7th International Building Physics Conference

IBPC2018

Proceedings

SYRACUSE, NY, USA
September 23 - 26, 2018

Healthy, Intelligent and Resilient Buildings and Urban Environments

ibpc2018.org | #ibpc2018

Experimental Study on the Impact of Passive Chilled Beam in a Room with Displacement Ventilation

Zhu Shi[1], Vishal Anand[1] and Qingyan Chen[1,*]

[1]School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907, USA

[*]*Corresponding email: yanchen@purdue.edu*

ABSTRACT

Previous studies have demonstrated that displacement ventilation (DV) can provide better air quality than mixing ventilation (MV), and may save energy in buildings. However, since DV introduces supply air to the occupied zone directly, the temperature of supply air it provides is normally higher than in a MV system, so the ability to remove cooling load is limited with the same amount of air. On the other hand, passive chilled beam (PCB) systems have been shown to be able to remove a large cooling load while saving energy. Therefore, this research studied a coupled configuration that combined DV and PCB, and examined its thermal and ventilation performances through the measurements of airflow velocity, temperature, and contaminant (simulated by sulfur hexafluoride, or SF_6) concentration at various locations. Measurement results were compared with those in the same room but with only DV system. A third set of measurements was also conducted to test how sensitive the results were to room layout and ratio of heat removed by PCB.

Experimental results showed that PCB increased the overall air flow velocity in occupied zone, although the maximum airflow velocity was still observed at floor level, which was similar as in a DV only system. When both PCB and DV systems were used, temperature gradient was observed in most locations of the room. Meanwhile, contaminant concentration stratification was seen to be destroyed by PCB in this experiment. Similar trend was observed in the third set of measurement which had a different room layout and a lower ratio of heat removed by PCB.

KEYWORDS

Passive Chilled Beams, Displacement Ventilation, Coupled System, Indoor Environment

INTRODUCTION

Starting from 1980s, displacement ventilation (DV) has been increasingly commonly used in both Europe and U.S. buildings, especially in industrial and office applications (Svensson, 1989; Burt, 2007). Although this ventilation method demonstrated stronger capability in improving air quality and saving energy, when compared with mixing ventilation (MV), one limitation it has is its relatively low ability to remove cooling load, since it supplies fresh air to occupied zone directly. To remedy this weakness, suggestions were made in previous literatures (Riffat et al., 2004; Schiavon et al., 2012) to conjugate DV with other systems. Among the different possible systems to combine DV with, passive chilled beam (PCB) seems to be a very potential option, due to its shown ability to remove large cooling loads (Kosonen et al., 2010). Hence, there needs an investigation on a conjugate system of DV and PCB, to explore how well the merits of these two methods could be integrated.

In the study of indoor environment design, experimentation has always been an important and necessary method for us to understand the physics inside a room, as well as to appraise the design. For example, to evaluate thermal comfort levels using two well recognized empirical models, PMV (predicted mean vote) (Fanger, 1970) and PD (percentage dissatisfied people due to draft) (ASHRAE, 2013), information on airflow velocity, temperature and turbulence intensity is needed as input. Also, to quantify the air quality via contaminant removal effectiveness, it needs contaminant concentration data at various locations of the room, which could be measured through experiment. Moreover, accurate experimental measurements can provide high-quality data for boundary condition specifications in simulations (such as computational fluid dynamics, or CFD simulations) and model validations.

Therefore, this investigation used experimental methods to measure the airflow velocity, temperature and contaminant (simulated by sulfur hexafluoride, SF_6) concentration in an indoor air quality (IAQ) chamber which was equipped with the conjugate system of DV and PCB. In the measurement of each type of data, experimental data was collected at 35 locations which were evenly distributed in the chamber that had an office layout. For comparison, a corresponding experiment was performed in the same chamber but with only DV system. This study also explored how sensitive the measured results were to the room layout and PCB cooling power by performing measurements in a third case that had a classroom layout. Through comparing results in the three measurement cases, this study summarized the impacts that PCB made on a DV system in several aspects.

METHODS

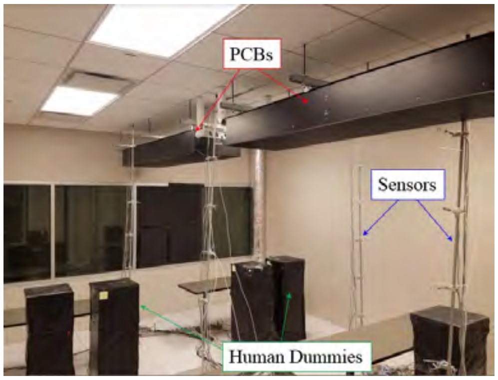
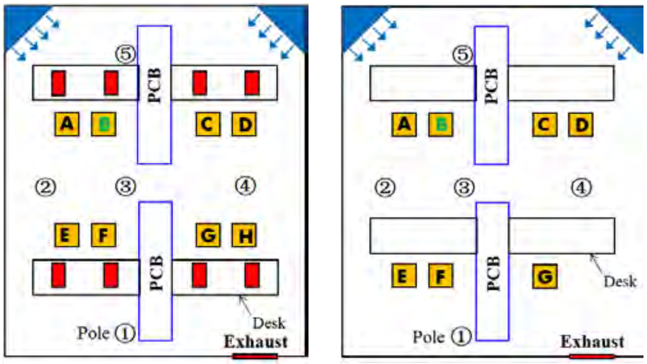


Figure 1. Inside view of IAQ chamber



(a) Office Case_0 and Office Case_1

(b) Classroom Case

Figure 2. Room layouts in 3 measured cases (Red box: PC; Yellow box: humman dummy)

Figure 1 shows the IAQ chamber where experiments were performed. In the chamber, two displacement ventilation diffusers were installed next to the floor, while the exhaust was placed near ceiling. Two pieces of PCBs were suspended on the central plane of the room, near the ceiling. Heated boxes were used to simulate occupants and computers in the room (Figure 2). Table 1 specifies the total cooling loads, number of heated items, and PCB utilizations in all three measured cases.

Table 1. Cooling loads and PCB utilizations in three cases

Case Name	Total Cooling Load	Cooling load breakdowns (Number of items)			Ratio of Heat Removed By PCB
		Light	Human Dummy	PC	

Office Case_0	61 W/m^2	4	8	8	0 (PCB not used)
Office Case_1	61 W/m^2	4	8	8	60%
Classroom Case	30 W/m^2	4	7	0	40%

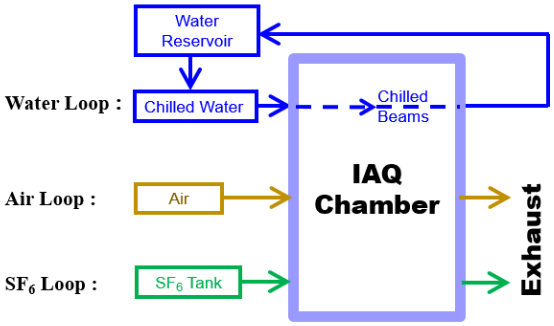


Figure 3. Three “loops” that run through the chamber

This experiment designed three loops that ran through the IAQ chamber, which is illustrated in Figure 3. Chilled water was supplied from water reservoir, and after travelling through pipes inside PCB’s, it still returned to water reservoir. Air was discharged into the room via displacement ventilation diffusers. With a developed LabView program, the air flow rate and temperature could be well controlled. Lastly, SF_6 was provided from an SF_6 tank outside of the chamber, and was discharged in the chamber on top of one human dummy (at a height of about 1.1m). All the operations of the three loops could be performed outside of IAQ chamber.

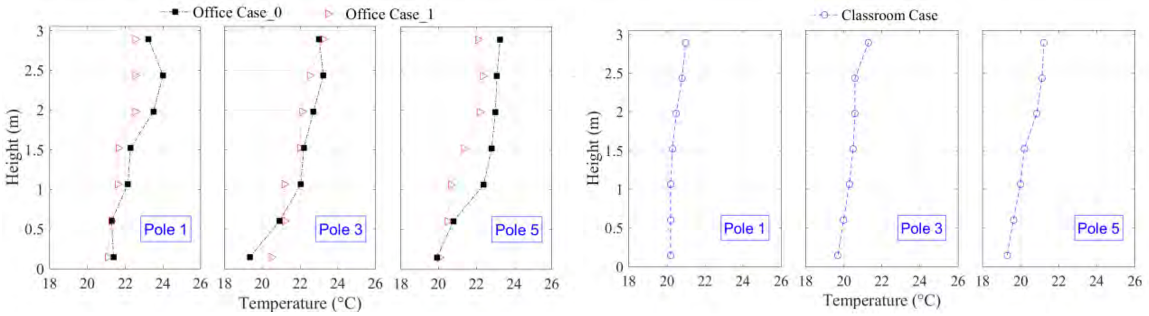
To obtain airflow velocity and temperature data, this experiment employed hot-sphere anemometer probes, whose temperature measurement accuracy is ±0.3 °C and velocity measurement accuracy is ±0.01m/s. In addition, a multi-gas sampler, monitor and analyser system was utilized to measure SF_6 concentration at desired sampling points. In each measurement case, data was collected on 5 poles in the room, with 7 heights at each pole.

RESULTS

This section illustrates and compares the results from the three measurement cases described in the above section. Due to the limit of space in this paper, results from only 3 of the 5 measured poles are demonstrated. However, three locations are sufficient to indicate the air flow characteristics and contaminant distributions in the three measured cases. Results from more measurement locations could be found in Shi and Chen (2018).

Temperature results

Figure 4(a) shows the temperature distributions in “Office Case_0” and “Office Case_1”. “Office Case_0” demonstrated a very typical temperature distribution in a displacement ventilation case, where a clear temperature gradient could be observed at various locations of the room. Temperature gradient was seen to be largest at near-floor region, especially when the measured locations were relatively close to displacement ventilation diffuser (like Pole 3 and 5), and gradually decreased as the height increased. Meanwhile, in “Office Case_1”, although PCB was turned on and was removing 60% of heat in the room, temperature gradient was observed as well in three measured locations. This indicated that the cold downward jet PCB generated was pretty local. In addition, it could be noticed that PCB was able to decrease the temperature gradient when “Office Case_0” and “Office Case_1” were compared.

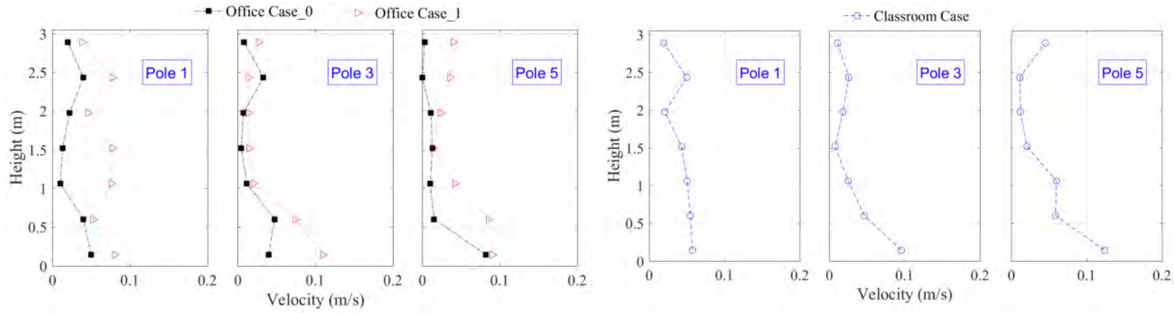


(a) “Office Case_0” and “Office Case_1” (b) “Classroom Case”

Figure 4. Temperature measurement results

“Classroom Case” also showed similar temperature distribution trend, as can be seen from Figure 4(b), although it had a different room layout and a different ratio of heat removed by PCB.

Velocity Results



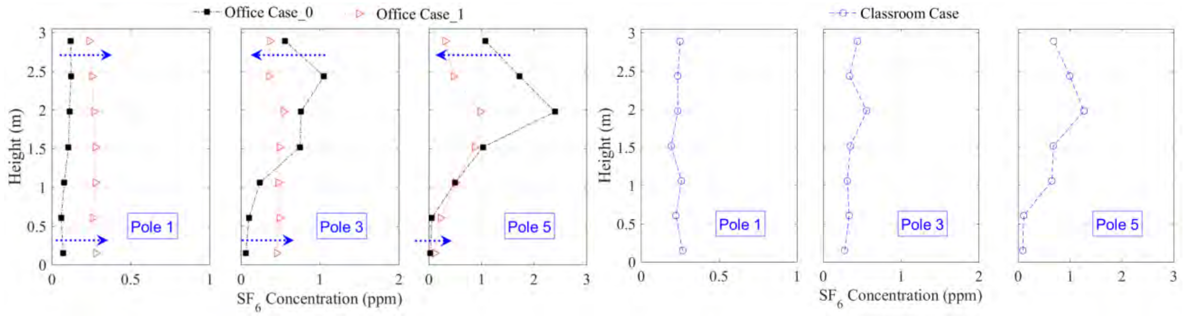
(a) “Office Case_0” and “Office Case_1” (b) “Classroom Case”

Figure 5. Velocity measurement results

Figure 5 illustrates velocity distributions in three measured cases. Again, results in “Office Case_0” showed a typical velocity distribution in a displacement ventilation, in which airflow velocity was largest near floor, and became very small as the height enters occupied zone. However, when PCB was turned on, although largest airflow velocity was still observed at floor level, PCB seemed to increase the airflow velocity in occupied zone, as could be observed in the comparison in Figure 5(a). This could be because the air movement was intensified by entrainment induced by PCB downward jet, which could also explain why airflow velocity was seen to have increased more at poles placed close to PCB than poles placed further away from PCB.

Airflow velocity distribution in “Classroom Case” showed a similar trend as “Office Case_1”, and its airflow velocity magnitude in occupied zone was seen to be between “Office Case_0” and “Office Case_1”.

Contaminant Concentration Results



(a) “Office Case_0” and “Office Case_1” (b) “Classroom Case”

Figure 6. SF$_6$ measurement results

Contaminant concentration distributions are demonstrated in Figure 6 (Note that scales in plots of three poles are different.). Results showed that in “Office Case_0”, there was a clear contaminant stratification at locations (e.g. Pole 3 and Pole 5) close to where SF$_6$ was released. At locations that were relatively far away from SF$_6$ release location, SF$_6$ concentration was seen to be always low from floor to ceiling levels. This could be explained by the fact that in a DV system, contaminant is lifted to the upper part of a room until leaving the room through exhaust, which verified the satisfying contaminant removal effectiveness of DV.

When PCB was turned on, however, the contaminant stratification seemed to be weakened, as observed at Pole 5. Meanwhile, at locations that were further away from PCB, overall SF$_6$ concentration was seen to be increased, although the concentration level was still quite similar from floor to ceiling. This was because PCB, while turned on, generated downward jet and pushed SF6 from top region to the lower region of the room. As a result, the SF$_6$ that was pushed down could re-distribute itself after it hit the floor or desk, and moved horizontally to other locations. In “Classroom Case”, the SF$_6$ distribution was seen to be similar as “Office Case_1”, The concentration levels at different locations, though, were about in between “Office Case_0” and “Office Case_1”, which could be due to that the ratio of heat removed by PCB (40%) in “Classroom Case” was in between of 0 and 60%.

DISCUSSIONS

This investigation reported detailed measurement results of airflow velocity, temperature and SF$_6$ concentrations at three experimental cases, which was valuable for improving the understanding of ventilation and thermal performances of a combined system of DV and PCB. To better evaluate an indoor environmental design, however, there might need more analysis of the measured data by employing indices for appraising thermal comfort and indoor air quality, such as PMV and contaminant removal efficiency. Besides, although measurements took place at as many as 35 locations in each of the measured cases, the resolution of data obtained from measurements was relatively low as compared to a validated CFD simulation. Therefore, at a later stage, adopting indoor environmental appraisal indices and employing CFD method would yield an even more comprehensive study to the current research.

CONCLUSIONS

This research leads to the following conclusions:

(1) With the experimental apparatus that was set up in this research, detailed measurements could be performed to obtain airflow velocity, temperature, contaminant concentration

data in the IAQ chamber. Results from "Office Case_0" showed a typical airflow and contaminant distribution in a DV only system.

(2) While PCB was used together with DV system, large temperature stratification was observed in most regions of the room, although PCB could produce a local downward jet. Besides, the downward cold jet was able to entrain ambient air, which resulted in slightly increased airflow velocity in occupied zone.

(3) Experimental results showed that PCB, while turned on, could weaken or even destroy the contaminant stratification built up by DV. The higher percentage of heat was removed by PCB, the more the contaminant stratification appeared to be destroyed.

(4) This research demonstrated that the observed impacts of PCB made in an office layout was also seen in a room with a different room layout, as could be observed in "Classroom Case". Therefore, conclusions (2) and (3) could still apply when room layout changes.

ACKNOWLEDGEMENT

The authors would like to thank ASHRAE for funding this research project via ASHRAE RP-1666.

REFERENCES

ASHRAE. 2013. *ANSI/ASHRAE Standard 55-2013*, Thermal Environmental Conditions for Human Occupancy. Atlanta: American Society off Heating, Ventilating and Air-conditioning Engineers, Inc.

Burt L. W. 2007. Life cycle cost of displacement ventilation in an office building with a hot and humid climate. *Ph.D. Dissertation*, University of Florida.

Fanger P.O. 1970. *Thermal Comfort*. Copenhagen: Danish Technical Press.

Kosonen R., Saarinen P., Koskela H., and Hole A. 2010. Impact of heat load location and strength on air flow pattern with a passive chilled beam system. *Energy and Buildings*, 42(1), 34-42.

Riffat S. B., Zhao X., and Doherty P. S. 2004. Review of research into and application of chilled ceilings and displacement ventilation systems in Europe. *International Journal of Energy Research*, 28(3), 257-286.

Schiavon S., Bauman F., Tully B., and Rimmer J. 2012. Room air stratification in combined chilled ceiling and displacement ventilation systems. *HVAC&R Research*, 18(1-2), 147-159.

Shi Z. and Chen Q. 2018. Thermal comfort analysis of displacement ventilation system coupled with passive chilled beams. Accepted by: *5^{th} International High Performance Buildings Conference at Purdue*.

Svensson A. G. L. 1989. Nordic experience of displacement ventilation system. *ASHRAE Transaction*, 95(2), 1013-1017.