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Mitigating particulate matter exposure in naturally ventilated buildings during haze episodes

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ABSTRACT

The effectiveness of a low energy fan-filter unit (FFU) in mitigating human exposure to airborne particulate matter (PM) during haze episodes in a naturally ventilated hostel room is presented. The study adopts a case-reference method by conducting a series of field tests in a test room equipped with FFU and in a reference room with no FFU. PM concentrations were monitored simultaneously indoors and outdoors; including mass concentrations of PM_{10}, $PM_{2.5}$ and PM_1 as well as differential number concentrations of particles ranging from 0.35 μm to 12.5 μm. On average the FFU system reduced PM_{10}, $PM_{2.5}$, and PM_1 particle concentrations by 80.9%, 80.4% and 78.5% respectively inside the test room relative to ambient air concentrations on a real-time comparison basis. The use of FFU operating with a MERV 13 filter during haze episodes is also effective in reducing human exposure to PM-bound toxic trace elements (TrElems) in naturally ventilated indoor environments. The majority of the TrElems (As, Be, Cd, Co, Cr, Ni, Pb, Mn, Zn and Cu) were reduced indoors with I/O ratio of much less than 1. Additionally, FFU demonstrates slight alleviation of thermal discomfort compared to the reference room (whose windows and doors were closed to prevent penetration of haze particles) and achieves thermal conditions within the 80%–90% in the adaptive thermal comfort zone described in ASHRAE Standard 55–2013. The improved thermal conditions with FFU is attributable to provision of increased air exchange (ACH of 4.1 h^{-1}) to displace the indoor generated heat and moisture.

1. Introduction

Transboundary smoke haze episodes originating from forest fires and peat land burning have been a frequent occurrence in South-East Asia resulting in adverse effects on human health due to exposure to PM in elevated concentrations [1–8]. Singapore is much affected by recurrent smoke haze due to biomass burning emissions from the neighboring countries [4,6]. In 2013, a new record for air pollution was set in Singapore when the Pollutant Standards Index (PSI) reached 401. PSI is an indicator of ambient air quality, estimated by the concentrations of six criteria air pollutants (SO_2, NO_2, O_3, CO, $PM_{2.5}$ and PM_{10}); PM_{10} and $PM_{2.5}$ refer to PM with aerodynamic diameter ((AD) ≤ 10 μm) and ≤2.5 μm respectively. The ambient $PM_{2.5}$ levels in Singapore are usually in the range of 10–25 μg m^{-3} during non-haze period [5–7]; however, the 24 h average $PM_{2.5}$ concentration reached 310 μg m^{-3} on June 20, 2013 while on October 20, 2015 the 1 h $PM_{2.5}$ concentration reached 442 μg m^{-3}. The PM_{10} and PM_1 (PM with AD ≤ 1 μm) levels were also reported higher during haze episodes (i.e. > 300 μg m^{-3}) [5–7]. Particles smaller than 2.5 μm can reach the alveoli and lead to pulmonary and other health complications [9–11]. Elevated exposure to smoke haze has been associated with a significant rise in patients with complaints related to rhinitis, asthma and respiratory problems in Singapore during the 1997, 2013 and 2015 haze episodes [4,5,8]. Residents with prevailing respiratory or cardiovascular complications are susceptible to aggravated conditions attributable to PM exposure [12–14]. Although the WHO guidelines did not mention $PM_{1.0}$, several studies implicated the adverse mortality and morbidity effects of exposure to $PM_{1.0}$. In a Childhood Asthma Management Program (CAMP) study, Yu et al. [15] reported the population average estimates indicated an 18% (95% CI, 5–33%) increase in the odds of asthma symptoms for a 10 μg m^{-3} increment in same-day particulate matter < 1.0 μm ($PM_{1.0}$). Chan et al. [16] reported that increased exposure to $PM_{1.0}$ affects heart rate variability (HRV) in both the elderly with lung function impairment as well as healthy young adults, and suggested that sub-micron particles are an environmental stressor which can disturb the autonomic function. Thus, exposure reduction efficiency for smaller size particles is very important.

Exposure to harmful PM containing trace elements (TrElems) causes

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additional serious health effects [17,18]. Exposure to TrElems leads to oxidative stress. Several PM-bound TrElems such as Co, Pb, Cr, As, Zn, Ni, Cu, Cd, V and Mn are toxicants for the cardiorespiratory system [17–20]. The study by Sorensen et al. [21] highlighted that V and Cr triggers sever oxidative stress and increases risk for DNA damage. Further, Ghio et al. [22] highlighted the risk of neutrophilic lung inflammation and increased levels of blood fibrinogen resulting from exposure to Fe, As, Se, Cu, Zn, V and Ni. Ostro et al. [23] described the relation between traffic markers (sulfate, Mn, Ti, V, Cu, Ca, Fe, Cl, Pb and Zn) and cardiovascular short-term mortality. International Agency for Research on Cancer (IARC) has classified heavy metals e.g. Cr, Cd, Ni and As as carcinogenic elements [24]. > Some previous studies have measured indoor PM concentrations in naturally ventilated and air-conditioned premises during haze [6,7,25]. A study by Lim et al. [26] reported both the indoor and outdoor status of $PM_{2.5}$ and associated TrElems. Other works analyzed the fractionation of PM-bound elements [27–29] or estimated the airway deposition of size-resolved PM-bound trace elements [30]; however, these studies did not explore the mitigation strategies to alleviate indoor exposure.

During haze episodes, penetration of haze particles indoors presents a formidable challenge to the health of building occupants, given that the majority of naturally ventilated premises has not been adequately designed to mitigate against their penetration [6]. As outdoor haze becomes severe with increased concentrations of PM, building openings such as doors and windows are kept closed to prevent the ingress of haze particles, seriously compromising thermal comfort and the dilution of indoor generated pollutants, including human bio-effluents and indoor emissions. Overall, comprehensive data on the effectiveness of air filtration solutions in reducing PM in terms of both mass concentration and number concentration, PM-bound toxic species and dealing with thermal comfort performance during haze episode are currently lacking in the literature.

The effective mitigation of penetration of haze particles from the outdoor environment should not be at the expense of other human requirements which include acceptable thermal comfort and indoor air quality. For naturally ventilated premises, relying on the closure of doors and windows may not effectively prevent PM-laden infiltration. Pressurization has the added advantage of achieving requisite ventilation and flushing of indoor contaminants, and removing human generated bio-effluents and moisture. The removal of moisture for alleviation of thermal discomfort is an important consideration in tropical climates.

This research adopts a case-reference study of a recently developed fan-filter unit (FFU) that incorporates these strategies. It evaluates the performance of the FFU when deployed in naturally ventilated premises during a haze episode.

2. Need for FFU technology for naturally ventilated premises during haze episodes

A modern air-conditioning and mechanical ventilation (ACMV) system is considered a valuable solution in reducing the exposure to PM and improving indoor air quality and attaining adequate thermal comfort in naturally ventilated buildings (such as homes, schools, etc.) [7]. However, the main drawback of all ACMV systems is that they are energy-intensive, contribute to greenhouse gas emissions and incur high capital and operating costs. Even if this is provided for use during the occurrence of a haze episode, filtration of an appropriate efficiency has to be implemented and maintained; furthermore, if the intent is to operate the premises as naturally ventilated, its provision contradicts this purpose, and is also not economically justifiable as a strategy that is invoked only during haze episodes.

A commonly adopted solution for removing indoor air contaminants which is simple and less expensive is the portable air purifier/cleaner [31–35]. Air purifiers are considered to be useful to individuals during high haze levels, especially those suffering from chronic respiratory problems. Portable air cleaners have some drawbacks such as: (1) limited effective radius (distance) as their effectiveness depends primarily on its clean air delivery rate (CADR) and the volume of room covered; (2) lack of ventilation; (3) does not prevent infiltration of outdoor PM; and (4) heat and moisture build-up is not removed leading to continual worsening of thermal comfort conditions.

We have designed a FFU, adopting low energy ventilation for achieving adequate indoor environmental conditions during haze episodes. The FFU system uses a variety of strategies to keep the air inside naturally ventilated environments clean, fresh and alleviates thermal discomfort:

1. Source control of penetration of outdoor airborne haze particles at the building façade level;
2. Pressurization to prevent infiltration of outdoor airborne haze particles;
3. High efficiency filtration of outdoor airborne haze particles to achieve acceptable indoor PM level within a reasonably short time duration;
4. Ventilation to dilute and expel human bio-effluents; and
5. Ventilation to alleviate adverse thermal discomfort.

As a low energy strategy, the FFU is not meant to achieve "air-conditioning type" thermal comfort as this requires sensible and latent cooling for tropical climates. It is hypothesized that the FFU mitigates against haze, whilst alleviating thermal discomfort and removing occupant generated bio-effluents. Being visible, the FFU achieves an important psychological assurance of continual ventilation. At the same time, the FFU overcomes limitations of other air-cleaning equipment that can be used during haze episodes [36].

3. Methodology

3.1. Experimental design and procedure

Field experiments were conducted in a pair of adjacent rooms within the same naturally ventilated apartment during the severe haze episode in October 2015. The apartment is located on the third-storey of a residential hostel block at the National University of Singapore. The dimensions of the test room where the FFU was mounted are 2.4 × 3.7 × 2.7 m, with a room volume of 24 m^3 and located at the corner of the apartment block. The test room is chosen as it is likely to have a greater exposure to haze particles with two exposed external walls. The adjacent room (24 m^3) was used as a reference room (without FFU) and operated with its windows closed and ceiling fans in operation during the haze episode. The furniture comprises a bookshelf, a large table and a bed. A detailed schematic of the hostel room layout is shown in Fig. 1. As the room was unoccupied, the furniture layout remained constant for the entire study.

The FFU was mounted onto the wooden frame and fitted onto the window opening as shown in Fig. 2a. The schematic of FFU designed in a push-through configuration with the MERV (Minimum Efficiency Reporting Value) 13 filter located downstream of the fan in the fan chamber is shown in Fig. 2b. The fan is selected with appropriate static pressure and flow rate characteristics to achieve adequate ACH in a hostel room. The fan used in the FFU system is a 250 mm diameter axial fan (50 Hz). The fan speed is kept constant around 1250 RPM (which achieves a flow rate of 735CFM); the fan unit consumes 47 W; and the noise level was no more than 39 dBA. The dimensions of the MERV 13 filter tested for FFU experimental studies were 300 mm × 300 mm × 25 mm. The gaps between the frame of the FFU and the window frame were sealed with a duct tape to prevent any air leak. Additionally, an incandescent bulb (60 W) was used to simulate the sensible heat gain from an occupant in the hostel room; a wet towel was placed at the center of the room to act as a source of moisture to simulate an occupant's latent load. Monitoring equipment was placed at