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# Performance evaluation of filter applications in fan-coil units during the 2015 Southeast Asian haze episode

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ABSTRACT

Fan-coil units (FCUs) see wide applications in buildings but few are integrated with high-quality filters for efficient particle removal. Driven by an attempt to protect the indoor space served by FCUs from elevated outdoor PM concentrations (e.g. periodic haze events in Southeast Asia), four different grades of filters (dust-spot efficiencies of 25%, 65%, 85% and 95%, denoted as $F_{25}$, $F_{65}$, $F_{85}$, and $F_{95}$ hereafter) were installed inside the cassette FCUs respectively in four similar rooms. Air exchange was controlled by the recirculation fans in FCUs and exfiltration via door gaps. Performance of the filters was evaluated through continuous monitoring of particle number concentrations. Energy consumption and noise levels were also recorded via field measurements. The overall particle removal efficiencies (via filter-integrated FCUs) generally increased with higher filter grades; however, $F_{95}$ didn't provide a significant improvement over $F_{85}$. Upgrading from $F_{25}$ to $F_{85}$ or $F_{95}$ decreased the size-resolved particle I/O ratios significantly (from 0.19 to 0.65 to 0.06–0.24 depending on the particle sizes). Installation of $F_{85}$ or $F_{95}$ alone was not sufficient to reduce the indoor $PM_{2.5}$ concentrations to the WHO guideline of 25 μg $m^{-3}$ under moderate and heavy haze scenarios. $F_{85}$ resulted in the lowest energy consumption in terms of chilled water energy and FCU electricity combined. $F_{95}$ application led to the highest noise level at ~46.6 dBA. The study advances the knowledge of particle attenuation effects by the FCU with different grades of filters and provides a basis for filter selection against compromised outdoor conditions in similar settings.



## 1. Introduction

Recurrent transboundary haze due to biomass burning has raised significant public concerns in Southeast Asia because of the potential health risks such as cardiopulmonary and carcinogenic diseases [1–3]. For ventilated buildings, outdoor particles transport into indoor environments mainly through the mechanical ventilation systems [4]. Indoor PM exposure may account for a large proportion of total exposure as people spend the majority of their time indoors, especially during the haze episode [5,6]. Singapore government suggests using HEPA filters for stand-alone air purifiers or at least MERV 13 for centralized mechanical ventilation systems during the haze episode [7,8]. However, space served by ceiling cassette fan-coil units (FCUs) is often not considered despite their popularity in small-scale indoor environments (such as rooms, small offices, canteens, retail stores, etc.). This is partially due to a lack of performance-based information on indoor air quality in fan-coil space during haze episodes, calling for the advancement of knowledge on this topic.

The extent of particle concentration reduction indoors largely relies on air filtration and ventilation. Filters with higher filtration efficiency can provide better PM removal in a single pass, but they may also entail issues such as reduced recirculation airflows and higher pressure drops. Furthermore, factors such as airflow rates may affect the in-situ filter efficiency [9,10], compromising the superiority of high-grade filters. Several studies have reported in-situ efficiencies of filters, but mostly in central HVAC office buildings [11–13]. Very limited information is available in fan-coil indoor environments, although FCUs are common. In addition, possibly high pressure drops with high-grade filters may result in elevated energy consumption. As energy efficiency has attracted more attentions in building design and operation, understanding of the energy impacts from filters is essential. Current energy assessment is mostly accomplished using simulation models [14–16], but the results may not fully represent those in practice due to: 1) direct

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usage of manufacturers' filter testing parameters without considering variations of these parameters in practice; 2) simplified assumptions on ventilation parameters and site characteristics which are inter-linked. Some studies have conducted field measurements to reveal impacts from low-efficiency and high-efficiency filters in rooftop units [17], residential homes and commercial buildings [18,19]. While those studies have provided some insights into the filter-energy relationships, the results cannot simply be applied to FCU systems given the system differences. It is beneficial to investigate the impacts on FCU systems based on field measurements.

Given the discussions above, the purpose of this study is to evaluate four different grades of filters installed in cassette FCUs and compare their capabilities to protect indoor environments from outdoor PM pollution. The evaluation was conducted during a haze event through 1) characterizing in-situ particle removal efficiencies of filters in FCUs; 2) quantifying particle I/O ratios in the fan-coil rooms; 3) quantifying indoor concentration levels of fine particles of outdoor origin with different grades of filters. Further assessment includes energy consumption and noise levels associated with filter installation. The study will supplement knowledge about fan-coil indoor environments and provide the rationale for filter selection during outdoor PM pollution events.

## 2. Material and methods

### 2.1. Site characteristics

The study was conducted at Nanyang Technological University (NTU) in Sep 2015 during a haze event. Five neighboring classrooms with similar dimensions, furnishing and interior layouts were selected (denoted as room A-E). The rooms are 9 m above ground facing north in an academic building, and accessible from an open corridor. The building is 50–80 m away from two main roads to its north and west with low traffic volume. Each room has a size of 8.0 m × 7.5 m × 2.75 m (L × W × H) and is equipped with two compact multi-flow (4-way) ceiling mounted cassette FCUs (DAIKIN model FWMJC8AV1). Every FCU has one ducting for fresh air intake but no return. Fresh air intakes are located at exterior corners of the rooms, facing north as well. The ducting has no filter installed and no boosting fan, so the fresh air intake simply relies on suction by the fan in the FCU and exfiltration through door gaps. The rooms have no windows and are slightly pressurized when the FCUs are operating. Indoor air leaks to the outdoors mainly through door gaps. There is no obvious particle source in the rooms.

### 2.2. Study design

Room A, without intervention, served as the control of this study. Four different grades of filters (dust-spot efficiencies at 25%, 65%, 85% and 95%) were installed inside the return grilles of FCUs in rooms B to E, respectively. The filters, made of synthetic fibre, were new at installation. They were flat filters with thickness of 1 mm for the 25% grade, 3 mm for the 65% grade, 4 mm for the 85% grade and 5 mm for the 95% grade. The filter was cut according to the dimensions of the mesh frame and then carefully locked back to the return grille of the FCU. In the following content, we will refer to these filters as $F_{25}$, $F_{65}$, $F_{85}$ and $F_{95}$. Table 1 presents the approximate MERV ratings and also the reference particle removal efficiencies of these filters according to ASHRAE standard 52.2 [20]. $E_1$ is the average of minimum efficiencies for the particle-size groups of 0.3–0.4 μm, 0.4–0.55 μm, 0.55–0.7 μm and 0.7–1.0 μm [20]. And the groups for $E_2$ are 1.0–1.3 μm, 1.3–1.6 μm, 1.6–2.2 μm and 2.2–3.0 μm [20].

**Table 1**
MERV ratings and specific $E_1$ and $E_2$ efficiency ranges of the filters according to ASHRAE standard 52.2 [20].

| Room ID | Filter application grade | | Ref. Particle removal efficiency | |
|---|---|---|---|---|
| | Efficiency | Rating | $E_1$(0.3–1.0 μm) | $E_2$(1.0–3.0 μm) |
| A | N.A. | N.A. | N.A. | N.A. |
| B | 25% | MERV 7 | N.A. | N.A. |
| C | 65% | MERV 11 | N.A. | 65-80% |
| D | 85% | MERV 13 | <75% | ≥90% |
| E | 95% | MERV 14 | 75-85% | ≥90% |

### 2.3. Room ventilation and airflows

Given the same airflow path through two FCUs in each room, Fig. 1 displays a simplified schematic diagram of the ventilation system and the airflow path by showing only one FCU. As shown in Fig. 1, the fan draws recirculation airflow up through the installed filters (applicable to rooms B-E). Filtered recirculation air mixes with fresh air and the mixture is cooled and dehumidified by the coil before resupplying back to the rooms. Exfiltration mainly takes place through the existing door gaps.

### 2.4. Instruments and quality control

We used Optical Particle Counters (OPC, model 9306 and 8220, TSI Inc., USA) and an Optical Particle Sizer (OPS, model 3330, TSI Inc., USA) to measure indoor and outdoor particle number concentrations (PNCs) at time intervals of 2 min. Each room had one unit of OPC or OPS at about 1 m above the floor. One unit was placed in the open corridor outside of the rooms at a similar height for ambient particle measurements. The measurement location was selected to avoid the direct airflows from the FCUs and was near the center of the room. Figure S1 in the Supporting Information shows a diagram illustrating the room with the sampling location. The monitoring campaign lasted from Sep 17 to Sep 25. We adjusted all the FCUs to the continuous operation mode and fixed the flow speed with the temperature setting at 24 °C.

Our study focuses on the fine particles (0.3–2.5 μm) because of the domination of particles in this range during haze episodes [1] and their association with various health concerns. Since the OPS and OPCs have different sizing cut points, disaggregation and merging of data are necessary prior to further analysis. Details of this process have been described by Zhou et al. [21] and the summary is presented as Figure S2 in the Supporting Information.

For quality control, we performed side-by-side collocation of OPCs and the OPS in an air-conditioned indoor environment for

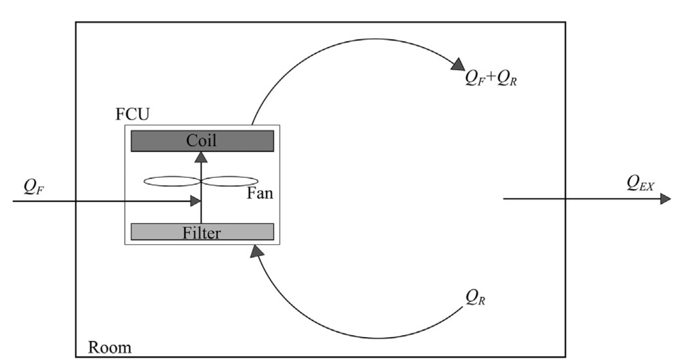


**Fig. 1.** Schematic diagram of the FCU system and the airflow path in the rooms. An FCU mainly contains a coil and a fan. Filters apply to rooms B-E. $Q_F$, $Q_R$ and $Q_{EX}$ represent the flow rates of fresh air, recirculation air and exfiltration, respectively.