO_2, CO, HCHO and TVOCs)

Continuous real-time chemical monitoring of CO_2, CO, HCHO and TVOCs were carried out at three indoor points and one ambient point. These points are coupled to the B&K multi-point sampler, Type 1312 and Bruel & Kjaer (B&K) multi-gas monitor, Type 1309 through polytetrafluoroethylene tubing as shown in Fig. 2. Air samples will be collected and analysed in the B&K analyser.

2.2.2. Measurements of air exchange rates

The air exchange rate in the office was measured using the tracer-gas decay technique. This technique involved an initial injection of sulphur hexafluoride (SF_6) tracer gas into the air space through the fan section of the air handling unit to provide a better tracer and air mixing in the office. The tracer gas was allowed to mix for 15 min to establish a uniform concentration in the air space. The B&K multi-gas analyser and sampler are used to collect and analyse the concentration of tracer gas over time. The concentration-decay of the tracer-gas profile was analysed to determine the air-exchange rate for the office (see Fig. 3).

2.2.3. Age of air and air change effectiveness

Evaluation of the air change effectiveness in a building is crucial as it provides information about the ability of the air distribution system to deliver ventilation

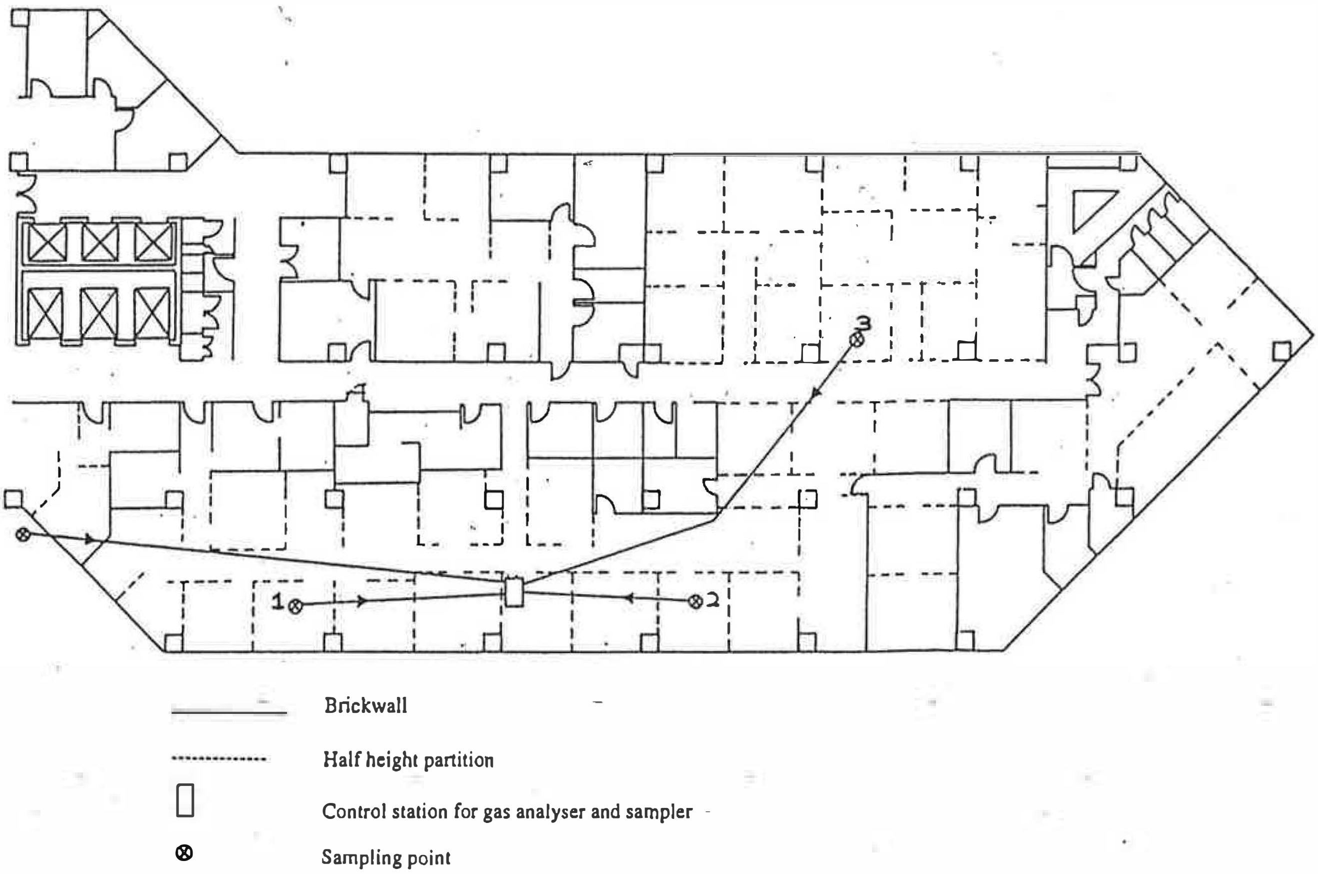

Fig. 2. Floor plan of the administration offices.

air to a building, zone or space [5]. Information on the ventilation rate of the building is adequate if the air distribution in the building is uniform. However, non-uniformities in air distribution can lead to localised indoor air quality problems due to air stagnation in certain areas in the occupied space.

Local air change effectiveness, ϵ_L, was evaluated in the office premises. This evaluation included measurements of local age of air at the three selected locations at the occupant level in the office and average age of air at the system exhaust. The age of air was measured using the tracer-gas decay technique. This technique involved an initial injection of SF_6 tracer gas into the office through the air-handling unit. The tracer gas was allowed to mix for 15 min to establish a uniform concentration in the air space. The decay of the tracer gas was monitored in the office space and at the exhaust duct using the B&K multi-gas analyser and sampler. The tracer-gas concentration data in the office and at the exhaust were analysed to determine the age of air, τ, (min). The local air change effectiveness was determined by dividing the nominal age of air (taking concentration measurements at the exhaust), τ_E, by the age of air at a particular location in the office, τ_L [5].

2.2.4. Thermal comfort measurements

The thermal comfort level of the indoor environment is measured using an Indoor Climate Analyser, Type 1213. It is a portable analyser that senses environmental conditions, via five separate transducers, simultaneously. The measurements taken through these transducers include room ambient temperature (dry bulb), relative humidity and air velocity.

2.2.5. Particulate measurements

The concentration of the suspended particulate (PM10) was measured using an environmental laser aerosol spectrometer, Grimm Portable Dust Monitor Series 1.105. It is capable of measuring particles from 0.1 to 10 μm in diameter, with an accuracy of ±5%. It allows for a real-time continuous measurement of dust to be stored as mass concentration, μg m^{-3}.

2.2.6. Biological samplings

A single-stage Andersen N6 sampler was used to carry out the biological sampling. The medium that is used for the collection of bacteria is Tryptic Soy Agar (TSA) while the collection of fungi is Potato Dextrose Agar (PDA). The sampler is connected to a pump via a poly vinyl chloride (pvc) tube to draw air samples at a rate of 28.3 l min^{-1} and impact onto the TSA or PDA petri-dish. Air samples for culture of bacteria and fungi are collected at the designated locations at 1.2 m above ground and at the air diffusers. This is to

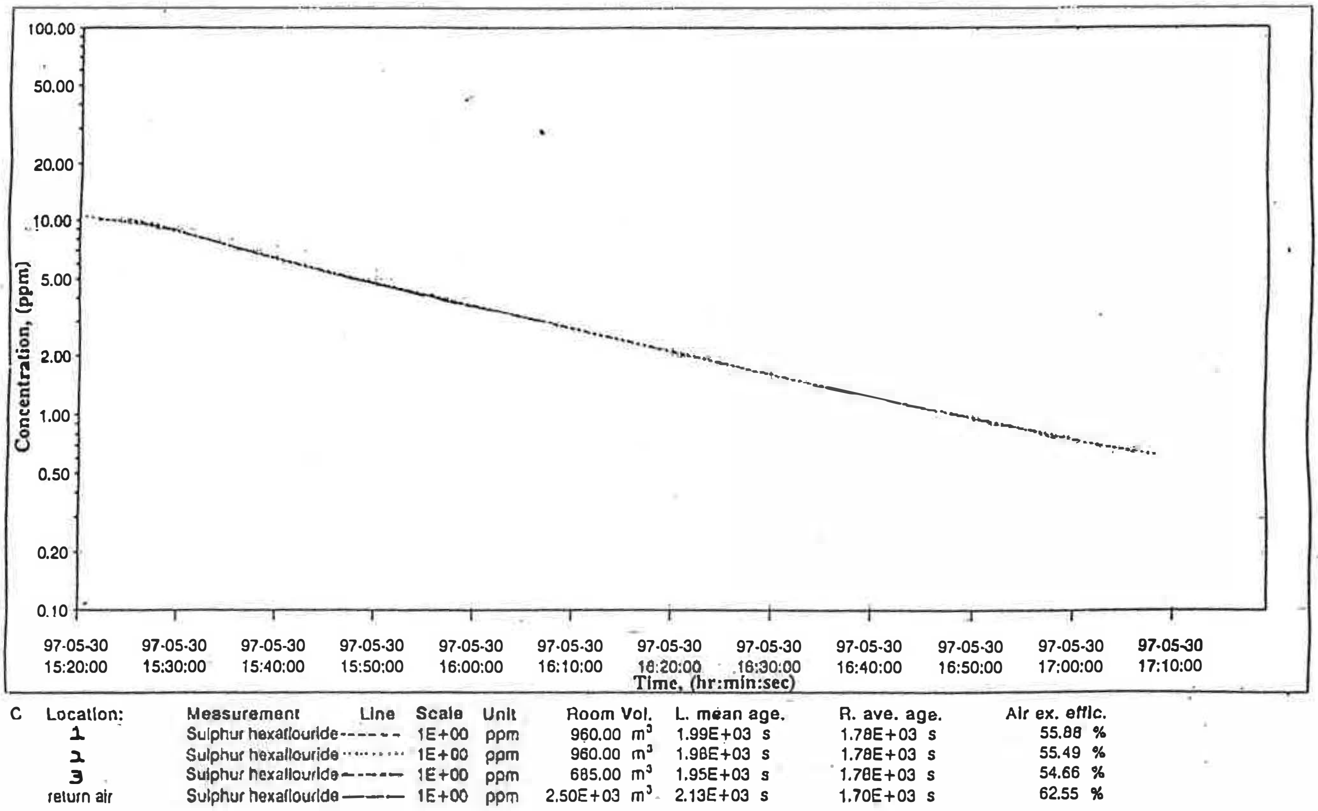

Fig. 3. Concentration-decay profile of tracer-gas at the administration offices.

determine the source of the bacteria and fungi. Each of these measurements was taken over a period of 4 min.

After collection, they will have to be incubated at different condition. TSA petri-dishes were incubated for 48 h at 37°C while the PDA petri-dishes were incubated at 25°C. After incubation is completed, they will be counted and the unit of measurement is in colony-forming units per cubic metre (CFU m^{-3}).

2.3. Subjective assessments — office survey

In addition to the objective measurements conducted in the office, the effects of the air quality on the health of the office staff were assessed subjectively. The questionnaire is divided into sections, namely, occupants' work; occupants' health; environmental conditions; individual control of office environment; and other aspects of the office environment such as cleanliness and odour. The questionnaires were distributed to the office's staff two weeks before the objective measurements were being taken.

3. Results and discussion

3.1. Evaluation of concentrations of indoor air pollutants

3.1.1. Carbon dioxide

The concentration of carbon dioxide in the office varied between locations. Measurements were taken over a period of four days. The measured concentration of carbon dioxide ranged between 450 and 700 ppm. These values are well below the ASHRAE standards [5] and Singapore Indoor Air Quality guideline [6] recommended value of 1000 ppm for an 8-h period exposure. An average concentration of about 580 ppm is recorded. During working hours, the concentration level went up to an average of 650 ppm and after office hours the level decreased to an average of 480 ppm. The increase in concentration level of CO_2 during working hours is attributed to the staff in the office. There is a relatively good distribution of fresh air over the conditioned air-space and the ventilation rate is sufficient.

3.1.2. Carbon monoxide

The recommended values of exposure for carbon monoxide should not exceed 9 ppm for an 8-h period as indicated by Singapore guideline [6] and Raatschen [7]. Measurements of carbon monoxide level concentration ranged from 0.05 to 0.7 ppm and this is well within the recommended thresholds. An office environment in Singapore should not have any sources of carbon monoxide since smoking is prohibited in air-conditioned offices.

3.1.3. Total volatile organic compounds

There is no general agreement on the threshold values for Total Volatile Organic Compounds (TVOC), but a recommended limit for acceptable indoor air quality is 3 ppm [6]. It is observed that the concentrations of TVOC at various locations were generally below 0.6 ppm and these are within the threshold limit. The continuous monitoring of TVOC shows that the level increases after working hours and decreases at the start of each working day. This may be attributed to the fact that the air-handling unit is shut down after working hours and dilution of the air within the premises is prevented. In addition, there may have been some internal sources such as solvents, cleaning agents, paints from the walls and varnishes from the new furniture but this is insignificant since the concentration is rather low.

3.1.4. Formaldehyde

The concentration of formaldehyde in the office varied with locations. The concentration at the study area ranged between 0.1 and 0.3 ppm, therefore exceeding the recommended limit of 0.1 ppm for an 8-h exposure [6,7]. These relatively high concentrations are attributed to the outgassing from the new building materials such as ceiling particle board and carpets. The new administration office had operated for only eight months when these measurements were taken.

3.2. Evaluation of air exchange rates

Measurements were carried out on a calm day with a north-westerly wind at a speed of 0.3 m s^{-1}. Air infiltration could be neglected as the external wind pressure was low. The concentration-decay of the tracer-gas is used to determine the air exchange rate in the offices. The air exchange rate and fresh air quantities are computed and tabulated in Table 1.

It is seen from Table 1 that the air change rate is 1.65 and the amount of fresh air provided to the various locations varies between 11 and 11.3 ls^{-1} (lps) per person on the basis of design occupant density (10 m^2/person). These figures are likely to be different when the fresh air provision is computed on the basis of actual occupant density. The Singapore Code of Practice [8] require 3.6 lps/person and the ASHRAE [5] requirement is 10 lps/person. This indicates that the provision of outside air for ventilation is adequate.

3.3. Evaluation of the age of air and local air change effectiveness

The various age of air (τ) and local air change effectiveness (ϵ_L) are presented in Table 2. The measurements showed that the average age of air at the three locations was between 1950 and 1990 s or about

Table 1
Measurements of air change per hour (ACH) and outside air quantities

Location	Vol. (m^3)	Area (m^2)	ACH[a]	Fresh air (lps)[b]	Design occupancy	
					Occ	lps/Occ
	A	$B=A/H$[c]	C	$D=0.9AC/3.6$	$E=B/10$	$F=D/E$
1	960	356	1.65	396	36	11
2	960	356	1.65	396	36	11
3	685	254	1.65	283	25	11.3

[a] Localised spot.
[b] Based on an effective space volume of 90% (total volume less furnitures in the office).
[c] Height of office = 2.7 m.

33 min (i.e., the length of the time for fresh air to remain in the office is about 33 min).

When there is a uniform distribution of air over the office air-space, $\epsilon_L = 1$. However, when there is a non-uniform distribution of air over the office air-space, values of ϵ_L are significantly less than 1. A value of $\epsilon_L > 1$ suggests that a degree of plug or displacement flow is present. The local air change effectiveness at locations 1, 2 and 3 were found to be 1.07, 1.08 and 1.09, respectively, and this implies that there is no short-circuiting of ventilation air on a global scale. The local air change effectiveness indicated a reasonably perfect mixed air in those locations.

3.4. Evaluation of thermal comfort

The thermal comfort parameters are presented in Table 3.

The air dry-bulb temperature recorded in this office is ranged between 22.1 and 22.4°C. This is slightly below the recommended range for acceptable indoor air quality of 22.5–25.5°C from the local indoor air quality guideline [6]; 49% of the respondents complaint of cold sensation and this is shown in Fig. 4.

3.5. Evaluation of particulate pollution

The recommended threshold level for suspended particulate matter (for particulate $\leq$ 10 μm) in the guideline [6] is 150 μg m^{-3}. Table 4 shows the average concentration of particulate indoor ranged between 29 and 86 μg m^{-3}. There is no cause for concern in terms of indoor particulate pollution. The average concentration value for outdoor environment was measured at 194 μg m^{-3} and this is above the recommended outdoor air quality standards of 150 μg m^{-3} [9]. This suggested that the outdoor air being introduced into the office premises was one of the contributors to the suspended particulate matter. This could be from the construction activities near the fresh air intake of the air-handling unit. Fortunately, the filters in the air-handling unit are efficient in removing particulate in the air.

3.6. Evaluation of microbial pollutants

The recommended threshold level for total bacteria and fungi growth is 500 CFU m^{-3} [6]. It is observed from Table 5 that the values obtained for total bacteria count and yeast and mould count are all below the 500 CFU m^{-3} threshold, with the highest bacteria count of 334 CFU m^{-3} at the occupant level of location 2.

3.7. Assessment of questionnaires

For this assessment, a total of 51 questionnaires were distributed to the staff and they were all completed and returned. A total of 66.7% of the respondents claimed that they experienced one or more physiological symptoms during working hours.

Fig. 4 shows the results of the survey for the physical parameters. 33% of the respondents claimed that

Table 2
Measurements of age of air and ventilation effectiveness

Location	Exhaust τ_E (s)	Local τ_L (s)	Local ϵ_L
	A	B	A/B
1	2130	1990	1.07
2	2130	1980	1.08
3	2130	1950	1.09

Table 3
Measurements of thermal comfort parameters

Location	Air temp. (dry bulb) (°C)	Relative humidity (%)	Mean air velocity ($m\ s^{-1}$)
1	22.1	62	0.12
2	22.1	64	0.14
3	22.4	60	0.16
Outside air	29.5	83	–

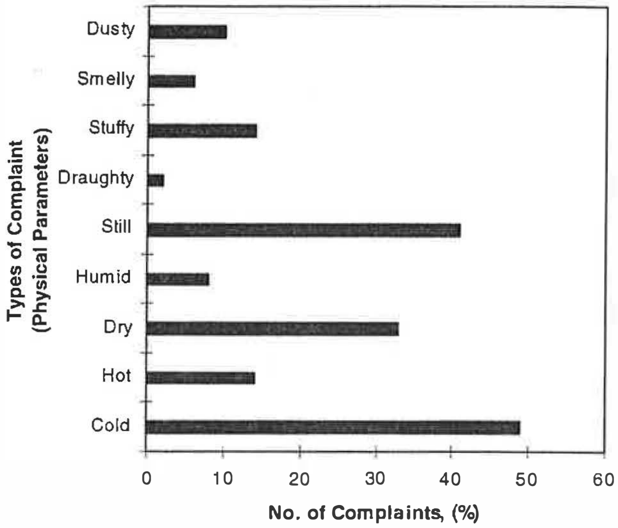

Fig. 4. Complaints from staff on physical parameters.

the environment was dry, consistent with the fact that the dry symptoms were prevalent amongst the respondents; 41% expressed that the air was still; and only 14% commented that the air was stuffy. This could be due to the low mean air velocity (0.12 m s^{-1}) but the outside (fresh) air provision to the premises is sufficient as determined from the ventilation analysis. Of the respondents 51% found that the thermal comfort level was acceptable and the remaining 49% expressed that it was uncomfortable. They claimed that the air was too cold and 56% of those respondents who felt uncomfortable (or 14 respondents) expressed that the environment was just slightly below the comfort level. Seven respondents perceived that the environment was slightly warm.

Fig. 5 shows the percentage of respondents' complaints on the physiological parameters at the offices. Dry symptoms were most prevalent among the respondents: 38% suffered from dry skin; 31% from dry eyes; and 8% suffered from dry or irritated throat. In addition, lethargy and headache were common symptoms — 46 and 15%, respectively.

In the indoor air quality survey, 82.4% of the respondents expressed that the air quality was acceptable, of which 30.9% of them (13 respondents) found that the quality of air was clearly acceptable.

There was very little complaint on the audio and visual environment, and 90% of the respondents were satisfied with their working environment.

Table 4
Measurements of particulate

Location	Particle concentration (μg m^{-3})
1	86
2	73
3	29
Outside air	194

4. Recommendations

The results for chemical monitoring show that most of the pollutants are within the threshold limit except for formaldehyde. The high level of formaldehyde could be due to the outgassing from the new building materials such as carpets, ceiling particle board and new partitions for the office cubicles. It is not practical to remove or isolate the sources and the only viable solution is to dilute the air in the premises. Dilution can be carried out by regular purging of the indoor air with fresh air from outside the building. Purging may be carried out during periods of reduced or zero occupancy when fresh outside air may be used for flushing the indoor air pollutants. The provision of higher fresh air intake or increasing ventilation rate during occupancy period may be another option. However, this is a potentially energy intensive method.

The fresh air provision and air change effectiveness of the system is sufficient in diluting and removing pollutants in the office premises respectively. The only cause for concern is the cold air as expressed by 49% of the respondents. In addition, the staff experienced dry symptoms though the measured relative humidity in the offices was between 60 and 64%. The people in this region may not be accustomed to such a level since the outdoor air is usually very hot (Air Temperature 30°C) and humid (Relative Humidity 90%) throughout the year. The ACMV system may have been over-designed based on the current low heat-load from the occupants or the system may not have been balanced. The particulate and microbials measure-

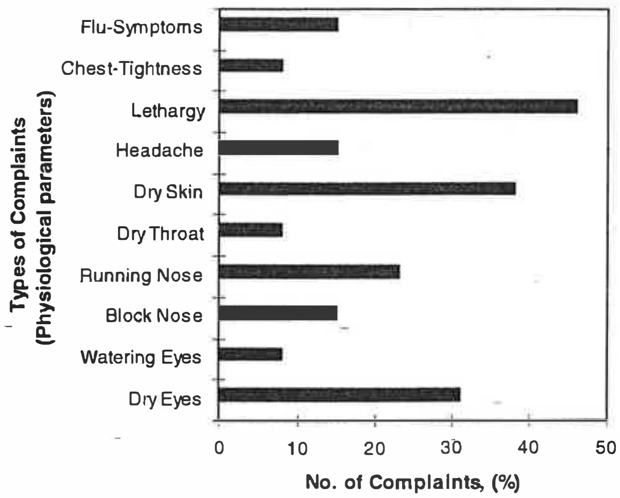

Fig. 5. Complaints from staff on physiological parameters.

Table 5
Measurements of microbial

Location	Total bacteria (CFU m^{-3})		Yeast and mould (CFU m^{-3})	
	Supply air level	Occupant level	Supply air level	Occupant level
1	62	88	79	132
2	70	334	88	132
3	158	79	62	70
Outside air	70	70	> 528	> 528

ments for all locations in the office premises are within the threshold limit.

The overall results obtained from the objective measurements and subjective assessment in this indoor air quality audit for these office premises show that the ACMV system is performing effectively in removing indoor pollutants and achieving good indoor air quality.

5. Conclusion

This indoor air quality audit methodology is very comprehensive in nature. Having performed the walk-through, objective measurements and subjective assessment, results can be collated and recommendations can be made. These recommendations are very useful to the building owner or facility manager as they can plan their maintenance program for remedial measures to be carried out either immediately or at a later date depending on the seriousness of the problems. The results from this audit will provide a better picture on the indoor air quality in their premises. In addition, they will be able to know how healthy their building is as compared to the local guidelines released by the Ministry of Environment, Singapore. This audit methodology has been successfully applied to determine the IAQ profile of the building in Singapore.

References

[1] Morey PR, Shattuck DE. Role of ventilation in the causation of building-associated illnesses. Occupational Medicine: State of the Art Review 1989;4(4):625–42.
[2] Helsing KJ, Billings CE, Conde J, Griffin R. Cure of a sick building: a case study. Environmental International 1989;15:107–14.
[3] Hawkins LH, Wang T. The office environment and the sick building syndrome. In: Proceedings of the Indoor Air Quality '92 — Healthy Buildings, 1992. p. 365–71.
[4] Briggs GG, Rodgers ML, Sharpe J. Building owner's in-house response to indoor air quality problems — Four case studies. In: Proceedings of the Indoor Air Quality '92 — Healthy Buildings, 1992. p. 386–9.
[5] ASHRAE. Ventilation for acceptable indoor air quality ASHRAE Standard 62-1989. USA: American Society of Heating and Air Conditioning Engineers Inc, 1989.
[6] ENV Ministry of the Environment. Singapore Guidelines for good indoor air quality in office premises, Singapore, 1996.
[7] Raatschen W. Demand controlled ventilating system-State of the art review. Sweden: International Energy Agency, 1990.
[8] Singapore Standard, CP13: 1980 Code of practice for mechanical ventilation and air-conditioning in buildings. Singapore Institute of Standards and Industrial Research, 1980.
[9] ASHRAE. Handbook: HVAC fundamentals. USA: American Society of Heating and Air Conditioning Engineers, 1997.