Review Article

Achieving 'excellent' indoor air quality in commercial offices equipped with air-handling unit – respirable suspended particulate

Abstract A study was carried out to investigate the feasibility of achieving ultra low respirable suspended particulates (RSP) in commercial offices without major modification of existing ventilation systems by enhancing the particulates removal efficiency of existing central ventilation systems. Four types of filters which include pre-filters, cartridge filters, bag filters and high efficiency particulates air (HEPA) filters were tested in a commercial building in Causeway Bay. The results show that an RSP objective of $< 20\ \mu g/m^3$ could be met by removing RSP from both the return air and outdoor air supply simultaneously. This level of performance is classed as 'excellent' by the Hong Kong Government, Environmental Protection Department. Filters with efficiency that exceed 80% placed both in the return air and outdoor air were sufficient to meet the objective. It is not necessary to install HEPA filters to achieve the 'excellent' class. The outdoor air filter has great influence on the steady state indoor RSP concentration while the effective cleaning rate is governed by the return air filter. Higher efficiency filters increased the static drop but the volume flow of the air fan was not affected significantly. The additional cost incurred was $< 5\%$ of the existing operation cost.

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Key words: Indoor air quality; Respirable suspended particulates; Filters; Offices; Air-handling unit; Cleaning rate.

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Practical Implications

This paper reports a field study of RSP control for an indoor office environment. The results are directly applicable to building service engineering in the design of ventilation systems using air-handling units. Field observations indicated that indoor RSP in an office environment could be suppressed below $20\ \mu g/m^3$ within 1 h by the simultaneous filtration of outdoor air and return air. Outdoor air filtration has a great influence on the steady state indoor concentration and return air filtration governs the cleaning rate. It is believed that the results of this study could be extended to the cleaning of other indoor pollutants such as volatile organic compounds.

Nomenclature

Q_f	Outdoor air flow rate;
Q_{if}	Infiltration rate of outdoor air;
Q_v	Return air flow rate;
N_f	RSP filter efficiency of outdoor air filters;
n_{if}	RSP penetration coefficient;
N_v	RSP filter efficiency of return air filters;
C_t	Indoor RSP concentration at time t;
C_{out}	Outdoor RSP concentration;
C_∞	Steady state indoor RSP concentration;
C_0	Indoor RSP concentration at start of experiment (time $t = 0$);
V	Effective room volume;
S	Indoor source of RSP;
K	Loss coefficient because of surface deposition and duct loss.;
R	Effective cleaning rate;
ψ	Cost per 1% system efficiency.

Introduction

People spend more than 70% of time indoors (Liao et al., 1997). Good indoor air quality (IAQ) can enhance the comfort level of the occupants, increase the productivity of the workers and improve the health of workers. A voluntary Indoor Air Quality (IAQ) Certification Scheme for Offices and Public Places was introduced by the Environmental Protection Department, HKSAR in 1999 (HKEPD, 2003a) and officially launched in 2004 (HKEPD, 2003b).

Certified buildings are grouped into two classes according to 12 IAQ parameters. When the IAQ is better than the 'excellent' class IAQ Objective, the building is classified as 'excellent'. When the IAQ is worse than 'good' class IAQ Objective, the building is not certified. For IAQ values in between, the building is classified as 'good'. The 12 parameters include physical, chemical, biological and radioactive parameters. They are room temperature, relative humidity, air movement, carbon dioxide, carbon monoxide, respirable suspended particulates (RSP), nitrogen dioxide, ozone, formaldehyde, total volatile organic compounds (TVOC), airborne bacteria and radon. IAQ certificates are granted by the IAQ Information Center and each certification is valid for 1-year. In early 2005, seven and 67 buildings respectively have been awarded the 'excellent' class and the 'good' class in Hong Kong.

To achieve the 'excellent' IAQ, it has been found that TVOC and RSP were the two determining parameters. VOC includes benzene, toluene, xylene, formaldehyde, carbon tetrachloride, trichloroethylene, tetrachloroethylene, chloroform, 1,2(1,3)-dichlorobenzene, 1,4-dichlorobenzene and ethylbenzene. RSP refers to particles in air with nominal aerodynamic diameter of 10 μm or smaller. RSP is a synonym for PM_{10}. Many studies (Lee et al., 2002; Liao et al., 1997; Tung et al., 1999a) indicated that RSP and TVOC could not meet 'excellent' class IAQ objectives in many buildings in Hong Kong. To achieve the 'excellent' class, new ventilation designs might be needed for the removal of RSP and TVOC. Other parameters were either not a problem or can be dealt with by good management or maintenance practice.

Control of RSP in indoor environments has been studied for many years. Offermann et al., 1985, studied the control of RSP by portable air cleaners. Jamriska et al., 2003; Kulmala et al., 1999 have studied the effect of outdoor air, filtration and ventilation on indoor concentrations using models. Jamriska et al., 2000 studied the effect of ventilation systems and filtration on submicrometer particles in an office building in Brisbane, Australia. This study was based on sub-micron size particles and not on PM_{10}. Reed et al., 2003 studied the effect of ventilation systems and air filters on decay rates of particles from indoor sources in an occupied townhouse in Reston, United States. A few studies (Koponen et al., 2001) were based on particle numbers and not on particle mass. Some studies concern residential premises and not office buildings. While all previous studies provide invaluable knowledge on indoor particulates control, further investigations are still needed for field applications.

The aim of this study was to investigate the feasibility of achieving low RSP values in commercial offices without major modification of existing mechanical ventilation [heating, ventilating and air-conditioning (HVAC)] systems. The concept was to enhance the particulates removal efficiency of an existing central ventilation system and observe whether the 'excellent' class RSP objective could be met. More important is that the indoor environment comfort levels should not be compromised. The IAQ RSP objective is composed of two parts – one is the concentration level and the other is the time. The RSP objective is to maintain an indoor 8-h average RSP below 20 $\mu g/m^3$. The first objective of this study was to observe whether a HVAC system could maintain the indoor RSP level below 20 $\mu g/m^3$. The second objective was to ensure that the cleaning rate was fast enough such that RSP fell below this level before 9:00 AM. If cleaning takes too long, the 8 h averaged RSP concentration would exceed 20 $\mu g/m^3$.

In general, HVAC in Hong Kong are composed of two types. One is the central air conditioning system where one large air-handling unit (AHU) controls the air conditioning of a very large area. It can either be of variable air volume (VAV) or of constant air volume (CAV). The other type is the fan coil system where each room is controlled using one or more fan coil units. As the retrofitting of higher efficiency filters in a fan coil system is almost impossible, this study focuses only on AHUs.

Field experiment

Experimental site

The experiment was conducted in a commercial building in Causeway Bay between March 2002 and July 2002. Causeway Bay is located on the north shore of Hong Kong Island. It is a major entertainment district with many commercial offices and residential apartments. The building had forty floors and was surrounded by many others high rise buildings. The north side of the building faced a six lane road with very high traffic flow. The outdoor RSP of this site was dominated by traffic emissions. Other emissions sources include kitchen exhausts. There are numerous restaurants in this area. There was a roadside air monitoring station close to the building, whose the annual average roadside RSP was about 100 $\mu g/m^3$.

An unoccupied office on low floors was reserved for carrying out the experiment. The entire zone was vacated with all partitions taken down forming one single unobstructed volume. The zone occupied a total floor area of 525 m^2 ($25 \times 21 \times 2.85$ m).

Equipment

Figure 1 shows the layout of the ventilation zone and the equipment arrangement. The AHU contained a centrifugal fan (3 kW), below called the AHU air fan. The designed volume flow (denoted as Q_v) of this fan was 3.5 m^3/s at 3 hPa static pressure. The outdoor air supply to this building was centralized. One air fan distributed outdoor air to more than 10 floors. For full control of outdoor air supply, the original outdoor air

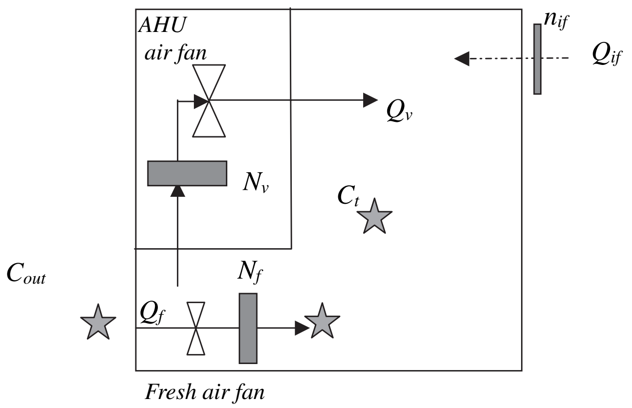

Fig. 1 Schematic diagram of the ventilation zone and the equipment setup

supply was isolated and sealed off. A temporary centrifugal fan (1.5 kW) was installed inside the test zone. It drew outdoor air directly from one of the windows of the test site. The designed volume flow (denoted as Q_f) of this fan was 0.5 m^3/s at 2 hPa static pressure. An inverter (Siemens PLC, Manchester, UK) was installed to control the flow rate of the outdoor air fan. A Socomec multifunction meter (model DIRIS M, Socomec, Cedex, France) was used to monitor the power consumption of air fans under different flow rates.

A TSI VelociCalc (model 8386, TSI Inc., Shoreview, MN, USA) air velocity meter was used. The volume flow rate of the return air and the outdoor air were acquired by measuring the cross-section profiles of the supply air duct of the AHU and the inlet air duct of the outdoor air fan respectively (ASHRAE standard 111–1988; ASHRAE, 1988). The volume flows were checked by measuring the face velocities at the filter compartment (return air). The accuracy of the anemometer was ±3% or 0.015 m/s.

Tracer gas technology was used to measure the air change rate (air changes per hour) according to the ASTM standard test method E741-2000 (ASTM, 2000). Sulfur hexafloride (SF_6) was used as the tracer gas. A Bruel & Kjaer (Model 1302, Bruel & Kjaer, Naerum, Denmark) photo-acoustic multi-gas monitor was employed. The precision of the SF_6 measurement was ±5 ppb. The air change rate value had several applications in this experiment. First, it was used to validate the outdoor air volume flow acquire from air velocity measurements. Second, it was used to evaluate the effective room volume of the ventilation zone. Third, it revealed whether the outdoor air and return air were well mixed or not. Fourth, it was used to evaluate the air-tightness of the ventilation zone. The outside air infiltration (Q_{if}) through uncontrolled path is unavoidable in this experiment. The exact amount of RSP which penetrated ($Q_{if}n_{if}$) through the building shell cannot be measured and this will interfere with the indoor concentration. As the ventilation zone, however, in an AHU system is designed to have a small positive pressure, the background Q_{if} measured when Q_v and Q_f are zero represents the maximum possible Q_{if}. The upper limit of the error caused by infiltration can be estimated using this technology.

Three TSI DustTrak (model 8520) RSP dust monitors were deployed. One monitored the outdoor RSP level, another one was located in the center of the room which monitored the indoor RSP level and the last one was placed near the face of the outdoor air filter which monitored the filtration efficiency of different filters. The dust monitors measured PM_{10} at 1 min intervals at a flow rate of 1.7 l/m. A Taper Element Oscillating Microbalance [TEOM, Rupprecht & Patashnick, (R&P) Thermal Electron Corporation, NY, USA] real-time gravimetric analyzer was deployed on site. The data of all three DustTraks were adjusted using the TEOM as a reference.

Filters

Four types of filters (American Air Filters, AAF International, Louisville, KY, USA) were used. They included pleated filters (pre-filter and cartridge filters), non-supported pocket filters (bag filters) and HEPA filters. Bag filters were only tested in the outdoor air fan and were not tested in the AHU because of limited space. The size and designed flow rate of all filters were 0.61×0.61 m and 3400 m^3/h, respectively. Table 1 shows the specifications of the filters used. The static drop of the filters under different flow rates was measured using both the VelociCalc and an inclined manometer.

The experiment

The experiment was to observe the equilibrium indoor RSP concentration (C_∞) and the time required to reach

Table 1 Specifications of AAF filters used

Model	Filter type	Rated efficiency* (%)	Initial pressure drop (Pa)	Cost per filter (HK$) year 2002
AM-Air 1100, 2″	Pre-filter	25–30	100	50
Dri-Pak 2000 MERV 12, 21″	Bag	60–65	82	250
Dri-Pak 2000 MERV 14, 30″	Bag	80–85	85	275
Dri-Pak 2000 MERV 15, 21″	Bag	90–95	134	300
Varicel MERV 11, 12″	Cartridge	60–65	100	470
Varicel MERV 13, 12″	Cartridge	80–85	130	500
Varicel MERV 14, 12″	Cartridge	90–95	145	530
Astrocel I, 11.5″	HEPA	99.999	350	2500

*Rated efficiency tested in accordance with: AM-Air 1100: UL standard 900.
Dri-Pak 2000 and Varicel: ASHRAE 52.2-1999.
Astrocel: Dioctyl Phthalate (DOP) photometer test and Polystyrene Latex spheres laser test.

C_∞ under different filtration efficiencies. An experiment has to start with a sufficiently high indoor RSP level and this was achieved by switching off the ventilation system and introducing outdoor air into the zone as the outdoor air was laden with RSP. When the indoor RSP concentration reached the outdoor level, all windows were closed. This initial RSP concentration is denoted as C_0. The outdoor air fan and the AHU air fan were then turned on. The decay of the indoor RSP level was recorded until C_∞ became steady. The static drop and RSP removal efficiency of the filters were monitored. The flow rate and power consumption of the two fans were also recorded. The air change rate was monitored using SF_6 tracer gas. When one case study was completed, the experiment was then repeated by replacing the outdoor air filter with another filter. When all filters listed in Table 1 were exhausted, the filter at the AHU fan was then replaced by a different type and the whole cycle of outdoor air filter replacement was repeated again. It took about 1–2 h to complete one case. In total about 40 different cases of filter combinations have been studied.

To avoid flow complications caused by other AHU units in the same building, all studies were carried out between 6:00 PM in the evening and 8:00 AM in the morning while all other air conditioning services were switched off in the entire building. Another reason why the case studies were carried out at that time was to avoid the movement of lifts pumping a large volume of outdoor air into the study zone. This interference had previously been found significant. For full control of outdoor air supply, all possible outdoor air supply paths such as lifts, staircases, duct openings, were identified and sealed with plastic sheeting.

Results

System efficiency and effective cleaning rate

Offermann et al. (1992) pointed out that air cleaner performance could be indicated by the system efficiency and the effective cleaning rate. System efficiency η indicates the difference between the steady state indoor RSP level and outdoor RSP level. The higher the system efficiency, the lower is the indoor RSP level. System efficiency is given by:

$$\eta = \left(1 - \frac{C_\infty}{C_{\text{out}}}\right) \times 100\% \qquad (1)$$

where C_∞ is the steady state indoor RSP concentration and C_{out} is the outdoor RSP concentration.

The effective cleaning rate (R) indicates the time required for the indoor RSP level to decay from a high value to the steady state low value. R was derived from a dynamic mass balance equation (Jamriska et al., 1999) where:

$$\begin{aligned}\frac{\mathrm{d}C_t}{\mathrm{d}t} &= C_{\text{out}}\frac{[Q_{\text{f}}(1-N_{\text{f}}) + Q_{\text{if}}(n_{\text{if}})]}{V} \\ &\quad + S - C\frac{[Q_{\text{f}} + Q_{\text{if}} + Q_{\text{v}}N_{\text{v}} + K]}{V}\end{aligned} \qquad (2)$$

When S and C_{out} are constants, the solution of Equation (2) is:

$$C_t = (C_0 - C_\infty)\mathrm{e}^{-Rt} + C_\infty \qquad (3)$$

where

$$C_\infty = \frac{\frac{[Q_{\text{f}}(1-N_{\text{f}})+Q_{\text{if}}(n_{\text{if}})]}{V}C_{\text{out}} + S}{R} \qquad (4)$$

and

$$R = \frac{Q_{\text{f}} + Q_{\text{if}} + Q_{\text{v}}N_{\text{v}} + K}{V}.$$

R is effective cleaning rate. It includes loss mechanisms because of the dilution of outdoor air, exfiltration, return air filtration, surface deposition and duct loss. The presence of the indoor RSP emission source makes the modeling of indoor RSP very complicated. This experiment was carried out with no indoor RSP emission source, that is $S = 0$. This is the major limitation of this work. A good literature review on IAQ models can be found in Jamriska et al., 1999.

Figure 2 shows a typical indoor RSP decay curve. Extraction of the values of C_∞, C_0, and R are also indicated. C_{out} was the average outdoor RSP level during this period.

AHU air fan equipped with a pre-filter while the filtration efficiency at the outdoor air fan increased

In many commercial buildings, the common practice is to fit pre-filters in an AHU air fan and no filter in an outdoor air fan. The first experiment was to explore the potential improvement brought by increasing the filtration efficiency on the outdoor air supply. Figure 3 shows the variation of C_∞/C_{out} with different outdoor air filters while the pre-filters at the AHU air fan remained unchanged. The air flow of the AHU air fan and outdoor air fan were 3.7 m^3/s and 0.45–0.54 m^3/s, respectively. Figure 3 indicates that very low indoor RSP levels could be attained by the filtration of the outdoor air supply alone. The higher the filtration efficiency, the lower the C_∞/C_{out} ratio. Significant indoor RSP reduction appeared when the outdoor air filter efficiency exceeded 60%. When an HEPA filter was used $C_\infty/C_{\text{out}} = 0.01$. For a hypothetical outdoor RSP level of 200 $\mu g/m^3$, the steady state indoor RSP C_∞ would be 2 $\mu g/m^3$ which satisfies the 'excellent' IAQ objective comfortably. Thus when there is no

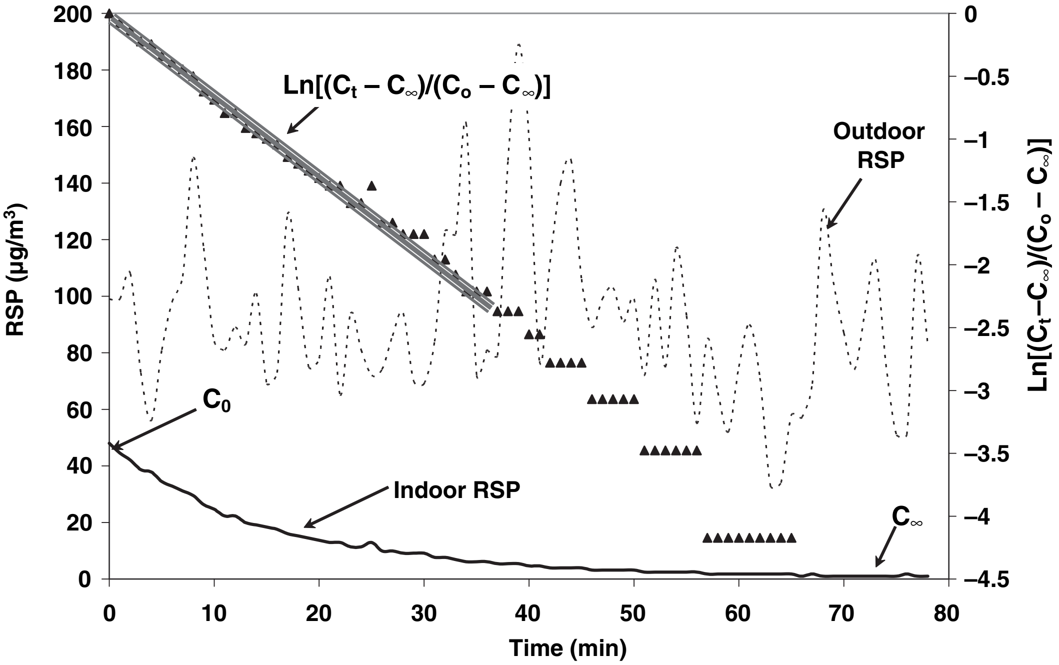

Fig. 2 Decay of indoor RSP (C_t) with time and the extraction of C_∞ and C_0. The triangle markers are $\ln\left[(C_t - C_\infty)/(C_0 - C_\infty)\right]$

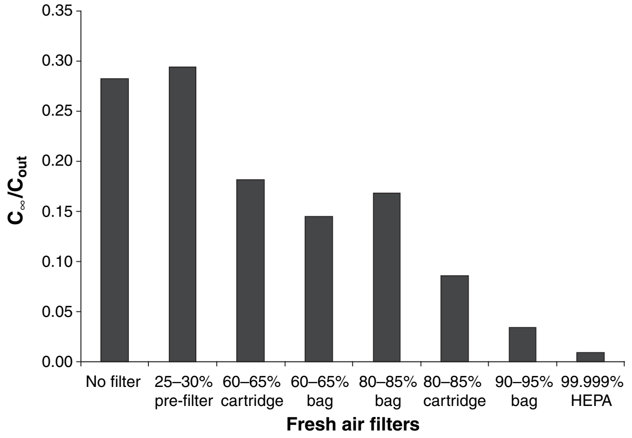

Fig. 3 The ratio of the steady state indoor RSP to the initial outdoor RSP (C_∞/C_{out}) under different outdoor air filters (AHU filter = pre-filter)

indoor dust source, it is possible to attain an 'excellent' IAQ in existing commercial buildings without major modification works.

An interesting point is that the C_∞/C_{out} value under a no outdoor air filter condition was 0.28. This result implies that even under minimal control, the indoor RSP level in a commercial building could be expected to be lower than the outdoor RSP level. The nearest comparison of this case can be found in Jamriska et al., 2003. Their modeling results showed that C_∞/C_{out} was about 0.26 for 30% filter efficiency at return air (no outdoor air filter) and for no filter at all C_∞/C_{out} was about 0.75. Although the modeled $C_\infty/C_{\text{out}} = 0.26$ is very close to our field result $C_\infty/C_{\text{out}} = 0.28$ (Figure 3), it is not legitimate to compare the two results directly because the model study was based on particle number and this field study was based on mass concentration.

To explore the reason why indoor RSP is always substantially lower than outdoors in an air-conditioned office, we looked at Equation 4. When $S = 0$:

$$\frac{C_\infty}{C_{\text{out}}} = \frac{[Q_{\text{f}}(1-N_{\text{f}}) + Q_{\text{if}}(n_{\text{if}})]}{VR} = \frac{[Q_{\text{f}}(1-N_{\text{f}}) + Q_{\text{if}}(n_{\text{if}})]}{Q_{\text{f}} + Q_{\text{if}} + Q_{\text{v}}N_{\text{v}} + K} \qquad (5)$$

In the above case where $N_{\text{f}} = 0$, $Q_{\text{f}} = 0.54\ \text{m}^3/\text{s}$, $N_{\text{v}} = 0.3$, $Q_{\text{v}} = 3.7\ \text{m}^3/\text{s}$, $Q_{\text{if}} = 0.027\ \text{m}^3/\text{s}$, $n_{\text{if}} = 0.8$ and assuming $K = 0$, C_∞/C_{out} is estimated to be 0.33 which is rather close to the field observation result of 0.28. The ratio of outdoor air volume flow Q_{f} to return air flow Q_{v} was about 1–7, the ratio of infiltration Q_{if} to Q_{f} was about 1–20. Particle gain from infiltration is one order of magnitude smaller than particle gain because of outdoor air supply which is one order of magnitude smaller than particle loss because of return air filtration. So it is to be expected that the value of C_∞/C_{out} would be about one-third in pre-filter fitted AHU systems and when no filter was placed at the outdoor air supply.

Another interesting point worth discussion concerns the difference between the estimated C_∞/C_{out} of 0.33 and the field observed C_∞/C_{out} of 0.28. If the difference was caused by K (deposition and other losses), then K would be 0.31 m^3/s. However when the same calculation was repeated for the second case in Figure 3 where a pre-filter was added to the outdoor air supply, K became −0.30. The average K for all eight cases in Figure 3 is almost zero and the standard deviation is 0.46 m^3/s.

Outdoor air fan equipped with a pre-filter/no filter while the filtration efficiency at the AHU air fan increased

The second experiment was to explore the potential improvement brought about by increasing the filtration efficiency on the return air. The right hand chart in Figure 4 shows the variation of C_∞/C_{out} under different return air filters while the pre-filter at the outdoor air fan remained unchanged. The left hand chart shows the variation of C_∞/C_{out} for different return air filters with no filter at the outdoor air fan. Bag filters could not be tested at the return air fan because of a technical difficulty. The air flow of the return air was between 3.3 and 3.7 m^3/s while the air flow of the outdoor air fan was about 0.5 m^3/s.

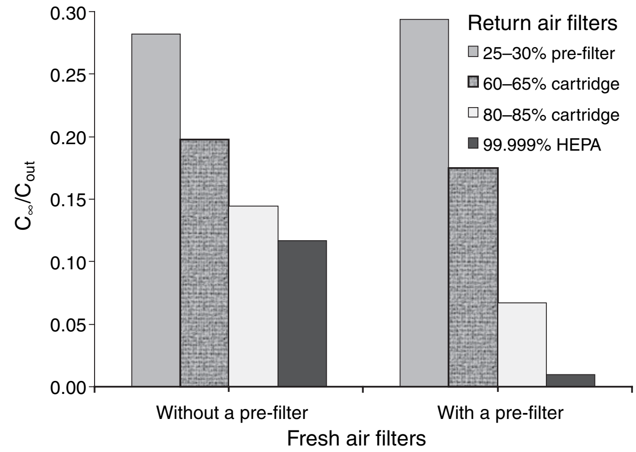

Fig. 4 The ratio of the steady state indoor RSP to the initial outdoor RSP (C_∞/C_{out}) under different return air filters (outdoor air filter = no filter and pre-filter)

The left hand chart in Figure 4 indicates that low level indoor RSP level could also be attained by the filtration of return air alone. The higher the filtration efficiency, the lower the C_∞/C_{out} ratio. When an HEPA filter was used C_∞/C_{out} was 0.12. For a hypothetical outdoor RSP level of 200 $\mu g/m^3$, the steady state indoor RSP C_∞ would be 24 $\mu g/m^3$ which means that the 'excellent' IAQ objective cannot be achieved on episode days even if the outdoor air is not treated. However, by simply adding a pre-filter to the outdoor air supply instead of no filter the C_∞/C_{out} ratio can be lowered substantially. This experiment leads to a practical recommendation. In cases where the removal of indoor RSP relies on return air filtration, adding a pre-filter to the outdoor air supply enhances the air cleaning performance considerably.

Filtration efficiency of AHU and the outdoor air fan both increased

The experiment continued to explore the improvement brought by various other return air/outdoor air filters combinations. Figure 5 shows the variation of C_∞/C_{out} for different outdoor air filters and different return air filters (Figures 3 and 4 are a subset of Figure 5). Figure 5 clearly indicates that outdoor air filters and return air filters both play a major role in the reduction of indoor RSP concentration. Increasing the filtration efficiency at outdoor air supply while the return air filters remain unchanged led to a lowering of indoor

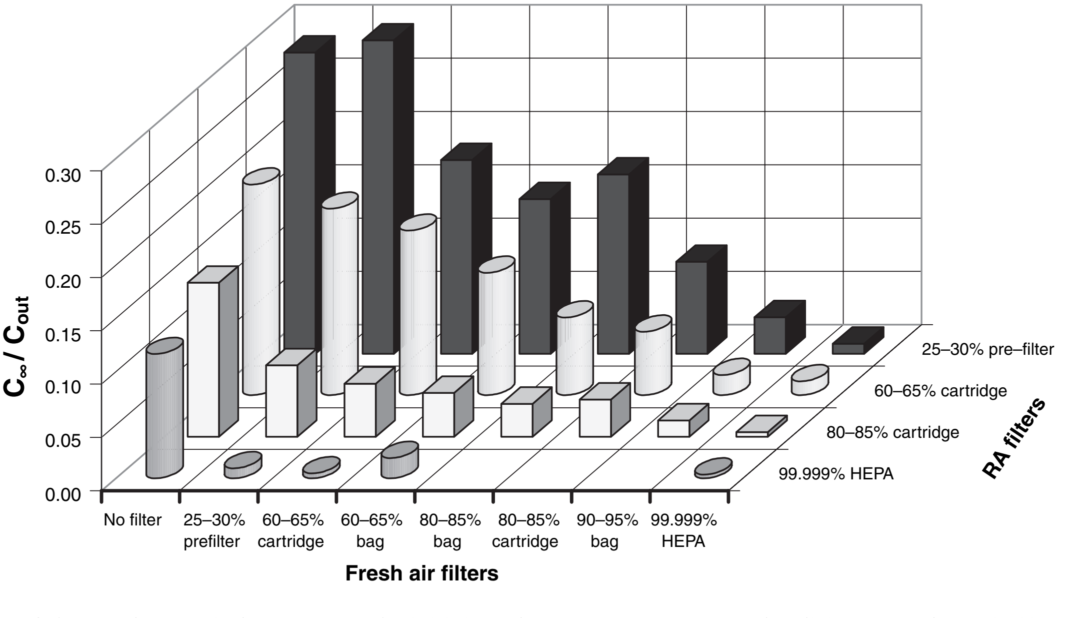

Fig. 5 The ratio of the steady state indoor RSP to the initial outdoor RSP (C_∞/C_{out}) under different outdoor air filters and different return air filters

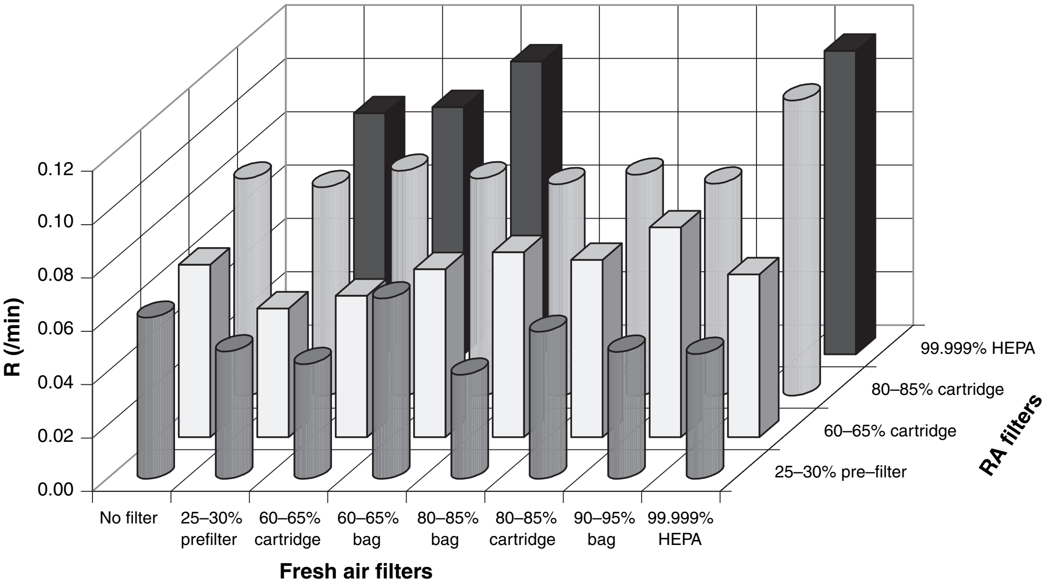

Fig. 6 The effective cleaning rate under different outdoor air filters and different return air filters

RSP level and vice versa. The maximum C_∞/C_{out} was about 0.3 when minimum RSP control was exercised at both fans. The C_∞/C_{out} dropped to zero when both fans were equipped with HEPA filters and the ventilation zone had become a clean room. For a hypothetical outdoor RSP level of 200 μg/m^3, the C_∞/C_{out} at 20 μg/m^3 RSP is 0.1. Figure 5 shows that quite many filter combinations could achieve values of $C_\infty/C_{\text{out}} < 0.1$. Thus the use of HEPA filters is sufficient but not necessary in this application. This is very encouraging as HEPA filters are much more expensive and inconvenient for daily electrical and mechanical (E&M) operations.

Effective cleaning rate

A good filtration system should have a high effective cleaning rate as well. From Equation 3, the slope of ln $[(C_t - C_\infty)/(C_0 - C_\infty)]$ vs. time *t* is *R* (Figure 2). The higher the effective cleaning rate *R*, the shorter time it takes for the indoor RSP level to reach C_∞. Figure 6 shows the effective cleaning rate *R* under different filter combinations. It can be seen that the outdoor air filters had no significant influence on *R*. There was no trend on each row where return air filter remained unchanged. But, *R* did increase when the return air filtration efficiency increased while the outdoor air filter remained unchanged. In general, *R* was governed by return air filtration.

Steady state indoor RSP levels C_∞ and effective cleaning time under three different scenarios

The next step was to study which filter combinations could achieve the 'excellent' IAQ in RSP terms. This means that the ventilation system has to bring C_∞ down below 20 μg/m^3 within 1 h. The reason for the 1 h time limit is because of office operations. Many commercial buildings in Hong Kong switch on the ventilation systems at 8:00 AM in the morning and switch off at 18:00 PM. Office hours are between 9:00 AM and 5:00 PM. So when C_∞ is below 20 μg/m^3 before 9:00 AM, the 8 h average during office hours will meet the 'excellent' IAQ objective.

Figure 5 shows the relative performance (C_∞/C_{out}) for different filter combinations in the control of indoor RSP levels (C_∞) but it cannot show whether the C_∞ is actually <20 μg/m^3. To compare the C_∞ values under different filter combinations, it is necessary to set a constant outdoor RSP level (C_{out}). Corresponding to the Air Quality in Hong Kong in 2000 (HKEPD, 2000), three representative outdoor RSP values (C_{out}) were chosen for this exercise. First, the highest 24-hr RSP average recorded in Hong Kong in the year 2000 was 208 μg/m^3. This figure represents a very polluted day and is taken as the worst scenario. Second, the annual RSP average recorded at Causeway Bay, a busy urban area, was 101 μg/m^3. This figure represents a normal day in Causeway Bay. Third, the overall annual RSP average for all stations in Hong Kong was 54 μg/m^3. This figure represents a fair situation in Hong Kong overall. Air quality in 2001 and 2002 has been noted also. As the 2001 and 2002 figures were slightly lower, the year 2000 figures are used. The C_∞ for different filter combinations under a constant C_{out} condition can be obtained by multiplying all C_∞/C_{out} values in Figure 5 by a selected C_{out}.

The time (*t*) required to reach the standard level (20 μg/m^3) is taken as the time between the start time of a case study ($t = 0$) and the time when *C* first reached 20 μg/m^3. *t* is given by:

$$t = \frac{\ln\left(\frac{20 - C_\infty}{C_0 - C_\infty}\right)}{R} \quad (6)$$

where R is the effective cleaning rate obtained in each case.

Case 1: control of indoor RSP for a fair situation in Hong Kong (outdoor RSP concentration = 54 $\mu g/m^3$). Figure 7 shows that all C_∞ values were $< 20\ \mu g/m^3$ including the cases when there was no outdoor air filter and only pre-filters were installed at the return air. As 54 $\mu g/m^3$ represents a fair situation for Hong Kong's outdoor air quality in RSP, it implies that 20 $\mu g/m^3$ could be achieved rather easily across the whole of Hong Kong when the outdoor air quality is good.

Table 2 shows that not all filter combinations could bring the C_∞ value below 20 $\mu g/m^3$ within 60 min. So the effective cleaning rate R is the determining parameter in this control exercise. As R is mainly controlled by the return air filter, the general practice of installing only pre-filter at return air (no outdoor air filter) could not achieve the 'excellent' IAQ objective in RSP terms even when the outdoor air quality is good. It is necessary to increase the filtration efficiency at both the AHU and outdoor air fans. A reasonable setting under this scenario is a 60–65% filter at the return air and a 60–65% filter at the outdoor air. It took about 50 min for this ventilation system to reach steady state.

Case 2: control of indoor RSP for Causeway Bay (outdoor RSP concentration = 101 $\mu g/m^3$). When outdoor RSP increased to 101 $\mu g/m^3$, not all cases in Figure 8 achieve a C_∞ value of $< 20\ \mu g/m^3$. When return air is cleaned by only pre-filters, the outdoor air supply must be controlled in order to meet the IAQ RSP objective Figure 8 shows that when the filtration efficiency of return air filters exceeded 60%, all C_∞ values were $< 20\ \mu g/m^3$ including the cases when there was no outdoor air filter.

Table 3 shows that cleaning time exceeded 60 min in more cases. So the effective cleaning rate R is the determining parameter again in this control exercise. It

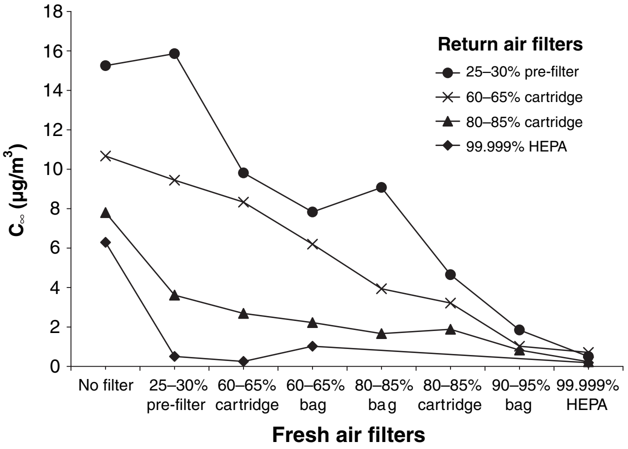

Fig. 7 The steady state indoor RSP concentration for different filter combinations when outdoor RSP is 54 $\mu g/m^3$

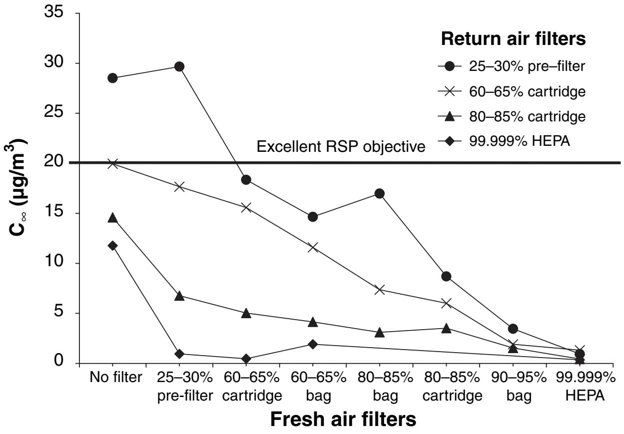

Fig. 8 The steady state indoor RSP concentration for different filter combinations when outdoor RSP is 101 $\mu g/m^3$

Table 2 The cleaning time t (in minutes) for different filter combinations when outdoor RSP is 54 $\mu g/m^3$

	Return air filters			
Outdoor air filters	25–30% pre-filter	60–65% cartridge	80–85% cartridge	99.999% HEPA
No filter	(61.3)	47.1	34.4	*
25–30% pre-filter	*	(60.7)	32.3	26.2
60–65% cartridge	(69.0)	53.5	29.3	25.4
60–65% bag	41.4	42.6	30.1	21.8
80–85% bag	(74.4)	36.6	30.5	*
80–85% cartridge	46.9	37.6	29.3	*
90–95% bag	51.1	30.8	29.9	*
99.999% HEPA	50.5	33.6	21.3	20.7

*Represents no data and numbers in parentheses represent cases that cannot meet the 'excellent' class (>60 min).

Table 3 The cleaning time t (in minutes) for different filter combinations when outdoor RSP is 101 $\mu g/m^3$

	Return air filters			
Outdoor air filters	25–30% pre-filter	60–65% cartridge	80–85% cartridge	99.999% HEPA
No filter	#	(129.8)	43.9	*
25–30% pre-filter	#	(91.0)	34.8	26.4
60–65% cartridge	(110.3)	(71.1)	30.9	25.5
60–65% bag	53.0	50.0	31.4	22.2
80–85% bag	(106.2)	39.8	31.5	*
80–85% cartridge	52.1	40.1	30.4	*
90–95% bag	52.9	31.4	30.4	*
99.999% HEPA	50.9	34.0	21.3	20.7

*Represents no data, # represents $C_\infty > 20\ \mu g/m^3$. Equation (6) has no solution, and numbers in parentheses represent cases that cannot meet the 'excellent' class (>60 min).

is necessary to control both the filtration efficiency of the return air and outdoor air. The reasonable setting for case 1 (60–65% filter for return air and 60–65% filter for outdoor air) still applies for this case. It took about 50 min for this ventilation system to reach steady state. As 101 μg/m^3 represents the general RSP level in Causeway Bay, it implies that the minimal RSP control effort can not achieve the 'excellent' IAQ level in downtown areas. Both the return air and outdoor air have to be treated to maintain a low indoor RSP level.

Case 3: control of indoor RSP for very polluted days (outdoor RSP concentration = 208 μg/m^3). When outdoor RSP increased to 208 μg/m^3, there were many more cases of C_∞ values exceeding 20 μg/m^3. On episode days, when there was no filter in outdoor air supply, all C_∞ values exceeded 20 μg/m^3 and C_∞ values could never reach the 'excellent' IAQ objective. When a return air was fitted with only pre-filters, C_∞ could not reach the 'excellent' IAQ objective unless the outdoor air supply filtration efficiency exceeded 80%. Therefore, to make C_∞ lower than 20 μg/m^3 under this scenario, filters with efficiencies exceeding 80% have to be used either at the return air or at the outdoor air.

As for cleaning time, Table 4 shows that apart from the use of HEPA filters, several non-HEPA combinations could also meet the 'excellent' IAQ objective. When only pre-filters were used in return air, 90–95% or better outdoor air filters could achieve the objective. When 60–65% filters were used in return air, 80–85% or better outdoor air filters were needed. When 80–85% filters were used in the return air, pre-filters for the outdoor air were adequate. The minimal setting for cases 1 and 2 (60–65% filter in return air fan and 60–65% filter in outdoor air fan) was not sufficient for this case.

As 208 μg/m^3 represents a very polluted outdoor environment, three filter settings can be recommended and all three options could achieve the 'excellent' IAQ objectives in RSP.

- pre-filters at return air and 90–95% filter at outdoor air,
- 60–90% filters at return air and 60–90% filters at outdoor air,
- HEPA filters either at return air or outdoor air. When an HEPA filter is used on the outdoor air side, a pre-filter must be used on return air side and vice versa.

Table 4 The cleaning time t (in minutes) for different filter combinations when outdoor RSP is 208 μg/m^3

	Return air filters			
Outdoor air filters	25–30% pre-filter	60–65% cartridge	80–85% cartridge	99.999% HEPA
No filter	#	#	#	#
25–30% pre-filter	#	#	44.3	27.0
60–65% cartridge	#	#	35.8	25.8
60–65% bag	#	#	35.1	23.2
80–85% bag	#	53.1	34.0	*
80–85% cartridge	(81.9)	48.8	33.3	*
90–95% bag	57.7	32.8	31.4	*
99.999% HEPA	52.0	35.0	21.5	20.9

*Represents no data, # represents C_∞ >20 μg/m^3. Equation (6) has no solution, and numbers in parentheses represent cases that cannot meet the 'excellent' class (>60 min).

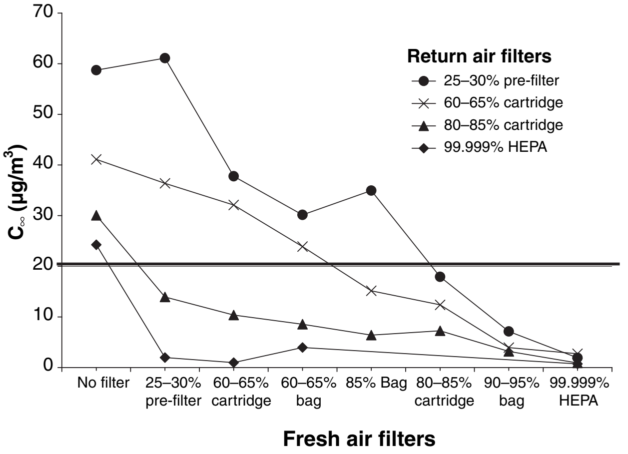

Fig. 9 The steady state indoor RSP concentration for different filter combinations when outdoor RSP is 208 μg/m^3

The results of Figure 9 and Table 4 imply that the 'excellent' IAQ objective could still be met even an episode days without the use of HEPA filters. The use of high efficiency filters (60–90%) was adequate to maintain a very clean indoor office environment.

When the outdoor environment is laden with RSP, to achieve a clean indoor environment, it is important to remove RSP from the outdoor air supply before the air enters indoors. This experiment has revealed that this is not a sufficient condition. It is the AHU air filters that govern the effective cleaning rate. Thus, both the outdoor air filter and return air filters are important. It is necessary to control both the filtration efficiency at the return air and outdoor air supply. Most of the existing AHU air fans are equipped with a filter compartment. No modification work is necessary for the installation of 80% return air filters. The difficulty lies in the control of outdoor air.

Static drop and flow at return air

The replacement of pre-filters in existing ventilation systems by higher efficiency filters will no doubt induce a higher static drop and lower the volume flow. This might affect the indoor comfort level. The static drop and flow rate of the AHU air fan for different filters are shown in Figure 10. It can be seen that higher efficiency filters have a higher static drop. The static drop of a pre-filter was small whereas the 60–90% filters were similar to each other. The HEPA filter had the highest

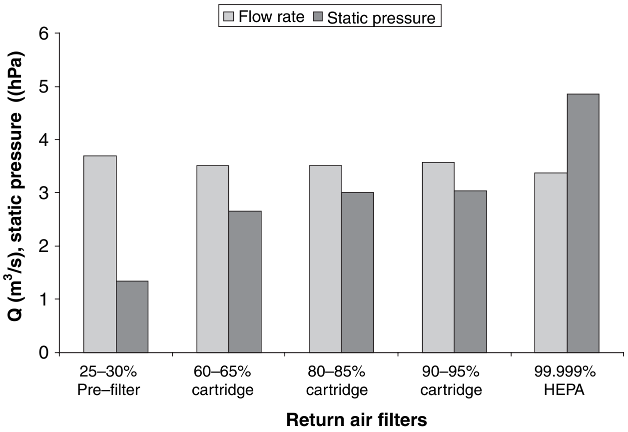

Fig. 10 Static drop and flow rate of return air when different filters were installed

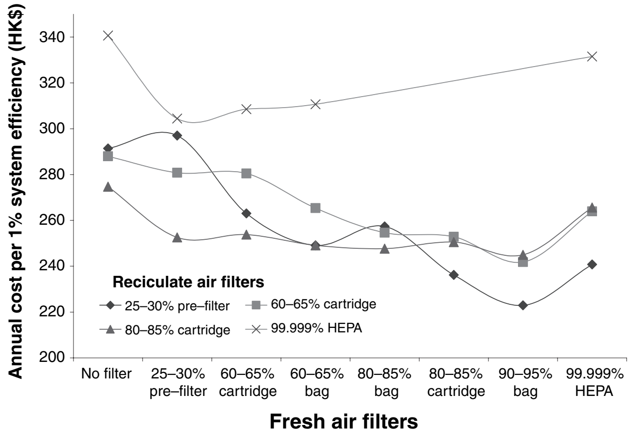

Fig. 11 Comparison of the total annual cost per 1% system efficiency under different filter combinations

static drop which was about five times that of a pre-filter. Surprisingly, the AHU air fan showed great tolerance to the increase in static drop. The volume flow only slightly decreased. The psychometric design of the ventilation system was not affected. This probably is because of the high static drop of the entire supply air ducting system.

Cost analysis

Economics considerations are one key to determining the feasibility of such ventilation systems. A straight forward methodology is to compute the sum of the electricity consumption and the filter costs and compare the totals for different filter combinations. However, this method does not account for the benefit incurred as a result of higher costs. Instead, a normalized cost per 1% system efficiency ψ is introduced to evaluate the total cost consumed for different filter designs.

$$\text{Cost per 1\% system efficiency} = \psi = \frac{\text{Total cost}}{\left(1 - \frac{C_{\text{steady}}}{C_{\text{out}}}\right) \times 100\%} \tag{7}$$

Total cost includes the capital cost of the AHU air fan and the outdoor air fan, the electricity cost and the cost of filters. The capital costs of the two fans were provided by the management office. The electricity consumptions of the two fans were recorded in all cases during the test using two power meters. The costs of the filters have been listed in Table 1. All filters are assumed to last 6 months.

Figure 11 shows the normalized cost ψ for different filter combinations. It is no surprise that installation of an HEPA filter at the return air (the top line) is the most uneconomical option because the HEPA filter cost is more than five times that of the other filters. Although it did make the indoor environment super clean, the gain in system efficiency by using an HEPA filter could not offset the increase in total cost. On the low efficiency side, using only pre-filters was also not an economical option. It is true that the total cost is the lowest but the low system efficiency associated with this option offset its cost benefit which is reflect by a high ψ. It came out that the most economical filter setting was to install pre-filters at return air and a 90–95% bag filter at the outdoor air. Figure 9 and Table 4 show that this filter combination can still achieve the 'excellent' IAQ objective under a very polluted exteriors air scenario. Other filter combinations that involve the use of cartridge or bag filters with filter efficiencies $>60\%$ were also good choices. Both the performance and cost of 60–65%/80–80% at return air and 60–65%/80–80% at outdoor air are not much different.

The additional cost incurred by the installation of better filters did increase the operational cost because new outdoor air fans are needed, better filters cost more and electricity consumption is increased because of higher static drop. If we adopt the 60–90% outdoor air/60–90% return air combination, the increase in total cost is $<5\%$ of the existing operational cost.

Limitation of this study

There are several limitations in this experiment. First, the indoor RSP emission sources were assumed negligible in the test zone. This assumption is generally valid in a non-smoking office environment (Koponen et al., 2001). In practice, shopping centers and restaurants do have significant RSP sources. Second, the ingression of outdoor air in the zone was fully controlled by sealing off all possible infiltration paths such as lifts, staircases and rescue doors. This procedure enabled the filtration efficiency of outdoor air supply to be measured accurately. In practice, control of the ingress of outdoor air in a commercial building requires much experience. Third, a background natural ventilation of 0.07 air changes per hour remained (obtained from SF_6 tracer gas technology). This represents the infiltration through window gaps and wall leakages. For Tung et al., 1999b estimated the dust penetration coefficient through an office building shell varied between 0.69 and 0.86. For one air change per hour, the error in RSP estimation because of building leakage would not exceed 6%. Fourth, although the effective cleaning rate R obtained in this experiment should be dominated by the outdoor air and the return air filtration, it did include surface deposition and duct loss (Nazaroff and Cass, 1989). Nevertheless, this experiment dealt with the actual decay time and thus the objective of this study was not undermined. Fifth, the test zone had no partitions. The indoor air flow was only obstructed by a few columns. In real life, the ventilation zone would likely be partitioned by walls which alter the flow pattern and the effective ventilation volume. Sixth, the lifetime of the filters was not tested.

Conclusion

It is feasible to achieve 'excellent' IAQ RSP levels in existing commercial buildings in Hong Kong. In buildings where the outdoor air supply is well defined and could be filtered, the 'excellent' IAQ RSP objective could be achieved by the following filter provisions: (i) pre-filters at return air and 90–95% filter at outdoor air, (ii) 60–90% filters at return air and 60–90% filters at outdoor air, (iii) HEPA filters either at return air or outdoor air. When an HEPA filter is used on the outdoor air side, a pre-filter must be used on the return air side and vice versa. An HEPA filter is not an economical option, so it is not necessary to install HEPA filters if outdoor air supply can be identified, isolated and controlled. For options (i) and (ii), the additional cost incurred by the installation of better filters was $<5\%$ of the existing operational cost. In buildings where outdoor air supply is not well defined, it is necessary to install additional outdoor air supply fans to regain control. HEPA filters might be needed in this case. The static drop of the AHU air fan will increase but the flow rate will not change significantly. The indoor comfort will not be compromised.

The outdoor air filters had great influence on the steady state indoor RSP level (C_∞) whereas the return air filters governed the effective cleaning rate (R). When indoor emission sources are small, good filters at the outdoor air intake are adequate. When indoor emissions are substantial, good filters at the return air are essential.

It is believed that the findings of this study could be extrapolated to the control of indoor TVOC. However, there are always significant indoor TVOC emissions. The control of indoor TVOC depends on whether a 80% or better TVOC scrubber is available and whether this scrubber could be connected to the existing return air.

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