Energy and Indoor Air Quality Analysis of Mixed Air and Displacement Ventilation Systems

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ABSTRACT

Indoor pollutants and particles pose a threat to human health as people spend 90% of their time in indoor spaces. A proper ventilation system should be able to remove indoor air pollutants, reduce particle depositions, at the lowest energy consumption by that system. In this work, particle concentrations and depositions are presented for two ventilation configurations (1) Displacement Ventilation (DV) and (2) the conventional ceiling supply and return. From previous work, energy analysis conducted showed that DV systems supported by chilled ceilings were able to supply cooling and reduce the total energy demand by 53% than the conventional system. Nonetheless, with this energy reduction, the DV system cannot remove as much particles as the conventional ceiling supply and return, causing more particles to deposit which is a problem as deposited particles can resurface again when there are floor disturbances like walking and vacuuming. To benefit from the energy reductions of the DV system supported by the chilled ceiling, a recommendation of a reversed DV system was numerically studied, showing lower particle depositions and concentration.

KEYWORDS

Indoor air quality, Particle Exposure, Ventilation systems

1 INTRODUCTION

Most heating, ventilation and air conditioning engineers and designers (HVAC) focus on indoor air quality (IAQ) and thermal comfort when designing any HVAC system for either commercial or residential buildings. Providing an appropriate IAQ to indoor spaces and occupants remain to be an important parameter and challenge to any HVAC system to limit contaminant formation or transport in those spaces with reducing the energy consumed by that system.

Commercially, introducing outdoor ventilation air, and adding more filtration are two methods of maintaining a suitable IAQ. The flow rate of outdoor air being to be supplied to an indoor space is specified in ASHRAE Standard 62.1, depending on the number of occupants, the floor surface area, and the human activity level of individuals in indoor spaces or zones. Outdoor ventilation air maintains an acceptable IAQ by diluting pollutants in indoor spaces. The higher the ventilation rate the more dilution there is for pollutants, the healthier indoor air is for occupants (Dimitroulopoulou, 2012). Nonetheless, this method is challenging due to the unpredictable variations in indoor spaces occupancy. This could result in engineers overdesigning the HVAC system to accommodate more people than needed. Higher outdoor ventilation rates will result in more energy consumption, which opposes the current need to have energy efficient buildings (Sheng et. al. 2018). Hesaraki et al. (2015) studied the effects of changing the fresh airflow rates, considering the corresponding CO_2 concentrations within indoor spaces, to limit the outdoor airflow rates, reducing energy consumption in cooling fresh air.

The other method of providing a suitable IAQ, is filtration. Filters now have different efficiencies and capabilities of removing contaminants, defined in the minimum efficiency reporting value (MERV). Most ventilation systems are equipped with filters to reduce particle concentrations in indoor air. Nonetheless, Weschler, (2003) reported that surface area of filters is always changing, depending on the particle sizes that are being trapped and time of which the filter was used. As the filter is trapping more particles the pressure difference through the filter increases, resulting in a drop of air flow to indoor spaces if not adequately and periodically cleaned. Researchers investigated an air-handling unit, equipped with several pocket filters and found that the indoor particle concentration levels decreased by 34% (Jamriska et al. 2000). Moreover, using high efficiency particulate air filters (HEPA) with MERV ratings of 19 and 20, have an extremely high-pressure drop, and require blowers with high static pressure supplies that are only present in air handling units, and commercial air package units to be able to supply air to indoor spaces (Rudnick, 2004). Such applications maybe suitable for commercial buildings and hospitals, but is unfit for residential applications, that have a lower cooling load and energy consumption demand.

Airborne particles removal from indoor spaces requires an in depth understanding of transport activities of micro particles under various ventilation systems. While ventilation systems are installed to ensure thermal comfort to residents and occupants, they are also designed to decrease the concentration of the pollutants in indoor spaces and ensure minimal deposition and re-deposition fractions over surfaces and floors (Gradon 2009), while including the likelihood of the direct inhalation of these particles by the occupants breathing close to these surfaces. For this reason, it is important to remove the particles from indoor environments by installing the proper ventilation systems (Makhoul et al. 2013).

The aim of this paper is to study the effect of mixed air (MA) and displacement ventilation (DV) systems capacity to remove indoor particles and pollutants, when particles were generated on the floor level and considering the energy consumption of both systems. A review on energy analysis of the DV system aided by chilled ceiling cooling will be explained from (Bahman et al. 2009). Furthermore, an experimental setup was built to test the particle removal capacities of both systems, and the coil load for the MA system was determined from experimental data. Later a new system bas on the DV system was suggested and the particle removal capacities of this system was also determined.

2 PARTICLE REMOVAL EFFECTIVENESS FOR DIFFERENT VENTILATION SYSTEMS

To determine the capability of each ventilation configuration in removing indoor contaminants, a ducting system was built to accommodate different ventilation systems, in a room of dimensions (4.95 m × 4.5 m × 2.5 m). The systems are (1) Mixed air ceiling supply and return, and (2) Displacement Ventilation (Floor Supply and Ceiling Return). The ducting system was designed and manufactured to ensure that each system operates separately, by adding volume control dampers (VCD) in each supply and return vent, to control the air-flow rate, and to shut the air supply and return when needed. (Figure 1)

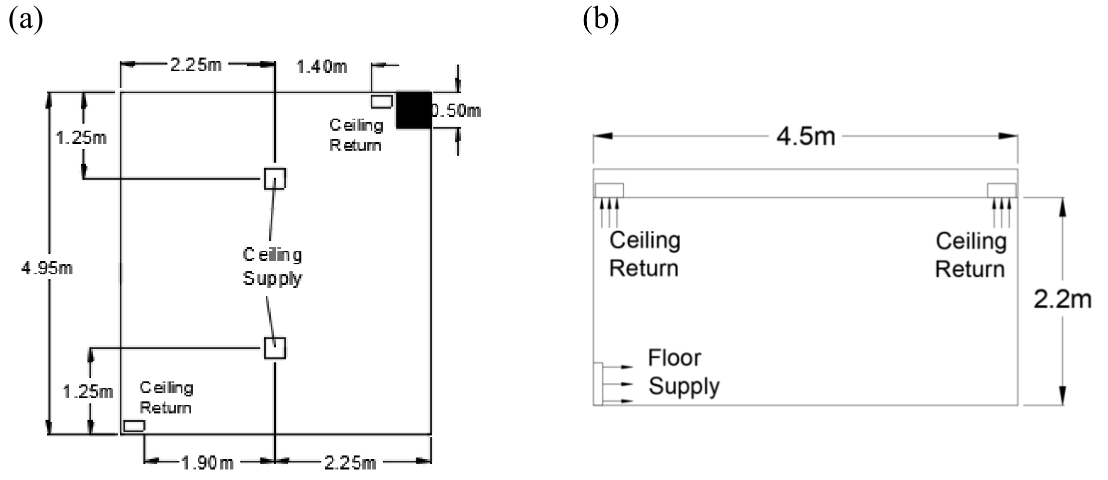


Figure 1: Schematic for both systems (a) Mixed air ceiling supply and return (b) Displacement Ventilation

For each ventilation configuration, the room temperature and humidity were maintained at 24°C and 50%, respectively. The lighting load of the room was at 10 W/m^2. A roof load of 222 W and a uniformly distributed walls load of 10.96 W/m^2 were present. System (1) has two supply diffusers each supplying 200 CFM and system (2) has one supply providing 400 CFM. To avoid infiltration through the building envelope, the total supply air flow is 400 CFM at 18°C, the return flow rate is 360 CFM, and the indoor pressure was maintained at 102.5 kPa. In addition, 40 CFM of fresh air mixed with the return air in accordance with ASHRAE Standard 62.1, for the flow per floor unit area and the assumption of two occupants in the room with activity corresponding to two seated adults.

Particles with known sizes and densities were generated via a Condensation Aerosol Monodisperse Generator. The generator was set to constantly produce particles of 2.5 μm diameter and 912 kg/m^3 density at a rate of 4 L/min with an aerosol geo-metric standard deviation lower than 1.1 (Figure 2a). The particles were generated simultaneously at different locations of the room on the floor level, to simulate the effect of having more than one source of indoor pollution. This was done by the means of a conductive tubing network composed of seven outlets was attached to the floor. Each outlet was equipped with a valve to control and equate the output flow rate of the particles (Figure 3). Particles where generated for 1 hour until steady state condition were reached. The Optical Particle Sizer (OPS) was used to measure the particle concentration by sampling 1 L/min of air at the desired location (Figure 2b).

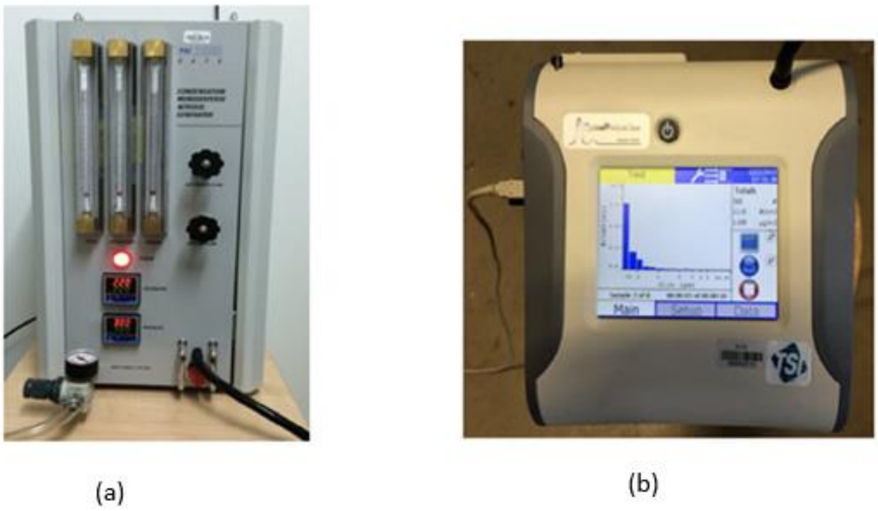


Figure 2: (a) Condensation Aerosol Generator and (b) Optical Particle Sizer

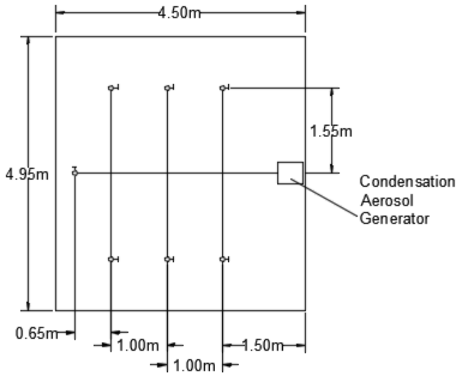
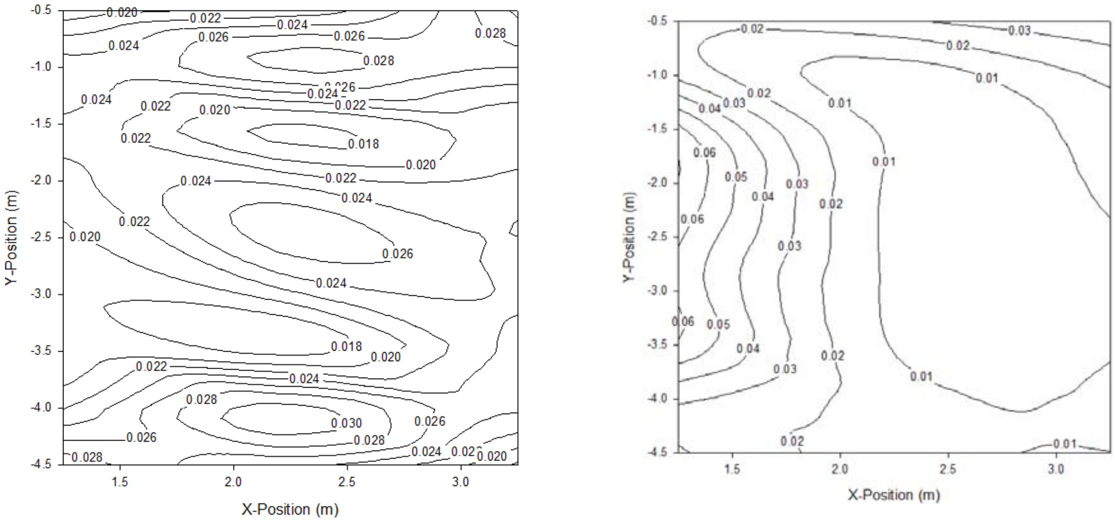


Figure 3: Position of particle outlets with valves on the floor

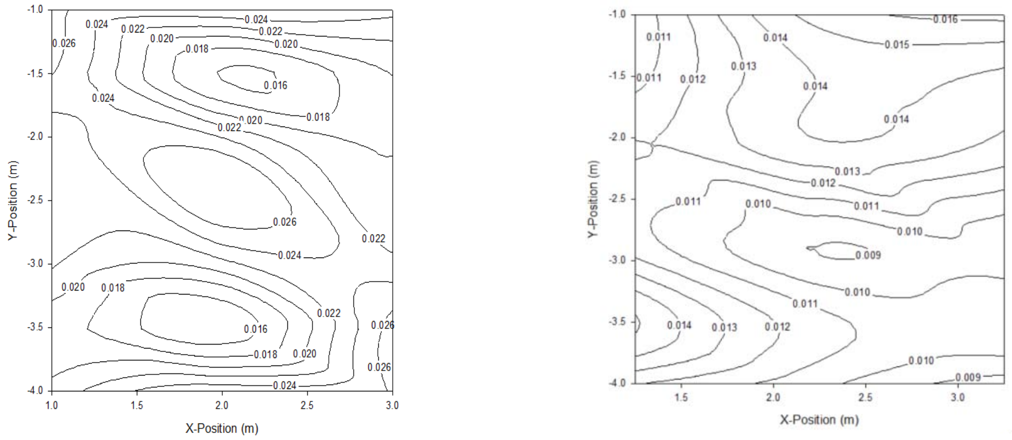
3 RESULTS AND DISCUSSION

Average normalized particle concentrations (AOC) is the ratio of the particle concentrations at a given position to the total particle concentration generated. The AOC percentages distributions for each ventilation system were compared at the floor level (Figure 4) and in the occupied zone (Figure 5). The occupied zone is the average concentrations from 20-cm to 180-cm from the floor level. The AOC percentages are in both figures as contour plots around the room.



(a) **(b)**

Figure 4: AOC percentages on the floor for (a) MA ceiling supply and return and (b) DV



(a) **(b)**

Figure 5: AOC percentages in the occupied zone for (a) MA ceiling supply and return and (b) DV

From Figures 4 and 5, it can be seen that the DV system has a higher AOC percentage on the floor than the MA ceiling supply and return. Whilst on the other hand, the AOC is higher in the MA within the occupied zone than the DV. This is not due the DV removing more particles the MA, but rather the fact the DV system is confining more particles below the 20 cm height from the floor, forcing them to deposit on the floor. To validate that, the AOC within the return vents are shown in Table 1, where the return AOC for MA is higher than the DV one, showing that less particles are going toward the return vents. So the DV system is incapable of removing particles from indoor air and is confining them to the floor, which is dangerous when floor disturbances occur due to walking, vacuuming, and movement of toddlers.

Table 1: AOC x 10^{-4} in the return vents for both configurations

Ventilation System	**AOC x 10^{-4}**
MA Ceiling Supply and Return	3.612
DV Displacement Ventilation	1.193

With that being said, a good ventilation system is able to provide a suitable IAQ to indoor spaces and occupants, with the least energy consumption. By looking at previous work, a suggestion of a suitable system that meets both criteria is needed. Firstly, studying the DV system assisted with the chilled ceiling (CC) has the several characteristics. The DV system here solely supplies 100% fresh to the room on the floor level, displacing the warmer air to the top part of the room, placing fresh cool air at the occupied zone of the room. All contaminated air is exhausted out of the room with non-recirculated back to the room. Designing the DV with the CC requires simultaneous knowledge and meeting several parameters including thermal comfort and IAQ in the room, avoiding presence of any humidity condensate on the CC. To achieve this the supply air conditions and the CC temperature need be continuously monitored and controlled. Figure 6 shows the DV system assisted by CC from Bahman et al. (2009).

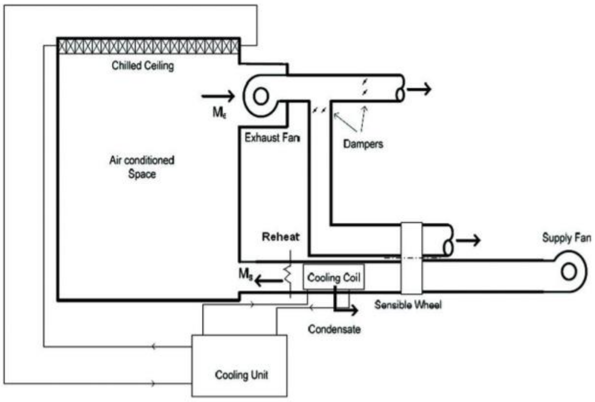


Figure 6: Schematic for the DV system with chilled ceiling system (Bahman el al. 2019)

Figure 7 compares the conventional system at 100% fresh air, with DV assisted by CC, in the month of July. As it can be seen, the conventional system has used almost twice as more energy than the DV assisted by CC. An estimated 53% reduction in energy consumption is recorded for the DV/CC system. Nonetheless, when the DV/CC is compared to 30% fresh air conventional system, the conventional system reported lower energy consumption rates. However, there will be lower air quality in the conventional 30% fresh air system than the DV/CC, as the DV/CC has 100% fresh air supplied to the occupied zone of the room.

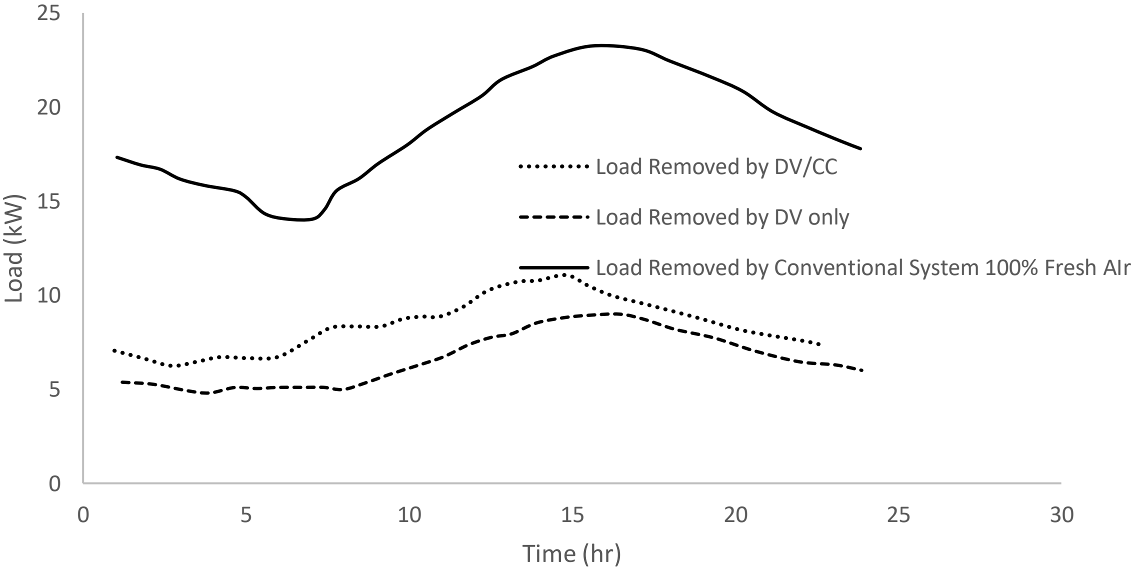


Figure 7: Hourly variation of system cooling load in July at 100% fresh air supply for conventional system and DV/CC system (Bahman et al. 2009)

Despite the good results of the DV/CC system, it is still expensive to have any ventilation system supplying cooled 100% fresh air, especially in hot and dry climates like Kuwait where HVAC consumes 70% of Kuwait's load in the summer, using low fresh air supply conventional mixed air systems. In this work, it is out of question to use 100% fresh air, so to save energy, ASHRAE standard 62.1 was used to determine fresh air quantity, which accounts for 10% of the room supply air flow rate.

The daily average coil load was evaluated for the MA ceiling supply and return and found to be 7.35 kW. When compared with the average coil load for the DV/CC, it was found to be 9.69 kW. However, keep in mind the the DV/CC is 100% fresh air, and if the fresh air is lowered and recirculated air is introduced, the coil load with significantly decrease.

A proposed solution is to obtain an energy efficiency similar to DV/CC, and provide a decent IAQ, while implementing a reversed displacement system that can remove more particles than both DV and MA ventilation systems. The DV systems assisted by chilled ceiling was more capable in cooling than DV working solely (Figure 7). DV/CC systems was capable of to reduce the energy consumption by 53% compared to the conventional system. Chakroun et al. (2019) numerically investigated a validated CFD model the reversed DV system and compared it to the MA ventilation system during vacuuming. Due to the difficulty and expenses of rebuilding the testing facility to accommodate a reversed DV, a validated CFD model on ANSYS/Fluent was more suitable to for this application. Figure 8 shows the drop in particle concentrations of 1 μm sizes between the MA ventilation system and the reversed DV system, where the drop is significant from the floor to the 180-cm. This shows that reversed DV systems can be used to improve indoor air quality, and if there is collaboration between the reversed DV and CC, then similar coil load reductions to the DV/CC can be achieved.

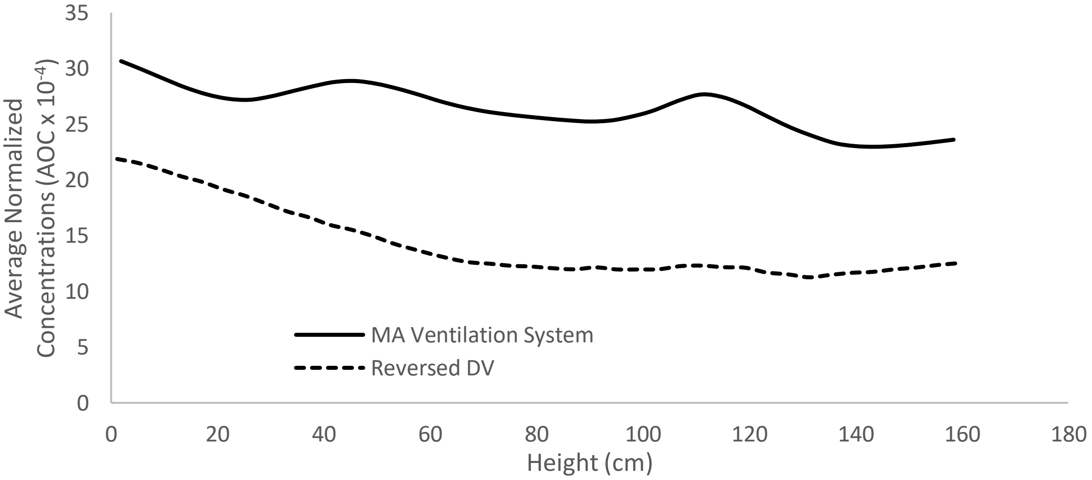


Figure 8: Comparison between MA system and reversed DV AOC's (Chakroun et al. 2019)

4 CONCLUSIONS

The effect of mixed air (MA) and displacement ventilation (DV) systems capacity to remove indoor particles and pollutants, and energy performance was investigated. A review on energy analysis of the DV system aided by chilled ceiling cooling will be explained from Bahman et al. (2009) and found that an estimated 53% reduction in energy consumption is recorded for the DV/CC system compared to conventional MA systems at the same fresh air rate. Nevertheless, it is still expensive to have any ventilation system supplying cooled 100% fresh air, especially in hot and dry climates like Kuwait where HVAC consumes 70% of Kuwait’s load in the summer, using low fresh air supply conventional mixed air systems. DV system is confining more particles below the 20 cm height from the floor, forcing them to deposit on the floor, unlike the MA ventilation system which is allowing more particles to escape to the return vents, A proposed reversed DV system was able to remove far more particles, and a lower energy consumption if applied with chilled ceiling.

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