LB-17-C005

An Efficient Ventilation Configuration for Preventing Bioaerosol Exposures to Health Care Workers in Airborne Infection Isolation Rooms

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ABSTRACT

An efficient ventilation configuration of an airborne infection isolation room (AIIR) is essential for protecting Health care workers (HCW) from exposure to potentially-infectious patient aerosol. This paper presents a Computational Fluid Dynamics (CFD) study to predict airflow distribution patterns throughout the AIIR and the bioaerosol dispersal originiating from an infectious patient for a range of AIIR ventilation configuration design considerations.

In the present study with ventilation configuration 1, the AIIR has two supply vents and 1 exhaust grille corresponding to that of a traditional ceiling mounted ventilation arrangement observed in existing hospitals.

Alternate ventilation configuration 2 retains the linear supply diffuser in ventilation configuration 1 but interchanges the Square supply and Main Exhaust locations.

The direct-control exhaust configuration evaluated in this study has the ceiling exhaust replaced with vented patient headboard mantle and canopy arrangement, while the supply diffusers locations remains the same as configuration 2.

Furthermore, the effects of shifting the HCW's location on the room air distribution and the bioaerosol dispersal behavior is studied to ensure whether the Direct-Control exhaust configuration is efficient in protecting the HCW from patient's contaminated air as the HCW standing near the patient's bed shifts positions while carrying out cough generating procedures.

The results show that the Direct-control exhaust configuration is the most efficient in preventing the patient's contaminated air from entering the HCW's region. Further evaluation of this configuration is recommended for potential adoption within new and existing AIIRs to reduce the potential impact of infectious epidemics on severe workforce absenteeism and our nation's significant financial losses.

INTRODUCTION

Many highly infectious agents such as SARS, Influenza, MERS-CoV Tuberculosis, and Ebola hemorrhagic fever (CDC Report 2015) are spread by airborne or droplet transmission in health-care settings [Assiri A (2013)]. There are about 12.6 million personnel designated as healthcare workers (HCWs) by the Bureau of Labor Statistics. HCWs providing direct patient care services are at high risk for occupational transmission of airborne infections [Zumla A (2014), Marchand et al., (2016), Petti S (2016)]. To protect HCWs from potential airborne exposures, the design of proper ventilation arrangements in an AIIR are strictly essential and pressurization is a critical contamination control strategy at the room boundary. Furthermore, airflow pattern (direction) and air change rate (dilution) are critical contamination strategies within a room.

Relevance to ASHRAE

METHODS

The transient, 3-D, incompressible Navier-stokes equations, including gravity, were solved with pressure-velocity coupling achieved using the Semi-Implicit Pressure-Linked equations (SIMPLE) algorithm. The energy equation was also solved to account for temperature variations. The transport equations were discretized using a second-order upwind scheme with second-order implicit discretization for the temporal terms. Turbulence was modeled using the realizable k-ε model. Numerical analysis was performed using the commercial CFD code FLUENT based on the finite volume method. Over each control volume, the SIMPLE algorithm was used to iteratively solve for these Governing equations.

The steady-state flow field in the AIIR was determined before the patient's coughing and HCW's breathing were initiated. The Convergence criteria for the steady state flow field were set at 10^{-4} for all equations. Next, the patient cough cycle consisted of a mixture of cough aerosol and air for a 0.5 seconds cough cycle.

The Lagrangian discrete-phase model in the finite-volume solver ANSYS Fluent 17.0 was used to track infectious bio aerosols within the AIIR. O'Rourke's stochastic algorithm was used to model droplet collision, and the Taylor analogy breakup (TAB) model was used for droplet breakup using CFD modeling program. The patient coughed for the time period of 0.5 seconds while the HCW continued breathing. At the end of the patient's cough cycle [Gupta 2008], the patient resumed normal breathing cycle of 4 seconds [Guyton and Hall 2011] and the cough aerosols dispersal throughout mock AIIR were tracked in time until all these aerosols were exhausted from the room by the exhaust ventilation or through bathroom door gaps.

VERIFICATION STUDY

Comparison of the patient's cough aerosols flow process obtained from the present CFD study to the visualization of Cough flow process from the experimental work by Gupta et al, 2009.

The cough flow process and the flow direction of cough predicted by the current numerical analysis (Figure 1A) is verified with the experimental work by Gupta 2009 (Figure 1B), showing the side view of a cough process from patient's mouth at the end of the patient's cough cycle (0.5 seconds).

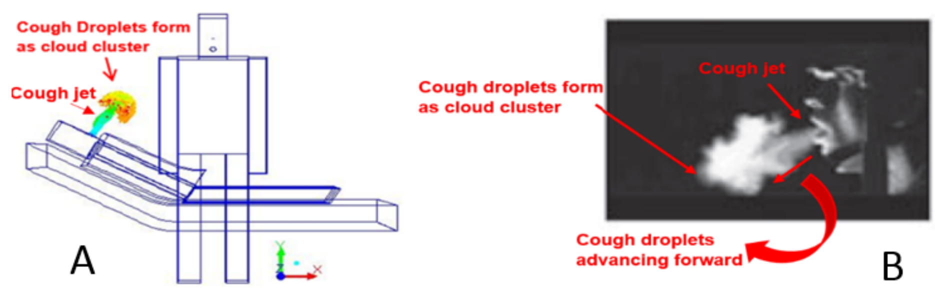

Figure 1(A-B) - Comparison of Patient's cough aerosols flow process in the current numerical study (A) to the experimental work by Gupta 2009 (B)

Comparing the numerically obtained dispersal of cough aerosols from patient's mouth (Figure 1A) to the flow visualization of cough by Gupta 2009 (Figure 1B), it can be observed that the cough aerosols are ejected as a jet from the person's mouth and travel through the room air in the form of a cloud cluster.

Grid Independence Test

To ensure accuracy and rationality of CFD results, a grid independence test was performed on the Original AIIR configuration. Three grid densities, 752,437 cells (Case 1), 1,375,914 cells (Case 2), and 2,820,484 cells (Case 3), were investigated to perform the gird sensitivity study. The grids are unstructured, and cells are tetrahedral. **Figure 2** presents the results of grid independence test.

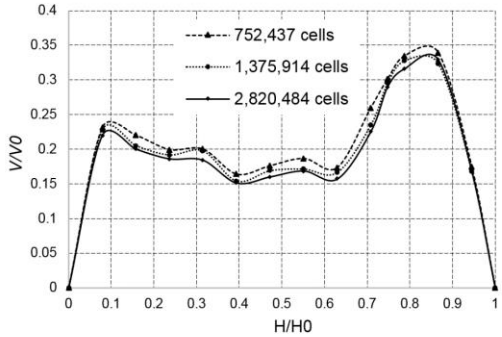

Figure 2 - Grid independence test

In **Figure 2**, V refers to the velocity magnitude of room air monitored at a specific location close to the patient, VO, the maximum velocity magnitude of room air at the boundary condition of velocity inlet, H the height of room air monitored at the specific location close to the patient and HO is the room height. The dimensionless velocity at the monitored points in Case 2 was quite close to that of Case 3. As the difference between Cases 2 and 3 was insignificant, it could be concluded that the grid system reached an independent solution. Therefore, the grid density with Case 2 was found to be sufficient and applied to carry on this present study.

RESULTS AND DISCUSSION

MOCK AIIR VENTILATION CONFIGURATIONS

The Mock AIIR at CDC's NIOSH's Alice Hamilton research laboratories in Cincinnati, Ohio was considered for the AIIR ventilation configurations shown in Figure 3. The AIIR ventilation design consists of 2 ceiling inlet supply vents (square and linear supply) and 1 ceiling exhaust grille, a Bathroom with exhaust vent, the room entrance/exit main door for Patient and HCW. The Boundary and Operating Conditions of the AIIR ventilation configurations are presented in Table 1 & Table 2 respectively. In the Ventilation configuration 1 (Figure 3A), the AIIR has two supply vents and 1 exhaust grille corresponding to that of a traditional ceiling mounted ventilation arrangement observed in existing hospitals.

Alternate ventilation configuration 2 (Figure 3B) retains the linear supply diffuser in ventilation configuration 1 but interchanges the Square supply and Main Exhaust locations. One strategy to establish a controlled air flow pattern is to place the supply vent at the side of AIIR opposite the patient, so that fresh air flows throughout the room and then exhausts from a location adjacent to the patient.

The Direct-control exhaust configuration 3 (Figure 3(C-E)) replaced the ceiling exhaust with a vented patient headboard mantle and canopy arrangement, while the supply diffuser locations remain the same as configuration 2.

INVESTIGATION OF AIR FLOW PATTERNS BASED ON VENTILATION CONFIGURATIONS IN AIIR

General ventilation systems such as that presented in the Mock Original AIIR (Figure 4A) are primarily intended to facilitate tempering requirements and to prevent stagnation of air as well as short-circuiting of air from the supply to exhaust. However, the results show, the fresh air from the square supply becomes contaminated by the patient source, then recirculates in the patient and HCW's region instead of being immediately removed by the exhaust. The presence of the room air recirculation in front of HCW and above the patient's body could diminish the dilution mixing effectiveness of the mock AIIR air supply and result in accumulation or prolonged presence of the contaminated air within the immediate presence of the HCW.

Table 1 –AIIR Ventilation Configurations 1, 2 – Operating Conditions

No.	Boundary	Boundary Condition	Boundary value required
1.	Linear Inlet diffuser	Number of slots in the Linear Diffuser	2
		Flow rate	55% of Q_{in} = 81.49CFM (0.0384 CMS)
		Angle	45^0
		Direction of flow: Towards the window (for the slot closer to window); Directly downwards for the 2nd slot furthest from window.	
2.	Square supply	Flow rate	45% of Q_{in} = 66.67CFM (0.0314 CMS)
		Angle	45^0
		Direction of flow: Outward, air flows into the room.	
3.	Main Room Exhaust	Flow rate	225 CFM (0.1061 CMS)
		Direction of flow: Into the exhaust vent, air extracted from the room.	
4	Bath Room Exhaust	Flow rate	80CFM (0.3775 CMS)
5	Main Door Gaps	Pressure at main door gaps	-0.01" W.G. (-2.49 Pascal)
6.	Bath Door Gaps *(Assuming bath receives 10% of its exhaust makeup air from leaks other than bathroom entry door)*	Flow rate	72CFM (0.0339 CMS)
		Direction of flow: In to bathroom, room air escapes through bath door gaps	
7.	Overhead Lights	Power (Watts)	0 (Isolated from room environment)
8.	HCW lower body	Temperature	294.11K (69.72^{O}F) (Room Temperature)
9.	HCW head and face		309.66K (97.71^{O}F) (Normal body Temp)
10	Patient head and mouth		311.33K (100.72^{O}F) (Patient with Fever)

Table 2 –Direct-Control Exhaust Configuration – Operating Conditions

No.	Boundary	Boundary Condition	Boundary value required
1.	Linear Inlet diffuser	Number of slots in the Linear Diffuser	2
		Flow rate	100 CFM (0.047 CMS)
		Angle	45^0
		Direction of flow: Towards the window (for the slot closer to window); Directly downwards for the 2nd slot furthest from window.	
2.	Square supply	Flow rate	150 CFM (0.07 CMS)
		Angle	45^0
		Direction of flow: Outward, air flows into the room.	
3.	Exhaust *(Three exhaust vents are placed at the mantle. One exhaust at the center top of the mantle and two exhaust at the side of the mantle)*	Total Flow rate	270 CFM (0.1274 CMS)
		Top Exhaust flow rate	90 CFM (0.04247 CMS)
		Side Exhaust1 -flow rate	90 CFM (0.04247 CMS)
		Side Exhaust2 -flow rate	90 CFM (0.04247 CMS)
		Direction of flow: Inward, air extracted from the room.	
4	Bath Room Exhaust	Flow rate	100 CFM (0.47 CMS)
5	Main Door Gaps	Pressure at main door gaps	-0.006" W.G. (-1.49 Pascal)
6.	Bath Door Gaps *(Assuming bath receives 10% of its exhaust makeup air from leaks other than bathroom entry door)*	Flow rate	90CFM (0.0424 CMS)
		Direction of flow: In to bathroom, room air escapes through bath door gaps	

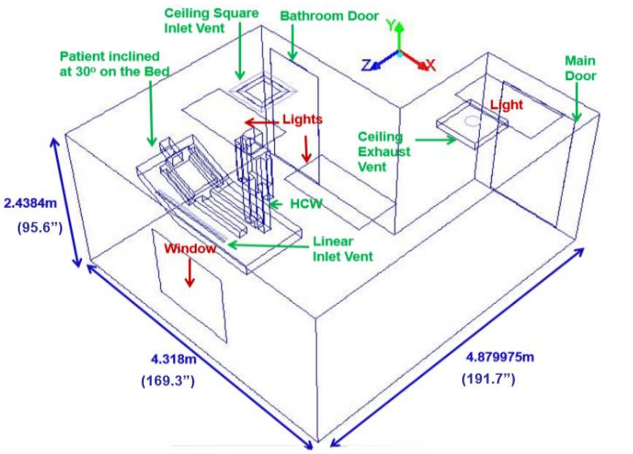

Figure 3A - Original AIIR Ventilation Configuration 1

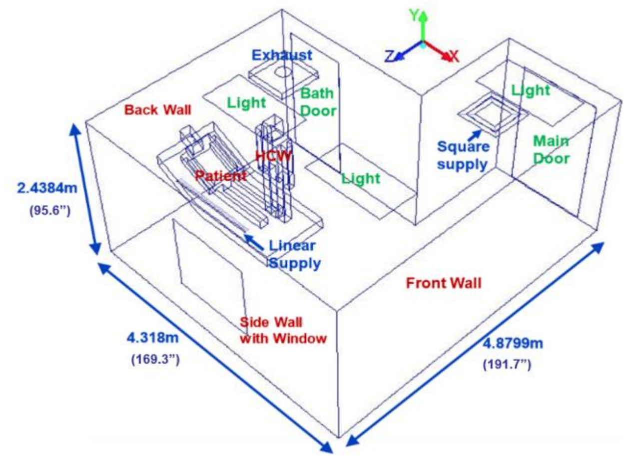

Figure 3B - Alternate ventilation configuration 2A

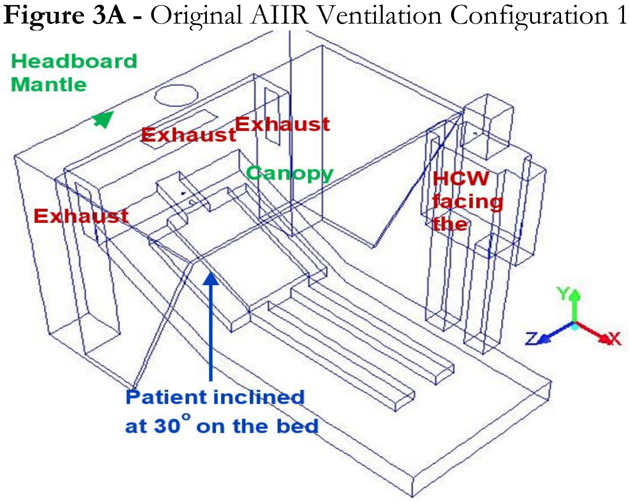

Figure 3C - Direct-control exhaust configuration representing Patient and HCWs Zone

A novel Direct-Control exhaust with retractable canopy configuration (Figure 3C) is proposed in this study to produce exhaust flow paths that directly capture and remove patient-source bioaerosols, thus achieving the room's airborne isolation objectives while also protecting HCWs standing next to the patient bed while performing cough generating procedures. Furthermore, the retractable canopy configuration provides immediate access to the HCW simply by pushing it back towards the wall (much like a baby carriage canopy). The mantle plus retractable canopy configuration provides immediate HCW access to the patient while allowing use of traditional medical gas wall plumbing strategies.

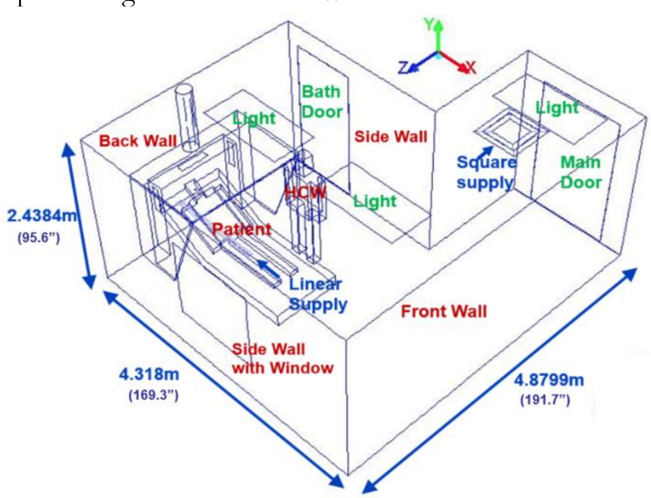

Figure 3D - Direct-control exhaust AIIR configuration 3 with a vented patient bed mantle headboard & canopy arrangement

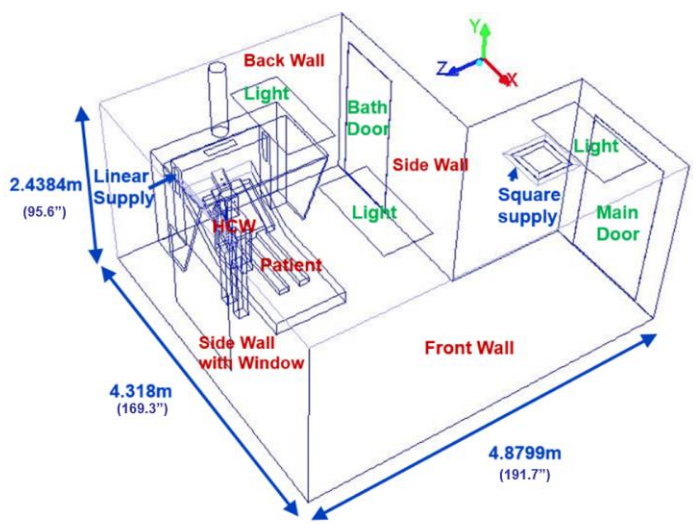

Figure 3E - Direct-control exhaust AIIR configuration 3 with HCW positioned on the opposite side of patient bed

Figure 3 - Mock AIIR Ventilation configurations

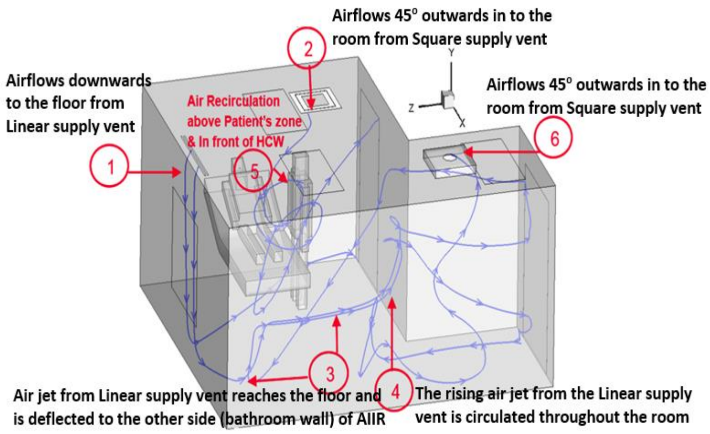

Figure 4A – Airflow distribution patterns in Original Mock AIIR

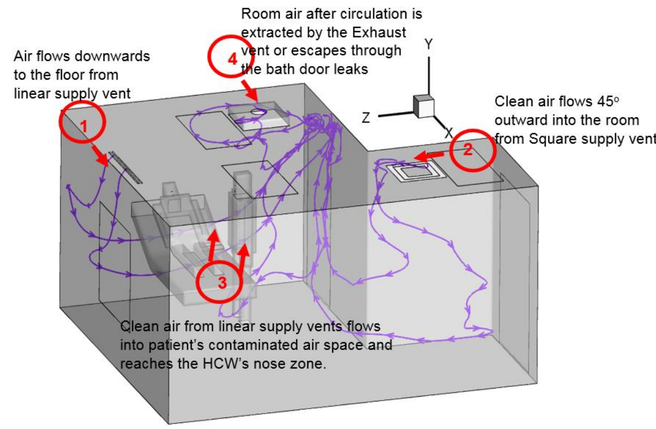

Figure 4B – Airflow distribution patterns in AIIR Ventilation Configuration 2A

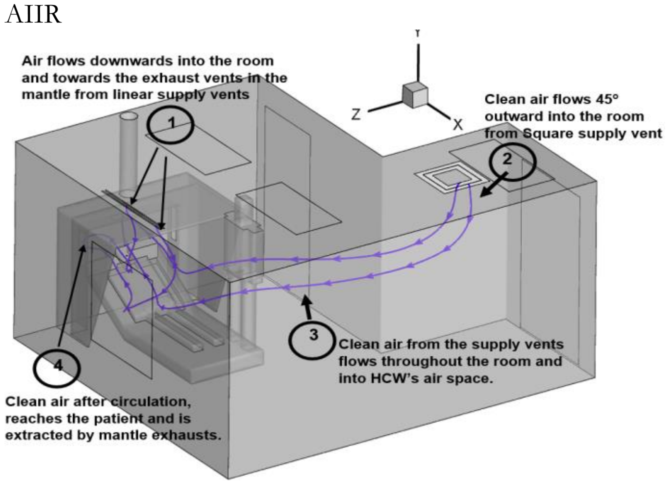

Figure 4C – Airflow patterns in Direct-control exhaust AIIR configuration 3

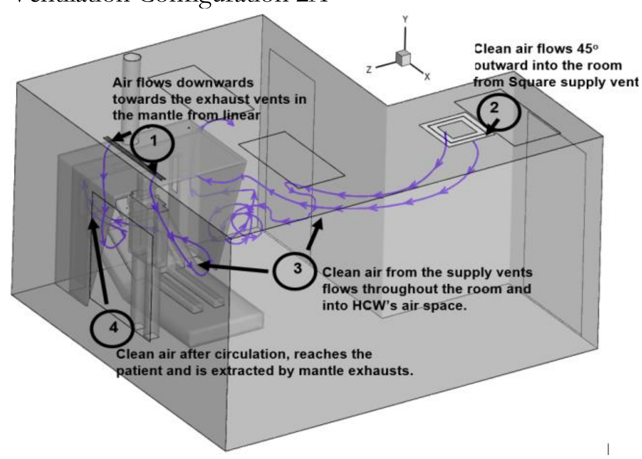

Figure 4D – Airflow patterns in Direct-control exhaust with HCW positioned on the opposite side of patient bed

Figure 4 - Investigation of air flow patterns based on ventilation configurations in AIIR

In the alternate AIIR ventilation configuration 2A (Figure 4B), the ceiling supply vents are positioned at locations 1 and 2, in order to distribute fresh air throughout the room. Nonetheless, clean air from linear supply vent flows into the patient's air space, becomes contaminated, then carries the contaminated air towards the HCW's breathing zone (at location 3). This suggests, even though the supply vent dilutes the contaminated air in the room, the rising air (particularly that originating from the linear supply vent) flows in the direction of patient's air space to the HCW's breathing zone, resulting in HCW's risk of infectious bioaerosol exposure.

In the Direct-control exhaust configuration (Figure 4(C-D)), fresh air from the supply vents flows throughout the room and into HCW's air space without becoming contaminated by the patient, as shown at location 3. Room air after circulation, finally reach the infectious source (patient) and is immediately extracted by the three exhaust vents (at location 4) in the mantle. Hence, the evaluated Direct-control exhaust configuration is the most efficient in controlling the contaminated patient source bioaerosol locally and preventing it from entering the HCW's region.

THE IMPACT OF AIIR VENTILATION CONFIGURATIONS IN THE CONTROL OF HCW's EXPOSURE TO INFECTIOUS BIOAEROSOLS

In the Original AIIR (Figure 5A) and Alternate Ventilation Configuration (Figure 5B), the cough aerosols gain momentum by cough velocity from patient's mouth and eventually spread throughout the room. These aerosols are carried by the airflow patterns and a portion are inhaled by the HCW. This exposure results in an increased risk of disease transmission from Patient to HCW. Even though, a portion of these aerosols are removed by the ceiling exhaust ventilation over time, the remaining cough aerosols re-enter and re-circulate within the HCW's zone, until they are eventually removed by the exhaust ventilation. These ceiling ventilated AIIR configurations created an unfavorable environment for the HCW throughout their stay in the room and were not effective in protecting the HCW from infectious cough aerosols. The results suggest that an AIIR ceiling ventilation arrangement can play a significant role in facilitating infectious exposures and potential disease transmission to HCWs.

Figures 5(C-D) presents the cough aerosols dispersal from patient's mouth in the Direct-control ventilation configuration with HCW shifting locations on either side of the Patient's bed. The bio aerosols from patient zone are captured and contained within the mantle and canopy arrangement. These infectious aerosols are immediately entrained by the mantle exhaust vents suggesting that this ventilation configuration protects the HCW from flu exposure risk, even while changing locations near patient's bed. Hence, shifting the HCW's location in the Direct-Control ventilation configuration does not affect the air flow patterns and the prevention of aerosol exposures to HCW. This further ensures that the Direct-Control ventilation configuration is efficient in protecting the HCW from patient's infectious aerosols as the HCW standing near the patient's bed shifts positions while carrying out cough generating procedures.

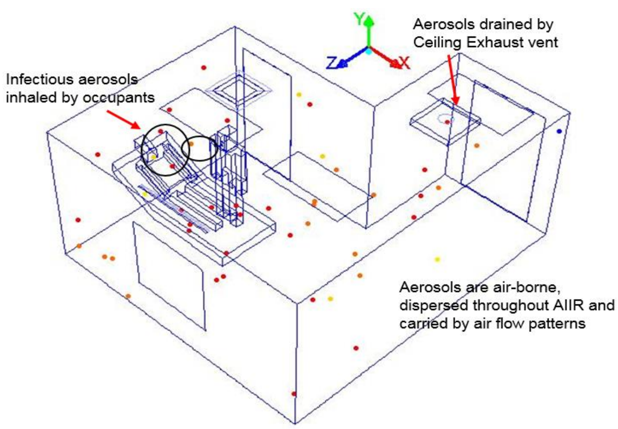

Figure 5A – Cough aerosol dispersal at time instant of 5 seconds in Original Mock AIIR

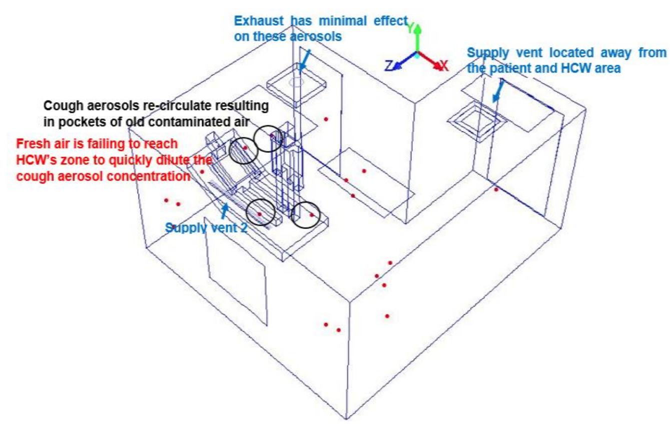

Figure 5B – Cough aerosol dispersal at time instant of 2 seconds in Alternate AIIR Ventilation Configuration 2

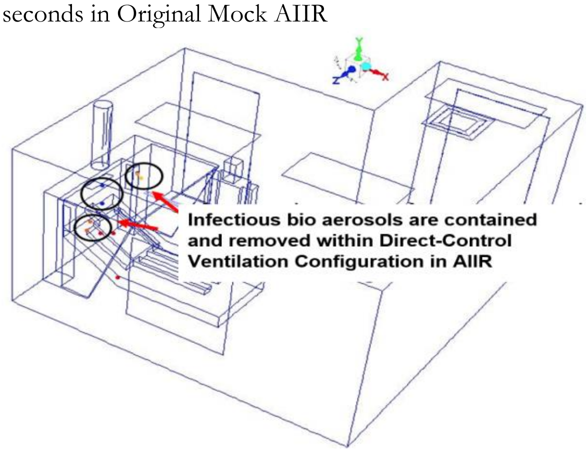

Figure 5C – Cough aerosol dispersal at time instant of 1.75 seconds in Direct-Control AIIR Exhaust Configuration

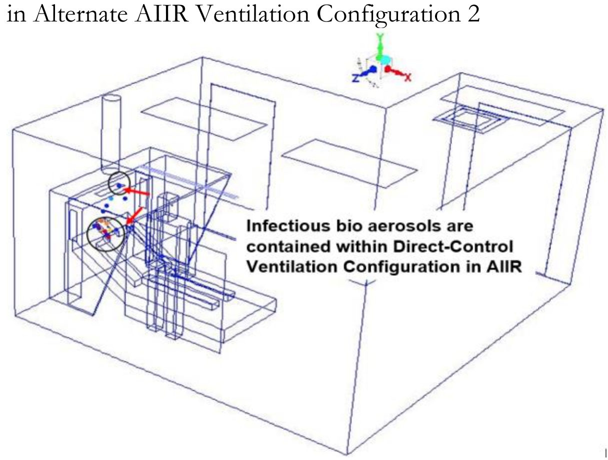

Figure 5D – Aerosol dispersal at time instant of 2s in Direct-Control Exhaust configuration with HCW positioned on the opposite side of patient bed

Figure 5 - Cough aerosol dispersal behavior assessment and the impact of AIIR ventilation configurations in the control of HCW exposure to infectious bioaerosols

CONCLUSIONS

This paper presents numerical modeling of airflow distribution patterns and bioaerosol dispersion in a Mock AIIR for a range of ceiling ventilated design configurations. Airflow distribution patterns in the Original and Alternate AIIR Configurations suggest that air recirculation regions in HCW's vicinity diminished the bioaerosol removal efficiency and prolonged the presence of contaminated air in the HCW's vicinity and throughout the room. The results also indicate, as cough aerosols are carried by the air flow patterns, they tend to break-up and disperse throughout the room causing an immediate risk of airborne infection to HCW within a short interval after patient coughs. Hence the evaluated AIIR ceiling ventilation configurations examined in this study were not effective in mitigating the infectious bioaerosols. Furthermore, in ceiling ventilated AIIRs, the HCW's risk of exposure to bioaerosols may substantially increase due to patient's successive coughing events.

The novel Direct-Control Exhaust with retractable canopy configuration proposed in this study demonstrates the best contaminant removal effectiveness to not only extract bioaerosols as soon as the patient coughs and provide an aerosol-isolation at the patient's zone but also to protect HCWs standing next to the patient bed while performing cough generating procedures. Hence, the Direct-Control exhaust technique produces airborne infection isolation within the AIIR patient room while improving worker protection from both long-range and short range infectious bioaerosols and should be considered within new and existing AIIRs to reduce the potential impact of infectious disease epidemics upon HCW health, workforce absenteeism and significant financial losses.

ACKNOWDGEMENTS

We express sincere gratitude for NIOSH sponsorship of this research, ASHRAE 2015-2016 Graduate Student Grant-In-Aid award support, the Ohio Supercomputer Center, the assistance of NIOSH employee Dylan Neu and all the members at The Computational Fluid Dynamics Research Laboratory, The University of Cincinnati.

DISCLAIMER

The findings and conclusions in this paper are those of the authors, and do not necessarily represent the views of NIOSH. Mention of any company or product does not constitute endorsement by NIOSH.

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