PERGAMON

Building and Environment 36 (2001) 527–541

BUILDING ENVIRONMENT

www.elsevier.com/locate/buildenv

Characteristics of bioaerosol profile in office buildings in Hong Kong

Anthony K.Y. Law[a], C.K. Chau[a,*], Gilbert Y.S. Chan[b]

[a]*Department of Building Services Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong*
[b]*Department of Applied Biology and Chemical Technology, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong*

Received 1 December 1999; accepted 29 February 2000

Abstract

A series of bioaerosol measurements have been conducted at two typical offices in Hong Kong for both a 4-day and a weekly period. Both the investigated offices were installed with heating ventilation and air-conditioning (HVAC) systems coupling with air handling units and fan coil units. Measurements were performed starting from early morning by the Anderson N6 impactor. The primary objectives of these measurements were to determine the temporal concentration profile of bioaerosol inside office environments during office hours, and to determine the effects of air change rate on the concentration profile. The highest bacteria concentrations were recorded to be 2912 CFU/m^3 at the early morning hours during the starting-up period of HVAC systems. The highest fungi concentrations were recorded to be 3852 CFU/m^3 during the weekend mornings. The results of studies also revealed that the air change rate inside the office environment had less significant effects than filtration on airborne bioaerosols. The background fungi concentration was found to have strong correlation with the indoor relative humidity level provided that the relative humidity level could be maintained for a certain period of time. Of the sampled bacteria 80% were found to be gram positive, while the dominating genera of fungi was found to be Cladosporium and Penicillium.

Keywords: Bioaerosols; Office environment; Indoor air quality

1. Introduction

Indoor air quality in the workplace has received great attention during the recent era. In 1998, the Hong Kong Environmental Protection Department (HKEPD) released a consultancy report on the Indoor Air Quality at work place. The report contained measurement results on various indoor contaminants in 40 office premises in Hong Kong. Bioaerosols, including bacteria, fungi, protozoa, pollen, and animal dander, were used as one of the indoor air quality indicators in the report. Although the report has adopted a 1000 CFU/m^3 as an indoor bioaerosol threshold level, it did not describe any details on the measurement protocol or daily exposure profile.

Unlike carbon monoxide, particulates, volatile organic compounds and many other types of pollutants, bioaerosol assessment poses some difficulties during the indoor air quality assessment of the workplace. Insufficient dose response data, and the restrictions in available measurement technology induce great difficulties in setting up a consensus standard governing the bioaerosol exposure level, or a standard protocol for bioaerosol sampling [1]. Although many new molecular detection techniques such as polymerase chain reaction have been developed for the monitoring process, most current microbiological investigations of indoor air still rely on the conventional culture-based methods, i.e. culturing on agar media. So far, the culture-based methods are considered to be the best assessment

* Corresponding author. Tel.: +852-2766-7780; fax: +852-2774-6146.
E-mail address: beckchau@polyu.edu.hk (C.K. Chau).

0360-1323/00/$ - see front matter
PII: S0360-1323(00)00020-2

methods since they can be used in both identifying the genera, and evaluating the total bioaerosol concentration [2]. This information is essential for the assessment of the total bioaerosol exposure in the workplace.

However, samplings by culture-based methods have their limitations as they cannot provide a continuous profile of microbial monitoring. Even with the latest developed continuous bioaerosol sampler, only an average concentration, but not the continuous profile can be determined [3]. In this study, a series of repeated high frequency sampling was used to determine the temporal variation of bioaerosol concentration within air-conditioned offices, and to determine the overall impression of worker exposure. The sampling frequencies depend on the type of sampling, specificity, level of sensitivity, speed, importance of total cell counts, and particulate size range required. Accordingly, in many research and environmental assessment studies, the sampling frequencies could vary from one to as many as nine times a day depending on the overall objectives, and the data analysis methods [4].

Although the temporal nature of the indoor bioaerosol concentrations induces considerable difficulties in assessing human exposure to the indoor air species, the temporal variability remains one of the four important issues that receives little attention [5]. So far, there were little integrated field studies showing the individual impact of the indoor environmental conditions (e.g. temperature and humidity), the operation of air conditioning, and the background construction materials on the temporal indoor bioaerosol concentrations. Since the temporal bioaerosol concentrations are affected by a series of compounding factors, the quantification studies are extremely difficult to analyze. Accordingly, most of the studies reported in the area of bioaerosol are qualitative in nature. Parat et al. [6] attempted to use the principal component analysis to reveal the possible dependencies of factors, like relative humidity, number of people and type of air-conditioning, on the total bioaerosol counts. However, they did not clearly distinguish the effect of heating ventilation and air conditioning system (HVAC) from other factors on the temporal bioaerosol concentrations.

In Hong Kong, over 90% of office environments are equipped with air conditioning systems. Although the HVAC system can help to remove and/or dilute more than 80% of aerosols from outdoor, they can also provide favorable breeding grounds for bioaerosol to colonize [7,8]. In this study, we attempt to reveal the possible temporal time variations of indoor bioaerosol concentrations through a series of longitudinal studies of two air-conditioned offices. A series of grab samples were collected during the operation hours at some office environments. They were conducted to reveal the

Table 1
Description of the sites and the HVAC operation schedule

Site	Building type	HVAC system	Operation schedule	Floor area (m^2)	No of occupants
A1	Commercial	AHU/FCU	Preliminary study: 8:00 am–6:00 pm. Phase one: intervention study 8:00 am–5:00 pm. Phase two: 8:00 am–5:00 pm	500	23–33
A2	University research office	AHU/FCU	Preliminary study: 9:30 am–5:00 pm. Phase one: intervention study 8:00 am–5:00 pm	40	6

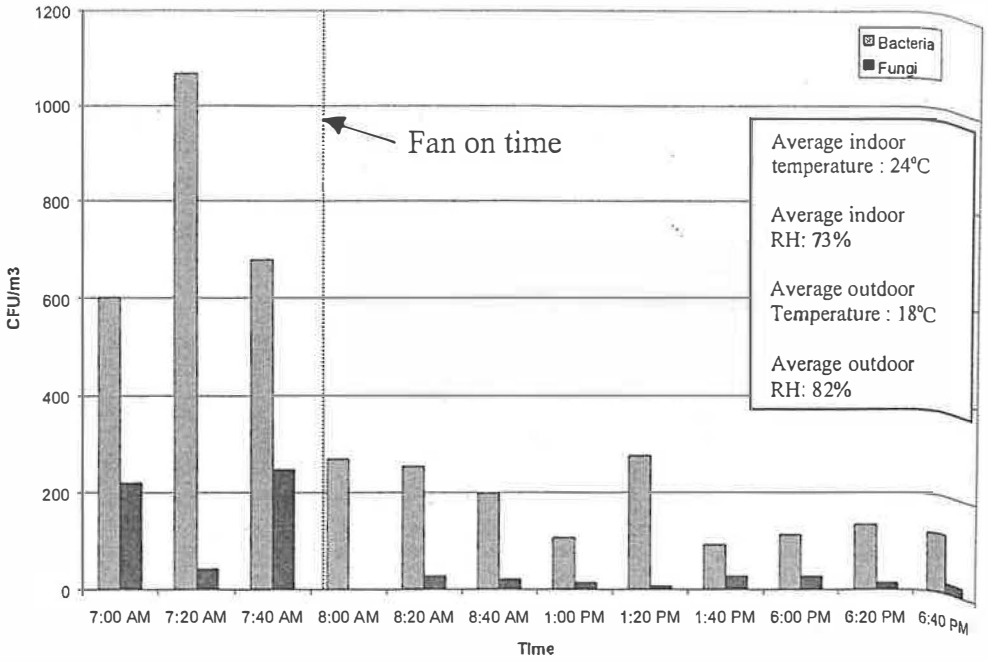

Fig. 1. A typical daily profile of airborne bacteria and fungi concentration levels in office A1.

continuous bioaerosol profile with respect to the air-conditioning system operating conditions in offices in Hong Kong.

2. Materials and method

2.1. Description of the sites

The two office buildings studied, with designated codes A1 and A2, were all located close to busy streets in Hong Kong. Office A1, which was located on the 14th floor, was purely for commercial purposes, while office A2 was a university research office located on the fourth floor. Both offices A1 and A2 were open plan offices without water damage or fungus problems, and they were equipped with air handling unit (AHU) and fan coil unit (FCU) systems. Detailed descriptions of the office premises are shown in Table 1.

For both premises, the air handling units were equipped with panel disposable pre-filters that consisted of a layer of aluminum screen and a layer of fiber filter. All fan coil units were equipped with an aluminum screen filter at the return air inlet covered by grilles. All pre- filters were claimed to be cleaned every 3 months and replaced within 6 months, while aluminum screen filters at the fan coil units were claimed to be cleaned every 3 months at both premises.

According to the schedule provided by the estate management of A1, the filters at the AHU and FCUs were cleaned 1 month before the measurement took place. The cleaning schedule was about the same in A2. However, the filters of the FCUs used in A2 were much older than that of the A1 s, which had been used for about 5 months.

2.2. Plans of study

Our study comprised of a preliminary study, which subsequently led to two phases of full scale survey. During our preliminary study, two office premises (A1 and A2) were selected for 1-day monitoring so as to design an appropriate measurement protocol for our later phases of study. During the first phase of our survey, the same two office premises (A1 and A2) were selected for a 4-day bioaerosol monitoring in order to evaluate the impact of air change rates on the total daily indoor bioaerosol levels. During the second phase of our survey, office A1 was selected for 7-day measurement as a control for comparing with the results from the first phase intervention study.

2.3. Preliminary study

As no standard measurement protocol was available, a preliminary study was conducted prior to the full scale studies with the objective to design an appropriate protocol for monitoring the bioaerosol concentration levels within office premises. The protocol should be designed in such a way that it could help to closely capture all the major variations on the daily

bioaerosol concentration with manageable sampling effort. After reviewing the daily office operation characteristics with regard to the bioaerosol concentration levels, a trial measurement protocol was designed such that samples would be collected in the following four time periods within a day, i.e.:

1. 1 h before the HVAC systems were turned on;
2. right after the HVAC systems were turned on;
3. right after lunch time;
4. right after office hours when the HVAC systems were turned off.

For each hourly measurement period, samples were collected every 20 min. The details of the preliminary results will be discussed in a later section of this paper. Nevertheless, the preliminary results revealed no significant statistical differences among the triplicate samples obtained within the hourly measurement. Major variations on bioaerosol concentration would have occurred during the first few hours around the system startup time, and the bioaerosol concentration would be diminished gradually during office hours. Accordingly, this provided us insight in designing a measurement protocol for our later studies that more samples should be collected within the first 3 h around the air-conditioning morning startup times, and fewer samples can be collected afterwards.

2.4. Phase one: intervention study

The intervention study was conducted in both premises A1 and A2 in order to study whether the cupant density or the air change rate had the domi ing influence on the indoor bioaerosol concentra level. The fresh air supply rate and the number of cupants were varied alternatively to rule out the co sponding influences.

The measurements were conducted on 4 consecu days in both premises. For the 4-day interven study, air samples for fungi and bacteria were colle once every hour between 7:00 am and 9:00 am, once every 2 h between 9:00 am and 7:00 pm. In dition, one outdoor air sample was also collected the morning each day. The indoor and outd sampling interval was chosen to be 5 min and 1 r respectively. During the first day, only half of number of the original occupants was present in offices with the fresh air supply remained in full lo This was done to simulate a situation of exces supply of fresh air and its influence on the bioaero concentration. The ratio of the fresh air supply r from outdoor to the circulation air rate was about for both premises. During the second day, no occup was present in the office, while the HVAC syste were not turned on and no fresh air was actively s

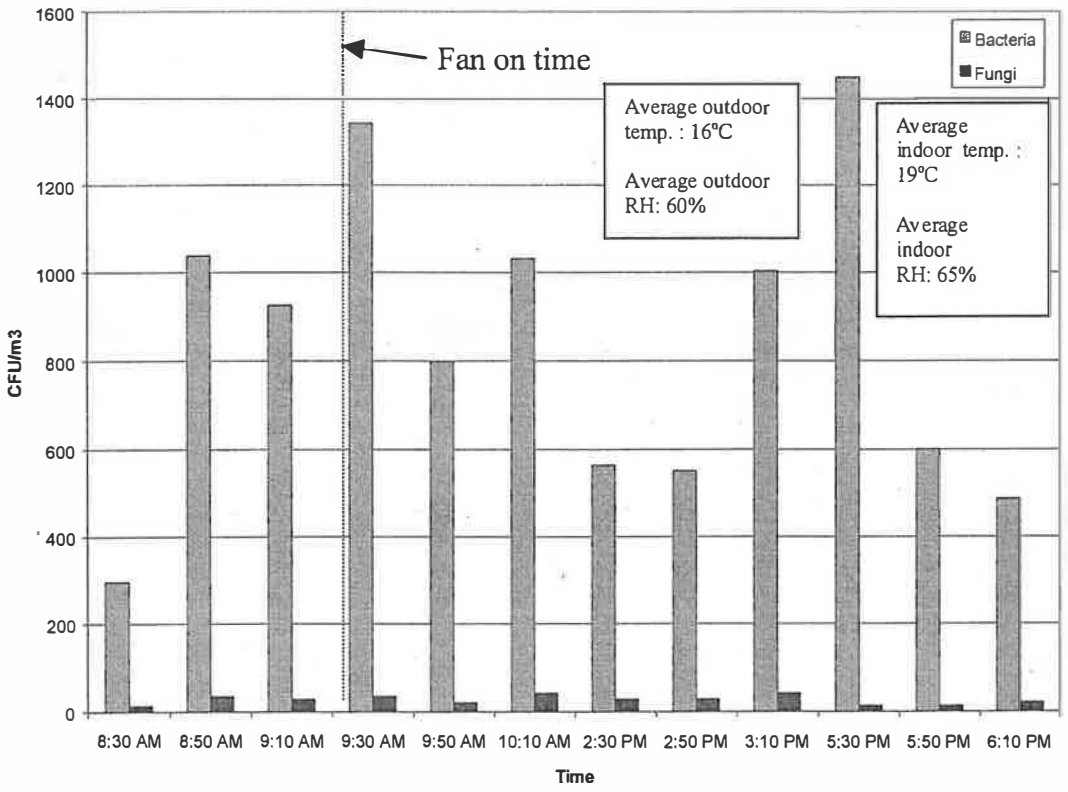

Fig. 2. A typical daily profile of airborne bacteria and fungi concentration levels in office A2 with frequent human activities.

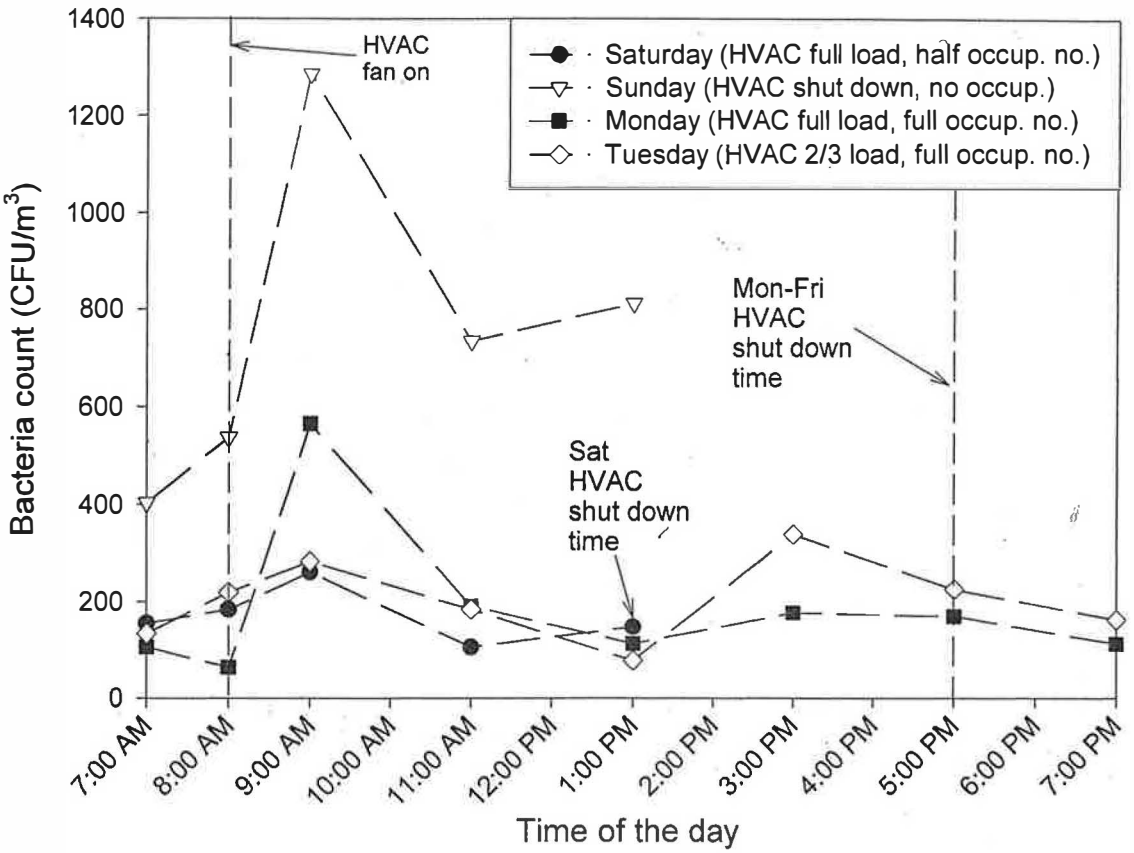

Fig. 3. Bacteria level in office A1 with intervention (Phase one study).

plied into the premises throughout the day. On the third day, the number of occupants returned to normal and the fresh air supply through the HVAC system returned to full load. On the fourth day, the fresh air supply rate was reduced to the two-thirds of the original settings in order to simulate the scenario of reduced air change rate.

2.5. Phase two: daily profile within a week

In this phase of study, a continuous measurement was carried out at the A1 premises for a whole week. Measurement was conducted according to the sampling schedule used in phase one of the study. The purpose of the study in this phase was to provide a control data set parallel to the phase one study. Since the phase one measurement was an intervention study inside the premises, an unaltered setting of the premises should also be studied so that the intervention measurement could be exclusive. In the daily base continuous measurement in A1, the fresh air supply rate remained unchanged during office hours. The AHU system was turned on at 8:00 am and turned off at 5:00 pm every day except Saturday and Sunday.

Table 2
The detail of intervention studies for offices A1 and A2

Day within the week	HVAC status	People load	Remarks
Saturday	Air-conditioning on	Half people load	The impact of people load can be estimated
Sunday	Air-conditioning off	No people load	Background source can be estimated
Monday	Air-conditioning on with full load	Full people load	Normal pattern with HVAC emission at the starting hour
Tuesday	Air-conditioning on with 2/3 of original fresh air supply rate	Full people load	The impact on the total microbial concentration by varying the air change rate can be estimated

During the weekend, the system was turned on at 8:00 am and turned off at 1:00 pm on Saturday, and totally shut down during Sunday.

For the 7-day non-intervention survey in the second phase, air samples for fungi and bacteria were collected once every hour between 7:00 am and 9:00 am, and once every 2 h between 9:00 am and 7:00 pm. However, samples could not be collected at 7:00 pm since there were security restrictions from the estate management.

2.6. Microbiological analysis

Ambient air was sampled from the center location in the two offices 1.1 m from the floor at the workstation level. The outdoor air was sampled at the level of the fresh air intake situated on the roof of the building. Air samples were collected by an Anderson 6 stages cascade impactor (Stage 6 corresponds to 0.65–1.1 μm, Stage 5: 1.1–2.1 μm, Stage 4: 2.1–3.3 μm, Stage 3: 3.3–4.7 μm, Stage 2: 4.7–7 μm, Stage 1: 7 μm or above) [9]. This enabled the counting and the identification of the viable microorganisms in the air samples. The collection efficiency and the reproducibility of this sampling device was previously validated [10–12]. Each impactor was connected to a pump, and a calibra orifice ensured an airflow rate at 28.3 l min^{-1}. The eration schedules of the preliminary study and the t phases are shown in Table 1. Tryptocase Soy A (TSA) was used for culturing bacteria and M Extract Agar (MEA) (3% malt extract, 1.5% ag 0.5% peptone, supplemented with 0.1 mg ml^{-1} chl amphenicol) was used for culturing fungi. One tenth the dishes were reserved for blank test. The Pe dishes were incubated 48 h at 30 ± 2°C for bacte and for 48 h at 25 ± 2°C for fungi. After applying positive hole correction procedure recommended Anderson [13], the results were expressed in colo forming unit per cubic meter ($CFUm^{-3}$). Four ty of fungi genera (i.e. Penicillium spp., Cladosporiu spp., Aspergillus spp., and Alternarias spp.) were t geted for identification by morphology and mic scopic examination while bacteria will be treated lacto-phenol blue stain for gram staining test.

2.7. Other parameters measured

Both the temperature and relative humidity we monitored continuously by a TSI Q-trak monit Meanwhile, the number of occupants and their acti

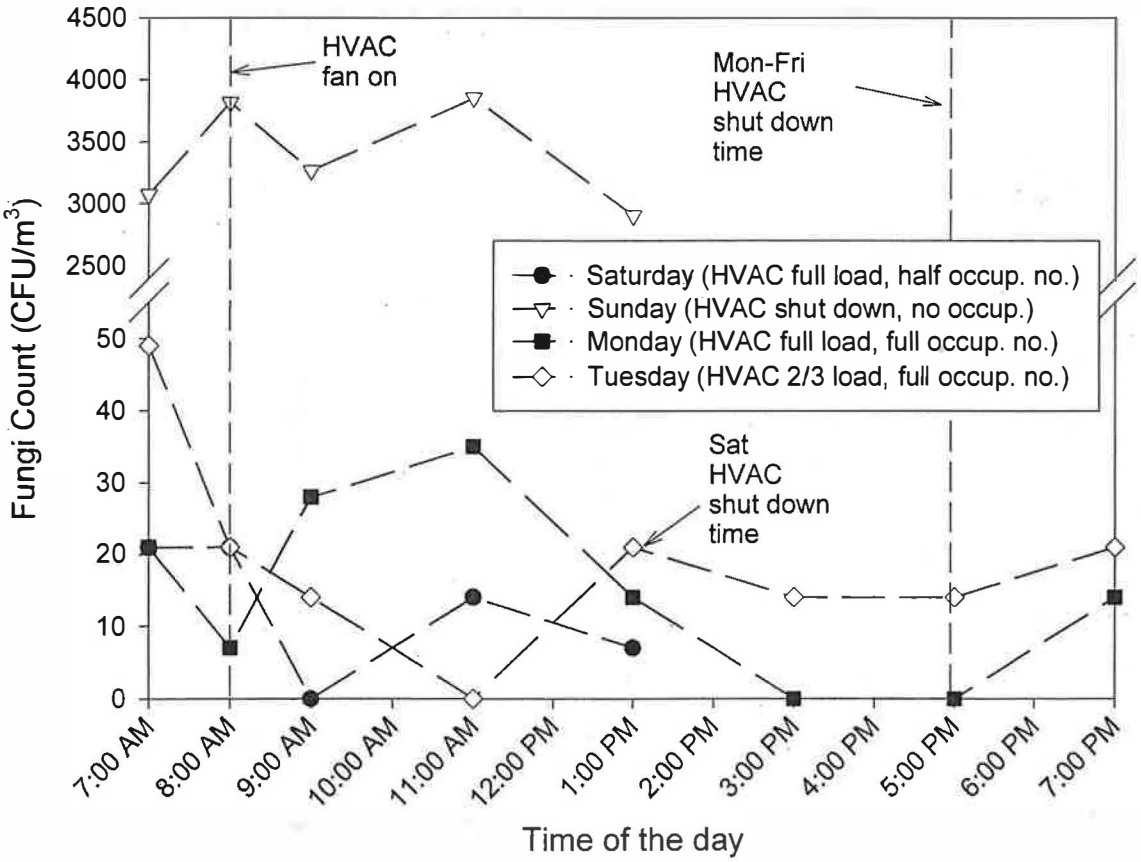

Fig. 4. Fungi level in office A1 with intervention (Phase one study).

Table 3
Summarized results and environmental parameters in offices A1 and A2 in Phase one study[a]

Time	Saturday ACH (AC on): 3.43 ACH (AC off): 0.44					Sunday HVAC was not operative ACH (AC off): 0.37					Monday ACH (AC on): 3.37 ACH (AC off): 0.57					Tuesday ACH (AC on): 2.08 ACH (AC off): 0.42				
	B	F	T°C	RH%	#P	B	F	T°C	RH%	#P	B	F	T°C	RH%	#P	B	F	T°C	RH%	#P
A1																				
7:00 am	155	21	20.5	67.8	1	403	3074	23.4	68.9	1	106	21	20.2	65.2	1	134	49	22.7	60.9	1
8:00 am	184	21	19.8	68.1	8	537	3816	23.4	67.5	1	64	7	19.2	66.0	8	219	21	22.3	61.0	5
9:00 am	261	0	20.1	76	15	1286	3265	23.4	70.3	1	565	28	19.5	69.0	23	283	14	20.2	68.3	25
11:00 am	106	14	20.6	77.8	16	735	3852	23.8	72.1	1	191	35	20.0	66.1	25	184	0	19.8	70.7	25
1:00 pm	148	7	20.4	74.7	5	813	2905	24.5	75.3	1	113	14	20.1	63.4	23	78	21	19.7	71.8	23
3:00 pm	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	177	0	20.1	64.6	22	339	14	19.8	71.8	22
5:00 pm	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	170	0	20.2	64.2	24	226	14	19.9	72.2	25
7:00 pm	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	113	14	20.7	63.5	5	163	21	20.8	72.6	8
Outdoor	110	14	19.8	72.5	N/A	92	7	22.5	70.2	N/A	64	0	18.9	64.0	N/A	125	7	18.8	69.0	N/A
	ACH (AC on): 1.12 AC (AC off): 0.77					HVAC was not operative ACH (AC off): 0.65					ACH (AC on): 1.24 ACH (AC off): 0.71					ACH (AC on): 1.08 ACH (AC off): 0.75				
A2																				
7:00 am	247	57	25.9	73.6	1	1420	686	22.4	72.5	1	933	1004	21.3	58.2	1	438	403	21.0	62.0	1
8:00 am	587	14	24.1	58.5	1	1576	777	22.3	71.5	1	742	8	21.6	57.2	3	445	367	20.9	61.6	2
9:00 am	269	14	21.6	63.5	2	1110	707	22.4	71.6	1	389	92	21.1	62.3	6	163	205	20.0	63.9	6
11:00 am	163	14	20.1	62.0	2	1371	735	23.1	68.4	1	523	92	20.3	63.2	6	608	177	19.0	64.6	6
1:00 pm	141	21	20.0	64.5	1	975	523	23.2	67.8	1	127	85	19.8	62.6	5	99	106	18.7	63.7	6
3:00 pm	671	28	20.8	63.8	1	1145	389	22.4	70.1	1	580	92	19.7	64.2	4	113	92	18.5	64.8	5
5:00 pm	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	276	21	19.9	64.9	1	261	35	18.5	65.5	1
7:00 pm	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	269	14	22.0	55.9	1	403	28	21.2	58.6	1
Outdoor	116	18	22.4	65.0	N/A	98	27	22.4	71.2	N/A	124	27	20.5	64.2	N/A	152	24	20.4	62.5	N/A

[a] ♯♯P, number of occupants; B, bacteria; F, fungi; ACH, air change rate; both bacteria and fungi records are in CFU/m^3.

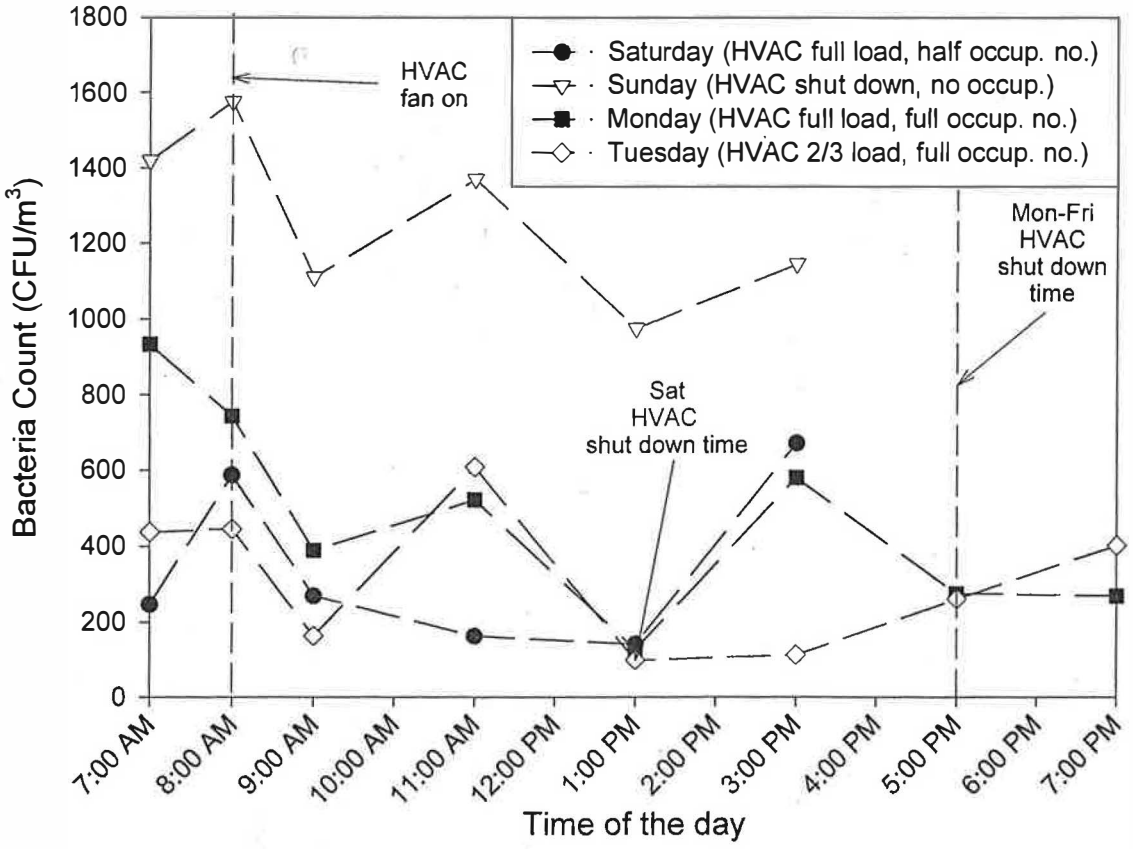

Fig. 5. Bacteria level in office A2 with intervention (Phase one study).

ties were also recorded. To further investigate the problem, the ventilation rates were measured by a trace gas method. The concentration of a trace gas, CO_2 in this case, was monitored after it was dosed into the space. The concentration decay of CO_2 was used to calculate the ventilation rates. The measurement was carried out twice a day, i.e. before and after turning on of the air-conditioning system.

3. Results and discussions

3.1. Preliminary study

3.1.1. Visual inspection

Before air samplings were conducted at the studied offices, the indoor environments were visually inspected with great care to search for the trace of mould growth. The inspected locations included the plenum of the false ceiling, the wall surfaces close to the HVAC diffusers, the desktop surfaces, and the exhaust at the pantry and restroom. For the two premises studied, only office A2 was found to have a mould problem in the pantry and storeroom wall surfaces. Although the owner of the premises claimed have cleaned the surface rather frequently, the mo problem recovered very rapidly. The A1 premi appeared to have no mould problem or stain on a indoor surfaces.

3.2. Daily bioaerosol profile

Although the measurements were conducted dur the wintertime, the average outdoor temperatures a relative humidity were recorded to be between 16 a 18°C, and 60 to 82%, respectively, while the aver indoor temperatures range from 19 to 24°C. The av age indoor relative humidity was recorded to be wit a range of 65–73%. Although the measured relat humidity was relatively high during this specific win time, the outdoor fungi concentration level v observed to be less than 50 CFU/m^3. This is similar fungi concentration reported in wintertime in anot subtropical region Taiwan [14].

Fig. 1 shows a typical profile of bacteria and fu concentrations in office A1 during a working day our preliminary study. Similar hourly indoor bacte and fungi concentration profiles were observed cons

ently throughout the week when comparing the results with the daily study in two subsequent phases. Elevated concentrations of bacteria and fungi occurred right after the morning HVAC system startup, and decreased within 1–2 h afterwards. This burst of emission of bacteria and fungi was probably due to the incubation of bacteria and fungi during the nighttime HVAC shutdown hours. Amplification of biological agents in HVAC reservoirs occurred since the favorable conditions were provided during the HVAC system shutdown hours. Burst of emission occurred as a result of pressure differences when the system was turned on [15,16].

Unlike the A1 premises, the indoor fungal and bacterial concentrations in office A2 fluctuated widely within a day, which is similar to the daily pattern reported for a nursery school [17]. Fig. 2 illustrates wide fluctuations in numbers of airborne viable spores that could occur as a result of variation of activity levels caused by a lot of come-and-go visitors in the university research office. The bioaerosol pattern in office A2 showed a rather different profile since the people activities dominated the profiles in this type of environment.

3.3. Phase one: impact of various parameters

In order to evaluate the impact of the various parameters, such as air change rates, on the daily indoor bioaerosol concentration, a set of intervention measures has been introduced to two studied offices. The details and the objectives of the intervention measures are shown in Table 2. The bioaerosol concentrations of 4 consecutive days were monitored for both offices during the phase one of the field measurement. Figs. 3–6 show the variations of the concentration of fungi and bacteria during two 4-day periods 13–16 March and 17–20 April 1999.

The measurements were started on Saturday at both offices and continued until Tuesday. During the Saturday morning, only half of the original number of the occupants was present in the offices but the fresh air supply rate remained the same. On Sunday, the HVAC systems were not turned on and there was no fresh air supplied actively into the premises. On Monday, the number of occupants and the supply of fresh air through the HVAC system returned to normal. On Tuesday, it was requested the fresh air supply rate be reduced to two-thirds of the original settings, introducing the effect of reducing the air change rate.

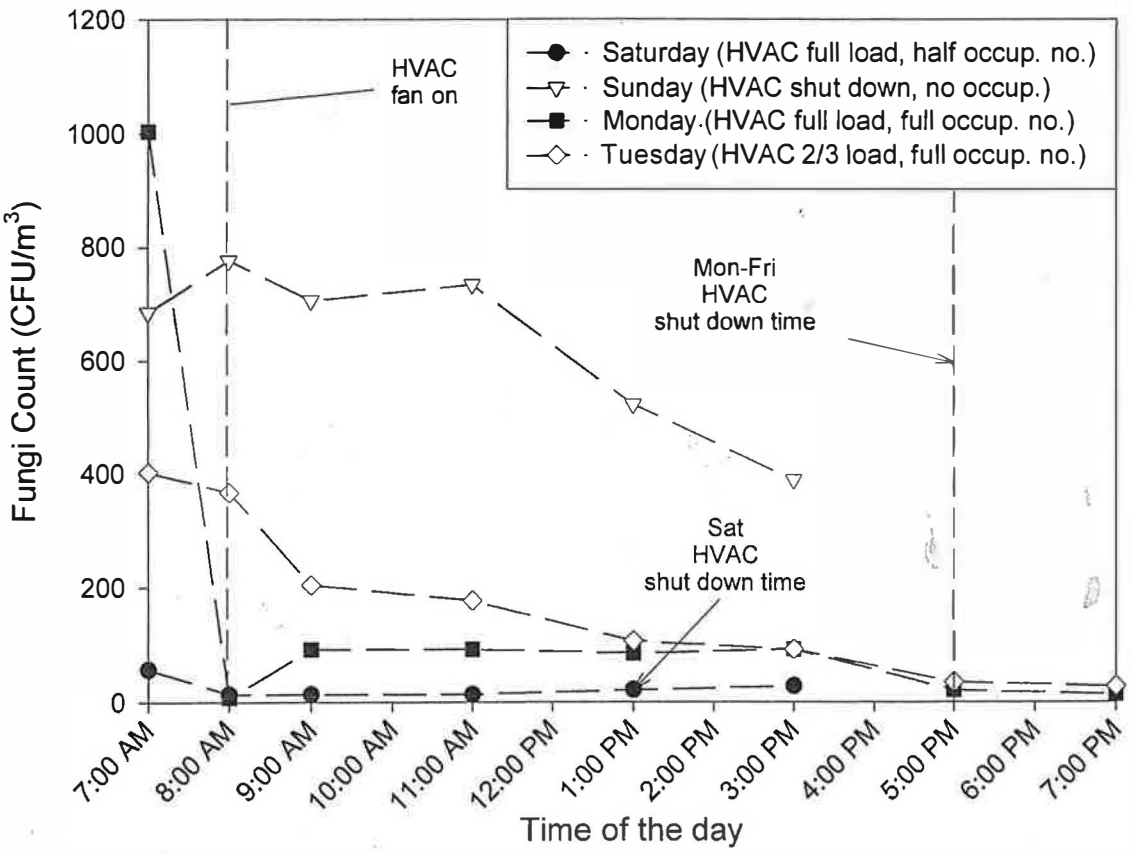

Fig. 6. Fungi level in office A2 with intervention (Phase one study).

During the 4-day survey in both offices, the air change rate was estimated by the CO_2 decay measurement. The measured air-change rates are recorded in Table 3. For office A1, a maximum air exchange rate (ACH) of 3.43 h^{-1} was observed during office hours on Saturday, while the minimum ACH was observed to be 0.37 h^{-1} on Sunday.

Figs. 3 and 4 show the variations of bioaerosol concentration during the 4-day studied period. The results of this measurement indicate that both airborne bacteria and fungi concentrations could effectively be reduced to below 200 CFU/m^3 at the maximum fresh air supply rate. Even though the fresh air supply was reduced to two-thirds of the origin value on Tuesday, there was no significant increase both bacteria and fungi counts. It indicates that the f ter of the FCUs could effectively reduce the airbor bacteria and fungi concentration even when the fre air supply rate was two-thirds of its original value.

The maximum bacteria and fungi concentrati level of office A1 reached 1286 CFU/m^3 and 38 CFU/m^3, respectively, during the Sunday period. Tl was a hundred times higher than the normal offi hours. The elevated levels were probably due to t emissions from the contamination of architectu elements within the buildings.

Table 4
Average bioaerosol concentrations in (a) office A1 and (b) office A2 during different periods within 4 days of measurement in Phase one study

Periods	Air change rate (ACH)	Average bacteria concentrations during office hours[a] (CFU/m^3)	Average fungi concentrations during offi hours[a] (CFU/m^3)
(a) Office A1			
Saturday			
		171	7
with air-conditioning on (8:00 am–1:00 pm)	3.43		
with air-conditioning off (1:00 pm–8:00 am)	0.44		
Sunday			
		945 (No office hours, average from 9:00 am–1:00 pm)	3340 (No office hours, average from 9:0 am–1:00 pm)
with air-conditioning inoperative	0.37		
Monday			
		243	16
with air-conditioning on	3.37		
with air-conditioning off	0.57		
Tuesday			
		222	13
with air-conditioning on	2.08		
with air-conditioning off	0.42		
(b) Office A2			
Saturday			
		191	16
with air-conditioning on (8:00 am–1:00 pm)	1.12		
with air-conditioning off (1:00 pm–8:00 am)	0.77		
Sunday			
		1152 (No office hours, average from 9:00 am–1:00 pm)	655 (No office hours, average from 9:0 am–1:00 pm)
with air-conditioning inoperative	0.65		
Monday			
		379	77
with air-conditioning on	1.24		
with air-conditioning off	0.71		
Tuesday			
		249	123
with air-conditioning on	1.08		
with air-conditioning off	0.75		

[a] Office hours are defined to be: 9:00 am–1:00 pm on Saturday; 9:00 am–5:00 pm on Monday and Tuesday; no office hours for Sunday (are shown for indicative purpose only).

The results of this measurement indicated that both airborne bacteria and fungi remained at the highest concentration throughout the Sunday period in both offices. The air change rate was also the lowest at both offices at that time. The average fungi concentration level recorded 3340 CFU/m^3 at office A1 during the Sunday period was a hundred times higher than the normal office hours, which indicated that a possible internal fungal source existed.

For office A2, the maximum and the minimum ACH were measured to be 1.24 and 0.65 h^{-1}, respectively. During the intervention study, it was determined that a wide fluctuation occurred, which was probably due to the effect of people activities. It is observed that further change in the ventilation rate did not help to alleviate the increase in the bioaerosol levels caused by vigorous people activities (see Figs. 5 and 6).

Table 3 shows the measurement results on bioaerosol and some other indoor air environmental parameters. Table 4(a) and (b) show the average bioaerosol concentration during the office hours in premises A1 and A2, respectively. For the two offices studied, the average bacteria and fungi levels recorded during the office hours were found to be 171–379 CFU/m^3, and 7–123 CFU/m^3, respectively. From the results of our microbial analysis, more than 80% of the total bacteria found indoor was gram positive. The major fungi genera were determined to be Cladosporium spp. and Penicillium spp.

3.4. Phase two: daily profile within a working week

In the second phase of our study, a continuous 7-day measurement was carried out at office A1. The sampling schedule followed exactly that of the first phase. The purposes of the second phase survey were to provide a control for comparison with the first phase intervention study, and to determine whether there would be any significant variation in bioaerosol concentration between morning starting-up and the other office hour. The results are illustrated in Figs. 7 and 8. Table 5 shows the conditions at which the sampling surveys were conducted during the weekly base continuous measurement in office A1. The fresh air supply rate during office hours was measured and found to be in the range 3.04–3.37 h^{-1}. There were no major fluctuations of temperature and relative humidity being observed during the operation hours. The recorded temperature ranged from 22 to 24°C while the relative humidity ranged from 56.8 to 71.6%. The

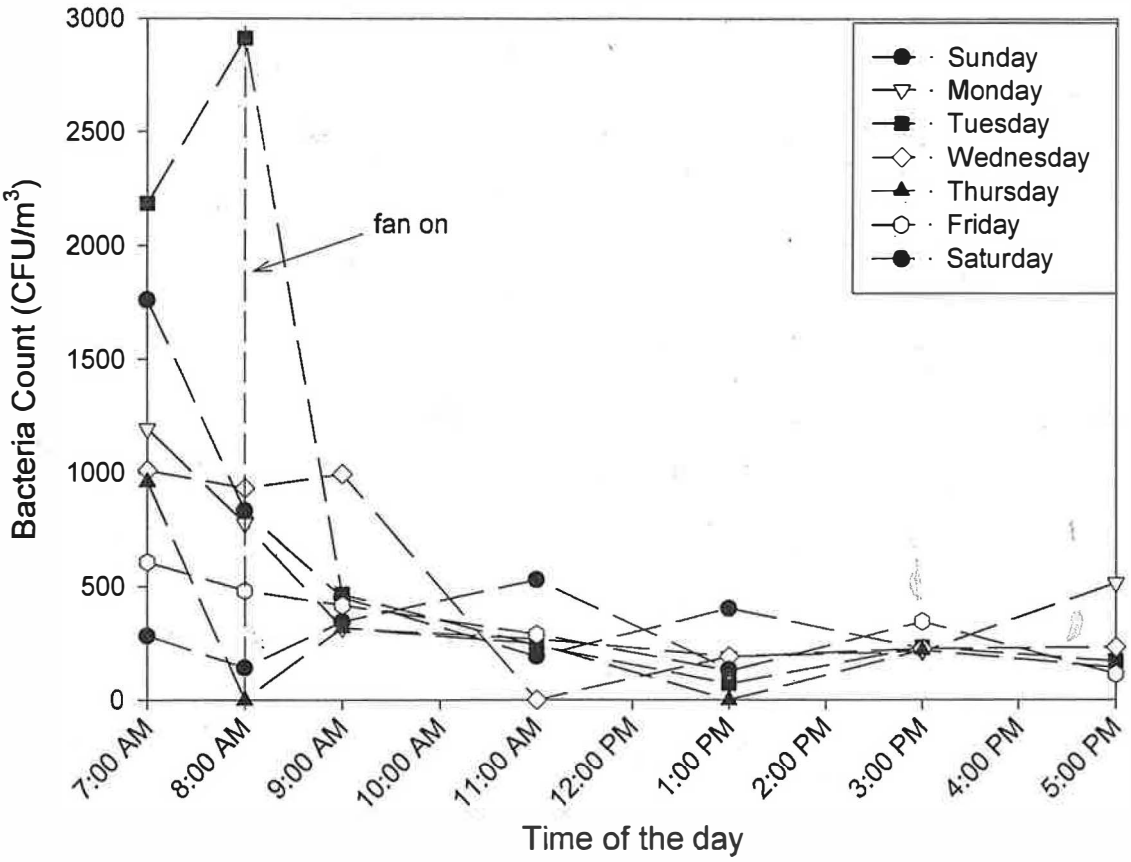

Fig. 7. Weekly bacteria profile in office A1 without intervention (Phase two study).

Table 5
Daily bioaerosol concentrations corresponding to various indoor environmental parameters in Phase two study[a]

	Sunday ACH (AC on): N/A ACH (AC off): 0.32					Monday ACH (AC on): 3.27 ACH (AC off): 0.37					Tuesday ACH (AC on): 3.06 ACH (AC off): 0.29				
Time	B	F	T°C	RH%	#P	B	F	T°C	RH%	#P	B	F	T°C	RH%	#P
7:00 am	1760	700	24.1	69.0	1	1194	339	24.1	67.7	1	2184	212	23.9	66.4	1
8:00 am	834	643	24.1	69.3	1	777	184	24.1	67.9	6	2912	205	23.9	66.1	5
9:00 am	452	975	24.1	69.7	1	318	99	23.8	65.4	23	466	92	23.7	66.4	23
11:00 am	191	311	24.2	69.3	1	269	92	22.8	71.5	25	240	99	22.1	67.4	26
1:00 pm	403	226	24.3	69.6	1	191	134	22.4	69.4	16	71	49	22.3	66.7	3
3:00 pm	226	127	24.3	69.7	1	212	191	22.2	67.1	23	233	28	22.1	68.3	23
5:00 pm	N/A	N/A	N/A	N/A	N/A	516	106	22	67.3	36	170	35	22.1	71.6	18
7:00 pm	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

	Wednesday ACH (AC on): 3.37 ACH (AC off): 0.33					Thursday ACH (AC on): 3.12 ACH (AC off): 0.42					Friday ACH (AC on): 3.04 ACH (AC off): 0.39					Saturday ACH (AC on): 3.1 ACH (AC off): 0.33				
Time	B	F	T°C	RH%	#P	B	F	T°C	RH%	#P	B	F	T°C	RH%	#P	B	F	T°C	RH%	#P
7:00 am	1011	473	23.4	70.1	1	961	1152	23.9	69.0	1	608	382	23.6	60.0	1	283	49	23.7	64.5	1
8:00 am	933	1025	23.4	68.9	20	721	283	24.0	68.7	6	481	148	23.7	60.0	6	141	92	23.8	64.6	8
9:00 am	996	502	23.6	68.6	20	318	85	23.7	65.2	25	417	120	23.9	56.8	23	346	0	23.9	62.5	12
11:00 am	184	155	23.2	68.9	21	247	99	22.7	63.5	30	290	57	23.1	57.3	20	530	21	22.9	63.3	12
1:00 pm	191	410	22.7	70.7	11	141	148	22.6	60.8	5	127	49	23.0	58.1	7	134	49	22.8	63.8	12
3:00 pm	226	205	22.9	69.9	19	219	141	23.0	60.1	23	346	28	23.0	59.4	17	106	127	23.1	64.2	1
5:00 pm	233	184	22.7	69.7	14	141	120	23.4	60.7	20	113	14	23.0	62.3	22	N/A	N/A	N/A	N/A	N/A
7:00 pm	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

[a] ♯♯P, number of occupants; B, bacteria; F, fungi; ACH, air change rate; both bacteria and fungi records are in CFU/m^3.

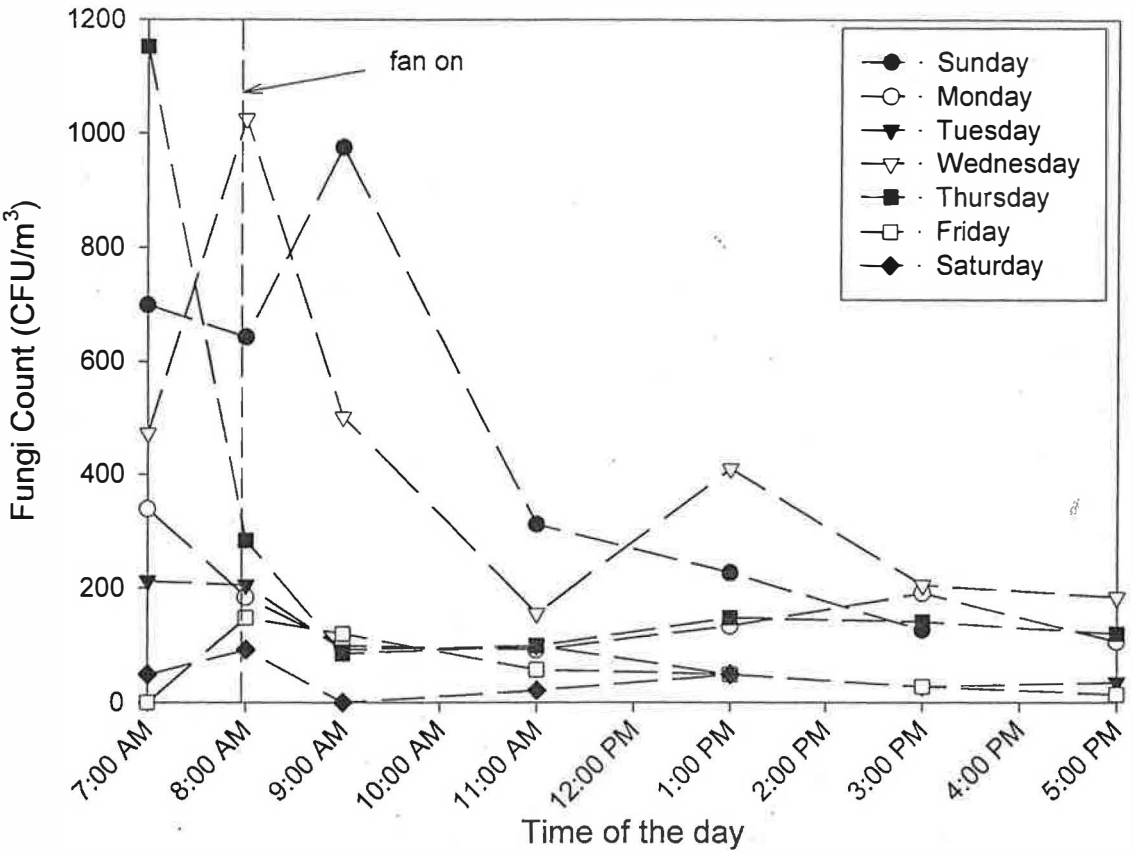

Fig. 8. Weekly fungi profile in office A1 without intervention (Phase two study).

obtained results confirmed with the results from the previous phases that elevated concentrations of bacteria and fungi would occur in the morning HVAC system startup and decrease afterwards.

The overnight shut-off of the ventilation systems could lead to the accumulation of micro-organisms during these periods. However, it is observed that a significant variation of the bioaerosol concentration occurred among the morning samples within the week.

The results from other studies indicate that there was no significant relationship found between the bioaerosol concentration and the instantaneous relative humidity [18]. However, the results from Fig. 9 indicate that the elevated fungi concentrations in the morning, when the HVAC was just turned on, were observed to be possibly correlated with the average values of indoor relative humidity in the previous 8 h. The concentration of fungi increases exponentially along with the average relative humidity value in the past 8 h. The trend also showed an optimal concentration at about 70% RH. With these findings, one could expect to encounter a fairly high concentration of airborne fungi during the morning if the HVAC system was shut down for more than 8 h and the indoor relative humidity remained at the range between 65 and 70%. It could become an alert for those occupants who were likely to develop some hypersensitive diseases. Although the HVAC system was observed to be capable of reducing the fungi concentration to less than 50 CFU/m^3, within 2 h of operation, occupants working during this period were exposed to a high risk of respiratory system infection. On the contrary, the bacteria concentrations showed to have no significant relationship with the average relative humidity in the previous 8 h, although the concentration of bacteria was always found to be the highest during the morning.

From the results of the second phase daily measurement, it was observed that the indoor bioaerosol concentration profile was closely related to the operation schedule and condition of the installed HVAC system. The results also demonstrated that if there were no major interference caused by the occupants, the daily indoor bioaerosol concentration would appear in a similar profile. Fig. 10 shows such a hypothetically constructed daily bioaerosol profile in an air-conditioned office environment in the absence of people activities. The peak shown in the graph was likely to be caused by the emission from the HVAC system components (i.e. soil of the ductwork, filter media).

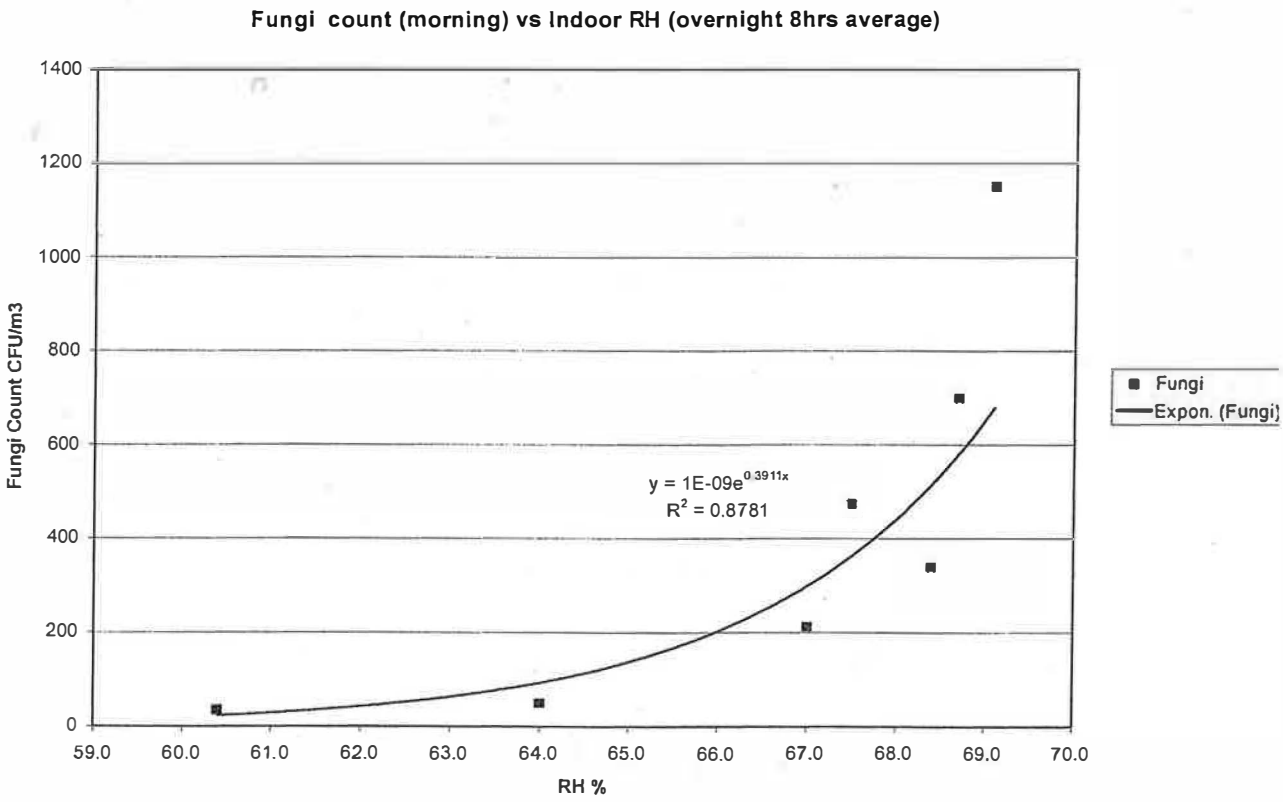

Fig. 9. The correlation between the indoor fungi concentration and the average indoor relative humidity level during HVAC shut down hou

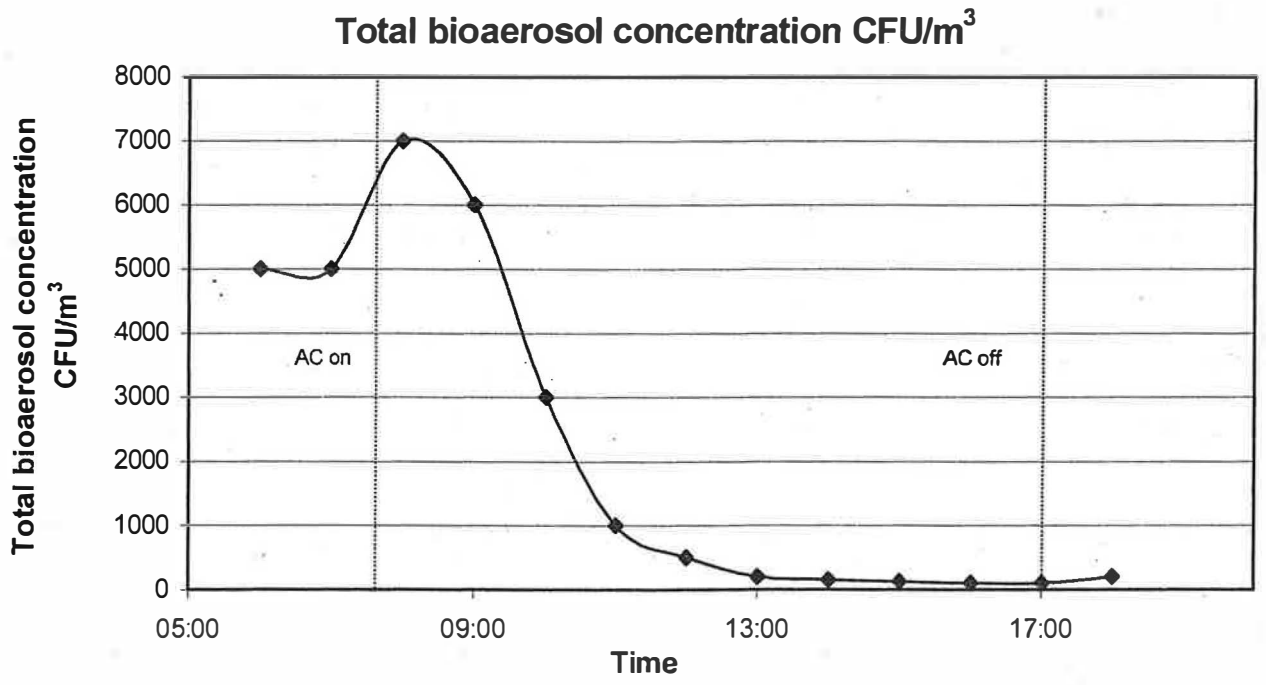

Fig. 10. A hypothetical daily bioaerosol profile inside office buildings operating with HVAC systems.

With further investigation of the breeding rate and emission rate of both bacteria and fungi under the specific indoor conditions and building material, it is possible to model such curve mathematically. A mathematical model could probably help understand the exposure characteristics of the occupants on bioaerosol provided that the background bioaerosol level and some indoor parameters were measured. This should be much easier and cost effective to do so as compared with the continuous bioaerosol measurement.

From both phases of our study, more than 80% of the bacteria was found to be gram positive at all time. Among four of the fungi genera identified, Penicillium was found to be the most dominating one which shared more than 80% of the total identified populations.

4. Conclusions

Concluding the overall results, the average bioaerosol exposure during office hours inside both offices was found to be less than 1000 CFU/m^3, which was considered to be lower than the recommended guideline. However, there exists a risk of high occupant exposure if they were working in the early morning when the system was not yet started, or during shut down hours on Sunday. As the highest value found exceeded 3800 CFU/m^3 during the morning, the occupants should be aware of the situation and avoid working in a non-ventilated environment. Although 1000 CFU/m^3 was not an acknowledged threshold value for bioaerosols, office environments observed to be deviating from this threshold value should alert the management to identify the source of the biological contaminants. Especially in a subtropical region like Hong Kong, the relative humidity would always exceed 65% during the night in the summer time. The experimental results have revealed that such an office environment would become an excellent microbial incubator. The situation was expected to be even worse after a long weekend. As filtration was found to have a major mechanism for bioaerosol removal, the cleaning of filters of the FCU should be frequently applied. Since there were emissions of bioaerosol observed during the morning HVAC system startup, further microscopic investigation on the filter media with respect to the breeding rate of micro-organisms should be a valuable subject for further studies.

Acknowledgements

This work was supported by the Central Allocation Grants Nos. 350/772 and APA-36 from the Hong Kong Polytechnic University. We are indebted to all our colleagues in the Departments of Building Services Engineering and Applied Biology and Chemical Technology of the Hong Kong Polytechnic University for their fruitful advice and help.

References

[1] Griffiths WD, DeCosemo AL. The assessment of bioaerosols: a critical review. Journal of Aerosol Science 1994;25(8):1425–58.
[2] Crook B, Sherwooe-Higham JL. Sampling and assay of bioaerosols in the work environment. Journal of Aerosol Science 1997;28(3):417–26.
[3] Stern MA, Allit U, Corden J, Millington W. The investigation of fungal spores in intramural air using a Burkard continuous recording air sampler. Indoor + Built Environment 1999;8:40–8.
[4] Rhodes WW, Rinaldi MG, Gorman GW. Reduction and growth inhibition of microorganisms in commercial and institutional environments. Journal of Environmental Health 1995;58(3):12–19.
[5] Flannigan B, Miller JD. Health implications of fungi in indoor environments — an overview. In: Samson RA, Flannigan B, Flannigan ME, Verhoeff AP, Adan OCG, Hoekstra ES, editors. Health implications of fungi in indoor environments. Amsterdam: Elsevier, 1994. p. 65–74.
[6] Parat S, Perdrox A, Hidalgo HF, Saude I, Grillot R, Baconnier P. Multivariate analysis comparing microbial air content of an air-conditioned building and a naturally ventilated building over one year. Atmospheric Environment 1997;31(3):441–9.
[7] Batterman SA, Burge H. HVAC System as emission sources affecting indoor air quality: a critical review. HVAC&R Research 1995;1(1).
[8] Burge HA. Approaches to the control of indoor microbial contamination. In: desiccant cooling and dehumidification by ASHRAE, 1992:13–15.
[9] Anderson AA. New sampler for the collection and enumeration of viable airborne particles. Journal of Bacteriology 1958;76:471–84.
[10] Buttner MP, Stetsenbach LD. Monitoring of airborne fungal spores in an experimental indoor environment to evaluate sampling methods and the effects of an activity on air sampling. Applied Environmental Microbiology 1993;59:226.
[11] Jensen PA, Todd WF, Davis GN, Scarpino PV. Evaluation of eight bioaerosol samplers challenged with bioaerosols of free bacteria. Am Ind Hyg Ass J 53(10):660–7.
[12] Jones W, Morring K, Morey P, Sorenson W. Evaluation of the Anderson viable impactor for single sampling. Am Ind Hyg Ass J 1985;46:294–8.
[13] Anderson Instruments. Operation Manual for Anderson Sampler, Viable (Microbial) Particle Sizes Samplers. Anderson Instruments, Atlanta, USA,1984.
[14] Kuo YK, Li CS. Seasonal fungus prevalence inside and outside of domestic environments in the subtropical climate. Atmospheric Environment 1994;28(19):3125–30.
[15] Maus R, Goppelsroder A, Umhauer H. Viability of bacteria in unused air filter media. Atmospheric Environment 1997;31(15):2305–10.
[16] Kemp SJ, Kuehn TH, Pui YH. Filter collection efficiency and growth of microorganisms on filters loaded with outdoor air. ASHRAE Transactions 1995;3853 (RP-625).
[17] Flannigan B. Air sampling for fungi in indoor environments. Journal of Aerosol Science 1997;28(3):381–92.
[18] Mendell MJ. Consistent pattern of elevated symptoms in air-conditioned buildings; a reanalysis of epidemiologic studies. American Journal of Public Health 1990;10:1193–9.