A CASE STUDY OF VENTILATION IMPACTS ON PARTICLE CONCENTRATION IN AIR-CONDITIONED SPACE LOCATED IN DESERT CLIMATE

Moshood Olawale Fadeyi, Assistant Professor, fadeyi.olawale@buid.ac.ae
Faculty of Engineering & IT, British University in Dubai, P.O. Box, 345015, Dubai, UAE

ABSTRACT

There are evidences suggesting that outdoor to indoor transport of particulate matter (PM) via ventilation mandated by regulatory requirements on minimum outdoor air provisions may have adverse health impacts on indoor occupants. This present study was conducted in an air-conditioned space with ventilation air system design typical to the United Arab Emirates (UAE). It examines the impact of ventilation on indoor particle number and mass, and size distribution concentrations, in region with outdoor environment potentially polluted with PM. Measured indoor particle concentrations were observed to be considerably higher when ventilation (with 2 ACH) mode was "on" than when it was "off", but still having infiltration rate of 1ACH. During the period when ventilation mode was 'on', sandstorm event further compromised the benefit of using ventilation to reduce concentration of pollutant generated from indoor space. This study is important because of its relevance to building sustainability vis-à-vis health and comfort of building occupants.

Keywords: Particulate matter, indoor environment and health, mechanical ventilation system, filtration, sandstorm

1. INTRODUCTION

Increase in ventilation rate has been associated with improved perceived air quality (Nordstrom et al. 1995; Seppanen and Fisk, 1999; Wargocki et al. 2000, 2002, 2004), and reduction of sick building syndrome (SBS) symptom intensity (Wargocki et al. 2000; Seppanen and Fisk, 2002). This improvement usually leads to increase in performance and productivity (Wargocki et al. 2000; Wargocki et al. 2004, Tham et al. 2003), and reduction in absenteeism (Milton et al. 2000; Fisk et al. 2003) at workplaces. However, there are contradictory evidences suggesting that ventilation could also cause poor perceived air quality and increase SBS symptoms intensity. Increase in ventilation rates can significantly increase prevalence of SBS symptoms (Jaakkola et al. 1994; Jakkola and Miettinen, 1995; Nordstrom et al. 1995). Seppanen and Fisk (2004) attributed negative effects of ventilation on indoor environment and health to poor design, installation, and maintenance and operation of ventilation air system. Such negligence may result in ventilation transporting polluted outdoor air into indoor environment.

In the UAE, outdoor to indoor transport of PM is of particular concern due to the desert nature of the region. Despite this, ventilation filters that can effectively mitigate threat posed by ventilation are not usually used. In the UAE, ventilation filter usage is mostly driven by consideration for PM_{10} and not $PM_{2.5}$. In most commercial buildings, outdoor air are usually treated with E4 rated wire mesh filter having maximum efficiency rating of ~30-40% and E7 rated bag filter with maximum efficiency rating of ~85% before being mixed with recirculated air. The supply air, which contains treated outdoor air (OA) mixed with recirculated air (R_rA) are usually treated with only E4 rated wire mesh filter. In some instances, outdoor air will not be treated before being mixed with recirculated air. In such instances, the only available E4 rating wire mesh filter in the fan coil unit is usually used to treat the supply air ($OA+R_rA$).

Such practice is common in residential and school buildings. Thus, it is not surprising that considerable amount of settled fine and coarse PM are usually found on indoor surfaces and equipment/materials, even those that are used on regular basis, of UAE air-conditioned building. This usual observation suggests considerable amount of PM may be settling on UAE building occupants' respiratory tracts. In addition to SBS symptoms (such coughing, runny nose, sore throat) that UAE building occupants may be experiencing very often, adverse consequences of PM exposure will depend on where it is deposited in the respiratory tract (Yeh et al., 1996), duration of exposure- which happens on regular basis in the UAE, vulnerability of building occupants- sick people, occupants with history of respiratory problem, children and elderly are most vulnerable set of people. PM_{10} can penetrate to the deepest part of the lungs such as the bronchioles or alveoli. This occurrence may trigger asthma attack. Pope et al. (2002) attributed high deposition of $PM_{2.5}$, on human arteries-gas exchange region of the lungs, to vascular inflammation and atherosclerosis. Atherosclerosis, defined as "hardening of the arteries that reduces elasticity", can cause heart attacks and other cardiovascular problems (Pope et al. 2002).

In a research study led by the University of North Carolina Gillings School of Global Public Health (2009) to examine the state of environmental health in the United Arab Emirates, indoor and outdoor exposure to air pollution of outdoor sources were found to be the leading environmental cause of excess death in the UAE. They attributed approximately 600 (with a plausible range of 200 to 1,100) excess deaths per year to PM and ozone in outdoor air which may also be transported indoor. Specifically on indoor air pollution, which may be generated from outdoor and indoor sources, they attributed pollution exposure to an estimated 250 (with a plausible range of 100 to 410) excess deaths each year. Exposure to PM of outdoor sources was reported to be responsible for respiratory diseases and cardiovascular diseases which caused estimated 8,330 (with a plausible range of 2170 to 17,100) and 5,370 (with a plausible range of 2170 to 17,100) hospital visits, respectively. The disturbing data on health implications of PM exposure in the UAE, especially those PM generated from outdoor environment is a concern to achieving building sustainability vis-à-vis health and comfort of building occupants. In such environment, poor building ventilation air system design, installation, maintenance and operation practices may put building occupants at risk. This study examines possible contribution of building ventilation to outdoor to indoor transport of PM number and mass, and size distribution concentrations in an air conditioned space located in the UAE having desert climate.

2. METHODS

2.1 Air conditioned space

The study was conducted in an actual air-conditioned space (4.2 x 3.6 x 2.8m; $43.3m^3$) occupied by one occupant. The study was done without disruption to the occupant's daily 'light' office activities, i.e. use of computer and reading. The space seems very clean and has flooring laid with carpet, office furniture, closed windows, and acoustic ceiling tiles. The space door was closed but not locked, throughout the measurement period. It was opened and closed immediately on few occasions when the occupant leaves the space or has visitors. On very few occasions when visitors were present, they did not spend more than 10 minutes in the space. The air handling unit (AHU) that serves this space is located at the rooftop of the studied space's building. Outdoor air (OA) is provided via an outdoor inlet designed-covered with metal lovers, inclined to prevent direct intake of outdoor air containing PM into the building air system. This is the common practice in the UAE. OA was filtered with E4 rating wire mesh filter and E7 rating bag filter with efficiency rating of ~30-40% and ~85%, respectively before being psychometrically mixed with the recirculated air (R_rA) to form supply air (SA). SA was filtered only with E4 rating wire mesh filter, and conditioned by the cooling coil before being distributed to the studied space via ceiling mounted diffusers. Ventilation filters for the studied space's building are usually maintained every six months. Return air (RA) is drawn from the space by way of return diffuser integrated into the suspended ceiling. Smaller proportion (about 10-20%) of the RA is exhausted, while the remaining proportion is recirculated. The building which house the space used for this study has a basement for car parking, seven floors-including the ground floor. The space is located on 2nd floor of the building. The building is surrounded by paved walkways with green areas and palm trees, roads, and extensive outdoor parking area. The building is located in vast sandy area. There are also construction activities in the vicinity of the building. The building was constructed less than 5 years ago while the measured space was constructed about 2 years ago.

2.2 Ventilation and infiltration rate

The ventilation rate in this study was ~2 air change per hour (ACH), while the infiltration rate was ~1ACH, which occurred when ventilation mode is switched "off". The ventilation and infiltration rate in the space were calculated using online *(http://www.veetech.org.uk/PHP%20Programs/phpco2.php)* ventilation rate and air quality CO_2 calculator. Calculation was done assuming the level of occupant activity is office work (100W), since the occupant performed simple activities such as reading and computer work. Assumed outside CO_2 concentration used for the calculation was 380ppm. Ventilation rate was calculated during the period when ventilation mode was switched 'on' and occupant was present. Infiltration rate was calculated during the period when ventilation was switch 'off' and occupant was present. During the measurement days when ventilation was used, Monday-19/03/2012 to Thursday-22/03/2012, ventilation mode was switched 'on' at 5am and switched 'off' at 4pm (16 O'clock). The only day when ventilation was not used throughout the day was on Friday (23/03/2012), non-working day in the UAE. Recirculation of conditioned air occurred throughout.

2.3 Instrumentation

Particle count, size distribution and concentrations were measured using optical particle sizer (OPS), TSI Model 3330, which was located in the middle of the space with its sampling inlet about 1.5 m above the floor. The OPS can measure particle concentrations (number and mass), over a large range of particle sizes- 0 to 3,000 particles/cm^3, with size resolution of < 5% at 0.5µm. There are a total of 16 channels: 0.3-0.374µm (1st channel); 0.374-0.465µm (2nd channel); 0.465-0.579µm (3rd channel); 0.579-0.721µm (4th channel); 0.721-0.897µm (5th channel); 0.897-1.117µm (6th channel); 1.117-1.391µm (7th channel); 1.391-1.732µm (8th channel); 1.732-2.156µm (9th channel); 2.156-2.685µm (10th channel); 2.685-3.343µm (11th channel); 3.343-4.162µm (12th channel); 4.162-5.182µm (13th channel); 5.182-6.451µm (14th channel); 6.451-8.032µm (15th channel); 8.032-10µm (16th channel). Indoor particle number and mass concentration were measured continuously for 5 days (19/03/2012 to 23/03/2012) at every 15 minutes interval.

Outdoor measurement was also conducted. However, outdoor and indoor particle concentrations were not measured simultaneously due to only one available OPS. Outdoor particle measurement was done to understand whether outdoor particle number and mass concentration during daytime is necessarily higher than that of night time, provided there is no sandstorm. On the site, where this measurement done, there is usually considerably higher human population and outdoor activities during daytime than night time. Outdoor particle concentration was measured for three days. The first and second outdoor measurements were done consecutively while third measurement was done three days after the second measurement. Outdoor measurement was done during the day, around 1pm, and at night, around 8pm. Each measurement was done for 10 minutes at 30 seconds interval. Indoor CO_2 concentrations were monitored continuously using a Graywolf Direct Sense IAQ- IQ probe 610. This was done in order to calculate ventilation and infiltration rate in the measured space. The instrument was located in the middle of the office space with the sampling sensor placed ~ 1.2 m above the floor.

2.4 Data Analysis

The data on the OPS and IAQ probe were logged at 15minutes average intervals. The OPS data were processed and analysed using Aerosol Instrumentation Manager Software from TSI. Indoor particle number and mass concentrations at various times were analyzed for each of the days when measurements were done. Both measured indoor and outdoor particle number and mass concentrations for various particle sizes were also analyzed for each of the measurement days. Particle number and mass concentration during the day time were compared with that of night time. In the case of indoor particle, measured concentrations from 11am to 2pm (14 O'oclock) were used to determine daytime concentrations, while measured concentrations from 9pm (21 O'Clock) to 12 am were used for nighttime concentration. These periods were chosen because particle number and mass concentration were steadied during those periods. For outdoor particle number and mass concentrations, average of 20 data samples, collected every 30 seconds interval for 10 minutes, were analyzed.

3. RESULTS AND DISCUSSION

3.1 CO_2 concentration profile

Figure 2 shows CO_2 concentration profile used for the ventilation and infiltration rate. CO_2 concentration profile steadied at 500ppm during the period when ventilation mode was "on", but occupant was not present.

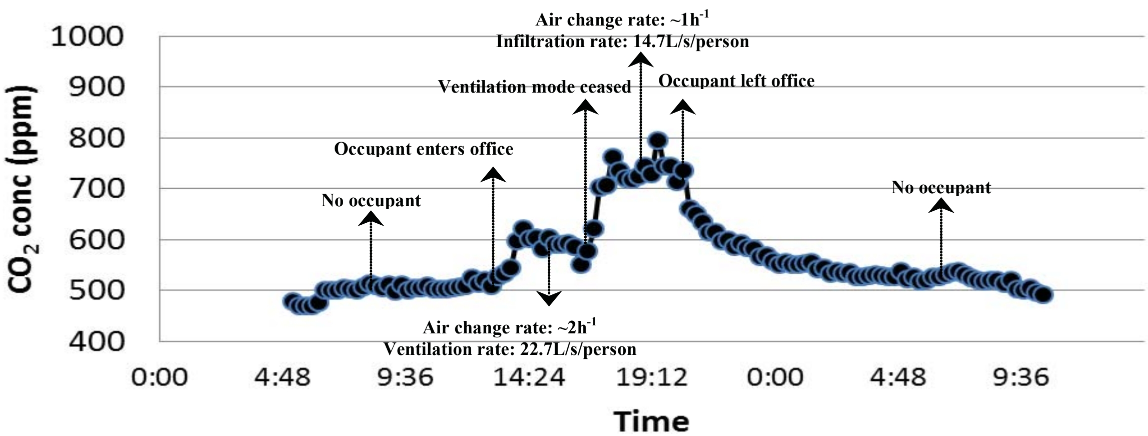

Figure 2: CO_2 concentration profile

3.2 Particle number and mass concentrations at various times for each of the days

State of ventilation mode, either switched "on" or "off", considerably influenced measured indoor particle number and mass concentrations. This is illustrated in Figure 3. Particle number and mass concentrations increases immediately, whenever ventilation mode is switched on at 5am. A plateau is usually attained after few hours of switching ventilation mode "on". Particle number and mass concentration decrease considerably whenever ventilation mode is turned "off". During the period when ventilation mode was "on", indoor particle number and mass concentrations were considerably influenced by outdoor environmental conditions. Sandstorm event, which was unexpected, increased indoor particle number and mass concentrations considerably than days with no sandstorm event. On 23/03/2012, ventilation mode was turned "off" throughout the day. On this day, particle number concentration was very low and relatively steady throughout the day. Peak number concentration on this day was about $9\#/cm^3$ as compared to other days having peak concentrations ranging from about $29\#/cm^3$ to $50\#/cm^3$ during the period when ventilation mode was "on". A slight, noticeable increase in particle mass concentration was observed around 5am to 9am due to sandstorm event that occurred very early in the morning on that day. Outdoor to indoor transport of polluted outdoor environment occurred via infiltration aided by recirculation of conditioned air that created negative pressure inside the measured space which is not air-

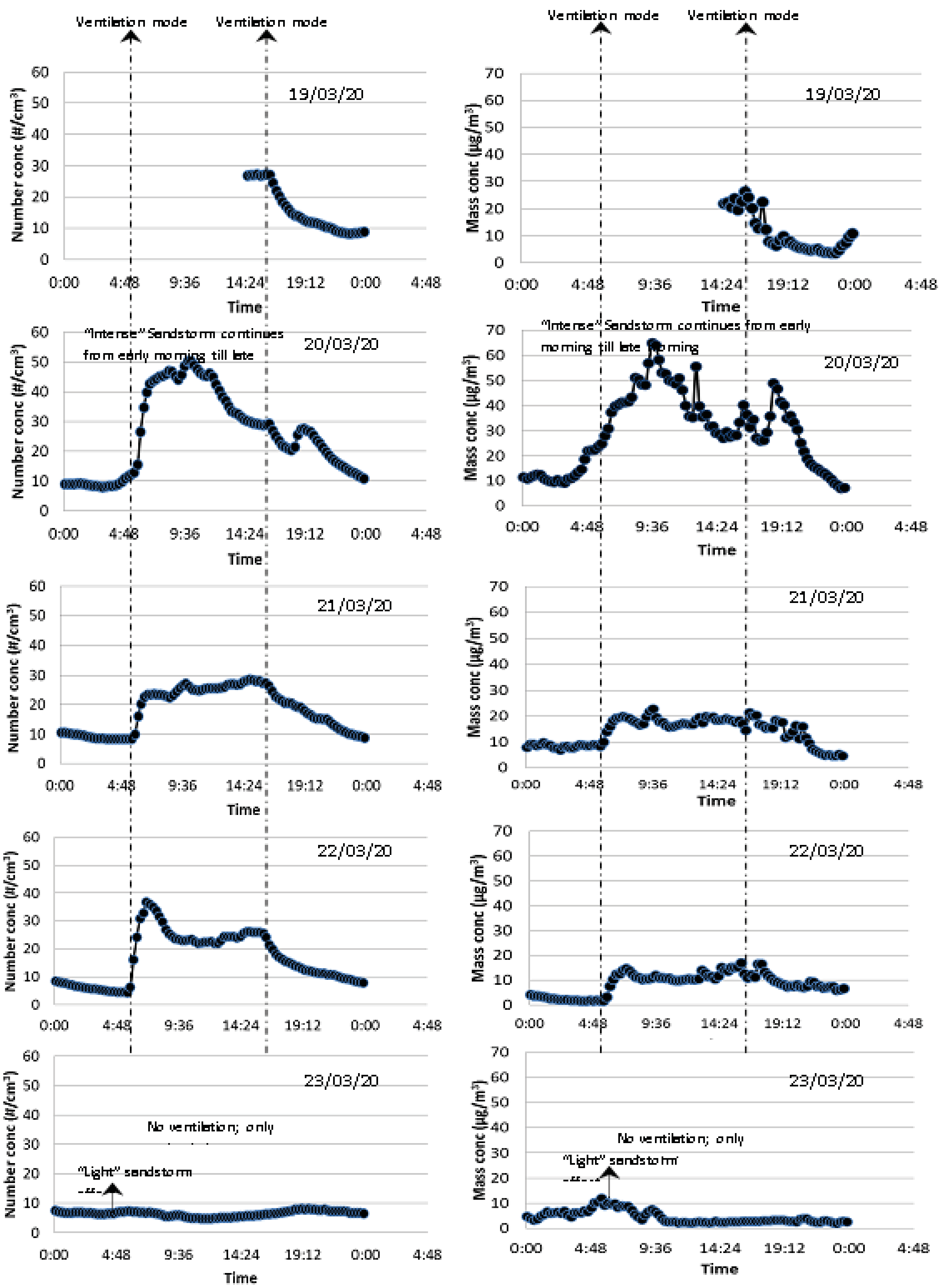

Figure 3: Particle number and mass concentrations at various times for each of the days

tight. Despite this sandstorm event, measured indoor particle mass concentration was not as high as that of 20/03/2012, mainly because ventilation mode was “off” on 23/03/2012. Sandstorm event on 23/03/2012 was not as intense as that of 20/03/2012 though. After 9am, indoor particle mass concentration steadied around 4µg/m^3 throughout the day due to relatively calm outdoor environment. Peak mass concentration on 23/03/2012 was about 10µg/m^3 as compared to other days, when ventilation was used, having peak concentrations ranging from about 18µg/m^3 to 65µg/m^3.

3.3 Particle number and mass concentrations for various particle sizes and day intervals

State of ventilation mode also played major role on indoor particle size distribution concentrations. This is illustrated in Figure 4. For all the days when ventilation was used, particle number and mass concentrations were higher when ventilation was switched “on” during the daytime than period when ventilation was switched “off” during the night time. To directly attribute variation in indoor particle number and mass concentration during the daytime (steady state period) and night time to ventilation, to clarify whether outdoor daytime concentration is not necessarily higher than that of night time, outdoor measurement was conducted. Outdoor measurements results suggest that, daytime outdoor particle concentration may not be necessarily higher than that of night time (see Figure 5). Outdoor particle concentration at any particular point in time is perhaps strongly influenced by environmental factor such as wind intensity

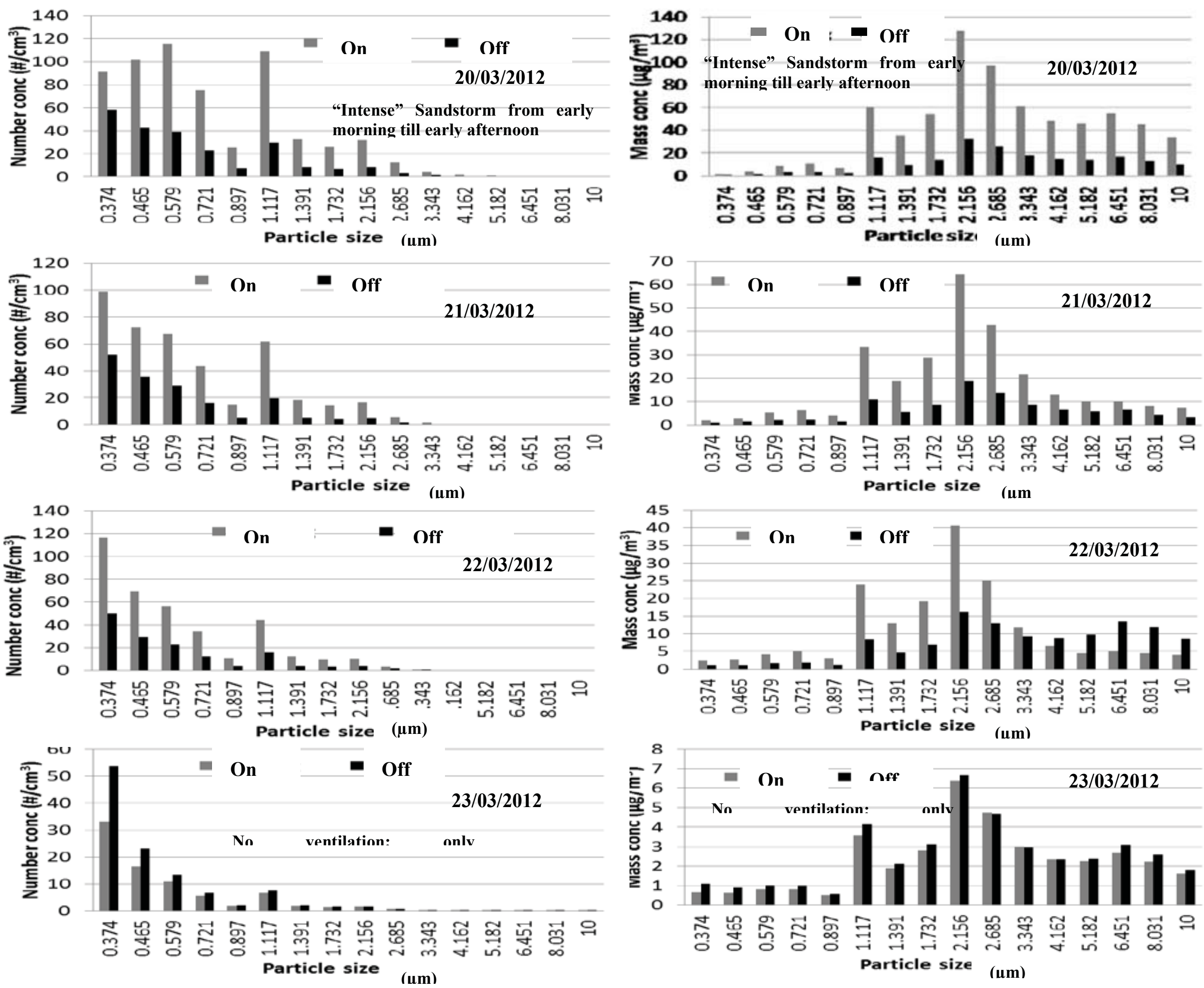

Figure 4: Indoor particle number and mass concentrations for various particle sizes and day intervals

and its direction. So if there is higher wind intensity at night time, and the prevailing wind direction is from south direction, night time particle concentration may be higher than that of daytime. Guerra et al. (2006) found wind intensity and direction, to be statistically significant for PM_{10} and $PM_{2.5}$ mass concentration. They found intense wind and predominantly south winds to cause higher particle mass concentration.

This present study suggests, that in situation where outdoor environment is polluted with PM either at daytime and/or night time, it is the ventilation mode, either “on” or “off”, that plays major role in determining the variation of indoor particle concentration. For example, if night time outdoor particle concentration is higher than that of daytime, daytime indoor particle concentration may still be considerably higher, than that night time if ventilation mode is “on” at daytime but “off” at night time. The degree of dominance of the daytime indoor particle measurement in such situation will be influenced by the effectiveness of outdoor to indoor particle mitigation strategies adopted in the ventilation system. The better the effectiveness, the lower the degree of dominance of daytime with ventilation mode “on” over night-time with ventilation mode “off”, and vice-versa. To further buttress this point, on Friday- 23/03/2012, when ventilation mode was turned “off” throughout the day, there was no much difference between daytime and night time measurements.

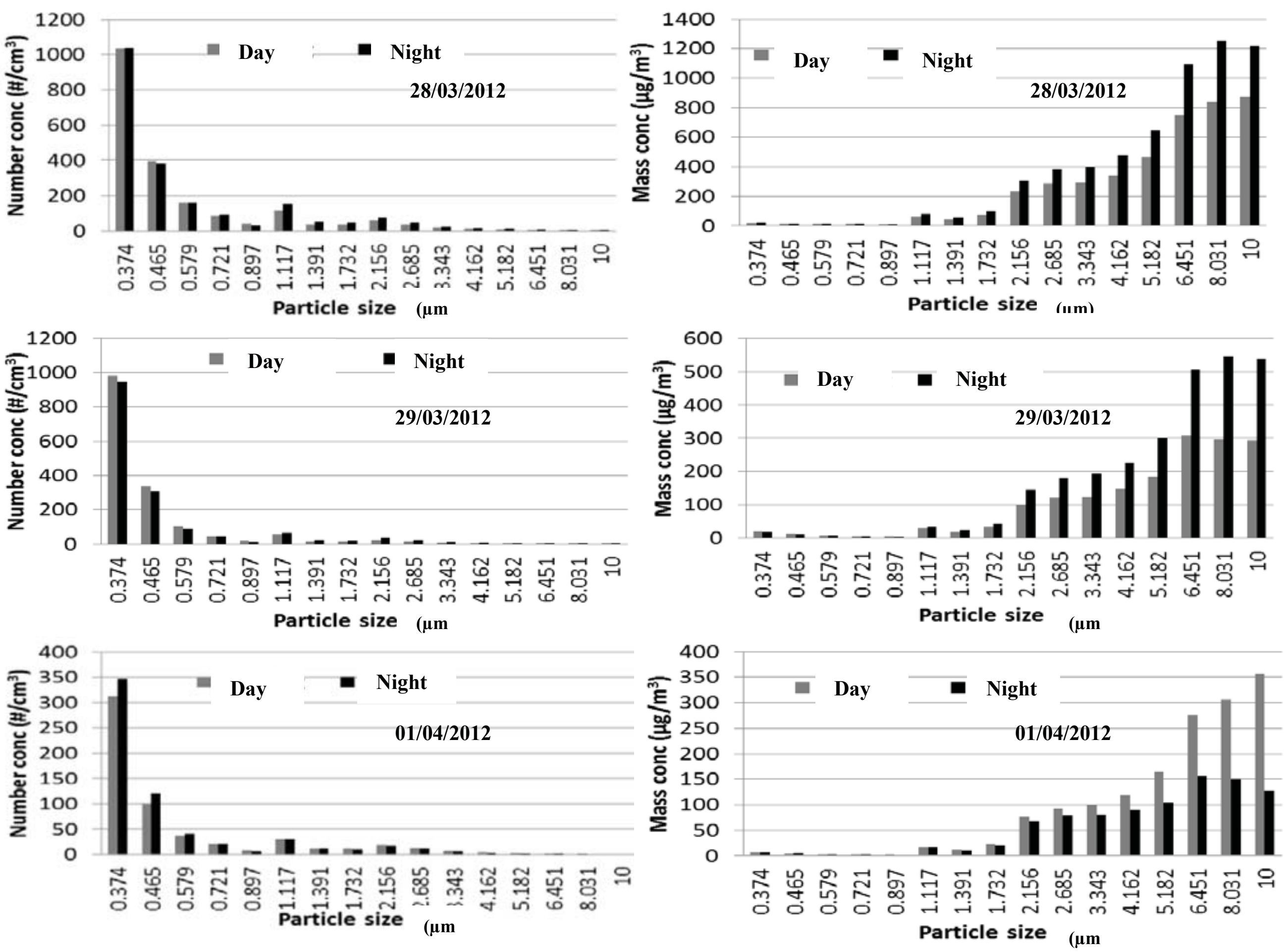

Figure 5: Outdoor particle number and mass concentrations for various particle sizes and day intervals

Figure 6 illustrates comparison of indoor and outdoor particle number and mass size distributions. Particle size-distributions based on mass concentration display peaks that occurred at larger particle diameters than the corresponding distributions based on number concentrations. This happens because air movement causes two particles to collide and stick together. This process known as coagulation reduces particle count per unit volume but retains the mass of each particle that joined together. Thus, increases the mass of the newly formed higher particle size within the unit volume of air. Measured outdoor particle mass concentrations were highest at 10µm (PM_{10} region) while measured indoor particle mass concentration peaked at 2.16µm ($PM_{2.5}$ region). This observation is due to filtration used in the measured space air system. Wire mesh filter (E4 rating) and bag filter (E7 rating) used in this building are relatively better at mitigating PM_{10} than $PM_{2.5}$. Measured indoor mass concentration for $PM_{2.5}$ is expected to be lower than what was observed in this study, assuming ventilation filter used in the air system are efficient at mitigating $PM_{2.5}$. Such mitigation strategy will help to reduce occupants' exposure to $PM_{2.5}$ that may cause atherosclerosis as suggested by Pope et al. (2002).

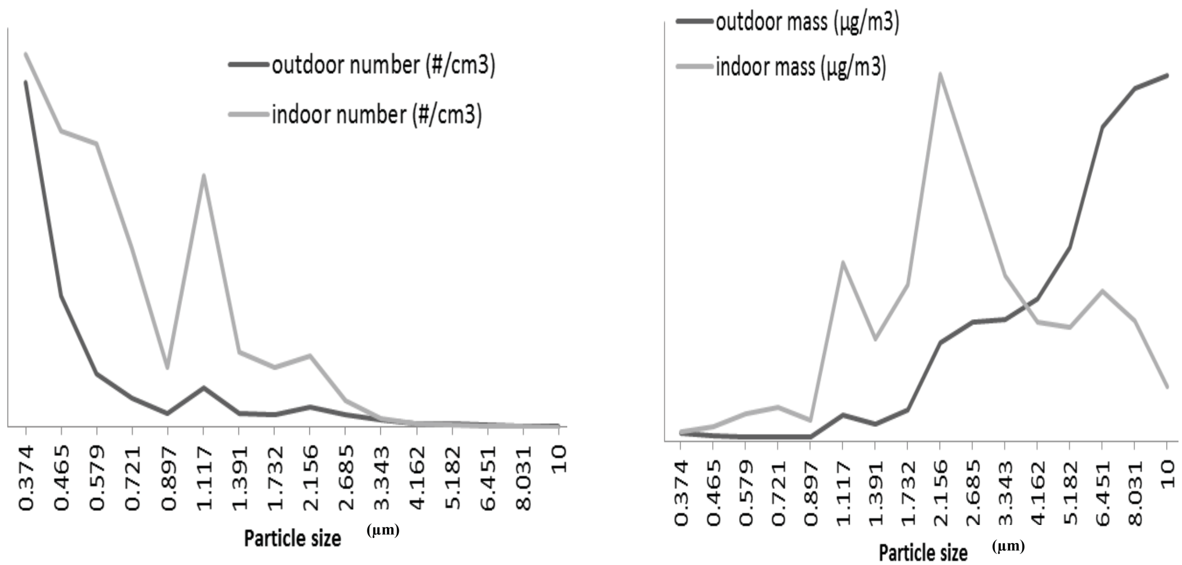

Figure 6: Comparison of representative indoor and outdoor particle number and mass size distributions peak

Unfortunately, since most commercial buildings in the UAE use only E4 rating wire mesh and E7 rating bag filter, building occupants may be exposed to more $PM_{2.5}$. In addition to higher $PM_{2.5}$ mass concentration that would occurred if only E4 rating filter are used in air system, a condition very common in the UAE residential and in some school buildings, PM_{10} concentration is also expected to be relatively higher than when E4 rating wire mesh filter and E7 rating bag filter are used in the air system. Such practices in design and operation of air-conditioned building may have considerable adverse health, performance and productivity implications.

4. CONCLUSION

Findings from this study may be considered not to be representative of UAE air-conditioned buildings. Particle number and mass, and size distribution concentration will vary depending on the design, installation, maintenance and operation of mechanical ventilation system adopted to mitigate outdoor to indoor transport of PM. However, it shows possible impact of ventilation and variation in outdoor environment conditions, such as sandstorm and non-sandstorm event, on particle number and mass, and size distribution concentrations. This study reiterates the importance of UAE Architectural, Engineering and Construction (AEC) professionals to adopt strategies necessary to mitigate building occupants' exposure to particulate matters (and not focusing on only PM_{10}) of outdoor sources as much as possible. This is necessary in order to maximize the benefits of using ventilation- to dilute pollutants of indoor sources, in desert climate.

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REFERENCES

Guerra, S.A., Lane, D.D., Marotz ,G.A., Carter, R.E., Hohl, C.M., Baldauf, R.W. (2006). Effects of wind direction on coarse and fine particulate matter concentrations in southeast Kansas. Journal of Air Waste Management Association; 56 (11): 1525-1531

Jakkola, J.J.K and Miettinen, P. (1995). Ventilation rate in office buildings and sick building syndrome. Occupational and Environmental Health, 52, 709-714

Jaakkola, J.J.K., Tuomala, P., Seppenen, O. (1994). Air recirculation and sick building syndrome : A binded crossover trial, American Journal of Public Health, 84, 422-428

Nordstrom, K., Norback, D., Akselsson, R. (1995). Subjective Indoor Air Quality in Hospitals - The influence of building age, ventilation flow, and personal factors. Indoor and Built Environment; 4; 1: 37-44

Pope III, C. A, Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K., Thurston, G.D. (2002). Cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. Journal of American Medical Association 287 (9): 1132–114

Seppanen, O.A and Fisk, W.J. (2002). Association of ventilation type with SBS symptoms in office workers. Indoor Air, 12, 2, 98-112

Seppanen, O.A and Fisk, W.J. (2004). Summary of human response to ventilation. Indoor Air, 14 (Supply 7): 102-118

Seppanen, O.A., Fisk, W.J., Mendell, M.J. (1999). Association of Ventilation Rates and CO_2 Concentrations with Health and Other Responses in Commercial and Institutional Buildings. Indoor air; 9; 226-252

Tham, K.W., Willem, H.C., Sekhar, S.C., Wyon, D.P., Wargocki, P., Fanger, P.O. (2003). Temperature and ventilation effects on the work performance of office workers (study of a call centre in the tropics). In: Tham, K.W., Sekhar, S.C. and Cheong, D. (eds) Proceedings of Healthy Buildings 2003, Singapore, Vol. 3, 280-286

University of North Carolina Gillings School of global public health, (2009). The state of environmental health in the United Arab Emirates: Preliminary summary. Report prepared for Environmental Agency, Abu-Dhabi, United Arab Emirates. [Retrieved on May 4, 2012] *http://www.soe.ae/English/Themes/AirQuality/Documents/SEH%20Summary%20Sept%202009.pdf*

Wargocki, P., Sundell, J., Bischof, W., Brundrett, G., Fanger, P.OGyntelberg, F., Hanssen, S.O., Harrison, P., Pickering, A., Seppanen, O. and Wouters, P. (2002). Ventilation and health in nonindustrial indoor environments. Report from a European multidisciplinary scientific consensus meeting. Indoor Air, 12, 113-128

Wargocki, P., Wyon, D.P., Fanger, P.O. (2000). Productivity is affected by the air quality in offices. In: Proceedings of Healthy Building 2000, Espoo, vol. 1, 635-640

Wargocki, P., Wyon, D.P., Fanger, P.O. (2004). The performance and subjective responses of call-centre operators with new and used supply air filters at two outdoor air supply rates. Indoor Air, 14 (Suppl. 8), 7-16

Yeh, H.C., Cuddihy, R.G., Phalen, R.F., Chang, I.Y., (1996). Comparisons of calculated respiratory tract deposition of particles based on the proposed NCRP model and the new ICRP66 model. Aerosol Science and Technology 25, 134–140.