Ventilation effectiveness and contaminant distribution in an occupied space conditioned with low exergy ventilation technologies in the tropics

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SUMMARY

Low exergy concept can be implemented in air conditioning system of the tropical buildings through a reduction of the difference between operational temperature of cooling system and indoor space whilst meeting thermal comfort requirements. Decentralized dedicated outdoor air system (DDOAS) coupled with radiant cooling system (RCS) are low exergy designs which can potentially reduce exergy destruction in cooling system of buildings while providing adequate air quality for occupants. In this study, ventilation effectiveness of a DDOAS-RCS design with floor supply – ceiling exhaust (FS-CE) and radiant ceiling panel has been investigated in an experimental setup located in Singapore. Air change efficiency (ACE) and contaminant removal effectiveness (CRE) of the designed system have been determined using tracer gas step down test under various ventilation rates. The results showed that ACE of DDOAS-RCS design with FS-CE distribution is close to that of mixing strategy and there is no significant difference for five considered ventilation rates in the range of 0.44-0.92 lit/s/m^2. It was also found that each change in occupancy for the space with 70 m^3 volume at ventilation rate of 0.62 lit/s/m^2 takes about two hours to reach a steady state CO_2 concentration and this change happens gradually throughout the space.

INTRODUCTION

The main goal of sustainable healthy buildings is to achieve healthy, comfortable and productive indoor spaces with least amount of exergy consumption and environmental impacts. Low exergy designs incorporating decentralized dedicated outdoor air system coupled with radiant cooling could be effective in achieving this for the tropical climate (Meggers et al., 2013). For conventional means of mechanical dehumidification, a design prerogative is to minimize ventilation rates, since dehumidification entails exergy destruction due to the required low temperatures. With improved ventilation effectiveness of the design, the minimum required ventilation rate can be lowered without compromising the indoor air quality. Depending on the location of air supply outlets, and exhaust grilles as well as ventilation rate and supplied air condition, air flow pattern could be close to the ideal scenarios of fully mixed (air change efficiency (ACE)=50%) or piston (ACE=100%) strategies. An indoor air pattern with ACE between 50-100 % is categorized as displacement flow and with ACE below 50%, it is called a short-circuit flow (REHVA Guidebooks No. 2, 2004).

Ventilation effectiveness indices including air change efficiency and contaminant removal effectiveness (CRE) are used to quantify the ability of air flow patterns to exchange air and remove air-borne contaminants, respectively. Several standards and handbooks provide guidelines on the procedure of calculating these values based on data from experiments or numerical modeling (ASHRAE 129, 2002; REHVA Guidebooks No. 2, 2004; REHVA Guidebooks No. 10, 2007). While it was shown by some studies (Awbi, 1998; Gan, 1995) that displacement ventilation is more effective, Simon and Waters (1998) and Lin et al. (2006) concluded that in operation, indoor air pattern with near floor supply diffusers is more complicated than expected. Depending on the location of heat sources and diffusers, near floor supply of air may not necessarily improve the air quality near occupants. Tomasi et al. (2013) investigated the ventilation effectiveness of residential rooms with mixing ventilation and floor heating and cooling and they found that ACE and CRE could give contradictory information on the effectiveness of air distribution. They recommended considering both values in the design process and accompanying experiments with computational fluid dynamics (CFD) simulations.

This study aimed to measure the ventilation effectiveness indices of a low exergy ventilation design depicted as decentralized dedicated outdoor system (DDOAS) combined with radiant cooling system (RCS) in the tropical context. These technologies have been installed in a freestanding test bed (called BubbleZERO) located outdoors in Singapore (Bruelisauer et al., 2013). In previous works, the performance of this setup has been investigated in terms of thermal comfort and indoor air quality under various system and space related parameters (Saber et al., 2013, 2014). In this paper, the evaluation criteria of these low exergy technologies have been extended by including ventilation effectiveness to reveal the ability of this combination for contaminant removal.

METHODOLOGIES

The ventilation effectiveness can be measured with different methods through injection of a tracer gas in the space. A step down tracer gas method has been used in this study and SF_6 was selected as the tracer gas. The experiments have been conducted in the freestanding test bed (BubbleZERO) located in outdoor space whose exterior is subjected to the ambient air but the interior is conditioned. The setup for the experiments including system components and location of sample points are shown in Fig. 1. Decentralized air supply units (green components) located within the floor take fresh air directly from the façade, condition it and distribute it through underfloor ducts and floor diffusers. Radiant cooling panels are installed at the ceiling and air exhaust flaps are located in the middle of panels where air leaves the space through exhaust ducts. During the test, two persons were seated in the center of the room and working with their laptops. Tracer gas has been injected in the center of the room and the concentrations of SF_6 as well as CO_2 have been monitored with a Photoacoustic multi-gas monitor Innova 1312. The gases concentration was measured at 10 points in the space by use of a Multipoint sampler Innova 1309. Two sample points were put at exhaust ducts (9&10), two sample points (1&2) in front of occupants at a height of 100 cm, and six other sample points (3-8) at heights of 170 cm at different locations throughout the space.

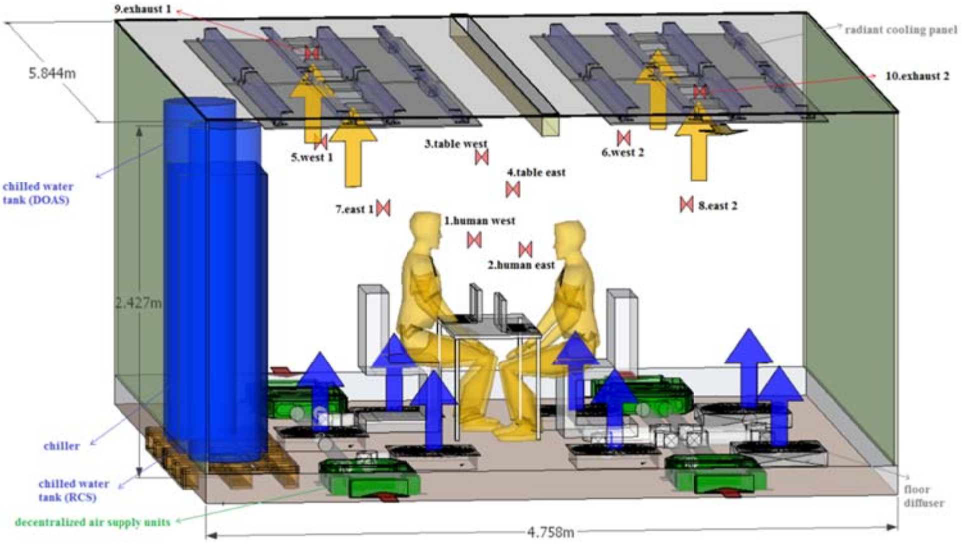

Fig. 1 Setup of ventilation effectiveness experiments including sample points

The concentration of tracer gas was measured for three hours after injection. Due to the small size of the lab, SF_6 dispersed uniformly in the space over a short period of time. The air change rate was determined through decay slope of logarithmic curve of concentration over time. The ventilation effectiveness indices ACE and LACI have been calculated based on the age of air concept. The age of air at a point is defined as the time elapsed for the incoming air to reach that point ($\bar{\tau}_p$). Nominal time constant (τ_n=V/q) is defined as local mean age of air at exhaust and can be calculated as the ratio between volume to ventilation flow rate of space. ACE is defined as the ratio of the lowest possible mean age of air (τ_n/2) and the room mean age of air $\langle\bar{\tau}\rangle$. CRE is defined as the ratio between steady state pollutant concentration in the space and exhaust air concentration. The latter value indicates how fast the generated pollutants are removed from the space. The indices of ACE, LACI (local air change index), and CRE were calculated using the following equations (REHVA Guidebooks No. 2, 2004),

$$ACE = \frac{\tau_n}{2\langle\bar{\tau}\rangle}.100\ [\%] \tag{1}$$

$$LACI = \frac{\tau_n}{\bar{\tau}_p}.100\ [\%] \tag{2}$$

$$CRE = \frac{c_e}{\langle c\rangle} \tag{3}$$

In the above equations, $\langle\bar{\tau}\rangle$ is the room mean age of air, c_e is the contaminant concentration in the exhaust air, and $\langle c\rangle$ is the steady state mean concentration of the space. The temporal and spatial variations of CO_2 level in the space with DDOAS-

RCS cooling system were assessed after changes in occupancy and ventilation rate of space. The outcomes revealed the ability of system in purging of generated pollutants in the case of sudden increase in the number of people inside the space.

RESULTS AND DISCUSSION

Ventilation effectiveness

The SF_6 concentration curve over time for a tracer gas test conducted in the lab is shown in Fig. 2. The maximum value reached around 15 ppm (particle per million) and it took about half an hour to achieve uniform distribution in the space. The exponential trendline of usable data part of curve was calculated and the power of this exponential decay (0.019 min^{-1}) is equal to ventilation rate of space. The room mean age of air was calculated from the weighted area under the usable part of curve and the ventilation effectiveness indices were determined using Eq. 1-3. This tracer gas test has been conducted twice for each specific ventilation rate to test the repeatability of the experiments. The variations of ventilation effectiveness indices for repeated cases as well as different locations were included in the presented values as error bars. The red line in Fig. 2 shows the usable data of curve for the calculation of ventilation rate and ACE. The exponential trendline of the usable data and the corresponding equation are also shown (green line) here.

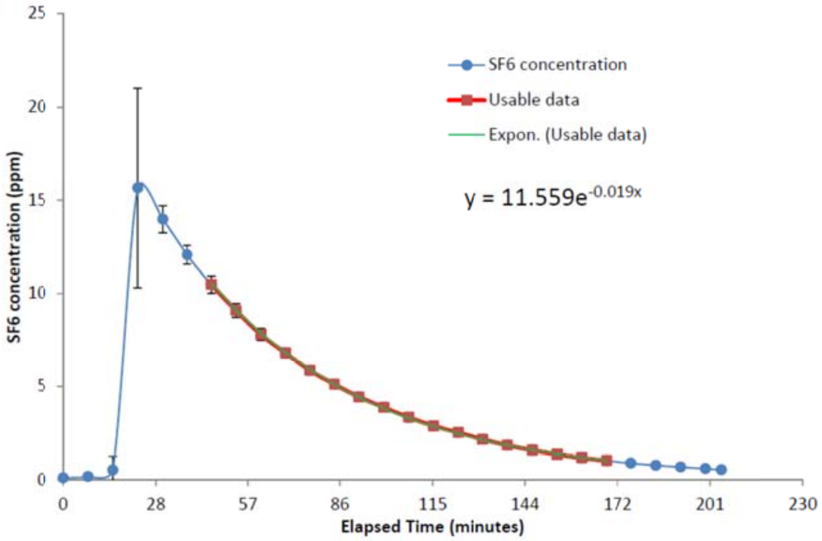

Fig. 2. Measured SF6 concentration and interpolated curve for a SF6 step down tracer gas decay test

The calculated ACE and LACI for the five considered ventilation rates are plotted in Fig. 3. This range of ventilation rates (0.44-0.92 lit/s/m^2) has been considered to include both values below and above of recommended ventilation rate in local standard SS 553 (0.6 lit/s/m^2). During the whole sets of experiments, the average surface temperature of radiant panel was around 20 °C. It can be seen that the ventilation effectiveness indices for DDOAS-RCS are close to the values of a mixing strategy. No profound correlation was observed between these indices and air change rate of space. This correlates with findings by Krajčík et al. (2012) who measured the ventilation effectiveness of a mixing strategy with floor heating and concluded that higher ventilation rates not always result in better ventilation effectiveness. A slight increase in the CRE level of the indoor space can be seen for higher ventilation rates (Fig. 4). However, these differences may be partially due to the propagation of uncertainty of measurements in ventilation effectiveness calculation. The propagated uncertainty for ACE and CRE were approximated to be around 4 % and 2 %, respectively.

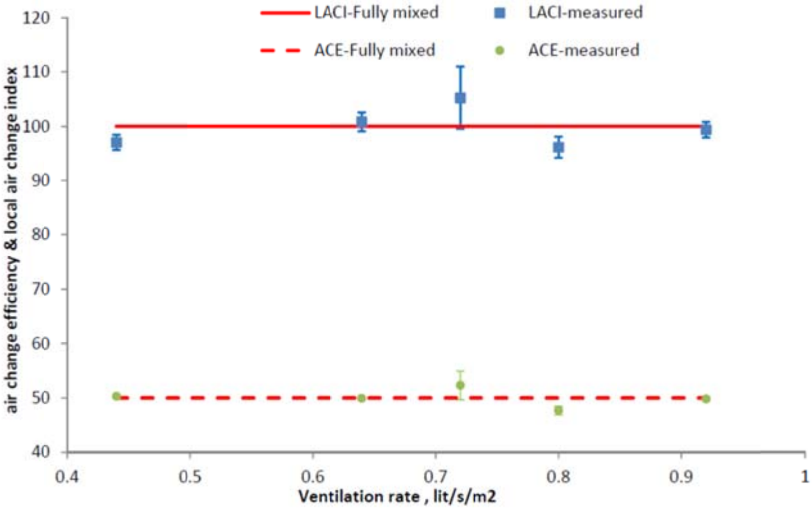

Fig. 3. Calculated air change efficiency (ACE) and local air change index (LACI) for five considered ventilation rates

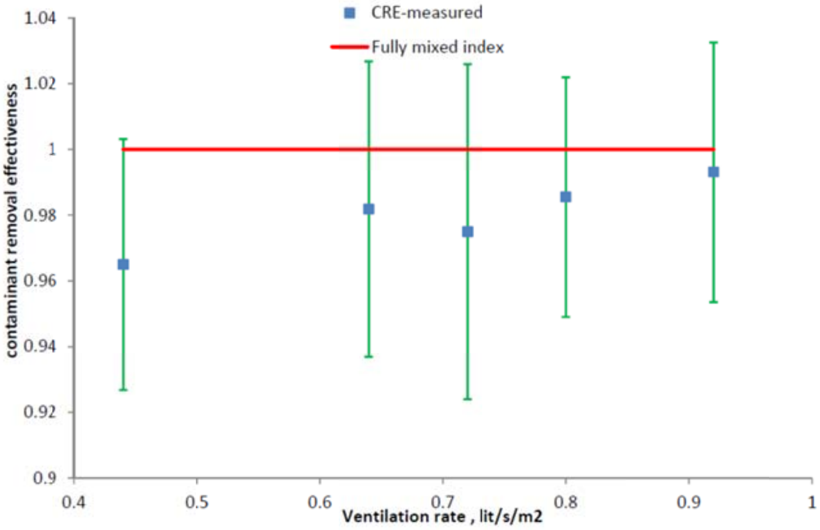

Fig. 4. Calculated contaminant removal effectiveness for five considered ventilation rates

Contaminant distribution

Carbon dioxide as the main human related contaminant in the indoor space has been monitored inside the test chamber. The variation of CO_2 concentration under steady state indoor conditions with different ventilation rates is shown in Fig. 5. At a ventilation rate of 0.44 lit/s/m^2, the CO_2 concentration is close to the threshold value set by local Singapore standard SS 554 (2009), while at higher rates, it is well below the limit. These results are consistent with the recommended ventilation rate for office spaces in Singapore set by local standard SS 553 (2009), which is 0.6 lit/s/m^2.

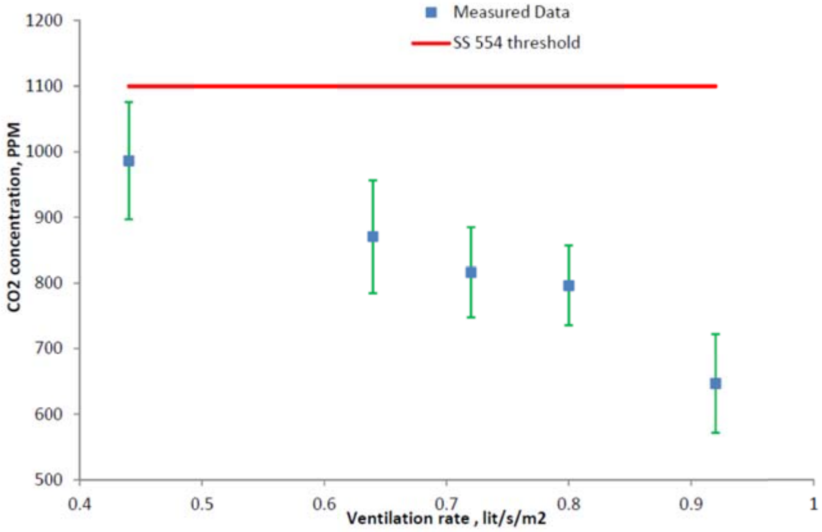

Fig. 5. Carbon dioxide concentration for five considered ventilation rates and threshold value set by local standard SS 554

One of the goals of this study was to investigate the spatial and temporal distribution of CO_2 level in the indoor space. The transient CO_2 level in the lab for a typical day with occupants entering and leaving the space is shown in Fig. 6. It can be seen that after each change in occupancy it takes about two hours to reach a steady state CO_2 concentration in the space. In addition, a 30% reduction in ventilation rate of space resulted in 100 ppm increase in steady state carbon dioxide concentration. The high points in Fig. 6 are representative of CO_2 level near breathing points of seated occupants. A spatial representation of CO_2 concentrations at different locations within the test chamber is provided in Fig. 7. Near the occupants (points 1&2), the mean CO_2 concentration is marginally higher than at other locations, while the variation of concentration is significantly higher than at other points. This observation shows that in area near occupants, on average basis, CO_2 level is similar to other points while fluctuation in concentration happens when exposed to breathing exhalation flow. It was also observed that the difference in the concentration of exhaust and interior is not significant which could be explained by exfiltration from the space.

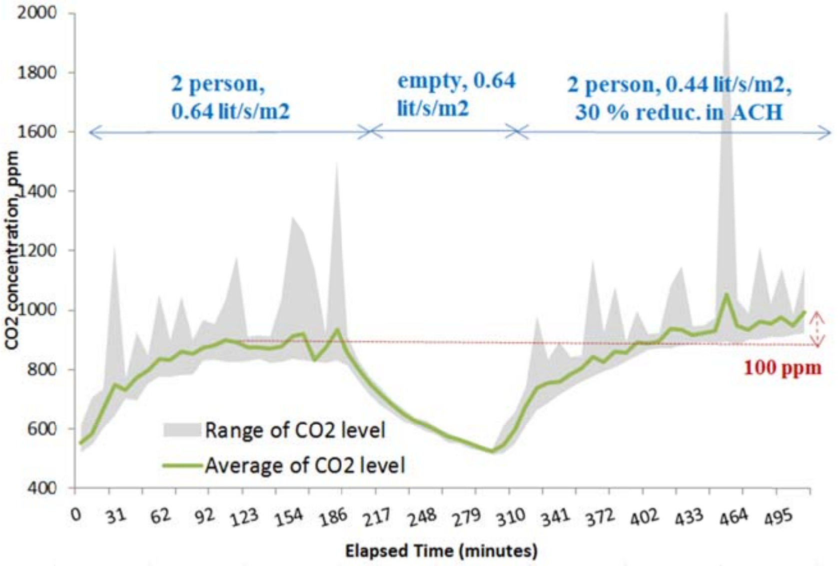

Fig. 6. Range and average of CO_2 concentration for transitional occupancy

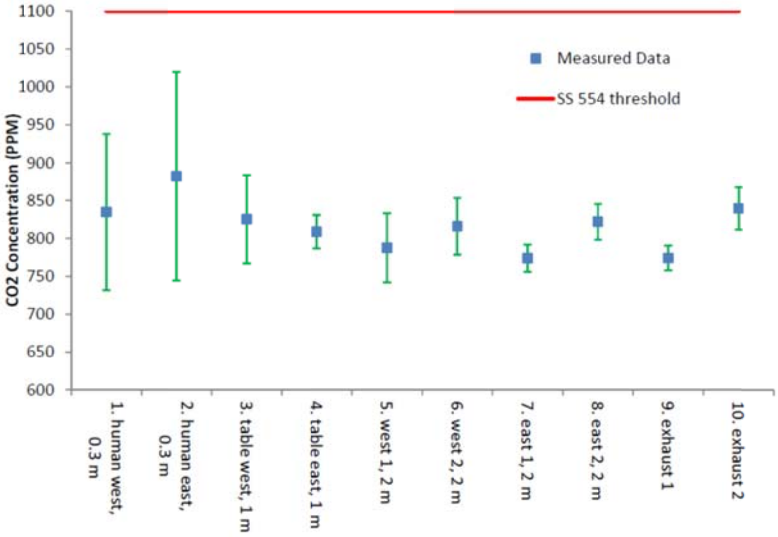

Fig. 7. Spatial variation of carbon dioxide in space in order of distance from occupants

CONCLUSIONS

The ventilation effectiveness and contaminant distribution for a test chamber conditioned with low exergy technologies have been investigated in this study. In this concept, a decentralized dedicated outdoor air system is coupled with a radiant cooling system with floor supply – ceiling exhaust distribution type. The main findings from this study are,

- Ventilation effectiveness of DDOAS-RCS design with FS-CE distribution is close to that of mixing strategy and there is no significant difference for five considered ventilation rates.
- For the coupled DDOAS-RCS concept, ventilation rate of 0.44 lit/s/m^2 closely fulfills the criteria of CO_2 concentration in the space and at rate of 0.62 lit/s/m^2 carbon dioxide level is well below the threshold set by local standards
- Each change in occupancy of the space with 70 m^3 volume takes about two hours to reach a steady state CO_2 concentration with DDOAS-RCS at ventilation rate of 0.62 lit/s/m^2
- There is no significant difference in mean CO_2 level near or away from seated occupants inside the space, which shows carbon dioxide changes gradually throughout the space with 70 m^3 volume at ventilation rate of 0.62 lit/s/m^2.

Numerical investigation is under progress to accompany this measured data with CFD simulations in order to further evaluate the ventilation effectiveness of DDOAS-RCS with FS-CE distribution.

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