DISPLACEMENT VENTILATION PERFORMANCE OF A HOSPITAL PATIENT RECOVERY ROOM IN AIRBORNE INFECTION PREVENTION

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Abstract

Environmental concerns, energy costs, and infection risks have revived interest in ventilation systems for health care facilities. Displacement ventilation has received attention as a means of providing a better air quality at a lower energy cost. The sensitivity of displacement ventilation to boundary conditions in removing airborne contaminants is of concern and studied experimentally/numerically in this work. Particles are injected into a simulated patient recovery room by a mechanical atomizer to simulate the coughs/sneezes of a patient. Size-resolved concentrations are measured at locations representative of an occupant (receptor). It is found that high injection velocities, low occupant metabolic rates, and low air change rates increase contaminant exposure, while vertical injections, side injections, and far occupant locations decrease exposure. The total exposure from a single cough or sneeze event can vary by a factor of 4 from the best to worst case.

Keywords: displacement, ventilation, hospital, recovery, infection, risk, prevention, airborne, computational fluid dynamics (CFD)

1 Introduction and Background

The spread of infectious diseases is of global concern for social and economic reasons. For example, seasonal influenza kills 200-500 thousand people annually. In 2009-2010, influenza A (H1N1) caused 17,000 deaths world-wide, many among whom were healthy adults (Wan et al. 2009). In 2002-2003, Severe Acute Respiratory Syndrome (SARS) killed more than 700 people and spread into 37 countries causing a cost of $18 billion in Asia (Noakes et al. 2006).

Aerosol disease transmission is known to be the main route for many diseases such as *Tuberculosis* and *Aspergillosis*. Also, recent research has shown that the importance of aerosol infection is underrated for common diseases such as influenza, especially during the cold season (Tang et al. 2009).

North American building codes are very conservative and require high air changes per hour (ACH) in most health care functional spaces. For example, ASHRAE 170 (2008) demands an overhead mixing type ventilation with a minimum of 6 ACH for patient recovery and 12 ACH for protective environment and isolation rooms. The European building codes allow other forms of ventilation (e.g. displacement and natural) on the grounds that they possibly improve air quality by enhanced aerosol separation/removal while reducing the building carbon footprint. The United Kingdom National Health Service (NHS) limits the use of mechanical ventilation to infection isolation rooms, operating theatres, and associated spaces (Atkinson et al. 2009). Careful research in the performance of low-energy ventilation systems (e.g. displacement) may reduce their perceived risks and allow more widespread adoption.

Yin et al. (2009) and Xu et al. (2009) found that displacement ventilation (DV) at lower 4 ACH in a patient recovery room outperforms overhead mixing ventilation at higher 6 ACH by removing tracer gas (SF_6) or particles (1 and 3μm in diameter) released steadily at a patient bed. Yin et al. (2009) showed that placement of diffuser and exhaust is very important so that best contaminant removal is obtained when the diffuser is in front and the exhaust is on top of the patient's head. Lee et al. (2009) used simulations to show that increasing ACH in DV eventually disturbs the thermal plumes by excessive mixing so that effective contaminant stratification/removal cannot be achieved. They also

showed that vertical diffusers for DV outperform swirl and linear diffusers since they induce less vertical mixing. Lee et al. (2009) and Xu et al. (2009) showed that under cooling mode (summer) DV systems have overall better performance. Under heating mode (winter) warm intake air may rise immediately due to buoyancy, perturbing the vertical contaminant stratification. As a result, DV is recommended with auxiliary radiant or convective heating. Xu et al. (2009) have used simulations to show that a transient vertical patient cough causes a short rise in contaminant concentration around the bed in the first 90 s of injection. Lee et al. (2009) showed that thermal plumes assist contaminant removal in DV if they direct contaminants towards the exhaust.

This study investigates DV in a patient recovery room under heating mode (winter) in further detail than state of the art literature. The objective is to evaluate sensitivity of the aerosol removal effectiveness to the boundary conditions for DV with low air change rates. Aerosols are injected in the room by a cough/sneeze simulator. The direction and momentum of injection, the metabolic rate and placement of thermal manikins, and the air change rate in the room are varied. Aerosol exposure is both measured and simulated using computational fluid dynamics (CFD) at multiple sitting, breathing, and upper zones.

2 Methodology

2.1 Experimental Setup

The experimental space is shown in figure 1. The room x,y, and z dimensions are 2.93 m, 3.68 m, and 3.77 m, respectively. Thermal manikins are used to emulate a patient and an occupant. Each manikin is 0.15 m x 0.30 m x 1.83 m and is equipped with light bulbs inside to produce thermal power corresponding to resting (45 W/m^2), light (70 W/m^2), or regular (80 W/m^2) metabolic rates. A low-throw swirl diffuser is used with diameter 0.25 m that introduces air at an angle of 35^0 from the floor. The exhaust grill is 0.25 m x 0.50 m. Five poles measure temperature at various elevations using type T thermocouples. These elevations are LL=0.10 m, L=0.85 m, M=1.63 m, and H=3.00 m. Wall temperatures are measured at similar elevations. Pole 1 is also equipped with aerosol sampling collectors at three elevations (sitting=1.13 m, breathing=1.64 m, and upper=2.98 m). These collectors deliver aerosols in the range 0.5-20 µm to a TSI Aerodynamic Particle Sizer (APS) (model 3321) for concentration measurements. The bed dimensions are x=0.56 m x y=0.45 m x z=2.15 m. An atomizer assembly with dimensions x=0.31 m x y=0.60 m x z=0.62 m is placed on top of the patient manikin. The atomizer operates on a nitrogen-assist nozzle manufactured by Spraying Systems Co. (model SUQR-220B). This nozzle sprays an oral fluid surrogate solution obtained from mixing 6 % glycerine (by volume) in deionized water. This atomizer is tuned to inject a fixed amount of fluid (3.8 mL) at three nitrogen injection velocities (low=185 m/s, mid=247 m/s, high=299 m/s). These injections lasted for 0.75 s, 0.51 s, and 0.40 s respectively. These simulate a range from a slow cough to a fast sneeze. A Thermo Air 6 omnidirectional anemometer is used to measure air flow velocity down stream of the exhaust in a round duct for air change rate measurements.

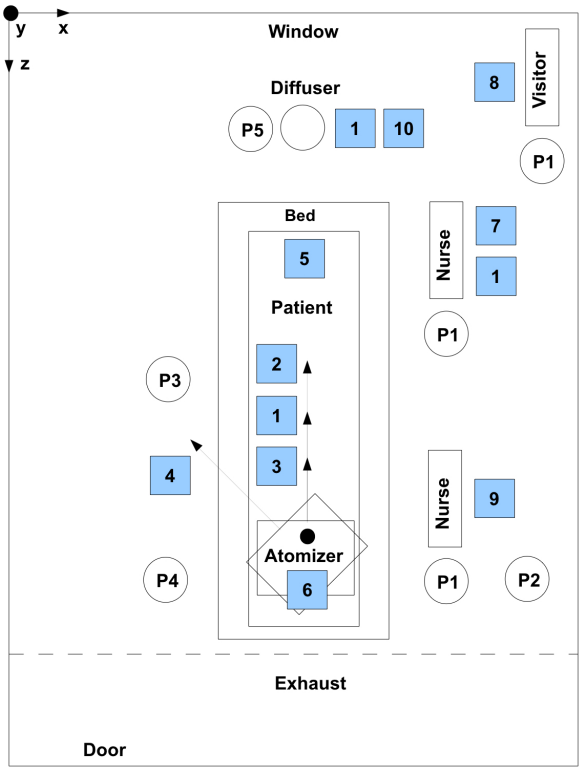

Figure 1. Ventilation test setup

Figure 1 shows 10 parametric test cases that are devised to cover a range of plausible changes in boundary conditions. The reference case (1) shows a mid velocity injection of aerosols at an angle of 45^0 from the floor. A regular metabolic rate for the occupant and a resting metabolic rate for the patient are used with ACH=0.8. Cases 2 and 3 inject aerosols at high and low nitrogen velocities. Case 4 injects aerosols at 45^0 away from the bed and at 45^0 from the floor. Cases 5 and 6 inject aerosols horizontally and vertically, respectively. Case 7 reduces the occupant metabolic rate to a light activity. Cases 8 and 9 move the occupant away and behind the injection source respectively. Case 10 reduces ACH to 0.6. A total of 9 tests were performed for each case. Three sets of 3 tests measure aerosol concentration over 600 s at sitting, breathing, and upper zones. Table 1 gives the location of each object in the room based on the distance between the closest vertex of the object and the origin.

***Table 1**: Object locations in the ventilation test setup*

Object	*Bed*	*Patient*	*Atomizer*	*Diffuser*	*Exhaust*	*P1 (base)*	*P1 (away)*	*P1 (behind)*	*P2*	*P3*	*P4*	*P5*	*Nurse (base)*	*Visitor (away)*	*Nurse (behind)*
x [m]	1.15	1.27	1.27	1.45	1.20	1.88	1.88	2.65	1.84	1.00	1.00	1.34	1.81	2.57	1.81
y [m]	0.00	0.45	0.60	0.00	3.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
z [m]	1.23	1.39	2.61	0.66	3.00	1.67	2.68	0.72	2.14	1.47	2.84	0.60	1.23	0.25	2.23

2.2 Numerical Approach

ANSYS FLUENT 12.1 was used for the computational fluid dynamics simulation of the same 10 parametric test cases that were introduced in the previous section. The developed mesh contained 316645 tetrahedral elements. The mesh resolution was refined near the boundaries, inlets, and outlets so that an accurate solution could be obtained (Figure 2). Near the boundaries, y^+ was about 100 for the first layer of mesh height. This allowed implementation of standard wall functions by the RNG k-ε turbulence model. A uniform number distribution of aerosols (0.5-30 μm in diameter) was assumed with a 6 % non-volatile volume fraction. This distribution matched the same volume distribution by the atomizer as closely as possible. Both heat and mass transfer and stochastic aerosol tracking models were solved so that aerosol evaporation and dispersion could be modelled. All species components in air were modelled (nitrogen, oxygen, carbon dioxide, and water). The energy equation was also solved so that buoyancy effects associated with thermal plumes could be accounted for. The solver used 1st order implicit Euler time advance, PRESTO! pressure, and 2nd order upwind space discretizations.

A transient simulation was performed to solve for aerosol dispersion during 600 s. At first the background ventilation was solved during the first 60 s. Then, nitrogen and aerosols were injected. The time advance was resolved close to the injection event. The time resolutions used were 6 s, 0.01 s, 0.1 s, 1 s, and 10 s for simulation times of 60 s, 61 s, 70 s, 200 s, and 660 s respectively.

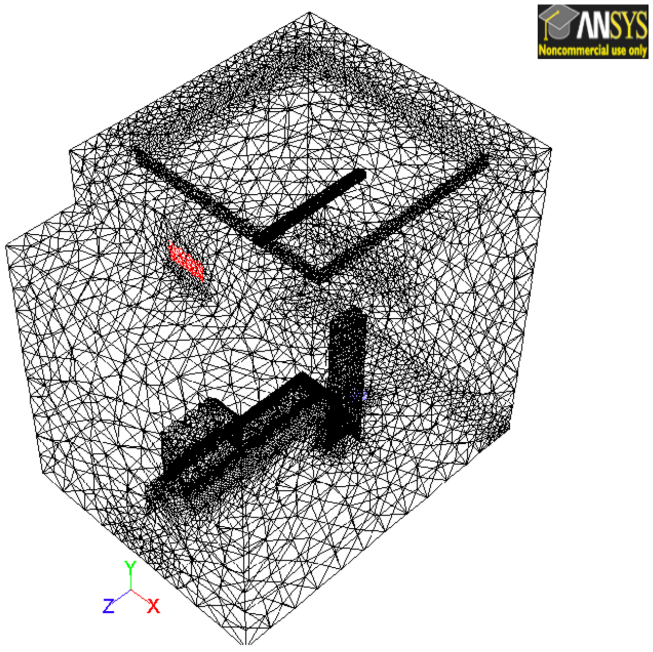

Figure 2. Numerical mesh for case 1

3 Results and Discussion

3.1 Experimental Results and Discussion

Figure 3 shows the interior temperature stratification as measured on the poles for the entire duration of the case 1 test. Except for a short cooling of the thermocouple that is on the way of injected spray (Pole1 H), the internal temperature of the room remains stable and vertically stratified.

The aerosol volume concentration was measured in 5 size bins of 0.5-1 μm, 1-2.5 μm, 2.5-5 μm, 5-7.5 μm, and 7.5-10 μm. The APS instrument did not measure substantial concentration for aerosols larger than 10 μm. The real time concentration of aerosols C(t) gives an instantaneous measure of exposure. For infection risk assessment, however, calculation of a cumulative exposure or simply exposure is desired. This is obtained by integrating C(t). Figure 3 also shows the breathing zone exposure for the entire time duration of the test in case 1.

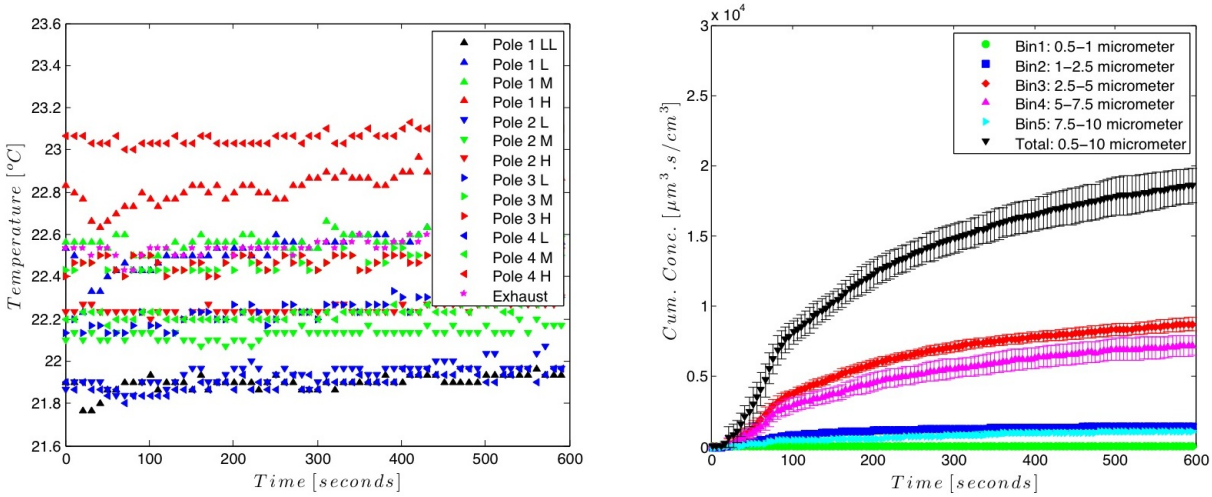

Figure 3. Temperature stratification (left) and exposure at breathing zone (right) for case 1

For the purpose of assessing sensitivity of exposure to varying boundary conditions, it is convenient to define the normalized exposure, which is exposure divided by the reference exposure (case 1),

$$\hat{C}(T) = \int_0^T C(t)dt \,/\, \int_0^T C_{Ref}(t)dt \tag{1}$$

Tables 2 and 3 give the normalized exposure over short (T=140 s) and long (T=600 s) times. Normalized exposure for all size bins followed similar time variations, so only the total exposure for all size bins combined are reported here. High injection velocity of case 2 increases mixing in the room so that exposure increases particularly at long time. Lower injection velocity of case 3 has the opposite effect so the exposure reduces. Cases 4 and 6 transport aerosols away from the occupant so they decrease exposure. Case 6 (vertical injection) is ideal since it results in a better vertical aerosol stratification. Case 5 (horizontal injection) impacts aerosols on the wall hence reduces the exposure except for the sitting position in the long time. The lower metabolic rate in case 7 weakens the thermal plume associated with the occupant. As a result aerosols are not transported to the ceiling as effectively as case 1. This results in a higher exposure. Cases 8 and 9 place the occupant at a further distance from the contaminants in a way that exposure reduces. The lower air change rate of 0.6 in case 10 reduced exposure at short time but eventually increased it at long time. This can be explained by speculation, considering two mechanisms of turbulent dispersion and aerosol removal by effective upward velocity of air. With a lower air change rate, the air turbulence is less effective than case 1 so the dispersion is weak at short time and exposure is reduced. However, at longer time the effective upward velocity of air is lower than case 1 for successful removal of aerosols, so the exposure is

increased. The operable range for ACH in our ventilation test is severely limited, but we expect higher ACH to significantly reduce exposure while lower ACH to increase it.

***Table 2**: Normalized exposure over short time (T=140 s)*

Case	*1 Base*	*2 High vel.*	*3 Low vel.*	*4 45^0 left*	*5 Horiz.*	*6 Vert.*	*7 Low Met.*	*8 Visitor away*	*9 Nurse behind*	*10 Low ACH*
Upper (y=2.98 m)	1.00 ±0.02	1.11 ±0.11	0.74 ±0.12	0.46 ±0.07	0.30 ±0.10	0.64 ±0.07	1.08 ±0.12	1.05 ±0.06	0.38 ±0.18	0.75 ±0.10
Breathing (y=1.64 m)	1.00 ±0.11	0.90 ±0.08	0.58 ±0.05	0.48 ±0.08	0.39 ±0.13	0.48 ±0.12	1.09 ±0.21	0.81 ±0.09	0.12 ±0.02	0.82 ±0.29
Sitting (y=1.13 m)	1.00 ±0.22	1.05 ±0.21	0.66 ±0.12	0.42 ±0.14	0.35 ±0.11	0.20 ±0.06	0.83 ±0.29	0.72 ±0.29	0.19 ±0.15	0.62 ±0.12

***Table 3**: Normalized exposure over long time (T=600 s)*

Case	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Upper (y=2.98 m)	1.00 ±0.05	1.51 ±0.09	0.56 ±0.06	0.77 ±0.08	0.40 ±0.10	0.72 ±0.05	1.07 ±0.08	0.97 ±0.06	0.53 ±0.11	0.91 ±0.07
Breathing (y=1.64 m)	1 ±0.10	1.35 ±0.11	0.54 ±0.07	0.68 ±0.07	0.50 ±0.10	0.65 ±0.07	1.11 ±0.13	0.83 ±0.06	0.36 ±0.12	1.04 ±0.16
Sitting (y=1.13 m)	1.00 ±0.22	1.41 ±0.23	0.60 ±0.10	0.57 ±0.16	0.99 ±0.71	0.34 ±0.11	1.04 ±0.44	0.71 ±0.22	0.40 ±0.17	0.71 ±0.13

3.2 Numerical Results and Discussion

Overall, stochastic aerosol tracking showed a better agreement with the experimental results than the species (tracer gas) transport. This is true since transport of aerosols, with a different density than air, is affected by gravity and aerosol relaxation time in addition to other transport mechanisms (e.g. aerodynamic drag and brownian force). Also CFD predicted the experiments better for short time of exposure due to error accumulation with time. Figure 4 shows the CFD results for the stochastic aerosol tracking approach compared with the experiments at sitting, breathing, and upper zones.

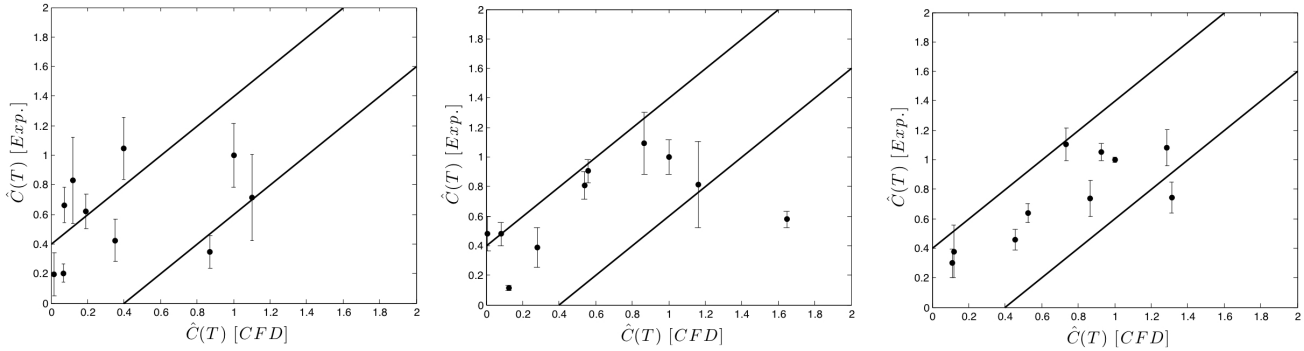

Figure 4. Measured [Exp.] and predicted [CFD] normalized exposure at sitting (left), breathing (mid), and upper (right) zones for short time (T=140 s)

The agreement at breathing and upper zones is better than the sitting zone. Within 40 % error, the model is successful in 50 %, 80 %, and 90 % of the 10 cases, predicting the experimental exposure for sitting, breathing, and upper zones respectively. It is speculated, that due to presence of objects and geometrical complexity at lower (sitting) level in the room, the turbulence becomes anisotropic with

lower Reynolds numbers, which in turn leads to a less accurate flow solution and a less successful tracking of aerosols by the stochastic tracking model.

4 Conclusions

The sensitivity of aerosol removal effectiveness to boundary conditions is studied in a hospital patient recovery room with displacement ventilation (DV) at low air change rates. The room consists of a patient who injects aerosol contaminants in the room by coughing/sneezing, and an occupant (suspect) that is exposed to the contaminants. Ten parametric cases are studied experimentally and numerically, in which boundary conditions such as injection momentum and direction, metabolic rate and location of the thermal manikins, and air change rate of the room are varied. It is observed that faster injections, weaker thermal plumes, and lower air change rates increase exposure, while slower injections, vertical injections, side injections, and far occupant locations decrease exposure. Vertical injections are favourable in aerosol stratification in contrast to horizontal injections, which disturb aerosol stratification. Computational fluid dynamics (CFD) is able to predict the experimental results for the breathing and upper zones successfully.

5 Acknowledgements

The authors acknowledge the financial support of Natural Sciences and Engineering Council of Canada (NSERC), Institute for Computing, Information, and Cognitive Systems (ICICS), Sustainable Building Science Program (SBSP), and Stantec Consulting. The authors also thank Kevin Asperin, Anne-Claire Fabry, Byron Roehrl, Ben Thomas, and Megan O'Brien for assisting with the development of experimental facility and numerical methodology.

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