Indoor air quality performance in air-conditioned museum gallery

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Abstract. The performances of IAQ in Malaysian museum galleries have not been well investigated. As a hot and humid country, air conditioning (AC) systems are used in enclosed galleries. Improper AC systems may affect IAQ levels as they may not only affect people but also artefacts deterioration. Selected IAQ parameters were measured in selected museum galleries in Peninsular Malaysia by using active sampling with multiple sensors at several points continuously. Results on average values for indoor temperature and carbon dioxide complied with people and artefact threshold level. However, air velocities were far below the recommended level. Visitors’ influx influenced CO2 levels but did not affect the resuspension and reposition of PM1. It started to increase when the CO2 decreased. This highlighted the contribution of this research as guideline for IAQ in museum is only up to the concentration of PM2.5. Poor Va and the existence of PM1 were expected due to the inefficiencies of the AC systems as higher cooling capacity did not influence better IAQ performance. It was concluded that, IAQ performance in the selected galleries did not perform well due to poorly ventilated cool air supply and improper layout of air inlets due to the ceiling heights and hanging decorative ceiling.

1. Introduction
Status of IAQ in the museum is a relatively new subject in Malaysia. Some prominent museums in Malaysia have rigorously upgraded their indoor environment since 2008 as a response to Pickup (2005). However there are still very few comprehensive evaluations on Malaysian museum galleries that have been done so far (Karim, Talib, & Sujak, 2012; Hanapi & Din, 2012; Dzulkifli et al., 2018). The concentration of indoor pollutants does not only affect people’s comfort, health and well-being, also pose risk to the artefacts as they can cause deterioration.

In the museum, air pollutants can attack not only artefact but also the visitors. Criteria on how to control IAQ in museum gallery as reported in Blades et al, (2000) amongst others are ventilation and location of air inlet. ASHRAE Standard 62.1 – 2007 indicates air class 1 in museum gallery which need to provide minimum ventilation rates in breathing zone based on occupant density at 100 people per meter square at 9cfm/person (ASHRAE, 2010).

As museum gallery has to control its indoor environment to conserve cultural heritage, special temperature and relative humidity are required, which can be obtained by using mechanical ventilation air conditioning (MVAC) systems (ASHRAE, 2007). Flow of air is another factor that may determine the spatial uniformity performance of the air diffusion systems in the MVAC (Ascione and Minichiello, 2010). Based on CFD simulation, higher air velocity values were only obtained in the upper zone, between 3.5 to 4 m height for 5 m high room and between 3.5 and 6 m height for 9 m high room. Air speed values were only as low as 0.18 m/s at the occupancy zone (Ascione and Minichiello, 2010).
2. Methods
The selected case studies used air conditioning system. Measurements were carried out in two different
galleries by using Delta Ohm 32.2, TSI Dustrak II Aerosol Monitor and YESAIR Channel multiple
sensors. Calibrations for all instrumentation were carried out prior to data collections according to
specific standard and requirement such as respirable mass per the ISO 12103-1 standard, A1 test dust
for the Dustrak. Calibrations for the gaseous parameters are done with calibration gas concentrations
3990ppm for CO₂. Sampling point is based on DOSH (2010). Numbers of sampling points for Gallery
1 (852m²) were 2 points and Gallery 2 (1487.24m²) were 3 points. Each point was measured for 9
continuous hours daily in 7 consecutive days with 1 minute interval before it was moved to the next
point. Bias uncertainties were performed based on Yau (2004) from a non-uniform indoor temperature
levels at one sampling point in the measured gallery. The acceptance levels were all at very low
percentages, less than 20 percent, which show that the results obtained during the field measurements
are all valid.

3. Results and Discussion
Data analyses were done by using SPSS version 24.0 and Microsoft Excel. The distributions were
checked for normality. ‘Natural log-transformed’ values and ‘indexed’ were adopted for the non-normal
distribution of the indoor parameters. The Kolmogorov - Smirnov tests were checked once again after
the transformation. Further, the relationship between variables by investigating the correlation
coefficient were done to look at whether they co-vary (Field, 2009). Table 1 briefly describes the gallery
typologies and their climate systems.

Table 1. Results on gallery typologies based on observation and unstructured interviews

| GALLERY SPECIFICATIONS | G1                      | G2                      |
|------------------------|-------------------------|-------------------------|
| Refurbishment work     | Completed 2007          | Completed 2008          |
| Floor area (m²)        | 852.00                  | 1,487.24                |
| Ceiling height (m)     | 6.15                    | Various ceiling height  |
| Climate systems        | • Air cooled package unit at 22.07kW
                         | • 13 diffusers with 28.31 m³/min | • Water cooled package unit and air
                         |                                | cooled split unit ducted at 25.74kW
                         |                                | • 21 diffusers with 28.31 m³/min
| Diffuser/indoor unit   | Swirling diffuser       | Swirling diffuser and Slot diffuser |
| Return air grille      | One return grille at the end of the gallery on the right wing | 7 return air grille throughout the gallery located in the same zone with diffuser |

3.1 Descriptive analysis
The readings on selected IAQ parameters in both galleries were compared descriptively against their
benchmark levels for people comfort and artefact requirement. As shown in Table 2, the average air
velocities in both galleries were below the recommended benchmark at 0.1 to 0.25 m/s for museum
gallery. Small standard deviations for $V_a$ at G1 showed closed dispersion of data compared to the
average value. This shows that the air flew uniformly throughout G1 compared to G2 with bigger
standard deviation. To maintain good indoor air quality, air velocity will influence the performance of
ventilation especially in an enclosed space when there is no cross ventilation that can provide good air
circulation. PM₁ were detected in both galleries. G2 was at risk of higher PM₁ at 0.11 µg/m³ compared
to the threshold level of 0.1µg/m³ (for sensitive collection based on PM₂.₅). G1 could also be at risk as
PM₁ level nearly reached the threshold level. In certain occasion, CO₂ levels exceeded the recommended
benchmark at 1000ppm.

Table 2. Average values of selected IAQ parameters

| IAQ     | PEOPLE COMFORT¹ | ARTEFACT BENCHMARK² | MUSEUM A | G1 | G2 |
|---------|-----------------|----------------------|----------|----|----|
| $T_a$ (°C) | 24 - 26          | 13 – 27              |          | 23.24 | 21.70 |
| $V_a$ (m/s) | 0.15 - 0.50      | 0.10 – 0.25          |          | 0.05 | 0.00 |
| CO₂ (ppm) | 1000            | Not stated            |          | 552.95 | 386.00 |

²: Values are mean ± standard deviation.
3.2 Ventilation

Limitations were experienced during the field experiments as the air change rates were not measured. Even though it is essential to confirm the value of the air change rate with the demand of people requirement on health, CO2 levels in all galleries were used as indicators of indoor air pollution. 15 mechanically ventilated office buildings in Slovenia used concentrations of CO2 as indicators of IAQ (Ncube, 2012). Lower CO2 than the recommended benchmark in museums seems to be typical situations in reference to other places (Zorpas and Skouroupatis, 2016; Lee et al., 2011; Ferdyn-Grygierek, 2014). If CO2 was used as ventilation indicator, during situations when the visitors were as high as observed in Table 3, it can be assumed that the ventilation performance in G1 would not cope with the density of the visitors.

| Museum gallery | Default values for occupant density based on (40 nos./100 m²)* | CO2 level during high occupancy (ppm) |
|----------------|---------------------------------------------------------------|--------------------------------------|
|                | Benchmark* | Maximum visitors | Minimum visitor | Average visitor |
| G1             | 852.00     | 340              | 455             | 155             | 253             | 608 - 1644 |
| G2             | 1,487.24   | 590              | 215             | 0               | 112             | 456 – 594.97 |

*(ASHRAE, 2010)

3.3 Location of air inlet

Results of low air velocity were at an average of 0.05 m/s in G1 and 0.04 m/s in G2. The ceiling height of G1 was about 6.15 m. The exposed suspended ducting with swirling diffusers was about 4 meters high from the floor. This is about 2.4 meters above the occupancy level. Various ceiling heights were recorded in G2. Lowest diffusers were located at a height of 4.83 meters from the floor and the highest was about 5.40 meters from the floor, about 3.23 meters to 3.80 meters above the occupancy level. These have not met the occupancy level recommended in Ascione & Minichiello (2010). G2 air inlets were also obstructed with suspended design elements from the ceiling in some places.

3.4 Correlation relationship

A correlation analysis was carried out to examine the correlation relationship between IAQ parameters with visitor occupancies throughout opening hours of the galleries as reported in Table 4. The significant relationships of air quality parameters in National Museum according to the strength of correlation coefficient are as shown in Table 4. Negative correlations were recorded between visitor and IAQ parameters except with CO2. Results on low air velocity affected the strength of significant correlation with other IAQ parameters. Investigations on particulate matter in indoor environment of old and cultural buildings which includes old museum buildings concluded that 92% out of 25 cases focused on PM2.5 and PM10 with the absence of study on particles ~0.5 - 1 μm (Grau-Bove & Strlic, 2013). PM1 is particles with aerodynamic diameter <1μm which can be found mostly in PM2.5(<2.5 μm) (Chen et al., 2017). Therefore, it seems acceptable if PM2.5 is used as the benchmark for PM1.

| Table 4. Pearson correlations of selected IAQ parameters in both galleries |
|-------------------------------------------------|
| Visitors | T_a | RH | V_a | CO2 | Outdoor PM10 |
|----------|-----|----|-----|-----|---------------|
| (N)      | (17583) | (17583) | (18433) | (18433) | (18433) |
| T_a      | -0.214** |       |     |     |               |
| RH       | -0.318** | 0.756** |     |     |               |
| V_a      | -0.018*  | -0.109** | 0.132** |     |               |
Figure 1. Negative correlations show that CO₂ level was decreased and PM₁ was increased in Gallery 1

Figure 1 investigates further relationship between CO₂, PM₁ and visitors based on one selected weekend from a long stretch of 5 weeks continuous measurement across 5 points. Even though the presence of visitors contributed to the accumulation of CO₂, as shown in boxes (a) and (b), PM₁ decreased most of the time as CO₂ concentration built up due to the increased number of visitors. As mentioned earlier, visitor correlated negatively with other IAQ parameters except with CO₂ (Table 4).

The build-up of CO₂ concentrations and movement from the visitors may create turbulence may not affect the deposition of particulate matter be it on the floors or anywhere in the gallery. Even though visitors may also bring outdoor particulate matter into museum through their clothes, coats and shoes (Zorpas & Skouroupatas, 2016), the deposition of these particulate matters and the resuspension of existing dust deposited in the gallery (e.g. floors, cabinets, story boards, etc.) seems to happen once CO₂ level decline.

Previously, no other findings provide the exact direct relationship between CO₂, visitor and PM₁ concentration. One might assume in general that once visitors enter the gallery, CO₂ will accumulate and simultaneously resuspension and deposition of new and existing particulate matter will happen based on visitor movement and crowd (Grau-Bove & Strlic, 2013). Not to forget, visitors may also emit water vapour (Camuffo, 2001). Relative humidity manifests itself as water vapour in the museum indoor environment. In the presence of water vapour, dust can be deposited and will settle. This is proven with positive correlation coefficient between RH and PM₁ at $r = .201(p<0.001)$.

Other arguments why CO₂ and visitor react in negative correlations with PM₁ was due to the size of its particle as <$1 \mu m$ particles will may usually not be directly suspended by visitors compared to $>1 \mu m$ (Grau-Bove & Strlic, 2013). Grau-Bove and Strlic (2013) added that deposition and resuspension of fine particles of <$1 \mu m$ could be negligible. Based on findings from this research, particles <$1 \mu m$ does have effect with significant correlation with CO₂. As mentioned earlier, fine particle may not easily react with visitor activity. During the accumulation of CO₂ and movement of visitors, PM₁ remained settled but started elevating when CO₂ decreased.

Further analyses on PM₁ profile when it was in its maximum level are shown in selected one hour duration (Figure 2) at another sampling point which was measured 9 continuous hours daily (visiting hours of the gallery) for 7 days in total. PM₁ values kept increasing until they reached the maximum level before beginning to decrease. In relation to the functions of other parameters as well as number of visitors during both days and time, there seems that no significant influence. Even though numbers of visitors increased in this gallery, PM₁ levels still decreased gradually. Further elaboration on these findings may relate to the significant results tabulated in correlation values.
Based on results of the Pearson Correlation for PM1 in both galleries, it was not a surprise that other parameters did not really influence the profile of PM1 even with significant relationship at p<0.01 (two tailed). Correlation coefficient with $T_o$ was as low as $r = .161$. PM1 has higher correlations with indoor temperature at $r = .310$ but negative correlations with the numbers of visitors recorded hourly at $r = -.180$. The only strong relationship was $r = .806$ between PM1 and outdoor PM10. Therefore it was estimated that outdoor PM10 was the major sources of indoor particulate matter especially PM1.

4. Conclusion
IAQ performance seemed to provide safe and healthy threshold level for people and artefacts. It was found that sources of particles, which contributed to indoor air pollutants, were very minimal with major contributions expected from visitors and their activities in the galleries, museum staff and maintenance staff as well as outdoor PM10. Very low air velocities were found in all galleries. It is suspected that the air-conditioning systems have not been performing well, even though the upgrading of the galleries only took place 3 years before this study commenced.

Height of the inlet air may also affect the performance of the $V_a$ in the occupancy zone in both galleries. Air inlets were located at as high as 5m from the floor level with obstructions from the suspended design elements considered to be the reason for uneven cool air supply distribution in the gallery. Visitors’ influx made this situation worst when negative correlation was found between number of visitor and $V_a$. The MVAC systems were also not performing well as the CO2 levels reached levels as high as 1644ppm. The museum management should consider changing or at least servicing the air filters at the air-handling unit (AHU) which can reduce the transmission of outdoor PM10 into the gallery as high correlation coefficient between PM1 and PM10 at $r = .806$ (p<0.001) was recorded in this study. Poorly maintained MVAC systems and improper air inlet layout have led to unacceptable air velocity, accumulation of PM1 which sooner or later may cause deterioration to the artefact. Exposure of PM1 to the visitors, however, may not be considered harmful compared to the museum staff spending eight-hours daily in the gallery.

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