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Effects of Semi-Open Space on Micro-Environmental Control

Meng Kong[1,*] and Jianshun Zhang[1]

[1]Department of Mechanical and Aerospace Engineering, Syracuse University, NY, USA

[*]*Corresponding email: mkong01@syr.edu*

ABSTRACT
Semi-open space (SOS) is defined as a space semi-confined by partitions in an open space environment. Most of the previous indoor environmental researches were focused on the open space environment, while only a few of them looked into the performance of the SOS. The existence of the SOS is for providing a certain level of privacy to the occupant, but it has been reported that it significantly affects the room air distribution, hence the thermal environment and indoor air quality. The micro-environment control system is defined as a system which provides heating, cooling or ventilation to the occupant locally. In this study, we evaluated the performance of a cubicle, as an SOS in the office, with different configurations, including opening size and orientation, and the combination of the micro-environmental control system and SOS in providing improved indoor air quality. The work included the computational fluid dynamics (CFD) simulation representing a typical office space with one cubicle. The results showed that the cubicle "protects" the occupants from background air flow but this protection may not always be favored, and the location of the pollutant source significantly influenced the performance of the cubicle. The combination of the micro-environmental control system helped create an independent micro-environment as well as offset the effect of the cubicle.

KEYWORDS
Semi-open space, micro-environmental control system, air quality, computational fluid dynamics, cubicle.

INTRODUCTION
Semi-open Space (SOS) is defined as a subspace created by semi-enclosed partitions in a larger open space. A semi-open space, on the one hand, is a partially open space with connections between one SOS and the others as well as the outside space. On the other hand, SOS also provides a relatively independent space. So far most of the ventilation studies are focused on the air distribution in open spaces.

Only a few studies have been conducted to investigate the performance of SOS (Zhang et al. 2007; Demetriou et al. 2008). Jiang et al. (1997) numerically studied two kinds of office configurations with five ventilation strategies and found that the use of partitions significantly affects the uniformity of the supply air distribution. Bauman (Bauman et al. 1991; Bauman et al. 1992) did a very comprehensive work to look into the influence of a series of partition configurations and environmental parameters in a ceiling-ventilated room regarding the thermal environment and ventilation efficiency. After this study, another work (Shaw et al. 1993; Shaw et al. 1993) investigated the effect of the cubicle partition on the air quality. It was concluded that the existence of a cubicle could cause a dead air space inside the cubicle and, hence, an increase of mean age of air. Nevertheless, due to the non-uniformity of the mixing ventilation, different configurations of the workstation and different air supply conditions, the effects of the partitions cannot be generalized.

The micro-environment control system (μX) or personal environmental control (PEC) system is defined as a system which provides heating, cooling or ventilation to the occupant locally. Integrated with an SOS, the μX has a big potential of saving energy while improving thermal comfort level and air quality around occupants as well as providing sound, light, and spatial privacy. This study is focused on investigating how the Semi-Open Space, equipped with or without a μX, would affect the air quality by using the Computational Fluid Dynamics (CFD) model.

METHODS

A CFD model based on the guidelines given by Russo's validated CFD case (Russo, 2011) was developed and further validated by the experimental work (Kong et al. 2017). A 1.8 m × 1.8 m cubicle placed in a typical office space was built in the CFD model (Figure 1). The air quality in all regions in the room was compared for scenarios with and without a cubicle. The effect of the openness of the cubicle was also investigated as well as the opening direction. This work also included the studies on the effects of the cubicle as an SOS in combination with a μX with local air purification.

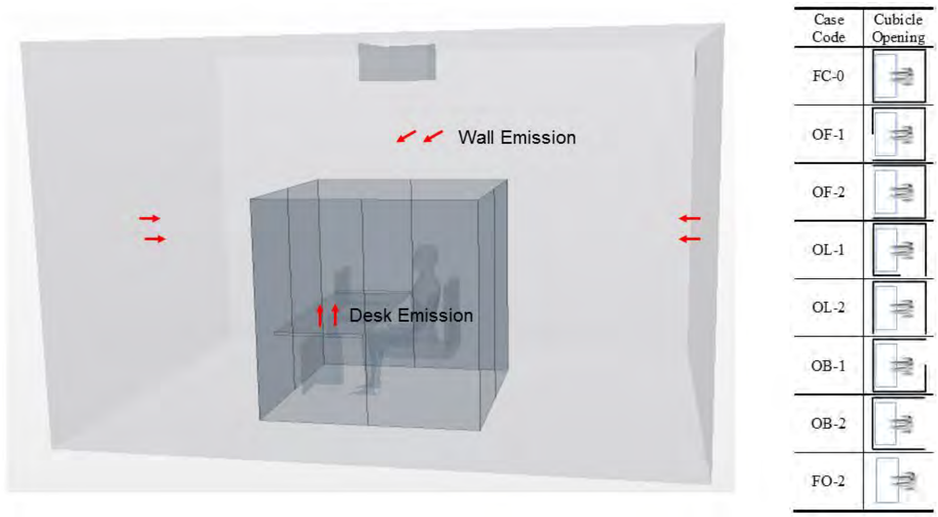


Figure 1 Computational domain and cubicle opening condition

The room modeled is the same as those used in the previous work (Kong et al. 2017). The cubicle was created symmetrically around the desk and seated occupant. The height of the cubicle partition was 1.8 m. All the four sides of the cubicle could be half or fully opened. The boundary condition of each segment of the manikin was set to be constant heat flux. The heat flux value came from the experimental results. The room wall was set to be the same with the indoor temperature set-point (return air temperature) – 26.1 °C for the cases with the μX (because the μX was designed to provide local cooling for elevated room temperature) and 23.9 °C for the case without the μX. The supply air temperature from the μX was set to be 23.0 °C at a flow rate of 0.014 m^3/s. Since this work focuses on how the cubicle configuration, as well as the μX, affects the indoor air quality instead of the actual distribution of specific contaminant, a tracer gas (sulfur hexafluoride, SF_6) was used to represent the pollutant emission. Two emission sources, the wall, and the desk, were simulated in this work (Figure 1). The emission from the wall is used to present the case in which pollutant sources are outside the cubicle and that from the desk to represent the sources inside the cubicle. The μX placed under the table has a supply duct attached to the bottom side of the table and two suction openings on both sides of the box (Kong et al. 2017). When the μX is on, the air purification starts to work by taking in contaminated air and supplying clean air.

In the current work, the Contaminant Removal Efficiency (also called Ventilation Efficiency, ε) and Blocking Coefficient (β), were used to quantify the performance of the ventilation strategies and SOS. The Contaminant Removal Efficiency or Ventilation Efficiency was calculated using Eqn. 1 where C_e is the pollutant concentration in the exhaust, C_s is the pollutant concentration in the supply and C_p is the pollutant concentration in the breathing zone, which is conventionally defined as the zone within a 0.3 m radius of a worker's nose and mouth (OJIMA 2012). Blocking Coefficient was calculated using Eqn. 2 where C_{SOS} is represented by the volume averaged SF6 concentration in the cubicle.

$$e = \frac{C_e - C_s}{C_p - C_s} \tag{1}$$

$$\beta = \frac{C_e - C_s}{C_{SOS} - C_s} \tag{2}$$

RESULTS AND DISCUSSIONS

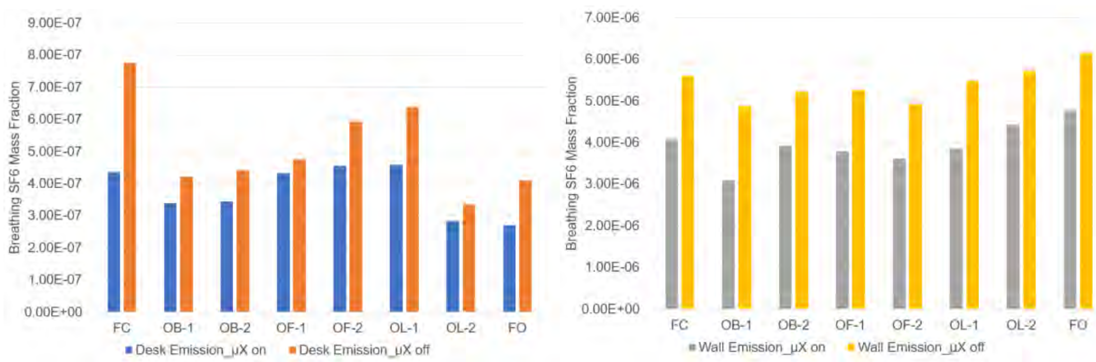
The partitions around the workstation changes the airflow pattern around it, hence the contaminant distribution. However, the performance of the cubicle is dependent on many factors, including the opening direction and size, the location of the contaminant source, as well as whether the μX is on or off.

Pollutant mass fraction level in the breathing zone

Pollutant mass fraction in the occupied space is a direct indication of the air quality. Figure 2a shows the mass fraction level of the SF6 when the pollutant was emitted from the desk. When the μX is off, FC gave the highest pollutant mass fraction in the breathing zone, and the pollutant concentration in the breathing zone was reduced with opened cubicles. After turning on the μX, the effect of the local purification was obvious regardless whether there was a cubicle even though the clean air was not supplied to the breathing zone directly. Figure 2b shows the mass fraction level of the SF6 in the breathing zone when the pollutant was emitted from the wall. Different from the cases of desk source, the pollutant mass fraction in the breathing zone was quite close to each other among the cases without local purification. This is because when the emission was from the walls, the distribution of the pollutant was very uniform, and the air was well mixed before it entered the cubicle. When the μX was turned on with local purification, regardless how the cubicle was arranged, the mass fraction was reduced by almost the same amount.

Contaminant Removal Efficiency

In order to examine the performance of the ventilation system under different configurations of the cubicle, Contaminant Removal Efficiency (e) was calculated in the breathing zone (Figure 3). The results show that when the pollutant was emitted from the desk, the air quality in the breathing zone was not better than the well-mixed condition for any of the cases with or without the μX. The worst efficiency was given by the FC case. The use of the μX could improve the efficiency by more than 20 percent when there was a fully closed cubicle or no cubicle at all. When the cubicle was opened partially the advantage of using the μX became unclear and sometimes negative. This means that when the cubicle was partially opened, adding a local purification in the μX is not necessarily better than adding purification process in the background mixing ventilation. When the pollutant was emitted from the wall, as mentioned before, a well-mixed condition was established in the room including the cubicle, so the *e* in the breathing zone of any cases was around 100%. However, different from the case of the desk source, the use of the μX with local purification always brought an improvement of the air quality in the breathing zone.



(a) (b)

Figure 2 SF6 mass fraction in the breathing zone (a. desk emission; b. wall emission)

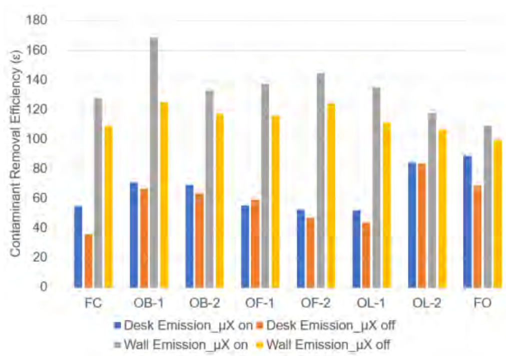
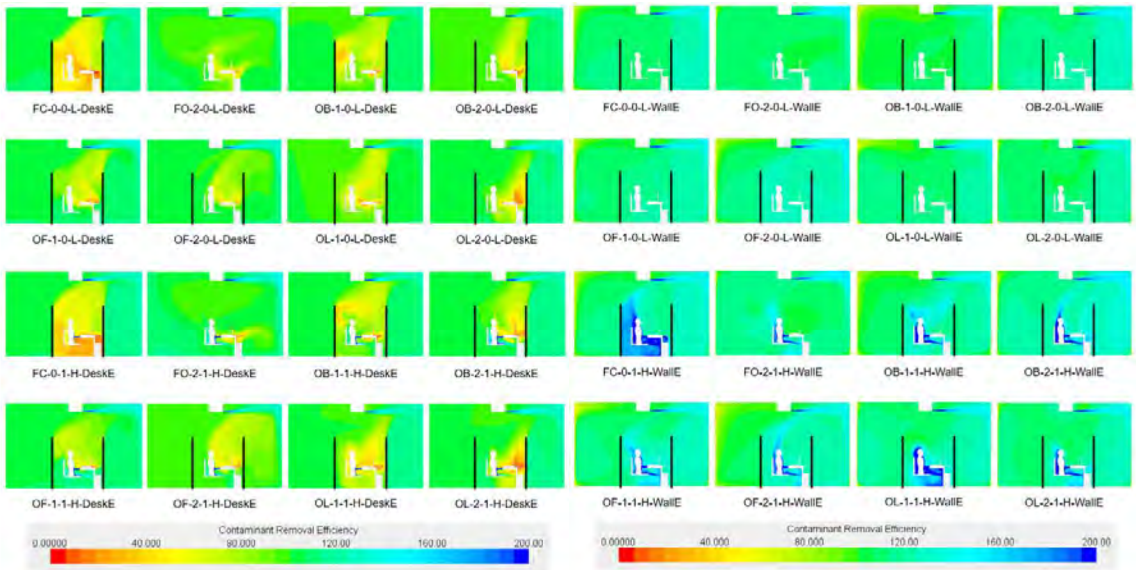


Figure 3 Contaminant Removal Efficiency in the breathing zone

Figure 4a shows the Contaminant Removal Efficiency contours for the cases with desk emission. It was demonstrated that the pollutant distribution in the cubicle was highly non-uniform, especially in the region close to the desk. The dirty air carrying the pollutant from the desk was mixed with the surrounding air in the cubicle and then was pulled out of the cubicle due to the entrainment of the supply jet of the background mixing ventilation. The make-up air entered the cubicle in different ways depending on the opening direction and size and diluted the air in the breathing zone. A local jet of clean air was observed when the μX was turned on. However, since the local supply air was maintained at a lower temperature than the ambient room air, most of the local clean air, instead of entered the breathing zone, was transported downward to the lower region and mixed with the dirty air carrying the pollutant from the bottom side of the desk. This should be the reason why the μX brought little improvement of the contaminant removal efficiency in the breathing zone. Figure 4b shows the Contaminant Removal Efficiency contours for the cases with wall emission. Different from the cases of desk emission, the pollutant distribution of the wall emission cases was much more uniform and well-mixed. When the μX was turned on, a clean jet, as well as a clean region, showed up around the occupant. This clean region effectively reduced pollutant concentration in the breathing zone and increased the contaminant removal efficiency. Comparing these cases with the cases of desk emission, the reason why the μX could improve the air quality more effectively is that in the lower region of the cubicle there was no pollutant source and therefore the cooler clean air remained clean before it was taken by the thermal plume to the breathing zone.



(a) (b)

Figure 4 Contaminant Removal Efficiency (a. desk emission; b. wall emission)

Blocking Coefficient

Blocking Coefficient (β) is an index to quantify the performance of the SOS. It is a ratio between the exhaust pollutant concentration and the pollutant concentration in the SOS. Figure 5 illustrates the blocking coefficient of the cubicle. When there was no cubicle, the blocking coefficient was around 100% regardless where the emission source was. When the pollutant was emitted from the desk, β was always less than 100%. A fully closed cubicle (FC) gave a blocking coefficient less than 40%, and a partially opened cubicle gave a blocking coefficient between 60% and 80%. In this case, the µX did not make a big difference because it reduced the pollutant level in the cubicle as well as the pollutant level in the exhaust. When the pollutant was emitted from the wall, the β was always higher than 100%. Without the µX, β was a little higher than 100% with a maximum of around 120%. Turning on the µX could significantly improve the blocking coefficient, and the most improvement was given by the fully closed cubicle in which the blocking coefficient was increased by 30%. This is because the fully closed cubicle could hold most of the clean air made by the µX inside the cubicle.

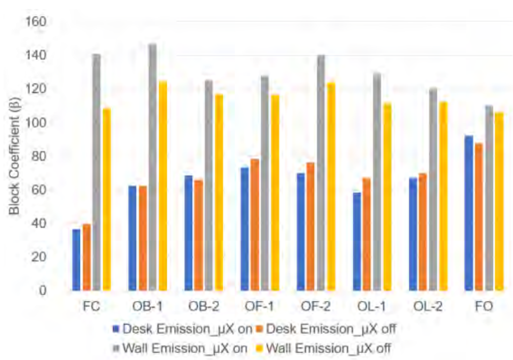


Figure 5 Blocking Coefficient of the cubicle

CONCLUSIONS

The effects of the cubicle and the combination of the μX with air purification in the cubicle on the air quality were evaluated using CFD simulation. The results indicate that the performance of the cubicle that defines the semi-open space was highly sensitive to the location of the emission location and it should be used and designed with caution. When the pollutant was emitted inside the cubicle, the use of the cubicle was unfavoured since it prevented the contaminant from being diluted by the mixing ventilation. However, when the pollutant was emitted from outside cubicle, the use of it should be encouraged since it helps prevent the contaminant from entering the cubicle. The use of the μX with local air purification could always improve the air quality in the breathing zone, and especially when the emission source was outside the cubicle, it demonstrated a big advantage. However, this combination might not be more efficient than adding the same amount of purified return air to the background mixing ventilation system when the emission source was inside the cubicle. In general, the use of the μX with local air purification is beneficial for improving the air quality in the breathing zone and the cubicle, reducing the pollutant concentrations by 10 to 44%.

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