A FIELD STUDY OF THE AIR CHANGE EFFECTIVENESS OF OVERHEAD AIR DISTRIBUTION AND DISPLACEMENT VENTILATION IN HEALTHCARE

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ABSTRACT

There is a considerable body of work demonstrating that the ventilation effectiveness of displacement ventilation (DV) systems are significantly higher than those of overhead air distribution (OHAD) systems (Lee et al, 2009), (Zhang, 2007), (Jung and Zeller, 2004). The objective of this study was to evaluate the performance of a displacement ventilation system in an occupied building. The ventilation effectiveness in two patient rooms equipped with displacement ventilation systems compared to that of an identical patient room with a mixing system in an occupied hospital in Modesto, California. The study included tracer gas measurements as well as computer modeling in order to evaluate the ventilation effectiveness of each system. The study indicates that the use of a displacement ventilation system reduced the average age of air in the patient rooms, compared to the mixing system, even at reduced air change rates. This result builds on prior work and provides additional motivation for the adoption of DV systems in patient rooms.

INTRODUCTION

Indoor environmental quality (IEQ) is one of the most important design considerations for the healthcare facility design engineer. The healthcare industry in general is also known to be one of the most energy intensive (Griffith et al., 2008). For years, codes and design best practices have ensured that these facilities provide the best protection against infection for the patient, healthcare providers and visitors. Lately, these design goals have been coupled with an effort to also create an environment that promotes recovery. To this end, patient rooms and waiting rooms, along with most other areas in a hospital, have prescriptive guidelines which outline the ventilation and air change rates in an effort to maintain the IEQ at an acceptable level.

The typical solution for patient and waiting rooms today is ceiling based air distribution where filtered air is injected at the ceiling level at high velocity. This air then mixes and dilutes the room air at a rate set by the American Society for Heating, Refrigeration and Air Conditioning Engineers (ASHRAE, 2008), the American Institute of Architects (AIA, 2006) or by local codes in order to fully change the air in these rooms several times per hour.

Recently, there has been growing interest in the use of alternative air distribution strategies in order to maximize IEQ while minimizing energy use in several non-critical areas in hospitals. One such strategy is displacement ventilation. Displacement ventilation has long been demonstrated to provide improved performance in all mechanically related areas of IEQ, namely, indoor air quality (IAQ), acoustics and thermal comfort. There are several indicators and methods to evaluate the IAQ in an occupied space, with air change effectiveness (ACE) and contaminant removal efficiency (CRE) being two of the most common. This paper evaluates a displacement ventilation system and mixing ventialtion system in a hospital patient room using ACE as defined by ASHRAE stanadard 129 (ASHRAE, 2002).

Background

Displacement ventilation (DV) in practice introduces cool air directly into the occupied zone of a room at low velocity. The supply air temperature is slightly lower, and therefore slightly more dense, than that of the room air, allowing it to fall to the floor. The velocity of the supply air is low enough to minimize entrainment of, and therefore mixing with, the room air. This low velocity also ensures that there is minimal air movement in the space allowing the formation of thermal plumes. These plumes form around heat sources where the surrounding air is warmed and becomes buoyant, rising and being replaced with fresh air from below. When these heat sources are people, it is their thermal plume that delivers the fresh air directly to the breathing zone, mixing little with the surrounding room air.

The resulting room airflow pattern, with cool fresh air initially at the floor, rising and warming in thermal plumes picking up pollutants along the way and collecting at a high level where it is exhausted or returned, is what makes displacement ventilation such an effective air distribution system. With the warm air trapped high in the room and with minimal air movement, the room airflow pattern is essentially one dimensional, moving vertically from floor to ceiling. This characteristic air pattern has been shown to provide superior ventilation effectiveness by Chen and Glicksman (2003), Jung and Zeller (2004), Sappänen (2007), Zhang (2007) and Lee et al. (2009).

METHOD

In September 2008, a field study was conducted on-site at a hospital located in Modesto, California. There were three paediatric patient rooms used in the experiment, one is a typical patient room with mixing ventilation, two are configured as prototype displacement ventilation rooms, shown in Figures 1 and 2. In order to retrofit the two DV rooms from patient rooms that were designed for mixing systems, the terminal unit sequence was re-programmed to change the airflow rate as well as the supply air temperature, in order to provide ~65°F air using a variable air volume (VAV) sequence of operation. The reference room, Room MV, was not changed and uses a control sequence with constant air volume (CAV), and supply air temperature reset for room temperature control. The first room using DV (DV-1) was setup to supply four air changes per hour (ACH), while the second DV room was tested in two configurations, one with four ACH, (DV-2a) and one with three (DV-2b).

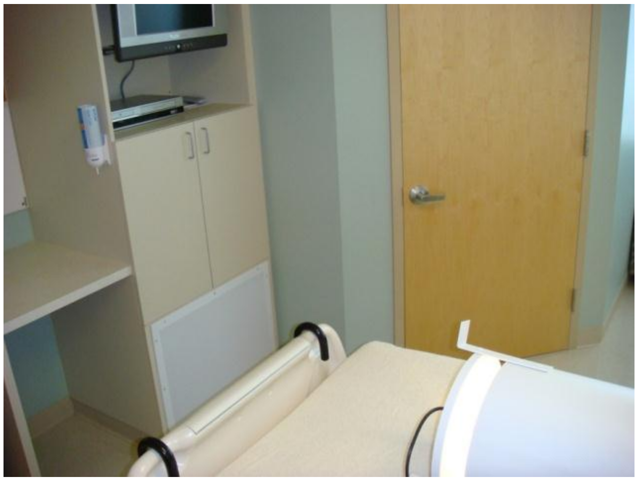

Figure 1. Diffuser Location in Patient Room DV-1

Figure 2. Diffuser Location in Patient Room DV-2

The study was designed to evaluate the age of air in the rooms using CO_2 as the tracer gas. Because this was an occupied healthcare facility, there were strict limitations on the type of tracer gas used, the maximum allowable concentration thereof, as well as the time available to conduct the tests. As a result, it was not possible to conduct the air change effectiveness study in strict accordance with ASHRAE Standard 129.

Table 1. Details of the Test Patient Rooms

	Room			
	(MV)	DV-1	DV-2a	DV-2b
Air Distribution System	Mixing (CAV)	DV (VAV)	DV (VAV)	DV (VAV)
Room Air Temperature	70°F (21.1°C)	75.5°F (24.2°C)	73.5°F (23°C)	75.5°F (24.2°C)
Air Volume, CFM (ACH)	285 (6.3)	180 (4)	180 (4)	120 (3)
Supply Air Temperature	69°F (20.6°C)	65.5°F (18.6°C)	63.5°F (17.5°C)	63.5°F (17.5°C)
Diffuser Location	Ceiling	Patient Foot	Patient Head	Patient Head
Room Occupant Load	925 Btu/h (270 W)	925 Btu/h (270 W)	925 Btu/h (270 W)	925 Btu/h (270 W)
Exhaust Location	Room and Toilet	Room and Toilet	Toilet	Toilet
Exhaust Temperature	70.5°F (21.4°C)	79°F (26.1°C)	73.5°F (23.1°C)	75.5°F (24.2°C)

Each room was instrumented with a series of carbon dioxide transmitters and PT100 RTD temperature sensors located at each of the occupied locations as well as at the supply air inlet and exhaust. The instruments for the occupants were located in the thermal plume for the patient, caregiver and visitor. The specific locations were:

a) Diffuser face – center

b) Patient location – head location, patient on bed

c) Caregiver location – 66”, 1.6m

d) Visitor location – 66”, 1.6m

e) Toilet – 66”, 1.6m

f) Return grille – center

A CO_2 canister with regulator was piped into the supply duct at the VAV terminal box, well upstream of the diffuser in order to achieve appropriate mixing between the supply air and CO_2 streams. The CO_2 sensors and RTDs were connected to a data acquisition system and were logged every 30 seconds with their values stored.

The step up procedure for each test was conducted with the patient room doors closed to the toilet and the hall. Once the air distribution in the room had stabilized, the background CO_2 was measured for a period of at least 10 time steps of 30 seconds and then the supply of CO_2 into the supply airstream was initiated. This supply was continued until the coefficient of variation, c_υ , given by:

$$c_\upsilon = \frac{\sigma}{\overline{C}_{i,average}} \tag{1}$$

of the averaged breathing zone concentration of the previous ten time steps reached a level below 1% for five subsequent time steps. The supply of CO_2 was then stopped and the decay procedure was initiated.

Figure 3. Instrumentation of Patient Room DV-1

Using ASHRAE Standard 129 as a guide, the concentration data collected during the step up procedure was analyzed to evaluate the age of air at all measurement locations, given by:

$$A_i = \left(t_{stop} - t_{start}\right)\left(1 - \frac{C_{i,avg}}{C_{i,t_{stop}}}\right) \tag{2}$$

and the decay data analyzed using:

$$A_i = \left(t_{stop} - t_{start}\right)\left(\frac{C_{i,avg}}{C_{i,t_{start}}}\right) \tag{3}$$

As there was only a single exhaust in the room, the nominal time constant is equivalent to the age of air of the exhaust:

$$\tau_n = \frac{Q_{ex} A_{ex}}{Q_{ex}} = A_{ex} \tag{4}$$

Figures 4 and 5 show the raw and corrected measured CO_2 concentration of the inlet and the exhaust, along with the averaged concentration in the breathing zone and c_υ over time, indicated by the nominal time constant. The values of concentration are normalized to the average inlet concentration during the test.

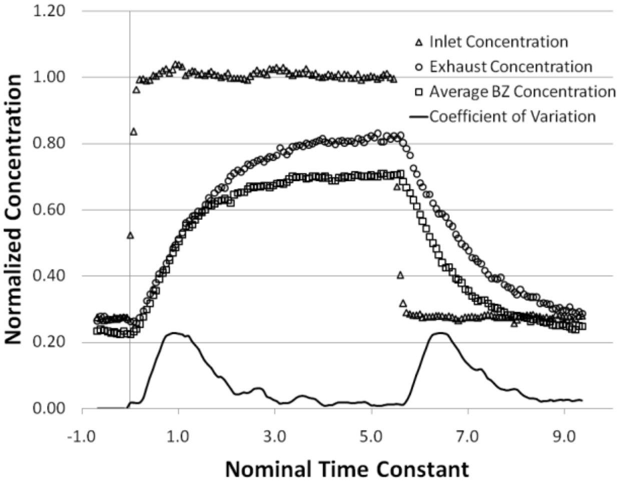

Figure 4. Concentration of CO_2 over Time for Patient Room DV-1

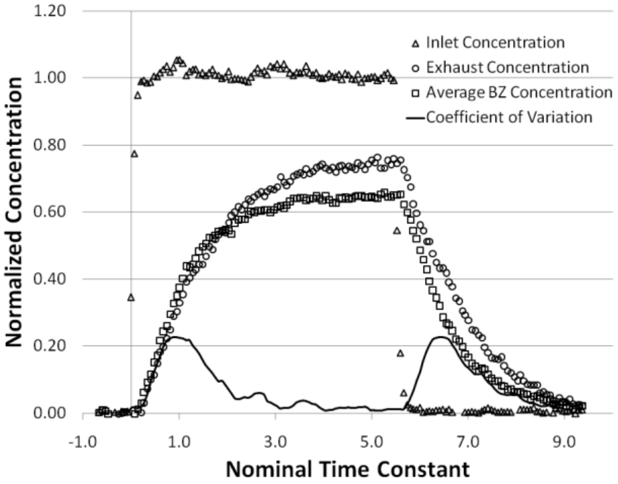

Figure 5. Corrected Concentration of CO_2 over Time for Patient Room DV-1

The data correction shown in Figure 5 has removed the time-averaged background concentration from the 10 time steps prior to the start of tracer gas:

$$C_i'(t) = C_i(t) - \frac{1}{10}\sum_{t=-300}^{0} C(t) \tag{5}$$

The graph indicates that there was stable introduction of CO_2 through the test. With the exception of the first two data points of the step up (t =0, 30s), the concentration is within ±4% of the time-averaged inlet concentration, well within the ASHRAE 129 requirement of ±15%. As expected, the concentrations of the exhaust and breathing zone track closely. Figures 6 and 7 show the concentration data split into the step up and decay tests for the DV-1 room as well as the MV mixing room.

Figure 6 shows the concentration rising in the breathing zone in relation to that in the exhaust during the step up test. It is noticed that the concentration in the breathing zone increases at a higher rate than that in the exhaust, there is then a point where the exhaust concentration passes that of the occupied zone. In a displacement ventilation system, the supply air is passed from the floor level to the return or exhaust level through thermal plumes. Each measurement location in the test, with the exception of the toilet, is associated with a heat source. As a result, one would expect the CO_2 to follow a path from inlet to low level in the room to thermal plume to exhaust, which would result in the concentration curves noticed in Figure 6.

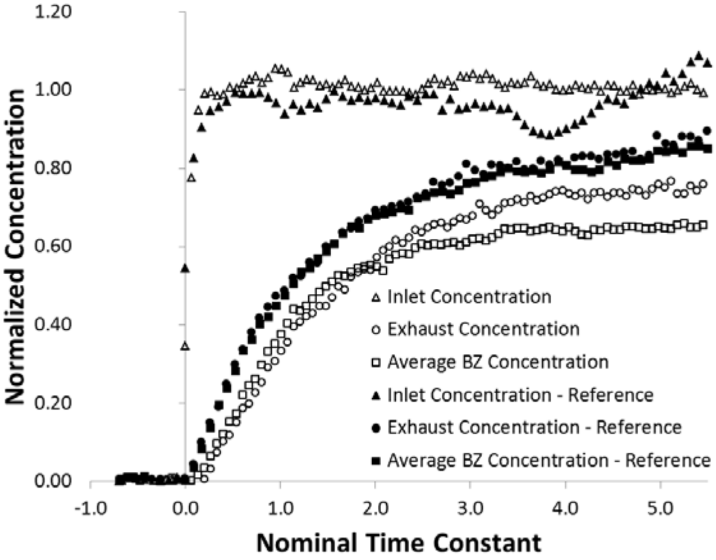

Figure 6. Corrected Concentration of CO_2 over Time for Patient Room DV-1 vs. MV

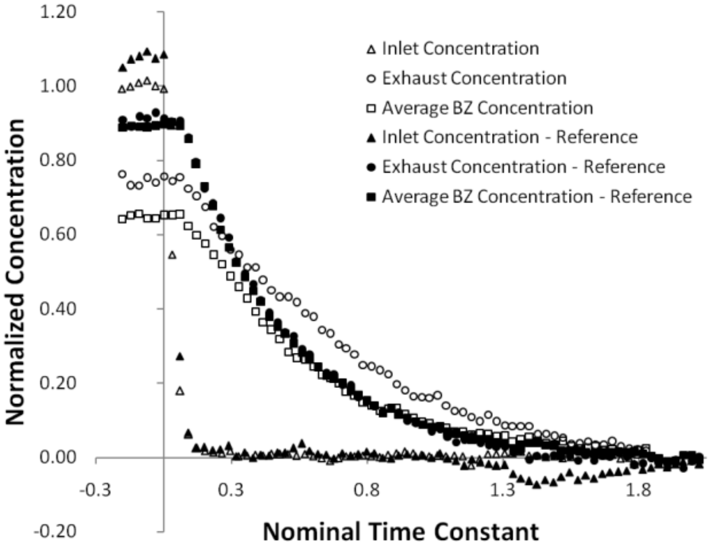

Figure 7. Corrected Concentration of CO_2 over Time for Patient Room DV-1 vs. MV

In contrast, the CO_2 concentration profiles for the the mixing system, the measured concentration in the occupied zone and the exhaust trend together with the exhaust increasing marginally sooner. This is expected due to the high discharge velocity of the momentum of the mixing diffuser churning the room air, causing the concentration to increase throughout the room in a homogeneous manner. The diffuser in room MR has an air pattern which is attached to the ceiling. In this case, if any location would see the CO_2 before the others, it would be the sensor located at the ceiling, on the exhaust. Though slight, it appears that the exhaust concentration is detecting the labelled air before the breathing zone.

Because the test was not completed strictly in accordance with ASHRAE 129 which requires that the exhaust concentration at the start of the test is less that 10% of that at the end, the ACE values are given for discussion purposes only, these were calculated as the ratio of the age of air at the exhaust (A_{ex}) to the age of air in the breathing zone according to:

$$ACE = \frac{\tau_n}{A_{avg}} = \frac{A_{ex}}{A_{avg}} \qquad (6)$$

Where A_{avg} is the arithmetic average of the ages of air measured at the breathing level within the test space. According to Eqn. 6, an age of air in the breathing zone which is less than that in the exhaust in patient room DV-1would lead to an ACE greater than unity. Table 2 provides the age of air and ACE values for the three patient rooms. Because the door to the toilet was closed for all tests, the data is presented for both the breathing zone without the toilet and the breathing zone with the toilet.

Table 2. Age of Air in Each Patient Room

	Location	Room			
		MV	DV-1	DV-2a	DV-2b
Supply Air CFM (ACH)		285 (8)	180 (4)	180 (4)	120 (3)
Step Up Procedure					
Age of Air (s)	Exhaust	344	445	535	264
	Breathing Zone Average no Toilet	371	346	567	234
	Breathing Zone Average with Toilet	453	353	563	238
ACE	Breathing Zone Average no Toilet	0.93	1.29	0.94	1.13
	Breathing Zone Average with Toilet	0.76	1.26	0.95	1.11
Decay Procedure					
Age of Air (s)	Exhaust	1082	980	1211	1425
	Breathing Zone Average no Toilet	1066	923	1194	1248
	Breathing Zone Average with Toilet	1212	943	1198	1293
ACE	Breathing Zone Average no Toilet	1.01	1.06	1.01	1.14
	Breathing Zone Average with Toilet	0.89	1.04	1.01	1.10

Table 3 provides the ACE values at each of the BZ measurement locations, as well as the average. The results shown in the tables indicate that the ventilation in all three displacement ventilation cases is more effective than in the reference mixing case, even at lower supply air rates.

Table 3. ACE values at various measurement locations

	Step Up Procedure				**Decay Procedure**			
	MV	**DV-1**	**DV-2a**	**DV-2b**	**MV**	**DV-1**	**DV-2a**	**DV-2b**
Caregiver	0.89	1.34	1.06	1.22	1.06	1.01	0.99	1.21
Patient	0.89	1.35	0.97	1.13	1.02	1.09	1.10	1.15
Visitor	1.01	1.18	0.83	1.05	0.97	1.09	0.97	1.07
Toilet	0.49	1.19	0.97	1.06	0.66	0.98	1.03	1.00
Average	0.82	1.26	0.96	1.11	0.93	1.04	1.02	1.11

DISCUSSION

Step Up Procedure

It is apparent from Figure 6 that the CO_2 concentration for the mixing system rises quicker than the DV system. This is largely attributable to the low velocity inherent to the DV system. The diffuser injects air into the room ~40fpm, a tiny fraction of that in the mixing case. The lack of momentum also results in low mixing, low turbulence and a one dimensional air pattern from floor to ceiling. The observed lag in the DV case is indicative of the air change effectiveness: the closer the lines are to each other, the closer the ages of air are to being equal and the closer the ACE is to unity. The lag observed with the DV data suggests that the age of air at the occupant is less than that of the exhaust, which is confirmed in Table 2 where the DV-1 room shows an ACE of 1.29 compared to 0.93 for the mixing case.

Decay Procedure

While the decay data is interesting, it is difficult to draw a conclusion from it. The procedure for calculating the ACE is intended for fully mixed systems where all locations have the same concentration at the start of the test. With a DV system this is not possible. In Figure 7, the exhaust and the BZ concentrations appear to decay at a similar rate, though when the data is normalized against the corresponding initial concentration, as shown in Figure 8, a slightly different picture emerges. The exhaust shows a slower decay than that in the BZ. This would indicate that the average value of the concentration through the test was higher. As they have been normalized to both have an initial concentration of unity, this higher average of the exhaust will translate to a higher age of air in the exhaust compared to that in the BZ and a corresponding ventilation effectiveness that is greater than unity. This observation, though anectodal, is in agreement with the value from Table 2 of 1.06. Due to the lack of clarity in the data asociated with the decay test, this procedure from ASHRAE Standard 129 appears to be inappropriate for evaluating the air change effectiveness of air distribution systems that are not fully mixed, such as displacement ventilation.

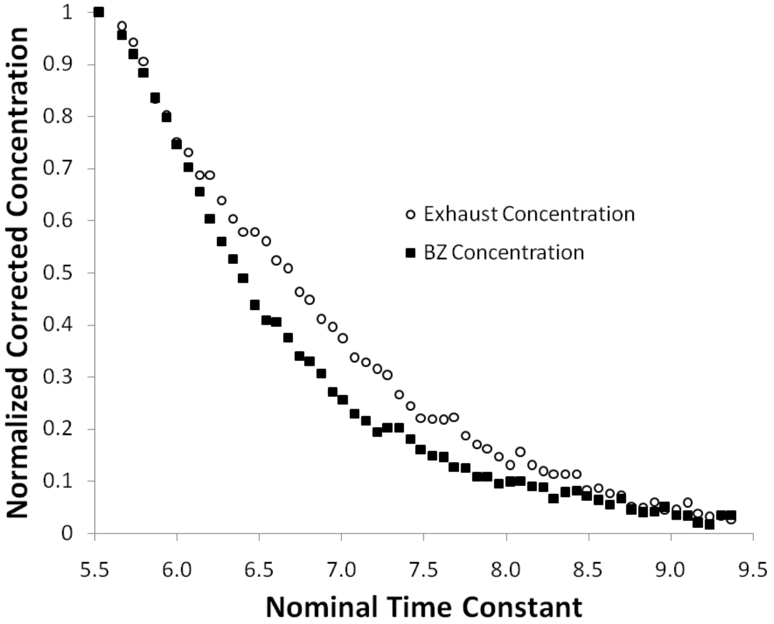

Figure 8. Normalized Concentration of CO_2 during decay test for Patient Room DV-1

Of interest is the improvement of the ACE between rooms DV-2a and DV-2b. The authors were interested in the impact of reducing the air volume further to identify a lower bound of ACH while maintaining air quality and were unable to locate one during the testing period. It is believed that as the supply air volume is throttled down in a displacement ventilation system, the thermal plumes entrain an increasing proportion of the supply air (labelled air, in the case of the step up procedure). This would cause a corresponding decrease in the volume of air that is available to displace the room air outside of the plumes, thereby lowering the average concentration of the label in the breathing zone by lowering the concentration (or the rate of concentration rise) in the sampled air outside of a plume. It is believed that increasing the number or the size of the thermal plumes while maintaining the same supply air volume would result in a similar observation. This result indicates further that the method of testing defined by ASHRAE 129 has limitations in determing the ACE of displacement ventilation systems.

CONCLUSION

This study has demonstrated that the air quality as it relates to the air change effectiveness is equivalent or better with a DV system when compared to a mixing system. The data presented in this study provide some experimental support for the DV system as an effective solution for patient room supply. This work provides field measured data to corroborate the opportunities afforded by using displacement ventilation in healthcare environments to improve the air quality, reduce the risk of cross infection as well as save operational energy, that has been shown to be possible by previous laboratory and computational efforts.

ACKNOWLEDGEMENT

The authors would like to thank KAISER PERMANENTE for the use of their facility as well as assistance provided on site.

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