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Ventilation in worker dormitories and its impact on the spread of respiratory droplets

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ABSTRACT

Most of the COVID-19 cases in Singapore have primarily come from foreign worker dormitories. This people group is especially vulnerable partly because of behavioural habits, but the built environment they live in also plays a significant role. These dormitories are typically densely populated, so the living conditions are cramped. The short lease given to most dormitories also means the design does not typically focus on environmental performance, like good natural ventilation. This paper seeks to understand how these dormitories’ design affects natural ventilation and, subsequently, the spread of the COVID-19 particles by looking at two existing worker dorms in Singapore. Findings show that some rooms are poorly orientated against the prevailing wind directions, so there is dominant stagnant air in these rooms, leading to respiratory droplets’ long residence times. These particles can hover in the air for 10 min and more. Interventions like increased bed distance and removing upper deck beds only showed limited ventilation improvements in some rooms. Comparatively, internal wind scoops’ strategic placement was more effective at directing wind towards more stagnant zones. Large canyon aspect ratios were also effective at removing particles from higher elevations.

1. Introduction

Singapore has experienced spikes in the number of Covid-19 infections from April to September 2020. As of Jan 2021, the total confirmed cases had crossed the 59,000 mark. Of these cases, a large fraction, 93.4%, can be traced to worker dormitories (MOH, 2020). There is a similar situation in Malaysia. The Teratai cluster, made up of factories and worker dormitories, is the country’s biggest cluster and has recorded more than 6000 cases as of Jan 2021 (Birruntha, 2021). The confirmed cases had crossed the 59,000 mark. Of these cases, a large fraction, 93.4%, can be traced to worker dormitories (MOH, 2020).

In a World Health Organization report, workplaces are encouraged to be well ventilated by opening the windows and doors whenever possible (WHO, 2020). One key reason is the conclusion of another research where COVID-19 transmission happens through pharyngeal viral shedding when symptoms are still mild (Wolfel et al., 2020). This means that large droplets that cannot enter the lung but land in the upper respiratory tract should be avoided. These large droplets come primarily through sneeze/cough-droplet ballistics. The larger droplet size is also why wearing face masks effectively reduces transmission (Bandiera et al., 2020) since the larger droplets are sprayed onto the mucus membrane. However, small aerosols are inhaled into the respiratory tract (Samet et al., 2021). Since deposition locations are mostly on the upper airways, there is also the possibility of secondary transmissions by the instant expelling of inhaled viral droplets (Shang, Tao, Dong, He, & Tu, 2021). Non-droplet transmission routes are also found possible, where SARS-CoV-2 particles were also found present in human excrections (Witkozyck-Kapischke, et al., 2021), and the particle sizes were found to be smaller than 10 μm (Guzman, 2020). This is similar to research regarding SARS, where the focus was on transporting droplets of much smaller sizes that are 1 μm or smaller (Zhao, Zhang, & Li, 2005). For viral loads corresponding to mild-to-moderate cases of COVID-19, however, droplets smaller than 20 μm at the time of emission were found unlikely to be of consequence in carrying infections (Anand & Mayya, 2020). Another study also inferred that larger droplets of 32-40 μm might potentially be more infectious due to higher viral content (Li et al., 2021).

Particle size is important for aerosol behaviour because small particles can remain air-borne indefinitely under indoor conditions unless removed due to mechanical or natural ventilation (Fennelly, 2020; Moschovis et al., 2021). Beyond the droplet size, many other factors affect the rate at which the droplets evaporate. Like mentioned, friction between the air and droplets play a huge role, and this is enhanced by

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https://doi.org/10.1016/j.scs.2021.103327

Received 7 March 2021; Received in revised form 31 August 2021; Accepted 31 August 2021

Available online 3 September 2021

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the buoyancy effect due to temperature differences and the drag force, produced from the friction between the droplet and air. It was found that buoyant flows in street canyons have unsteady flows and thus more complex models are needed to accurately model them (Allegrini, Dorer, & Carmeliet, 2014). The complexity comes from the interaction of buoyancy and wind, where they may potentially reinforce or counteract one another (Hunt & Linden, 1999). Being non-linear and multi-dimensional, their combined impacts cannot be concluded simply through addition. The evaporation rate is also improved when droplets are produced at higher velocities and lower temperatures relative to surrounding air (Montazeri, Blocken, & Hensen, 2015).

Thus, the built environment plays a key role in ensuring proper ventilation of spaces such that the droplets do not land on crucial surfaces nor linger around areas of large crowds. For example, in one case, the COVID-19 virus was identified on various surfaces up to 17 days after the cabins were vacated on the Diamond Princess cruise. This is especially important for worker dormitories, where large crowds tend to gather, and ventilation rates tend to be insufficient due to the space layout design. In a study of schools in the US, it was concluded that older buildings were associated with greater outdoor airflows, and this translated to lower transmission probabilities (Pavilonis, Lerardi, Levine, Mirer, & Kolvin, 2021). This is similar in a University campus with HVAC systems, where increasing the ventilation rate led to a decrease in the number of infected people (Mohktari & Jahangir, 2021). However, the behaviour of particle transport is quite complex and not linearly dependent on air velocity alone, as found in a hospital ward study in Africa (Adeniran et al., 2021).

A look at particle position and residence times showed that droplets could travel several meters away, and smaller sized particles stayed longer in the air. In a dispersion model using PM10 sizes, it was concluded the particles travelled up to 9m away from the source in an outdoor environment (Mostafa & Reza, 2021); more than 6 feet in a hospital (Stern et al., 2021); surviving for 3hrs and reaching 7-8m away (Cao et al., 2021). Droplets less than 250 μm were found likely to remain suspended in the air for a study in a bus (Mesgarpour et al., 2021). Cough droplets were found to include 15 μm aerosols and 60-100 μm ballistic droplets, where the settling velocities were 3mm/s (Tan, Silwal, Bhatt, & Raghav, 2021). The extraction of particles in a room can be based on thresholds defined in different standards, and in one study on outpatient clinic rooms, it was found that lower than standard air changes per hour could lead to increased risks of viral spread (King et al., 2021). 15% of air-borne virus-laden droplets remained in a classroom study even after 90 min due to a low ventilation rate (Yamakawa, Kita gawa, Ogura, Chung, & Kim, 2021).

Particle deposition entering the breathing region of a human body is also crucial. The aspiration efficiency, defined as the ratio of particle concentration entering a sampling inlet to the particle concentration at an undisturbed upstream location (Beliaev & Levin, 1972), gives an indication of the inhaled fraction based on the inhalation area, inhalation velocity and time. The flow field can be studied using human nasal cavity models based on particle diameters, inhalation flow rates and freestream velocities (Intahavong, 2020). Other considerations include walking speeds, where it was shown that higher speeds reduced transport of contaminants (Wang & Chow, 2011; Tao, Intahavong, & Tu, 2017); and thermal plumes from the human body, where it is strong in the upper body and produces an upward flow which causes particles to rise quickly into the breathing zone (Li, Intahavong, & Tu, 2012).

1.1. Research gap and objective

From literature, most studies for COVID-19 viral spread has not considered natural ventilation in the built environment and specifically for medium-low rise buildings with high living densities like worker dormitories. Worker Dormitories in Singapore presents unique living conditions. The foreign workers typically spend little time in the dorms because of the nature of their work. Yet the dorms are densely populated because the leasing for worker dorms are short-term and developers want to cut costs by packing many workers into one room. This lack of consideration for the living conditions often translate into uncomfortable conditions and natural ventilation is not considered. This paper shows originality in presenting results based on two current worker dorm conditions and presenting solutions using simple changes that can be deployed with relative ease. With so many COVID-19 cases in this building type, this study will shed light on particle transmission routes and proposed interventions’ effectiveness.

This paper seeks to study how droplets between 10 and 100 μm can travel, using the two worker dormitories as case studies. Both macro-level and micro-level approaches will be conducted to study the airflow from natural ventilation and how respiratory droplets are transmitted. The viral spread will be quantified in terms of residence times. This is important as the inter-building transmission is likely to happen if the droplets can be air-borne for even a few minutes. A previous CFD study on the spread of SARS using CO2 tracer gas showed that inter-building air-borne transmission was nearly comparable to intra-building transmission (Wu & Niu, 2017). The micro-scale approach will be conducted to see how droplets from even one infected person
spread around the room and what proportion of droplets escape the room due to natural ventilation.

1.2. Research scope

Studies for SARS coronavirus found non-negligible roles for fomite routes, but this will be excluded from this study and only air-borne routes are considered (Xiao, Li, Wong, & Hui, 2017). Another similar study for COVID-19 transmission only looked at large respiratory droplets’ single droplet motion and their evaporation into aerosols (Cheng, Chow, & Chow, 2020). However, this study will look at droplets across an entire distribution. A lab study found that equipment layout stopped 17% of pollutant particles’ effective discharge since they lingered under vortex influence (Liu et al., 2020). However, this will not be included in this paper’s scope since worker dorms do not have much equipment except for their personal belongings and bed structures, which are included in this study. A study on airline cabins found that cough flow could be locked in the local environments of passengers, significantly increasing residence times (Yan, Li, Yang, Yan, & Tu, 2020). However, workers will not be modelled in this study due to its transient nature and complexity of their movements. The foreign workers come from different countries, like Bangladesh and China, and they have very different living habits. At the time of study, physically entering the worker dorms or interviewing the workers was not possible due to the COVID-19 situation. With no way to verify their living patterns and due to its transient nature, human behaviour was intentionally left out of the study. The authors will consider this point in future studies.

2. Research methodology

2.1. Worker dormitories

Two worker dormitories are studied, for different purposes, in this paper. The first, ‘Dorm A’, is in the eastern part of Singapore. Detailed specification drawings are available, and thus more micro-scale simulations will be conducted. These simulations will look primarily at airflow within the dormitory and how particles can be transmitted from bed-bed and room-room. Surrounding buildings around Dorm A will not be modelled due to reasons regarding Intellectual Property (IP) rights. The second worker dormitory, ‘Dorm B’, is in the North-East part of Singapore and is the Dorm with the largest number of confirmed COVID-19 cases in Singapore. For Dorm B, there are only rough building layouts and approximate dimensions from publicly available sources.

Simulations will thus be more macro-scale, looking at intra and inter-building wind flow and particle transmissions.

As shown in Fig. 1, Dorm A is an 11-storey building block, oriented 21o from the North, with six rooms with bunk beds and an attached toilet. The rooms are of different sizes, shown in Fig. 2, but each room ranges from 36-40m² in area and has 16 beds. All rooms have a 3.2 × 1.1m window, and rooms 1, 2, 3, 5 and 6 have additional side windows for better ventilation. Dorm B, shown in Fig. 3, is a cluster of long buildings located in proximity. Each building is more than 80 meters long and about 11m tall, with four storeys. Level 1 is set aside as open areas for canteens, shops and open areas, while levels 2 to 4 are for worker bunks. The building blocks are modelled with rooms without beds and other furniture to conserve computational resources to study particle transmission.

2.2. Environmental conditions

The predominant North-East and South wind directions will be used as inputs, with wind speeds of 2.9m/s and 2.8m/s. This is based on Singapore’s Building Authority technical guidelines (BCA, 2015). A constant 30°C for DBT and 70% RH will be used, based on average afternoon values in Singapore, as shown in Fig. 4.

2.3. Sneeze particles

For each case, particles of 10 μm and 100 μm will be studied. These sizes are chosen to represent the considerable variation in droplet sizes from a human sneeze. The human sneeze has complex chemistry which is not easily modelled. Since this study aims to study the particles’ transportation routes, a tracer gas using CO2, with its density changed to match that of sneeze particles, is employed instead.

2.4. Computational settings

The geometry models are first drawn using Rhino 6.0 software. These models will then be imported as Parasolid files to run the CFD simulations using the ANSYS Fluent 18.2 software.

2.5. Proposed solutions

Based on the simulations results, solutions will be proposed and studied for their effectiveness in facilitating better wind flow, less exposure time to particles and decreased probabilities for transmission. The solutions studied include removing upper decker beds, increasing distance between beds, and strategically placed wind scoops. The case configurations are shown in Table 1.

2.6. Grid sensitivity study

Three grid sizes (coarse, medium, fine) were tested to determine mesh independence. The area-weighted average wind velocities were taken to compute the Grid Convergence Index. A standardized area at 1.6m height was chosen that entirely bounds the worker dormitory floor area. Fig. 5 shows an example of the wind velocities contour extracted and how the mesh distribution looks like. All three grids adopt either 4-node tetrahedrons or 8-node hexahedrons, with body sizing of 0.12m, 0.2m and 0.23m for the grids.

Richardson Extrapolation assumes discrete solutions f to have a series representation in grid spacing h. By combining two different discrete solutions, f1 and f2, a more accurate estimate of f∞,0, the continuum value at zero grid spacing, can be derived. Where a grid doubling is conducted, the grid refinement ratio is 2, and this allows a simplified equation where:

\[ f_{x=0} = f_1 + \frac{(f_1 - f_2)}{(r^2 - 1)} \]  

(1)
However, to use Eq. (2), $f_1$ and $f_2$ must be taken from the same points. The error in a fine grid solution, $f_1$, is then approximated by comparing it to a coarse grid $f_2$ and is defined as

$$E_{1/\text{fine}} = \frac{\varepsilon}{\Gamma - r^p}$$

(2)

$$\text{GCI} = F_s \cdot E_{1/\text{fine}}$$

(3)

where, $\Box = f_2 - f_1$; $r =$ refinement factor; $p =$ formal order of accuracy of algorithm; $F_s =$ Factor of safety (1.25 in this study).

The order of accuracy, $p$, can be calculated using three solutions with constant $r$, as below:

$$P = \frac{\ln((f_3 - f_2) / (f_2 - f_1)) / \ln(r)}{\ln(r)}$$

(4)

Finally, by comparing two GCI values over three grids, the asymptotic range of convergence can also be computed as follows:

$$\text{GCI}_{32} = r^p \cdot \text{GCI}_{12}$$

(5)
Using the above Eqs. (2)–(6) and area-averaged wind velocity values taken from 1.6 m height, the grid convergence results can be summarized as tabulated in Table 2 below:

Since the asymptotic value is approximately one, the solutions are well within the asymptotic range of convergence. The area-averaged wind velocity is estimated to be 0.503 m/s with an error band of 3.33%.

3. Results for Dorm A

3.1. Wind flow

The green building rating system in Singapore is the Green Mark Scheme by BCA Singapore. At its highest Gold and Platinum awards for new built residential buildings, a wind flow of 0.4-0.6 m/s, covering 70% of occupant area, is recommended. Results were extracted at 1 m and 1.6 m heights to represent the wind flow when occupants are sitting down and standing up, respectively. The results for are shown in Figs. 6 and 7. As shown, the air is mostly stagnant in Room 4 (NE Wind) and Room 1 (S Wind), where there is almost no ventilation at all. More than half the room area has stagnant air in the other areas while the other half is well ventilated.
These results are crucial when one considers that the rooms were modelled with open doors and windows. Windows were also by no means small, measuring 3.2m by 1.1m. Also, except for rooms 4 and 6, all other rooms had two windows of such size. Thus, it can be concluded that merely having open windows and doors are insufficient for adequate ventilation, and there needs to be careful consideration for prevailing wind directions. Suggestions to improve ventilation are proposed in the latter part of this paper.

3.2. Particle transmission

3.2.1. Bed-to-bed transmission

In addition to looking at wind flow, the movement of particles is also considered. Since sneeze particles are small and light, they are positively affected by wind direction and turbulence intensity. Using streamlines in ANSYS Fluent, several cases of bed-to-bed, room-to-room, intra-building and inter-building transmission can be observed. As mentioned above, two particle sizes, namely 10 μm and 100 μm, are modelled. In some cases, particles transmission routes were the same for both sizes.

This can be seen in Figs. 8 and 9 showing residence time of the particles, where the transport of particles is similar for both sizes. When an occupant sneezes on the eastern side of Room 1 while seated down, the particles get directed to the room’s western side beds before being extracted out through the door in 40 s and out of the building after 80 s. Some particles are transported into the corridor of the building.

In many cases, however, there are differences in transmission routes from the different particle sizes. One example is shown in Figs. 10 and 11. This case shows an occupant sneezing from the eastern side of Room 3. For both cases, there are bed-to-bed transmissions due to the dominant NE wind. For the 10 μm case, particles are very quickly extracted out of the room, in about 30 s, before being directed out of the building through the corridor. However, for the 100 μm case, the heavier
particles circulate within the room from bed to bed and from lower to upper deck beds before getting blown out of the room only after about 90 s.

Significant bed-to-bed transmissions are not exclusive to 100 μm cases, however, and can also be seen in the 10 μm cases (Fig. 12) where wind flows are more turbulent. In this case, for both particle sizes, the particles hover around the same area in the room, moving from lower to upper deck beds for more than 2 min before being directed out of the building through the window.

Air is almost entirely stagnant, and the particles can remain within the room for a long time and increase exposure risk to its occupants. This can be seen in Fig. 13, showing Room 1 for South winds. In this case, even the smaller 10-micron droplets are barely under any wind influence and remain in the room even after 10 min. This is non-ideal as there is a high risk that other occupants will inhale those particles.

There are, however, also good examples in this study where particles are quickly extracted out of the room due to adequate ventilation. This can be seen in Rooms 2 and 3 for South winds in Figs 14 and 15. For both rooms and particle sizes, the sneeze particles are quickly removed from the room and building within 20 s or less. These results should be the end goal of well-ventilated rooms.

3.2.2. Room-to-room transmission

Another channel for the particle transmission routes is from room-to-room. This is another crucial aspect that looks at wind flow in transient...
spaces like corridors and not just within rooms. There are a few critical cases where this transmission happened and is shown in Figs. 16–18. From the NE wind, particles released from Room 2 leave the room in less than 30 s, but some particles are then carried into the western side of Room 5 (Fig. 16). The inverse happens for S wind, where particles from either side of Room 5 are transported to Room 2 (Fig. 17). However, it must be noted that the particle transport process from room-to-room only takes less than a minute and gets extracted out quickly after. Furthermore, the particles tend to hug the side of the wall and do not circulate except for the eastern side of Room 5, S wind, 10 μm (Fig. 18). Thus, the severity of the inter-room transmission is arguable.

3.2.3. Residence time in room

Table 3 shows the residence time of the particles. Since many particles are released per sneeze, the residence time below is calculated when most of the particles are extracted. From compiled data like this, key areas where intervention is needed can be identified. In this case, the criteria are if residence time exceeds more than a minute, posing a high risk of transmission. The identified areas are highlighted in Table 3. There are a few cases where residence time exceeds 10 min. The particles do not even exit the room indefinitely for the eastern side of Room 4 from NE wind.

3.3. Wind scoops

One intervention tested in this study is to strategically place wind scoops within the dormitory to redirect wind from more well-ventilated areas to areas with stagnant air. The V-shaped scoops are thin, full-height boards angled to capture both the dominant NE and S winds. Its effects are shown in the overview contours in Table 4, with the wind scoops’ locations circled in red. The wind scoops are, expectedly, more effective in some areas and less in others. The effects in Room 1 from S wind are the most obvious, shown in Fig. 19. The wind scoops improve the room’s airflow from almost no wind to having at least 1 m/s wind across a large coverage area. Although particles are now redirected to other beds, they are quickly extracted through the window in less than 10 s due to the excellent wind flow. The wind is also clearly redirected in Room 3, shown in Fig. 20. For the NE and S winds, particles are more directed out of the building at
about 20 s and 50 s more quickly. Finally, for Room 5, the wind scoop even redirects the particles to a storeroom rather than a dormitory room, as shown in Fig. 21. From these examples, the benefits of installing interior wind scoops can be seen.

### 3.4. Removal of upper deck beds

The Singapore government proposed this strategy to solve overcrowding issues in worker dormitories in Singapore. This move inevitably reduces the risk of person-to-person transmission since fewer people are based in a single room. However, the effects on air ventilation are not immediately evident from the removal of the upper beds. Suppose a room is poorly ventilated due to its orientation relative to dominant wind direction or poor design. In that case, it is theorized that removing a deck of beds will not improve the situation. Fig. 22 shows an example of the NE wind contours from removing the upper deck beds. Except for Room 3 where there was an improvement in ventilation for the lower half of the room, all other rooms similarly showed little airflow change.

The particle streamlines are studied next to see how they move when upper deck beds are removed. While removing upper beds can potentially improve wind flow and remove particles more quickly, that improvement can also possibly lead to more turbulent vortices. This can be seen in a few cases. Fig. 24 shows an example of particle streamlines where they are more quickly extracted from the building. Particles are removed more quickly from between 30 and 80 s for the cases. Fig. 25, on the other hand, shows the particle streamlines where vortices were formed from the removal of the upper beds. This happens for Rooms 2 and 6 for NE wind, and Rooms 1, 4 and 5 for S wind. These vortices lead to the extended hovering of particles within the room and subsequently takes a longer time to be removed. This is not good as it increases occupants’ exposure to the particles and happens in both wind directions. However, for Room 6 NE wind, it may seem like the vortices are similarly bad, but the particles are mostly directed upwards toward the ceiling before exiting the window. The time spent in the room is almost half that of the double bed case. Room 5 S wind also needs to be highlighted as the removal of upper deck beds even led to increased room-to-room transmissions.

#### 3.5. A larger distance between beds

In addition to the mentioned strategy in 3.4., the Singapore government has also proposed a more considerable distance between beds to improve social distancing among workers. The proposed increase is from the current 50cm to 1m between beds. In theory, the increased 50cm distance should reduce transmissions since the workers are placed further apart. However, increased bed distance can also potentially lead to more complex wind flows.

While the general wind patterns show little discernible change from the top view, the changes are seen more clearly when sectional views are taken. Room 1, 2 and 3 all show improved wind velocities. These results must be taken with caution; however, as improved wind velocities can also mean more turbulent winds. This can be seen in Fig. 26 that show particle streams from the NE wind. In cases like rooms 2 and 3, wind flows became more turbulent, leading to increased bed-to-bed transmissions. In room 4, a vortex was even formed, and the particles were still hovering inside the room even after 6 min, (Fig. 27).

Mixed results are similarly seen from the particles stream from S wind. In room 2, particles are removed from the room more slowly by about 10 s. In the case of room 3, particles even hover around the entire room, going from bed to bed for about 2 min before going out of the room (Fig. 28). Room 4 is the only exception, where particles exit the room more quickly, from the original 2 min to less than 20 s, (Fig. 29).

### 4. Results for Dorm B

As mentioned in Section 2, Dorm B consists of long rows of dormitories spaced closely to one another. Unlike Dorm A, which is one single building, Dorm B consists of 8 such long buildings. Thus, this is an excellent case to study macro-scale ventilation.

#### 4.1. NE wind

Like Dorm A, both NE and S wind were studied. Due to the Dorm orientation, very little wind enters the Dorm, with wind speeds mostly less than 0.2 m/s. The only exception is at the top-most building, where it directly faces the wind, as shown in Fig. 30. In this row of dorms, the wind speeds can go up to about 0.4 m/s.

Despite the narrow distance between each building, wind flow is relatively significant and reaches up to 0.4-0.7 m/s at the corridors. Much of this wind flow from east to west, with only a little wind entering the dorm buildings. Fig. 31 shows a sectional view of wind entering the dorms. The first observation is that the closely spaced buildings lead to an overall skimming flow, with velocities higher with higher elevations.
A close-up view of the section shows the airflow being directed from lower to higher elevations, with little wind (0.1 m/s) entering the dorm buildings.

With such wind flow, five sneeze particles were simulated to be released across different buildings and at different elevations. Three were placed at level 1, one at level 2, and one at level 4. Fig. 32 shows the overall streamflow (left) and the sectional view (right). Like concluded from the wind flow, since ventilation is lacking within the dorm rooms, much of the sneeze particles stay within each room for at least a few minutes without being extracted. The only exceptions are buildings 2 and 5 (from North), where the particles were extracted after 2-3 min. No inter-building transmissions occurred, and the particles were quickly transported upwards and out of the urban canyon.
Fig. 21. Room 5 showing redirecting of viral droplets into storeroom rather than dorm room.

Fig. 22. Wind velocity contours in room 4 (left-double deck beds; right-single deck beds).

Fig. 23. Wind velocity contours for room 2 (left-double deck beds; right-single deck beds).

Fig. 24. Room 3 NE wind showing faster extraction of particles.
4.2. South wind

Fig. 33 shows the overall wind contour and vector for South wind at Dorm B. The results are significantly different from NE wind due to the orientation of the Dorm. In this case, there is relatively good wind flow on the Dorm’s south-facing rooms, where large areas of the rooms were receiving about 0.4 m/s of wind.

Fig. 34 shows the sectional view of the overall wind flow and a close-up vector. The wind flow is like that from NE wind, except wind speeds are faster, and there is no stagnant air even in the lower elevations. There is also more significant wind flowing into the south-facing facades, but north-facing facades have stagnant air.

With such wind flow, the five sneeze particles were released from the same locations as from NE wind. The overall streamline results, in Fig. 35, show similar results to those of the NE wind. 2 of the sneeze particles remain in the room and never get extracted from the urban canyon even after about 5 min. The other particles can be seen from the close-up views in Fig. 36 that particles get extracted out of the room after
about 4 min and get extracted upwards out of the urban canyon.

5. Results discussion

5.1. Tracer gas

In this study, CO2 was used as a tracer gas, with its density changed to match the density of water droplets. This was done to emulate previous CFD studies on SARS (Wu & Niu, 2017). The authors acknowledge that there are differences between the transport characteristics of particles and gases. However, a tracer gas was ultimately used due to two reasons. Firstly, a prior study on the evaporation of water droplets of sizes between 10 and 100 μm showed that droplets evaporated within a few seconds (Zheng, Yuan, Wong, & Cen, 2019). Based on the Wells
Fig. 31. Sectional view of NE wind entering Dorm B.

Fig. 32. Locations of the 5 sneeze particles.

Fig. 33. S Wind contour and vector for Dorm B.
evaporation falling curve of droplets (Wells, 1934), the larger respiratory droplets fall on the ground and leave fomites, which is outside the scope of this study. The smaller droplets evaporate rapidly but leave dry residues of droplet nuclei that cease falling (settle) and drift with the surrounding air. The evaporation time depends on saturation levels, and thus these droplets take longer to evaporate in the humid climate of Singapore. Using water particles with ANSYS Fluent cannot capture these droplet nuclei, and thus the visualization of the viral spread will be grossly underestimated. Also, since this study aims to visualize the spread of the particles in the environment and the influence of natural

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Fig. 34. Sectional view of wind flow from S wind.

Fig. 35. Streamlines of sneeze particles for S wind.

Fig. 36. Close-up view of streamline for S wind.
ventilation, it is more meaningful if the droplet nuclei’s drifting can be visualized.

5.2. Particle settling

The amount of time the respiratory droplets take to settle can be calculated using the Stokes terminal velocity (Stokes, 1851), where the terminal velocity is given by:

\[
v = \frac{2}{9} \left( \frac{g \rho_p - \rho}{\mu} \right) g R^2
\]

where: \( g \) is the gravitational field strength (m/s²); \( R \) is the radius of the spherical particle (m); \( \rho_p \) is the mass density of the particles (kg/m³); \( \rho \) is the mass density of the fluid (kg/m³); \( \mu \) is the dynamic viscosity (kg/(m·s))

Assuming that the density of respiratory droplets is like water, the Stokes terminal velocity 10-micron droplets is 3 mm/s, while that of the 100-micron droplets is 300 mm/s. This implies that the time for the smaller droplets of a diameter of 10 μm to settle from a height of 1-1.6 m is of order 300-500 s, while the larger droplets of a diameter of 100 μm will settle within a time scale of order 3-6 s.

Particle settling is an essential consideration for designing natural ventilation within Worker Dorm rooms because the settling time can be used as a gauge. The larger 100-micron droplets only take a few seconds to settle onto the floor and leave fomites. So, in this case, optimal natural ventilation must be able to vent out these larger droplets before they settle. However, as shown from the residence times for the larger droplets in this study, most cases could not achieve this.

6. Summary

In summary, wind flow and viral spread were studied in Dorms A and B based on their present configurations, and findings can be tabulated as such:

6.1. Worker Dorm A

For the NE wind, particles in rooms 1, 4 and 5 are shown to hover for a few minutes, but other rooms are well ventilated, and particles get extracted in less than a minute. For S wind, room 1, 2, 3 and 4 have bad particle extraction results. For both, viral spread can exist from bed to bed, upper to lower deck and even room to room. It was also shown that since 10-μm droplets are more susceptible to vortex movement, they can reside longer within rooms before being extracted.

6.2. Worker Dorm B

For NE wind, there is poor ventilation in all rooms except for the top-most rooms, so this poses a high risk of viral spread within rooms. However, the high aspect ratio in the urban canyon leads to the quick extraction of sneeze particles and this stop viral spread between rooms from happening. This is the same for the S wind, except the S wind provides good ventilation for most S-facing rooms. N-facing rooms still face poor ventilation and high risk for viral spread.

6.3. Interventions

Several interventions were tested for their effectiveness, and other recommendations can be made based on the results.

Firstly, wind scoops were proven to be effective at directing wind towards areas with stagnant air based on the prevailing wind directions. However, orientation is essential and preliminary wind studies must be conducted first. Secondly, increasing the bed distance and removing upper deck beds both showed mixed results where particles were extracted more quickly in some areas, but suspended in the air for longer periods for other areas. The general recommendation is that if the room is already poorly orientated for wind flow, to begin with, then none of these measures will improve wind flow and other solutions must be sought.

The high urban canyon aspect ratios in Dorm B led to skimming flows which helped extract particles from higher elevations. However, it also led to more stagnant air at lower elevations, so orientation to prevailing wind directions are still important. Finally, room openings were proven to be useful in Dorm A, where particles were allowed to be extracted out of the building more quickly. Comparatively, Dorm B had no openings for cross ventilation and the particles stayed within the rooms for long periods.

In conclusion, pandemic resilience in buildings must start from the design stage. Some parameters like an orientation to prevailing wind direction, canal aspect ratio, and room openings placement are difficult to execute once construction has been completed. This study has shown the importance of cross ventilation especially since worker dorms are typically densely populated. For already built buildings, interventions include removing beds, increasing bed distance and installing temporary wind scoops. However, these interventions must consider the building’s specific context, surroundings, and the prevailing wind. Building owners must be careful not to undertake sweeping measures with no consideration for context. Using the results from this paper, similar studies can be conducted for other worker dorms with similar objectives to improve wind flow and remove droplets as quickly as possible. Wind velocities of at least 0.5 m/s were found to be useful, though even high velocities are ideal. Droplets residence time in the room are also ideally short as possible. The crucial points are where droplets remain in the room for long periods. This will lend confidence to worker dorm owners that their buildings are prepared for pandemics.

Future work will look at the role of fomites from the deposition of large droplets since droplet nuclei on surfaces can be re-aerolized into the air from human movement. Related to this, antiviral coatings are increasingly used, and its effectiveness can be tested. Further interventions like the use of mechanical ventilation, its placement, and its effectiveness can also be studied so that effective measures can be proposed and adopted for real-world use. A closer look at the dynamics of human breathing and human behaviours can also be considered. Finally, real-world data can be collected as validation for these models.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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