Effects of ceiling fan and window exhaust on aerosol transmission risk during home quarantine situation

Toby Cheung and Kwok Wai Tham

1 Department of the Built Environment, National University of Singapore, Singapore

Abstract. SARS-CoV-2 has been recognized to be airborne transmissible. With the increased transmissibility leading to increasingly reported positive cases, home quarantine is adopted for the infected patients who are not seriously ill. However, the risk of household aerosol transmission is not well studied. We conducted tracer gas experiment to simulate the exhaled virus laden aerosols from a patient under home quarantine situation inside a residential testbed. The Sulphur hexafluoride concentration (SF₆,conc) was measured both inside and outside the quarantine room under various scenarios including, (i) air-conditioning (AC) vs natural ventilation (NV), (ii) operation of ceiling fan, and (iii) operation of window exhaust fan. The ratio of outside-to-inside SF₆,conc (O/ISF₆) was an indicator for potential exposure of occupants in the same household. Our findings showed, without an exhaust fan, the in-room SF₆,conc in AC settings was 4 times higher than in the NV scenarios. Meanwhile, we found the exhaust fan was effective in reducing the O/ISF₆ in the AC scenarios (with or without ceiling fan), but its function was diminished in the NV setting with ceiling fan. We suspected the effectiveness of exhaust fan was reduced by air infiltration from other window openings in NV situation. Meanwhile, the operation of ceiling fan continuously pushing tracer gas outwards from the quarantine room through the door gap. Our results suggested that natural ventilation with windows open or switching on a window exhaust fan could reduce aerosol transmission risk from the quarantine room. This study provides useful evidence in recommending low risk ventilation strategies for home quarantine situations.

1 Introduction

It has been 3 years since the outbreak of Coronavirus disease 2019 (COVID 19). Thanks for the vaccine development, our lives are slowly getting back to normal. Governments and health authorities started recommending the infected patients with non-severe symptoms be self-isolated at home instead of quarantining in hospital and isolation facilities [1]. However, residential facilities are not designed to serve quarantine purpose, even though the infected person is staying in an isolated bedroom, airborne viruses could have escaped outside. It is of even higher concern for those newer variants that are more transmissible (e.g., Omicron variant) [2] meaning that it only needs a small amount of the virus leakage from the quarantine room to potentially infect other family members living in the same house.

The intra-house transmission of the aerosols in a residential house is mainly from the leakages through the gaps between the door and its frame or the floor. The operating strategy of the isolation room, such as the settings of the air conditioning (AC), the fan, and the window operating status, plays a particularly vital role in terms of the airborne pollutant transmission across the door [3, 4]. An opened window [5] or ventilating fan [6] can enhance air exchange rate in diluting in-room aerosol concentration, but the airborne transmission across the door the other space within the house remains unknown. A normal operating ceiling fan tends to move air downward under the blades coverage area and further pushes the air along the floor level [7]. Provided that doors in residential buildings are normally not well sealed (i.e., a larger gap between door and floor), ceiling fan operation may enhance the possibility of aerosol leakage even when the door is closed. Apart from the aerosol leakage via door gap, aerosol transmission is possible through some necessary door-opening activities, such as food delivery and trash removal. The impact of the door-opening activity on the aerosol transmission between spaces has been well studied in healthcare facilities [3] and pressurized clean room [8]. However, there is no reported study focusing on the impact of the door opening on aerosol transmission in a residential facility.

The tracer gas methods are widely used to experimentally study the pathogen airborne transmission risk due to its reliability and repeatability characteristics [9, 10]. Among the potential tracer gas choices, sulphur hexafluoride (SF₆) is the most used gas because of its detectability at low concentrations, low toxicity, and scarcity in the background environment [11, 12].
In this study, we aim to evaluate the intra-house transmission risk during the COVID-19 home recovery program via the tracer gas method in a residential testbed. We sought to 1) compare the common operating scenarios in the residential room, and 2) evaluate the currently recommended measures for homes prior to lowering the transmission risk.

2 Methodology

This study was conducted in a residential testbed in the National University of Singapore. Our experiment was set up in the master-bedroom of this smart facility to mock-up a quarantine room for COVID-19 positive patients serving stay home recovery. Figure 1 shows a plan view sketch of the quarantine room illustrating the experimental setups. The master-bedroom is 3.2 m (W) x 3.6 m (L) x 3 m (H) in size. An individual toilet approximately 3 m² is attached to the test room. Two operable windows (1 m² each) are available. Other openings that allow air exchange were the door gaps, both to the toilet and the living room, each 100 cm (W) x 1.3 cm (H) in size. In addition, the toilet window was opened throughout all tested scenarios. The test room was installed with a split-type air-conditioning unit and a 52-inch ceiling fan (2.65m from floor) for air circulation. In addition, a 12-inch desk fan was introduced into the test room, functioning as a window exhaust in this study. The desk fan was positioned 15 cm from the window, elevated 140 cm above the floor, tilted at 20° angle from horizontal, and moved air from the room outside the window.

![Fig. 1. Plan view for the experimental setup both inside and outside to quarantine room.](image)

A total of three operating scenarios were tested, including air-conditioning without fan (AC_only), air-conditioning with ceiling fan (AC_C-fan), and natural ventilation with ceiling fan (NV_C-fan). We intentionally dropped the NV only scenario because this condition is not realistic for home quarantine purpose with the hot and humid climate in Singapore. Under AC scenarios, the air-conditioner was operated at 25 °C set-point with all windows and doors closed, while the windows and toilet door were fully opened in the NV condition. The door to the living room was closed throughout the experiment, except for the designated door opening procedure. The ceiling fan was operated at 96 rpm (i.e., 0.94 m/s measured directly under fan). The desk fan was used as an exhaust fan dragging air outside the quarantine room at an airflow rate of 170 L/s. The exhaust fan on and off status were both applied to all three testing scenarios in our study. The location and speed for all fans were fixed throughout the experiment.

We used tracer gas (Sulphur hexafluoride, SF₆) technique to simulate the transmission of exhaled virus-laden droplets from the infected person under quarantine in this study. SF₆ was continuously released at a constant dosing rate of 0.1 L/min inside the quarantine room on the bed (see Figure 1). The gas releasing tube was attached to a ping-pong ball with multiple holes on its surface, thus SF₆ was distributed uniformly in all directions. The SF₆ concentration (SF₆_conc) was measured both inside and outside the quarantine room through an INNOVA 1309 multi-channel sampler with a detection limit of 0.01 ppm and an accuracy ±2% of the measured value. The two sampling points were located at 0.1 m height above floor and 0.5 m away from the door as illustrated in Figure 1. The in-room and hall-side sampling probes at 0.1 m were used to determine the SF₆ leakage rate (i.e., outside-to-inside SF₆_conc ratio, O/ISF₆) via door gap. The sampling frequency was approximately 2 minutes per cycle.

All experimental conditions were setup inside the quarantine room and the monitored the background SF₆_conc for 30 minutes before tracer gas has been released. A full-scale experiment was divided into two phases (i.e., without and with the operation of exhaust fan). In the first phase (without operation of exhaust fan), tracer gas was continuously released at a dosing rate of 0.1 L/s for 180 minutes. The first 90 minutes allowed SF₆ to attain a stable level inside the quarantine room, and the next 90 minutes was taken to be the steady state condition providing representative SF₆_conc for analyses in each operating scenario. The assumption of steady state concentration in the latter 90 minutes was estimated by multiple pre-tests under different room operating settings at the given tracer gas dosing rate (i.e., 0.1 L/s). In the middle of the first phase experiment, we opened the quarantine room door for 10 seconds to mock-up a food delivery / trash cleaning activity. The second phase experiment started right after the first phase, and it began with switching on the window exhaust fan. Similarly, the second phase experiment procedure was a duplicate of the first phase except for the operation of exhaust fan. The experiment ended with tracer gas cut-off after the second phase procedures.

3 Results and discussions

Figure 2 summarizes the time series SF₆_conc data for the two sampling locations measured under three different operating scenarios: (a) AC_only, (b) AC_C-fan, and (c) NV_C-fan with both window exhaust fan On and Off conditions. The SF₆_conc pattern in all scenarios are divided into three stages. First, the SF₆_conc started to accumulate when tracer gas was emitted in the quarantine room. Meanwhile, tracer gas started to leak outside of the quarantine room, leading to a rise in the hall-side SF₆_conc. Second, when the exhaust fan was turned on, the
SF₆,conc reduced and gradually stabilized for both in-room and hall-side sampling points. Lastly, the SF₆,conc from all sampling locations reduced to zero after the cut-off of the emission source. In addition, a rapid increase in SF₆,conc was detected at the hall-side sampling point whenever the door was opened.

3.1 SF₆ concentration without exhaust fan

Assuming the later 90 minutes in each experimental phase (i.e., from 90 – 180 min and 270 – 360 min in Figure 3, excluding the door opening outliers) as a representative steady concentration period, the corresponding mean and standard deviation value for SF₆,conc in different test scenarios are summarized in Table 1. When the window exhaust fan was not operating, we found slightly higher in-room SF₆,conc in ACC-fan than AC-only cases, while the concentration in AC conditions were ~4 times higher than in the NV C-fan condition (p \( \leq \) 0.05, U-test). We suspect that the operation of ceiling fan in quarantine room enhances air movement, as well air mixing, resulting in higher SF₆,conc when compared to AC-only scenario. The openings from windows and toilet door in NV scenarios enhance air exchange (both infiltration and exfiltration) rate in the quarantine room, leading to lower SF₆,conc at equilibrium.

The hall-side SF₆,conc was not significantly differ between AC-only and ACC-fan conditions (p > 0.05, U-test), but we observed a smaller fluctuation (i.e., smaller standard deviation value) in ACC-fan scenario. Considering that the aerosol leakage to hall-side was mainly due to air movement and aerosol concentration difference, we think the operation of ceiling mixes the in-room SF₆,conc very well and steadily pushing the source to hall-side via the door gap. This explains a smaller variation of the measured SF₆,conc in ACC-fan scenario. Meanwhile, at the hall-side sampler, the SF₆,conc has been reduced by 90% when switching from AC to NV cases (p \( \leq \) 0.05, U-test). Apparently, enhanced air change rate inside the quarantine room through window or door openings would effectively reduce tracer gas accumulation, which minimized the chance of gas leakage to the hall-side.

### Table 1. Measured mean (standard deviation) of SF₆ concentration at separated locations and conditions.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>In-room (ppm)</th>
<th>Hall-side (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without exhaust fan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC-only</td>
<td>54.8 (1.7)</td>
<td>20.8 (7.3)</td>
</tr>
<tr>
<td>ACC-fan</td>
<td>59.4 (1.0)</td>
<td>23.3 (3.9)</td>
</tr>
<tr>
<td>NV C-fan</td>
<td>15.8 (1.6)</td>
<td>1.6 (1.2)</td>
</tr>
<tr>
<td>With exhaust fan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC-only</td>
<td>10.6 (1.5)</td>
<td>0.2 (0)</td>
</tr>
<tr>
<td>ACC-fan</td>
<td>12.6 (0.6)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>NV C-fan</td>
<td>8.6 (0.5)</td>
<td>0.8 (0.5)</td>
</tr>
</tbody>
</table>

3.2 SF₆ concentration with exhaust fan

After the exhaust fan was switched on, the SF₆,conc dropped substantially in all AC testing conditions at both in-room (reduced by ~80%) and hall-side (reduced by ~100%) samplers. Figure 3 illustrates the air flow direction in ACC-fan scenario with window exhaust fan. When the exhaust fan is turned on, it drives air to the outdoors through the window creating a negative pressure in the quarantine room. Air is forced to flow into the quarantine room continuously from the toilet and hall-side via the door gaps diluting the SF₆,conc at floor level. The SF₆,conc at hall-side were all reported (close to) zero for the two AC test conditions. Figure 3 illustrates the air is forced to flow into the quarantine room via the door gaps when exhaust fan is operating, which explains the phenomenon of low SF₆,conc being detected at the hall-side (i.e., less tracer gas leaked to hall-side), except for the door opening situation.

![Fig. 3. Forced air flow through the door gap by the exhaust fan in AC condition with window closed.](image-url)
the air exchange through multiple openings (i.e., toilet door and windows) in NV settings which reduces the effectiveness of exhaust fan operation. Firstly, under NV, the toilet door remains open, creating an additional volume for the tracer gas to be distributed. Secondly, exhaust fan is exfiltrating the same volume of room air at a lower SF$_{6\text{conc}}$. Nevertheless, the window exhaust is still effective in enhancing the room air change rate (i.e., reducing the in-room SF$_{6\text{conc}}$) in NV conditions. Its contribution towards reducing room concentration is expected to be higher when NV air exchange is limited in low or no wind conditions.

At the hall-side, the SF$_{6\text{conc}}$ for NV$_C$ fan case has been reduced by 50% after switching on the exhaust fan. Surprisingly, we found higher SF$_{6\text{conc}}$ at the hall-side in NV scenario, despite a lower steady state in-room SF$_{6\text{conc}}$ when compared to the AC conditions ($p \leq 0.05$, U-test). When exhaust fan is operating at AC scenarios, it creates a negative pressure inside the quarantine room and draws air into the room from the only two door gaps, thus the hall-side SF$_{6\text{conc}}$ approaches zero. However, the multiple openings in NV scenario reduced the “negative pressurization” effect of exhaust fan resulting in a portion of tracer gas still leaking through the door gap. Furthermore, we suspect that the air movement through the door gap in NV$_C$ fan is dominated by the ceiling fan, pushing air in one direction from the quarantine room towards the hall-side (see Figure 4). The exhaust fan can only reduce in-room SF$_{6\text{conc}}$ by increasing air exchange rate through other openings, but unable to compensate for the positive pressure created by ceiling fan at the door gap, resulting in a continuous tracer gas leakage to the hall-side in the NV$_C$ fan scenario.

3.3 Outside-to-inside SF$_6$ concentration ratio

While the absolute SF$_{6\text{conc}}$ values could inform us how high or low the tracer gas level under different scenarios at the two fixed sampling locations, the risk level of tracer gas leakage prior to ventilation effectiveness should have both in-room and hall-side SF$_{6\text{conc}}$ into consideration and revealed by the outside-to-inside SF$_{6\text{conc}}$ ratio (O/I SF$_6$) (i.e., hall-side SF$_{6\text{conc}}$ / in-room SF$_{6\text{conc}}$ from the same sampling cycle). Time series O/I SF$_6$ of the three testing scenarios are plotted in Figure 5.

Fig. 4. Schematics of the airflow pattern for ceiling fan operation in naturally ventilated scenario with windows and toilet door open.

Fig. 5. Time series O/I SF$_6$ under (a) AC only, (b) AC with ceiling fan, and (c) NV with ceiling fan scenario. (The exhaust fan operation and door opening indicators are the same as in Figure 2).

By selecting the steady state O/I SF$_6$ data (i.e., during 90 – 180 mins when exhaust is turned off and during 270 – 360 mins when exhaust is turned on), the values, i.e., mean (standard deviation), were found comparable between AC$_{\text{only}}$ (0.38 (0.13)) and AC$_{\text{C-fan}}$ (0.39, 0.06) condition when exhaust fan was not operating ($p > 0.05$, U-test). Similarly, we observed substantial drop of O/I SF$_6$ (almost close to zero) in both AC settings after the window exhaust was turned on. The observation can be explained in Figure 3, when the quarantine room is negatively pressurized by the exhaust fan, the make-up air is flowing in one direction from hall-side (or toilet) into the quarantine room. It means that operating the exhaust fan not only reduces in-room SF$_{6\text{conc}}$ but effectively minimizes leakage outwards to the hall-side in both AC$_{\text{only}}$ and AC$_{\text{C-fan}}$ scenarios. We did not see significant impact on the aerosol leakage rate in air-conditioned quarantine room by the operation of ceiling fan. Hypothetically, the aerosol leakage rate in air-conditioned quarantine room with window closed is dominated by aerosol concentration difference between in-room and hall-side.

Compared to the AC settings, the O/I SF$_6$ in NV$_C$-fan setting was much lower (0.1 (0.08)) when exhaust fan was not operating ($0 \leq p < 0.05$, U-test). It can be explained by (i) lesser tracer gas diffusion rate to hall-side due to lower in-room SF$_{6\text{conc}}$, and (ii) comparable temperature between quarantine room and hall-side (i.e., no temperature gradient being established). When exhaust fan was switched on, however, we observed higher O/I SF$_6$ in NV$_C$-fan conditions (0.09 (0.06)) than in the AC settings ($p \leq 0.05$, U-test). We believe the difference in O/I SF$_6$ value is due to (i) higher tracer gas leakage initiated by the continuous forced air movement from
ceiling fan through the door gap (see Figure 4), and (ii) the reduced exhaust fan efficiency at the door gap due to multiple openings available in NV room settings. It suggests that the operation of exhaust fan in NV_C-fan setting can only reduce in-room SF$_6$$_{conc}$ (see Figure 2) but unable to stop the avoid in-room air from leaking to hall-side due to forced airflow generated by the ceiling fan. It also indicates aerosol leakage rate in naturally ventilated quarantine room is substantially dependent to the air flow pattern: both the wind direction from windows openings and the forced air flow initiated by fans.

### 3.4 Effects of door opening

The quarantine room door supposes to be closed at all the time, but there are situations when it is opened for food delivery and trash clearance. Figure 5 shows clear spikes of the O/ISF$_6$ in all the AC scenarios when the door was opened, but not in the NV_C-fan setting. The rapid increase in O/ISF$_6$ was caused by an avalanche of high SF$_6$$_{conc}$ air flowing out from the quarantine room when the door was opened, with simultaneous hall-side air interchanged with the in-room air, diluting the SF$_6$$_{conc}$ inside. Higher SF$_6$$_{conc}$ accumulated inside the AC room without effective ventilation could be an explanation in more rapid gas exchange once the door is opened than in the NV scenario. Even when the exhaust fan was switched on, the O/ISF$_6$ still stood out when door was opened. In addition, the air density variation driven by temperature difference between in-room (25 °C with AC) and hall-side (30 °C for common afternoon in Singapore without AC) air may also enhances air exchange when the door was opened. The outstanding O/ISF$_6$ implies a higher risk of infection if someone is at the hall-side, say the one who delivers the food or cleans up the trash. Interestingly, the spikes of O/ISF$_6$ initiated by the opening door were all short, episodic responses without any observable lasting effect, indicating the SF$_6$$_{conc}$ could have been diffused and settled back to steady quickly at the hall-side. Family members are suggested not staying too close to the quarantine room especially when the door is opened. If necessary, food delivery should be placed at the hall-side before the door is opened or the trash should be cleared sometime after the door has been closed.

Surprisingly, we are unable to see any effect on the O/ISF$_6$ due to the door opening for NV_C-fan scenario. We suspect the reasons leading to this observation are two-fold. First, the steady state SF$_6$$_{conc}$ is relatively low for NV settings with multiple openings. This leads to a lower diffusion rate of SF$_6$$_{conc}$ to the living room even when the door was opened (comparison between AC_C-fan and NV_C-fan). Second, as shows in Figure 4, the ceiling fan establishes a circulation cell which upward momentum at the door substantially maintains most of the air within the room. The portion that flows along the floor and leaks outwards is somewhat similar, irrespective of the door opening status. This explains a similar O/ISF$_6$ variation across the experiment period for NV_C-fan setting.

### 4 Conclusion

We conducted tracer gas (SF$_6$) experiments in a residential testbed to evaluate the airborne transmission risk through different operating scenarios during home quarantine situations. We found the tracer gas concentration (SF$_6$$_{conc}$) in quarantine room and the potential exposure risk for other household members (i.e., the outside-to-inside SF$_6$$_{conc}$ (O/I SF$_6$)) were differed among operating scenarios.

1. In situations without exhaust fan, we found the in-room SF$_6$$_{conc}$ was up to 4 times higher in AC than in NV settings. The opened windows in NV scenarios enhanced the air change rate through cross ventilation inside the quarantine room, which further reduced the amount of trance gas leakage to the hall-side.

2. The window exhaust fan is an effective device in reducing in-room aerosol concentration and exposure risk to other household occupants, specifically for air-conditioned quarantine room. The in-room SF$_6$$_{conc}$ was reduced by 80 % and 45 % when switching on the window exhaust fan, respectively, for AC and NV scenarios. The reduction in exhaust fan effectiveness in NV setting was likely attributed to air infiltration from multiple windows or door openings. In addition, the O/ISF$_6$ value dropped significantly in both AC_only and AC_C-fan scenarios after operating the exhaust fan, meaning a lower potential risk of airborne transmission, but not in the NV_C-fan setting. We believe airflow from the ceiling fan continuously pushing the tracer gas outward through the quarantine room’s door gap, outweighing the effect of window exhaust.

3. We observed higher risk of aerosol transmission when the quarantine room’s door was momentarily opened. Family members are suggested to stay away from the quarantine room. Food delivery should be placed at the hall-side before the door is opened and the trash should be cleared sometime after the door has been closed.

This research is supported by the National Medical Research Council, Singapore, under its COVID-19 Research Grant (Grant number: COVID19RF3-0080).

### References


2. F. Rahimi, A.T.B. Abadi, Gene R 27, 101549 (2022)


