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Infection control and sustainability measures for a healthcare facility

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SUMMARY

Potential disease outbreaks and climate change scenarios of recent past demand balancing of infection control as well as energy use within healthcare settings as need of the hour, although it is quite challenging and often overlooked. In this study, infection risk posed through aerial dispersion of Middle East Respiratory Syndrome Coronavirus (*MERS-CoV*) in a typical semi-enclosed mechanically ventilated ward cubicle in Hong Kong is analyzed through Computational Fluid Dynamics and annual energy consumption of ward is estimated through building energy simulation tool (Energy plus). Fundamental transport and deposition mechanism of droplet nuclei of size 0.167µm under different air change rates ($3h^{-1}$-$13h^{-1}$) are evaluated and their effectiveness is estimated through infection risk indicators. Results suggest that ventilation rate can be critical while laying out infection control strategies and an air change rate between $6h^{-1}$-$9h^{-1}$ would be optimal to sustain comfort as well as well-being of ward users while reducing carbon footprint.

KEYWORDS

(*Ventilation, Hospital inpatient ward, Computational Fluid Dynamics (CFD), Middle East Respiratory Syndrome Coronavirus (MERS-CoV), Energy consumption)*

1 INTRODUCTION

Climate change is an existential danger faced by humanity and its consequences are unevenly spread across the globe. The widespread presence of infectious diseases, heat related disorders, air pollution are few of the noted adverse health related conditions arising from climate change. The outbreak of infectious diseases such as Severe Acute Respiratory Syndrome Coronavirus (*SARS-CoV*) as well as Middle Eastern Respiratory Syndrome Coronovirus (*MERS-CoV*) resulted in fatality rates of 9.6% and 34.4% respectively (Munster et al. 2020). At the hindsight of these outbreaks, a strong link between dispersion of infectious pathogens and ventilation had been established in indoor environments. However, the ventilation design strategies are not well defined in most of the generic patient environments (Noakes et al. 2012). In Hong Kong, buildings consumes about 90% of the city's electricity and electricity generation for these buildings account for over 60% of its carbon emissions (EB 2018). Moreover, air conditioning is one of the prime consumers of electricity in Hong Kong, which is located in a typical subtropical climatic region. Buildings under healthcare segment such as hospitals are quite energy intensive as it has to maintain a stable microclimate, operate under several air change rates and also function under strict temperature as well as relative humidity set points (Ascione et al. 2013).

Understanding the correlation between airflow distribution, infection risk, thermal comfort and energy usage have become increasingly important in presumed low risk areas such as inpatient facilities of hospitals. Based on the current climate scenario, the need for studies addressing the development of low-energy healthcare buildings and effective ventilation design strategies that balances the thermal comfort as well as infection control is important more than ever before. In this numerical study, fundamental transport, dispersion and deposition mechanism of droplet nuclei of *MERS-COV* under different air change rates ($3h^{-1}$-$13h^{-1}$) in a typical semi-enclosed mechanically ventilated inpatient ward cubicle is analysed through Computational Fluid Dynamics (*CFD*) and annual cooling energy consumption of the ward is estimated through building energy simulation tool (Energy Plus). Based on the CFD simulation results, infection risk indicators are plotted and cooling energy consumption data generated through physical expressions as well as Energy Plus to maintain acceptable thermal comfort for different air change rates is estimated.

2 METHODOLOGY

2.1 Infection transmission scenarios in ward cubicle

The infection transmission scenario is classified into two categories in this study, namely, i) Cross infection within ward patients, ii) Infection spread from cubicle to other spaces.

2.1.1 Cross infection within ward patients

Exhalation activities such as sneezing, coughing of infected patients are known to transmit infection to others. Scenario where deposition occurs on to other patients' body is accounted by Equation 1, where Ex_i is the fractional exposure count for patient i, ex_j is the fractional emission from patient j, m is the total number of patients inside the ward cubicle, to determine the location within ward cubicle having the most and least risk of infection. Surface contamination is accounted by Equation 2, where m_s is the number of particles emitted through sneezing by an individual patient, m_{ce}, m_{wa}, m_{fl} are the number of deposited particles onto ceiling, wall, and floor, d_{ce}, d_{wa}, d_{fl} are the ceiling, wall and floor deposition ratio.

$$Ex_i = \sum_{j=1}^{m} ex_j ;\, j \neq i \tag{1}$$

$$d_{wa} = \frac{\sum_{i=1}^{m} m_{wa_i}}{m * m_s};\; d_{ce} = \frac{\sum_{i=1}^{m} m_{ce_i}}{m * m_s};\; d_{fl} = \frac{\sum_{i=1}^{m} m_{fl_i}}{m * m_s} \tag{2}$$

2.1.2 Infection spread from cubicle to other spaces

The spread of infection from cubicle to corridor due to the dispersion of infectious pathogens exhaled by infected patients can result in spreading of the infection to adjoin ward spaces. Equation 3 accounts for the number of particles escaped to the corridor (m_{es}), where E_{es} is the exhausted ratio.

$$E_{es} = \frac{m_{es}}{m_s} \tag{3}$$

2.2 Annual cooling energy estimation:

The annual cooling energy consumption (E_c) for the ward cubicle is estimated by the division of total hourly heat gain, i.e., envelope heat gain (H_{en}), ventilation heat gain (H_{vent}) and internal heat gain (H_{in}) with respect to the hourly AC operation schedule $\phi_{AC,h}$ for a year with h = 1-8760 hours by the coefficient performance of the air-conditioner (*COP*) as shown in Equation 4.

$$E_C = \sum_{h} \frac{\varnothing_{AC,h} \left(H_{en} + H_{vent} + H_{in} \right)_h}{COP_h} \tag{4}$$

The hourly envelope heat gain for a year is calculated using Energy Plus, while the hourly ventilation heat gain and internal heat gain is estimated using the physical expressions as shown in Equation 5-6 (Wong and Mui, 2008), where L_{sen} is sensible load, L_{lat} is latent load, M_h is the number of users/occupants at hour h with random distribution of 1-6, density of air ρ = 1.2 kg m^{-3}, heat capacity of air C_{pa} = 1.01 KJ kg^{-1}°C^{-1}, latent heat of evaporation of air hfg = 2436 kJ kg^{-1}, indoor set temperature T_a = 24°C, outdoor temperature T_o (°C), indoor air moisture content w_a in kg kg^{-1}, dry air, can be determined from the psychometric chart using the assumption of set indoor temperature = 24°C and indoor relative humidity = 60%, outdoor moisture content w_o in kg kg^{-1}, dry air, V_{vent} is the average ventilation rate per person (0.0168-0.0731 m^3 s^{-1}), p_w (kPa) is the vapour presure, p_{ws} (kPa) is the saturated vapour pressure and $R_{h,o}$ is the outdoor relative humidity in %, equipment power density d_{eq} = 15.715309 W/m^2, lighting power density = 6.673624 W/m^2, floor area A_{fl} = 45m^2.

$$H_{vent} = L_{sen} + L_{lat} \quad ; \begin{cases} L_{sen} = M_h \rho V_{vent} C_{pa} \left(T_a - T_o\right) \\ L_{lat} = M_h \rho V_{vent} h_{fg} \left(w_a - w_o\right) \end{cases} \tag{5a}$$

$$w_o = \frac{p_w}{101.325 - p_w} \times 0.622 \quad ; \quad p_w = \frac{R_{h,o}}{100} \times p_{ws} \tag{5b}$$

$$H_{in} = \left(d_{eq} + d_{li}\right) \times A_{fl} \tag{6}$$

2.3 Numerical simulation

2.3.1 CFD prediction of airflow and particle distribution

A finite volume based CFD code (Ansys Fluent 13.0) was used to analyse the airflow distribution and dispersion mechanism of bioaerosols within a mechanically ventilated semi-enclosed inpatient ward cubicle. The Eulerian framework is adopted to solve the governing equations of continuity, momentum and energy for the continuum phase (air), whereas the discrete phase (particle) was modelled under the Lagrangian framework. The numerical simulation treats the three dimensional airflow within the ward cubicle as a steady state incompressible turbulent flow. The Reynolds Averaged Navier Stokes (RANS) based turbulence model, Re-Normalization Group (RNG) k-ε was adopted to model the air turbulence in this study, as it offers better accuracy and stability for indoor airflow simulations (Zhang and Chen, 2006). The computational domain of the ward cubicle as shown in Figure 1a. was volume meshed with hexahedral cells and near wall cells were fine enough to capture the viscous sub-layer ($y+ < 5$). Based on the grid convergence index (GCI) approach, grid system with 3202k hexahedral cells were adopted for this study. The particle trajectories were tracked for individual particles using the Lagrangian framework. The drag coefficient for particles used in this study is defined by Equation 7 (Wong et al. 2015).

$$C_D = \frac{K_D}{Re_b} ; Re_b < 1 \; ; \; K_D = \frac{d_b^2}{2} \tag{7}$$

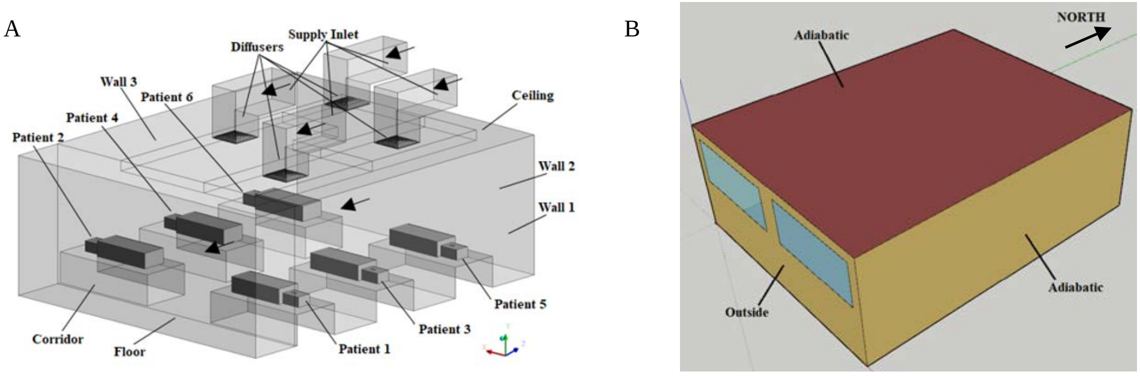

Figure 1. a) CFD model of cubicle, b) Cubicle envelope model for cooling energy estimation

Table 1. Parameters for CFD simulation.

Computational domain	7.5m(L) × 6m(W) × 2.7m(H), RNG k-ε turbulence model with enhanced wall treatment
Total supply airflow rate	0.1240kg·s^{-1} for ach=3, 0.2480kg·s^{-1} for ach=6, 0.3720kg·s^{-1} for ach=9, 0.5374kg·s^{-1} for ach=13, 285K (air temperature)
Diffuser (0.6m×0.6m)	Four supply diffusers, 4-way spread pattern, air supplied at an angle of 15° from the ceiling, adiabatic
Corridor (6m×2.7m)	Outflow with flow rate weighting, 295K (backflow temperature), adiabatic, escape boundary condition
Exhaust grille (0.5m×0.2m)	Outflow with flow rate weighting, 295K (backflow temperature), adiabatic, escape boundary condition
Walls, ceiling, floor and beds	No-slip wall boundary, adiabatic, trap boundary condition
Patient	Six patients, no-slip wall boundary, 23.3Wm^{-2} for each patient, trap boundary condition
Mouth of a patient (0.05m×0.05m)	Single-shot release with an upward velocity v_b=50ms^{-1}, n_s=10,000 virus particles, bioaerosol density ρ_b=1,100kgm^{-3}
Species (aerodynamic diameters)	MERS-*CoV* (0.167±0.012µm)

Brownian, thermophorectic and Saffman lift forces were also taken into account due to the nature of particle size and non-isothermal flow conditions. The discrete random walk (DRW) model was utilized to model the dispersion of particles resulting from air turbulence. Further details for numerical simulation can be noted from Table 1.

2.3.2 Prediction of Envelope heat gain (H_{en}) by Energy Plus (*EP*)

The building simulation tool energy plus was utilized in this study for predicting the envelope heat gain for the ward cubicle. The three dimensional geometry of the ward cubicle was created in Trimble SketchUp 2017 using the OpenStudio Plug-In as shown in Figure 1b. The interior partition surfaces are treated to be adiabatic surfaces, as adjacent spaces within the ward cubicle is assumed to have same temperature set points. Only one surface with window is exposed to outdoor conditions and variations in outdoor conditions are accounted by using the 1989 Hong Kong weather data (Mui and Wong, 2007). The indoor temperature set point as well as indoor relative humidity set point is kept as 24°C and 60% respectively for simulation. The building envelope construction set was created with reference to the design standards (ASHRAE, 2006; ASHRAE, 2009).

3 RESULTS AND DISCUSSION

The ventilation strategy incorporated within the inpatient ward cubicle is such that the cubicle is positively pressurised towards the corridor. Under this scenario, the maximum risk of cross infection through exposure to pathogens (*Ex*) is for patients located at 1.625m away from corridor (i.e. Patient 1 and 2), whereas the least risk of infection is for patients located at 5.875m away from corridor (i.e. Patient 5 and 6) as shown in Figure 3a. As the air change rate increases from 3-13h^{-1}, the pathogen exposure count increases for patients 1 and 2, whereas it subsides for patient 5 and 6. The *Ex* for patients located at 3.75m away from corridor (i.e. patient 3 and 4) as well as for patients located at 5.875m away from corridor tends to decrease at 6-13h^{-1}.

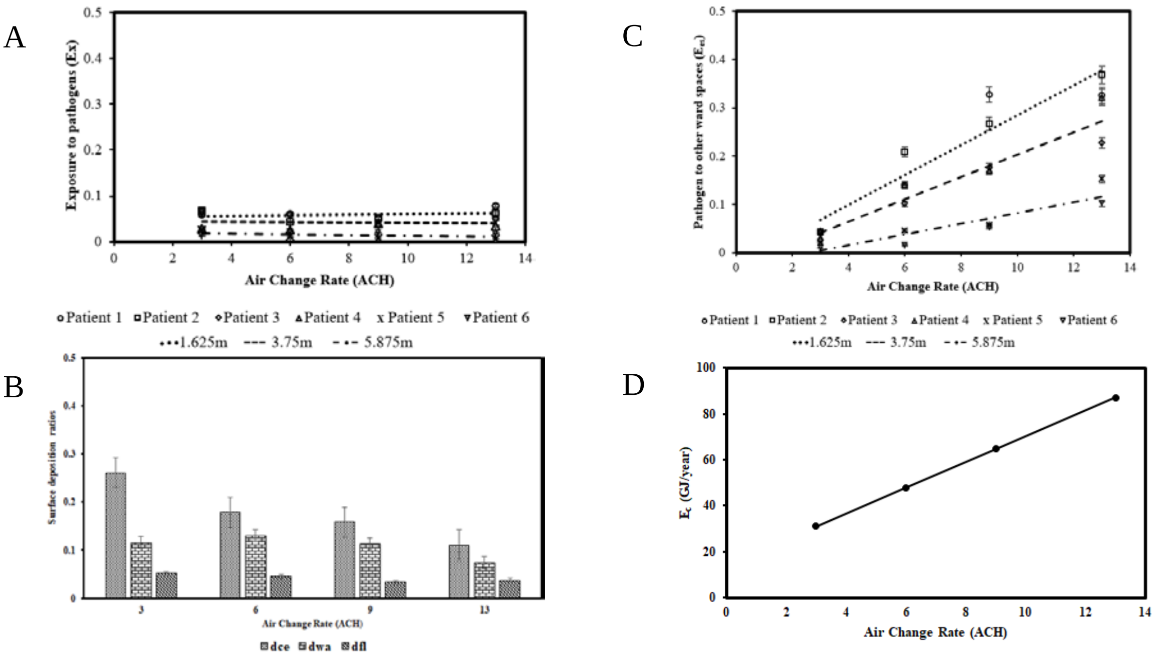

Figure 3. a) ACH vs Exposure to pathogens (*Ex*) b) ACH vs Surface deposition ratios c)ACH vs Pathogens to other ward spaces (E_{es}) d) ACH vs Annual cooling energy consumption (E_c)

The deposition of particles within ward surfaces such as ceiling (d_{ce}), wall (d_{wa}), floor (d_{fl}) can cause surface contamination leading to infection transmission. The deposition of particles onto ceiling is comparatively high at low air change rate of 3h^{-1}(d_{ce}>0.25), whereas subsequent reduction in surface deposition onto ceiling is observed with increase in ACH ($d_{ce} \approx 0.17$ at 6h^{-1} (34% reduction) and $d_{ce} \approx 0.11$ at 13h^{-1} (57% reduction)) as shown in Figure 3b. The reduction is associated with the increase in supply air momentum with increase in ACH, causing the movement of particles away from ceiling to other ward surfaces. Although, deposition onto different surfaces is noted to occur irrespective of the ACH adopted. The risk of infection to others outside the cubicle due to dispersion of particles towards the corridor is contributed the most by patients 1 and 2. The viral load reaching the corridor is noted to increase with increase in ACH, with maximum exhausted ratio ($E_{es} > 0.25$) reported at 13h^{-1} from patients 1 and 2 as shown in Figure 3c. In this case, the increase in ventilation rate tends to increase the risk of infection. These results are indicative of the importance of ward design, ventilation strategy and location of infected patient in the infection transmission dynamics.

Apart from Infection control, an effective HVAC system must also function to ensure an acceptable thermal comfort for ward users. It is essential to have a minimum ventilation rate to maintain good indoor hygiene, but as can be seen from Figure 3d, ventilation rate comes at a cost. The total annual cooling energy consumption (E_c) tends to increase linearly with increase in ACH as shown in Figure 3d. The building envelope, occupancy pattern and user behaviour, equipment load, ventilation system can all play an integrated role in reducing the infection risk and carbon footprint from healthcare buildings. In order to build low energy consuming buildings, a hierarchy of measures need to be further investigated and developed. Identifying locations for installation of local exhaust grilles for infection control, recirculation of air facilitated through exhaust grilles to reduce energy consumption, improving building envelope quality, ventilation strategy to reduce the contaminant dispersion within spaces are few of the critical factors that needs to be further addressed by the research community.

4 CONCLUSION

An insight in to the field of infection control along with identification of risk exposures and measures to account the annual cooling energy consumption of a healthcare facility is done through this study. Ventilation rate plays a decisive role in particle distribution as well as in cooling energy consumption. High ventilation rates such as 13ACH is recommended to be used with caution for infection control and it also proves to be costly in terms of energy consumption. The location of an infected patient is also noted to be critical in causal of infection spread to users of the facility. Furthermore, despite the ventilation strategies in place, good housekeeping practices are encouraged within healthcare environments to enhance infection risk mitigation. Moreover, good quality building envelope and an effective ventilation system design can play an integrated role in achieving energy efficiency. In view of infection control and energy consumption, it is suggested to use an air change rate between $6h^{-1}$ & $9h^{-1}$ within inpatient wards. This study would serve as a reference for hospital management to achieve their infection risk mitigation and energy saving goals.

5 ACKNOWLEDGEMENT

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