DISPLACEMENT VENTILATION AS A VIABLE AIR SOLUTION FOR HOSPITAL PATIENT ROOMS

Julian Rimmer, P.Eng.
Price Industries
Senior Product Manager,
Sustainable Technologies

Brad Tully, P.Eng.
Price Industries
General Manager,
Price Mechanical West

Alf Dyck, P.Eng.
Price Industries
Vice President, Engineering

Mike Buck
University of Minnesota

Corresponding email: julianr@priceindustries.com

SUMMARY

In few environments is the indoor air quality as important as that in hospital patient rooms. The air system must provide protection for the patient, caregiver as well as any visitors that may be in the room. Current codes and standards have been developed with this in mind, often by prescribing an air change rate, thereby ensuring a minimum amount of air movement and purge rate. These have all been put in place on the assumption of a mixing air supply system. Displacement ventilation offers a means of improving the air quality in these spaces, with the indication of lower air change rates. This in turn saves energy and reduces operating costs for the healthcare system. This paper presents the results of a particle study that quantifies the improvement of the air quality in a displacement ventilation system over that of a mixing system in a patient room. The exposure potential of these systems was evaluated along with maximum concentration and decay rate following a sneeze event. The displacement ventilation system showed significant improvement over the mixing ventilation case, even at lower air change rates.

INTRODUCTION

In no industry is indoor environmental quality (IEQ) more important that in that of healthcare, an industry also known to be one of the most energy intensive. 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) [1], the American Institute of Architects (AIA) [2] 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.

Background

Displacement ventilation (DV) in practice introduces cool air directly into the occupied zone of a room at low velocity. The temperature of the supply air is slightly lower and therefore slightly more dense than 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, from floor to ceiling. This characteristic allows for a reduction in the room design cooling capacity of the supply air [3].

METHODS

This study intended to determine whether a displacement system would provide an adequate level of IEQ for a patient room, particularly at lower air change rates. To this end, both thermal comfort and particle distribution studies were carried out in order to evaluate the relative performance between the DV system and a mixing (MR) system from an occupant perception standpoint.. For this study, the MR airflow rate was set to match that required by ASHRAE [1] to six air changes per hour (ACH). The DV airflow rate was set to four ACH which is equivalent to six ACH in the occupied zone for patient rooms with a 3m ceiling height. The particle study was carried out on the standard patient room shown in Figure 1. These rooms include a patient lying on the bed, a caregiver and visitor in the vicinity of the bed (all shown in pink), a television mounted to the foot wall and a window to simulate the perimeter loads for various climates.

Two displacement diffusers were installed in the corners of the room (shown in blue), but only one of these was active for the test. The return, red, was located at the ceiling level, above the door.

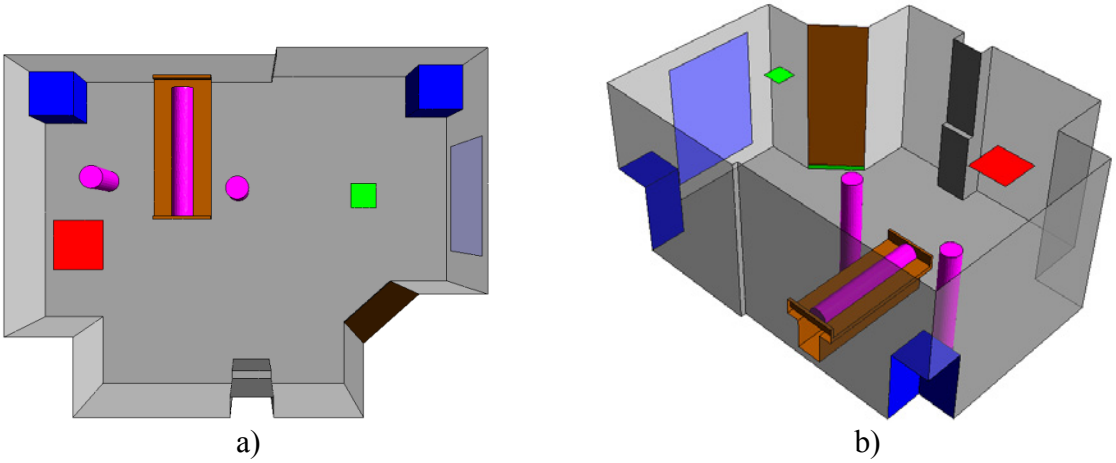

Figure 1- Plan (a) and isometric (b) views of the patient room under study

Particle Distribution

The patient room was set up in the mockup room at an air distribution lab located in Winnipeg, Canada. A procedure for evaluating the effect of displacement ventilation on the exposure of occupants to particles was developed in conjunction with two international engineering firms. It was determined the standardized particle study, developed by the team, would be conducted to evaluate the indoor air quality of the room with a mixing system and a DV system. The particles were generated and injected into the room with a common nebulizer and the values were measured with a particle counter. The location of both instruments was varied from test to test, according to Table 1, for the test conditions outlined in Table 2.

Table 1. Particle Tests

Configuration	Location of Nebulizer	Location of Particle Counter
1	Patient Bed	Caregiver
2	Caregiver	Patient Bed

Table 2. Details of test patient rooms

	Room	
	MR	DV
Air Distribution System	Mixing	DV
Room Air Temperature	23.3°C (74°F)	25°C (77°F)
Supply Air Volume (ACH)	137L/s (6)	85L/s (4)
Supply Air Temperature	18.3°C (65°F)	18.3°C (65°F)
Diffuser Location	Ceiling	Low Level, Across from Bed
Room Occupant Load	250 W	250 W
Exhaust Location	Room and Toilet	Room and Toilet
Exhaust Temperature	24.4°C (76°F)	26.7°C (80°F)

For both the MR and DV layouts, the supply air was filtered with a HEPA 99.97% efficient filter to ensure that it contained a minimal count of particles. The nebulizer was selected to provide a range of particle sizes in line with sizes of common pathogens.

Table 3. Characteristics of the compressed air nebulizer

	Operating Pressure	Flow Rate (1/min)	Output Concentration	Droplet Size Distribution	
				MMD (μm)	GSD
Nebulizer	10	11	16	4.2	1.8

Where MMD is the mass mean diameter and GSD is the geometric standard deviation of the droplet size distribution.

At the start of each test, fan filter units equipped with HEPA filters were used to clear the room of particles. These were run for 15 minutes (5 air changes). Once shut off, the room was allowed to stabilize for 5 minutes. The nebulizer pump was then run for 30 seconds. The particle counter then monitors the local concentration of particles as they decay over time. The counter was allowed to run for 45 to 60 minutes after the pump was shut off to give a good description of the concentration decay.

RESULTS

For the analysis, the data was corrected to a background concentration of 0 particles as each run had a slightly different, though low, background concentration when the tests were initiated. To accomplish this, the average background concentration was taken for each run during the five minute stabilization period. This average value was then subtracted from the measured particle count during the test. The magnitude of this correction varied from 0.4% of the test average count for the 0.5μm particles to 1.5% of the test average for the 2μm particles. Figure 2 shows the data for the study where the particle source was at the patient location and the particle counter at the caregiver's location. Time 0 is at the moment when the injection of particles start, with the duration of the injection shown in grey.

In the figure, the MR cases (shown in orange and red) indicate a more gradual increase and decrease in particle counts than the two displacement cases (shown in blue). This is not unexpected because lateral air movement in a mixing system can be significant, causing the injected particles to move in all three dimensions. In contrast, displacement ventilation systems have a bulk air motion that is largely one dimensional, from floor to ceiling. This would cause the particle counter located directly above the source to have a near immediate response to the injection of particles, as is noted from Figure 2. Table 4 and Table 5 show the decay of the measured particle count through the first ten minutes of the test.

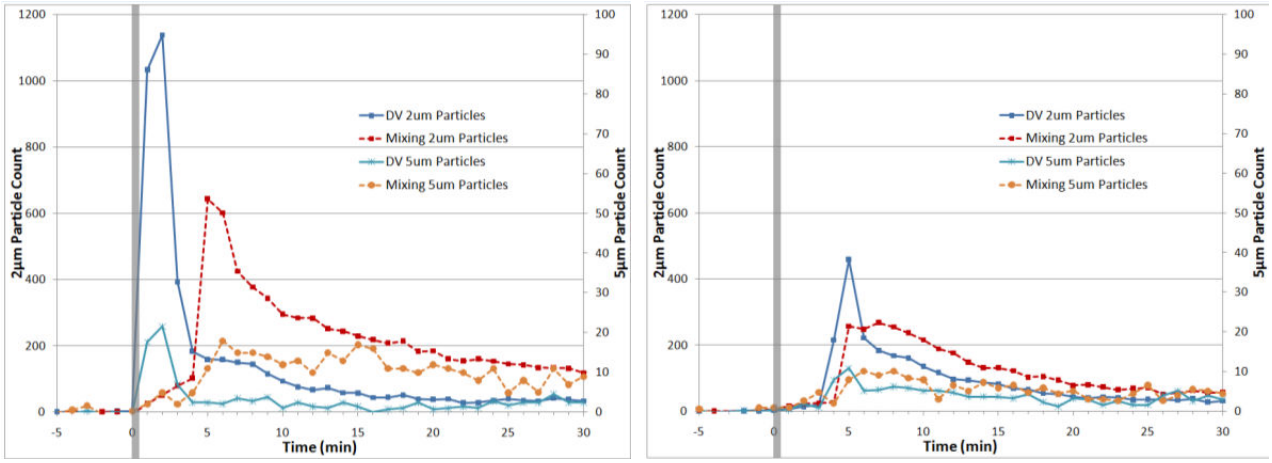

Figure 2 - Concentration of 2 and 5 micron particles vs. time for (a) particle source at the patient and counter at the caregiver and (b) particle source at the caregiver and counter at the patient

Results for the mixing and DV systems are given in Table 4 for the case of the particle source located at the patient and particles measured at the caregiver. As indicated in the table, the measured particle count in the DV system decays in number of particles 93-94% in the first 10 minutes, whereas the mixing system caused a decay of 11-80%. What is notable is that the quicker decay is realized even at a lower air change rage, 4ACH for the DV system vs. 6ACH for the mixing system.

Results for the mixing and displacement ventilation systems are given in Table 5 for the case of the particle source located at the caregiver and particles measured at the patient. In this case, the decay for the DV system is 66-85% in the first 10 minutes, compared to 36- 87% for the mixing system. Again, these results are for a lower air change rate for the displacement system.

Table 4. Particle count decay, source located at the patient and measured at the caregiver

Room	ACH		0.3µm Particles	0.5µm Particles	1µm Particles	2µm Particles	5µm Particles	10µm Particles
MR	6	Peak Count	74832	15093	2366	643	18	2
		Count after 10 min	15852	3037	622	229	16	0
		Difference	58980	12056	1744	414	2	2
		% Reduction	79%	80%	74%	64%	11%	99%
DV	4	Peak Count	132147	30720	4619	1139	22	3
		Count after 10 min	9801	1827	269	68	2	0
		Count Reduction	122346	28893	4350	1071	20	3
		% Reduction	93%	94%	94%	94%	93%	100%

Table 5. Particle count decay, source located at the caregiver and measured at the patient

Room	ACH		0.3µm Particles	0.5µm Particles	1µm Particles	2µm Particles	5µm Particles	10µm Particles
MR	6	Peak Count	67109	13090	951	268	10	0
		Count after 10 min	10695	1710	332	103	7	0
		Difference	56414	11380	619	165	4	0
		% Reduction	84%	87%	65%	62%	36%	100%
DV	4	Peak Count	15677	3026	1653	459	11	3
		Count after 10 min	2997	538	252	83	4	0
		Count Reduction	12680	2488	1401	376	7	3
		% Reduction	81%	82%	85%	82%	66%	00%

It is interesting to note that though the values for particle count in Table 5 shows a slightly lower reduction as a percentage of the peak value than that in Table 4, the peak itself is approximately an order of magnitude lower. It is unlikely that this is solely caused by a fluctuation in particle generation between tests, but is more likely attributable to the manner in which DV systems move the air in the room.

From the tables, the maximum number of particles observed between the tests for the mixing varies less than 10%, suggesting that the tests and particle distribution are repeatable. As previously discussed, the air pattern generated with the DV system is generally one-dimensional, from floor to ceiling. This would account for the variance found in the magnitude of the particle spikes for the DV case with the lower value being where the source is downstream (above) from the measurement location. By contrast, the characteristics of mixing systems also explain the very little difference observed in the peaks because the air pattern tends to distribute the particles throughout the room.

When the decay data is normalized for each particle size to the magnitude of the respective count peaks, or

$$Count_{i,N} = \frac{Count_i}{Count_{i,Max}}, \qquad (1)$$

a trend is clearly visible. Figure 3 shows the 0.3 - 2µm normalized decay curves which are nearly identical for the displacement case, and are largely similar for the mixing case. The curves for the 5 and 10µm were omitted due to their relatively low magnitudes and high noise levels. Fundamentally, we would expect to see very good agreement between these curves because the range of particle sizes which are presented are also those that exhibit aerosol behaviour and do not settle. The fact that they remain in suspension means that they can be used to track the motion of air in the room and that the time required for the particles to be noticed (peak) by the caregiver should be indicative of the effectiveness of the air distribution system at delivering fresh air to the occupants.

Figure 3 shows that the time to peak for the DV and mixing systems are approximately two and five minutes, respectively. The response time indicates that the DV system is 2.5 times more effective at delivering air to the occupants than the mixing systems. This value is not outside of the range of ventilation effectiveness (VE) values typically associated with DV systems. The data is only presented for the case where the source is located at the patient because in VE studies this is akin to the step-up procedure where the label is added to the airstream upstream of the measurement location.

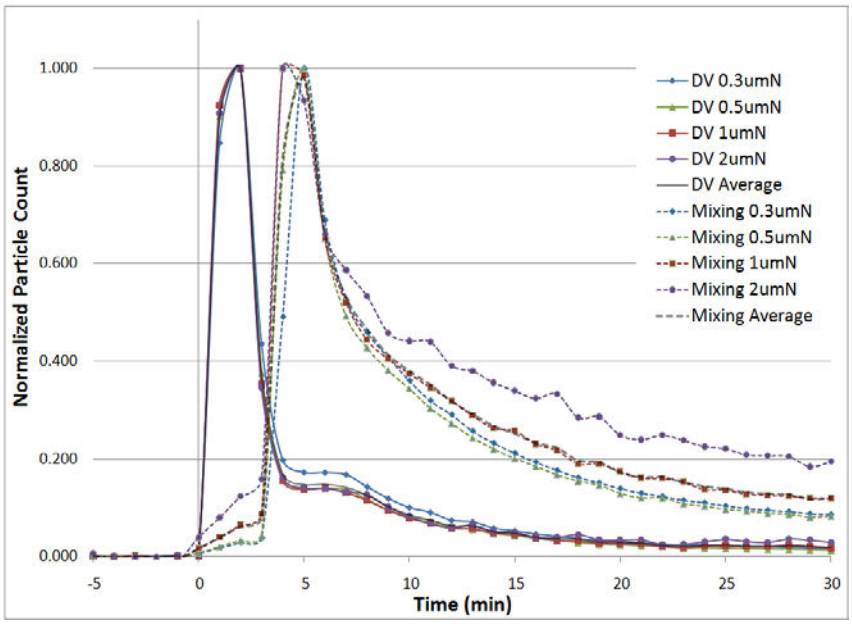

Figure 3 - Normalized particle counts for the DV and mixing systems for the case with patient source, measured at the caregiver.

The stability of the displacement ventilation curves is an indication of the low turbulence experienced with a DV system. The count decay curves for all of the particles that display aerosol behaviour are nearly identical, whereas they are not for the mixing case, with the more massive particles decaying at a slower rate.

Exposure Potential

In infection control it is the exposure potential, or number of particles in a period of time, that influences whether cross-infection can take place. The area under the curves from Figure 2 defines this exposure in particle-minutes. It is expected that the particle count vs. time curve is smooth and therefore Simpson's Rule was used to evaluate the area under the curves in Figure 4. When evaluated with a particle count, p, though time and n = 15 intervals of 2 minutes each, the exposure potential can be determined from:

$$EX = \frac{1}{3}\left[p_0 + 4p_1 + 2p_2 + 4p_3 + 2p_4 + \ldots + 4p_{29} + p_{30}\right] \qquad (3)$$

Using this method, the exposure potential in particle-minutes for the two systems is shown in Table 6 and Table 7.

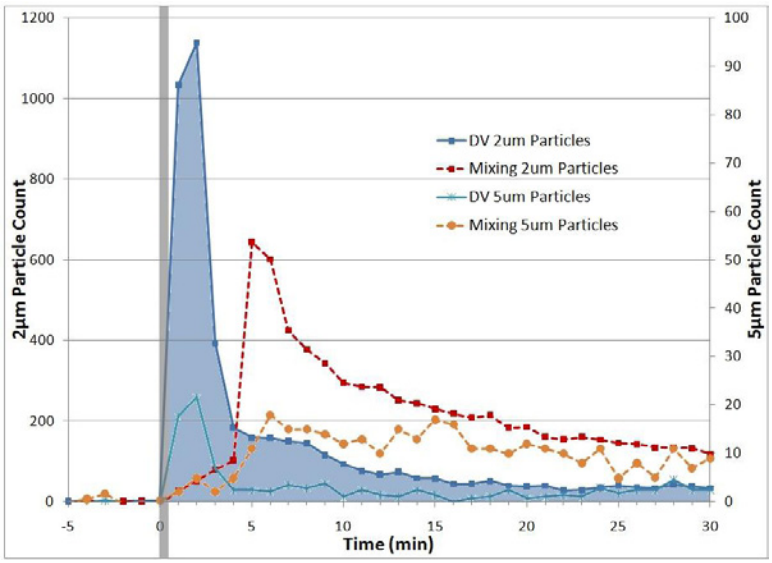

Figure 4 - Area under the concentration curve of the 2 micron particles vs. time with displacement ventilation

Table 6. Exposure potential to caregiver, source at patient

	ACH	0.3µm Particles	0.5µm Particles	1µm Particles	2µm Particles	5µm Particles
Mixing DV	6	537398	107047	19554	6663	309
	4	548964	116345	17710	4530	105
Difference % Difference		-11566	-9298	1844	2133	204
		-2%	-9%	9%	32%	66%

As shown in Table 6, the difference between the exposure potential for the DV case at four ACH and the mixing case at six ACH, respectively, is minor for the 0.3, 0.5 and 1.0µm particle sizes. The difference is more pronounced for the larger particle sizes with the DV system showing significantly less exposure to the caregiver than the mixing system, even with the higher maximum particle count observed in Table 4.

Table 7. Exposure potential to patient, source at caregiver

	ACH	0.3µm Particles	0.5µm Particles	1µm Particles	2µm Particles	5µm Particles
Mixing DV	6	384873	65904	11776	3612	164
	4	92092	16866	9174	2803	118
Difference % Difference		292781	49039	2602	809	46
		76%	74%	22%	22%	28%

Table 7 presents the data for the exposure potential to the patient with the source at the caregiver. In this case, there is a large reduction in the exposure of the patient to the smaller particles. Again, due to the fact that these exhibit aerosol behaviour and the single-pass air pattern generated by the DV system, one would expect that the particles whose movement is dominated by the air transport would show this characteristic. This trend continues to the more massive particle sizes which show a significant reduction in the exposure of the patient to the particles injected at the caregiver location.

Conclusions

This study has demonstrated that the air quality as it relates to measured counts of particles exchanged between room occupants is equivalent or better with a DV system when compared to a mixing system. The fact that these results are achieved at 1/3 less airflow is an indication that the DV system improves the effectiveness of the air delivery system's ability to protect the occupants. The data presented in this study provide some experimental support for the DV system as an effective solution for patient room supply. That the DV system demonstrated this level of performance at a lower air change rate suggests that the healthcare provider can use DV technology to provide superior air quality while reducing the amount of energy required to operate the system. If the DV system is implemented in similar environments within the facility, there is also the possibility of larger scale reductions in air volume and the other mechanical advantages that stem from this such as reduced ductwork and smaller mechanical equipment.

DISCUSSION

It is expected that the displacement ventilation system is an appropriate choice for patient rooms due to the improvement in indoor air quality and opportunity for air volume and energy savings. It is also believed that this result should be applicable to more non-critical spaces in a healthcare facility including waiting rooms, exam rooms, MRI rooms, cafeterias, Atria, respite rooms, family rooms as well as nurse station and corridors. This result highlights a significant opportunity to save energy in hospitals by adopting a more efficient DV system for a significant percentage of the building footprint.

ACKNOWLEDGEMENT

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