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Aerosol transmission of SARS-CoV-2 due to the chimney effect in two high-rise housing drainage stacks

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ABSTRACT

Stack aerosols are generated within vertical building drainage stacks during the discharge of wastewater containing feces and exhaled mucus from toilets and washbasins. Fifteen stack aerosol-related outbreaks of coronavirus disease 2019 (COVID-19) in high-rise buildings have been observed in Hong Kong and Guangzhou. Currently, we investigated two such outbreaks of COVID-19 in Hong Kong, identified the probable role of chimney effect-induced airflow in a building drainage system in the spread of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). We injected tracer gas (SF6) into the drainage stacks via the water closet of the index case and monitored tracer gas concentrations in the bathrooms and along the facades of infected and non-infected flats and in roof vents. The air temperature, humidity, and pressure in vertical stacks were also monitored. The measured tracer gas distribution agreed with the observed distribution of the infected cases. Phylogenetic analysis of the SARS-CoV-2 genome sequences demonstrated clonal spread from a point source in cases along the same vertical column. The stack air pressure and temperature distributions suggested that stack aerosols can spread to indoors through pipe leaks which provide direct evidence for the long-range aerosol transmission of SARS-CoV-2 through drainage pipes via the chimney effect.

1. Introduction

More than one year into the pandemic, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) had led to more than 3 million deaths worldwide by early 2021 (WHO, 2021). Following the detection of the virus in fecal and anal swabs of infected patients (e.g., Wang et al., 2020) and the isolation of viable viruses from human feces (Holshue et al., 2020) in the early phase of the pandemic, the possible fecal–oral route of transmission has been debated (e.g., Hindson, 2020). Fecal aerosol transmission was shown to be probable in a high-rise housing outbreak in Guangzhou and two similar outbreaks in Hong Kong, China (Kang et al., 2020). These three coronavirus disease 2019 (COVID-19) outbreaks involved only vertically aligned flats, where all secondary infected persons resided in flats above the index case flat, and shared the same connecting drainage stack. The widely accepted theory of the airborne transmission of SARS-CoV-1 via fecal aerosols in the 2003
Amoy Gardens outbreak in Hong Kong, where more than 300 people were infected (Yu et al., 2004), has caused fear of similar spread of SARS-CoV-2. In Hong Kong, the local government has since implemented a stricter interventional measure whenever a vertical spatial pattern of infected cases is identified, namely, immediate lockdown of the affected building block or vertical flats. The 14-day quarantine period imposed on the residents also provided an opportunity for conducting investigations and measurements in the affected flats (with the consent of the residents).

Stack aerosols were likely transported via vertical drainage pipes, as supported by tracer gas measurements and the observed spatial pattern of the affected flats in three outbreaks of SARS-CoV-2 (Kang et al., 2020). Similar tracer gas measurements were conducted in the affected building blocks in seven similar vertical outbreaks in Hong Kong (Li et al., 2021, unpublished) and confirmed the hypothesis of Kang et al. (2020). To demonstrate the airborne transmission of stack aerosols of SARS-CoV-2 via the drainage system, two major questions must be answered. First, is the source of the virus feces or respiratory mucus? The number of secondary infections in the 2003 Amoy Garden SARS-CoV-1 outbreak were two orders of magnitude greater than the 13 reported vertical outbreaks of SARS-CoV-2 in Hong Kong and Guangzhou at the time of writing. This might have occurred because SARS-CoV-2 is not as viable in wastewater when compared with SARS-CoV-1, and these SARS-CoV-2 outbreaks were due to respiratory mucus. SARS-CoV-1 can survive for 14 days in sewage at 4°C and 2 days at 20°C (Wang et al., 2005). In contrast, while live SARS-CoV-2 has been found in stool samples from two patients (Wang et al., 2020), no viable SARS-CoV-2 has been detected in wastewater (Foldatori et al., 2020).

Thus, respiratory aerosol/droplets likely play a more important role in the SARS-CoV-2 pandemic. Therefore, an alternative non-faecal source of the virus in the stack aerosol was suspected, i.e., washbasin-collected oral/nasal mucus. Second, what is the ventilation flow rate in the drainage pipes? Kang et al. (2020) hypothesized the role of the chimney effect in the spread of virus-containing aerosols. However, there were no measured data to support the chimney effect. The chimney effect, if present, is related to the air flows induced by stack pressure, wind pressure at exterior openings, and exhaust fans in bathrooms or kitchens (Li and Delsante, 2001). Chimney effect-induced flows can also ventilate drainage pipes, including vertical stacks. Air temperature and humidity in the drainage stacks may also affect virus viability (Paul et al., 2021).

To answer these two questions, we measured the chimney effect in two housing blocks where vertical COVID-19 outbreaks were observed in early 2021, i.e., Kensington Plaza in Kowloon and the Wai Lee Building in Quarry Bay in Hong Kong Island. Environmental samples were also collected from washbasin drains for SARS-CoV-2 detection.

2. Methodology

The dates of symptom onset (Table 1) and the flat numbers of the residents with confirmed COVID-19 in the two outbreaks were obtained from the Centre for Health Protection (CHP), Department of Health. The epidemiological investigation performed by the CHP on the secondary infected residents did not identify any connection with persons with COVID-19 outside of the affected building. The building data, site plans, and details of the drainage systems of the two buildings were obtained by on-site inspections and measurements.

All of the confirmed cases were admitted to a public hospital managed by the Hospital Authority in Hong Kong. Patients were isolated in an airborne isolation room and a real-time reverse transcription polymerase chain reaction (RT-PCR) assay was performed, as described previously (Wong et al., 2020). SARS-CoV-2 genome sequencing and subsequent sequence analysis were also performed, as described previously (Tse et al., 2021), using archived clinical specimens from these patients with laboratory-confirmed COVID-19 patients from the corresponding public hospitals (e.g., Queen Elizabeth Hospital, Queen Mary Hospital, and Pamela Youde Nethersole Eastern Hospital). The study protocol was approved by the Research Ethics Committee of the Kowloon Central/Kowloon East Cluster (HA.KC/KE-20–0321/ER-2) and the Institutional Review Board of the University of Hong Kong/Hospital Authority Hong Kong West Cluster (UW 13–372) and the Institutional Review Board of Hospital Authority Hong Kong East Cluster (HKECREC-2021–051).

2.1. Housing block

In this paper, a flat is an apartment unit. Flat # refers to a specific flat number, whereas -# flats refers to a vertical column of flats in a high-rise building.

Kensington Plaza is an 18-story housing block in Kowloon that was built in 1999. There are 90 flats total with 6 flats on each floor (Fig. 1a). The index case (case K1) resided in Flat C on the 5th floor (Flat 5 C) during the sub-clinical infectious period, and was confirmed to have

| Table 1 |
| List of the confirmed COVID-19 cases in the Kensington Plaza outbreak and the Wai Lee Building outbreak. |

| Building          | No. of patients | Hong Kong case No. | Gender (age) | Flat | Date of symptom onset (2021) | Date of confirmation (2021) |
|-------------------|-----------------|--------------------|--------------|------|----------------------------|----------------------------|
| Kensington Plaza | 1               | K1                 | M (70)       | 5 C  | Jan 15                      | Jan 16                     |
|                   | 2               | K2                 | M (21)       |      | Jan 15                      | Jan 18                     |
|                   | 3               | K3                 | F (9)        |      | Jan 14                      | Jan 18                     |
|                   | 4               | K4                 | F (46)       |      | Jan 16                      | Jan 18                     |
|                   | 5               | K5                 | F (29)       |      | Asymptomatic                | Jan 18                     |
|                   | 6               | K6                 | M (54)       |      | Jan 17                      | Jan 18                     |
|                   | 7               | K7                 | M (70)       | 6 C  | Asymptomatic                | Jan 20                     |
|                   | 8               | K8                 | F (41)       | 7 C  | Asymptomatic                | Jan 22                     |
|                   | 9               | K9                 | M (14)       |      | Feb 1                       | Feb 3                      |
|                   | 10              | K10                | F (27)       | 17 C | Jan 20                      | Jan 22                     |
|                   | 11              | K11                | F (22)       | 5 A | Asymptomatic                | Jan 22                     |
|                   | 12              | K12                | F (51)       |      | Jan 22                      | Jan 24                     |
|                   | 13              | K13                | F (7)        |      | Asymptomatic                | Jan 24                     |
|                   | 14              | K14                | M (41)       | 6 D | Jan 21                      | Jan 24                     |
| Wai Lee Building  | 1               | W1                 | M (54)       | 1404 | Feb 3                       | Feb 6                      |
|                   | 2               | W2                 | M (18)       |      | Feb 2                       | Feb 6                      |
|                   | 3               | W3                 | F (38)       |      | Feb 5                       | Feb 7                      |
|                   | 4               | W4                 | F (49)       |      | Feb 5                       | Feb 7                      |
|                   | 5               | W5                 | M (17)       | 1704 | Feb 3                       | Feb 9                      |
|                   | 6               | W6                 | F (15)       | 1811b| Feb 3                       | Feb 9                      |
|                   | 7               | W7                 | F (60)       | 2104 | Feb 7                       | Feb 9                      |
|                   | 8               | W8                 | M (72)       | 1405 | Feb 7                       | Feb 9                      |
|                   | 9               | W9                 | F (55)       |      | Feb 2                       | Feb 10                     |

* The flat has subdivided units. Subdivided units in Hong Kong refer to those formed by dividing a small flat into several smaller units for rent.
COVID-19 on January 16, 2021. A compulsory testing notice was issued on January 17, 2021 by the government to everyone who stayed in Kensington Plaza for more than 2 h within the previous 14 days (CHP, 2021b). Additional infected residents were identified through this active case finding, and a vertical transmission pattern was observed after the preliminary investigation performed by the CHP. As a result, a multi-disciplinary response team (MDRT) investigation, which included representatives from the CHP, Environmental Protection Department, and government experts, was conducted on January 22, 2021. A quarantine order was issued to all asymptomatic residents of -C flats of all floors of Kensington Plaza (3rd floor to 20th floor) (CHP, 2021a).

The Wai Lee Building in Quarry Bay is a 23-story housing block with 430 residential flats. Its floor plan is shown in Fig. 1b. The building has two wings, a main street-facing wing of 23 stories where – 04, – 05, and – 06 flats are located, and an interior wing where – 11 flats are located (Fig. S1). Four cases were identified in the building during February 3–5, 2021, one of whom lived in a – 04 flat on the 14th floor (Flat 1404). Approximately 860 residents underwent RT-PCR testing for SARS-CoV-2 under the Government compulsory testing order between 19:30 on February 7, 2021 and 02:00 on February 8, 2021.
8,2021, and 3 additional people with COVID-19 were found. A preliminary epidemiological investigation performed by the CHP demonstrated vertical transmission pattern was observed involving three – 04 flats. An MDRT field investigation was conducted on February 8, 2021, and a quarantine order was issued to all asymptomatic residents of – 04 flats (1st floor to 23rd floor) (CHP, 2021c).

There are 6 columns of flats in Kensington Plaza and 22 columns of flats in the Wai Lee Building. Both buildings have a one-pipe drainage system with one vertical stack, which conveys both soil and wastewater to the drain, and one vent pipe. Both the stack and vent pipe are built along the exterior wall of the building. In Kensington Plaza, the bathrooms and kitchens in each column of flats share a vertical drainage stack. -C flats and -D flats share a semi-open light well, and the drainage stacks and vents of the two columns of flats are located toward the deep end of the light well. The drainage systems in both buildings had observable modifications. The schematic of the drainage system is shown in Fig. 2. The CHP investigation team also collected and tested environmental samples from both buildings.

Fig. 2. Field experimental setups and schematics of the drainage system in (a) Kensington Plaza and (b) the Wai Lee Building. (c) Measurement of the differential pressure between the drainage pipe and the bathroom. The filled red circles represent the locations of the temperature and relative humidity iButton sensors (DS1923-F5, iButtonLink, Whitewater, USA). The schematic of the drainage system is based on observations from the on-site inspection. In the Wai Lee Building, the dashed lines represented the postulated structure of the underground drainage pipe connection.
2.2. Tracer gas release and detection

We used a tracer gas (SF6) as a surrogate for stack aerosol containing virus-laden droplets and monitor the tracer gas concentration in the bathrooms of the affected and some non-infected flats after we injected the tracer gas into the drainage pipe. Such a tracer gas approach has been shown to represent well the ventilation removal of fine aerosols. A number of experimental studies conducted tracer gas measurements to simulate the movement of infectious aerosols (Bjørn and Nielsen, 2002; Bolashikhov et al., 2012; Zhang et al., 2009). Gormley et al. (2021) investigated the aerosol and bioaerosol particle size in a test rig of plumbing system due to toilet flushing, and showed leaked particles from the drainage system with an equivalence of someone talking loudly for over 6 and a half minutes.

In Kensington Plaza, tracer gas was released into the drainage pain through the water closet (WC) in Flat 5C for 15–20 min on February 3–4, 2021, and the gas concentrations were monitored in the two affected flats (Flat 7C and Flat 17C), one non-affected flat (Flat 10C), the facades, and the roof vents. Because there were only two sets of tracer gas monitoring instruments, only two or three locations could be simultaneously monitored. For example, we monitored the concentration variation in Flat 7C and the roof vent, and then Flat 17C, Flat 10C, and the roof vent in another test to collect data on the affected flats and roof vent.

Similar tracer gas measurements were conducted in the Wai Lee Building on February 16, 2021 while the – 04 flat residents were under quarantine. The tracer gas was released for 30 min through the WC in Flat 1404 on February 16, 2021, and we monitored the tracer gas concentrations in an affected flat (Flat 2104) and the roof vents simultaneously. When we released the tracer gas in the bathroom of Flat 1404, we monitored the concentration variations in the light well near the 14th, 18th, and 21st floors. No permission was given for access to other flats then, including the affected Flat 1704.

A 24-channel multipoint sampler, a photoacoustic gas monitor (Innova 1412i and 1409, LumaSense Technologies, Ballerup, Denmark), and a 6-channel multipoint sampler and multi-gas monitor (types 1303 and 1302, Brüel & Kjær, Nærum, Denmark) were used at both affected buildings to monitor the variation of the SF6 concentration near the floor drains, facades, and roof vents. Before each test, we used tape to seal visible openings connected to the drainage system (e.g. water basin), except for the bathroom floor drains in Kensington Plaza and the kitchen floor drains in the Wai Lee Building.

Two sets of tracer gas experiments were performed: (1) injection of the tracer gas into the drainage stack via the WC of the index flat (e.g., Flat 5C in Kensington Plaza and Flat 1404 in the Wai Lee Building) at a flow rate of 0.2 L/min, with the concentrations within the flats and roof vents being recorded; (2) release of the tracer gas in the bathroom of the index case flat at a flow rate of 0.2 L/min, with the concentrations along the facades in the light well being measured.

2.3. Air temperature, humidity, and pressure measurements

In Kensington Plaza, iButton sensors (DS1923-F5, iButtonLink, Whitewater, USA) were hung in the drainage stack at two points (Fig. 2a) from the rooftop, which recorded the air temperature and relative humidity at 1-minute intervals throughout the measurement periods. The two measurement points were 18 m and 24 m from the roof, respectively. We also used the same sensor with a radiation shield to record the air temperature and relative humidity above the roof and inside the light well (near the 7th and 13th floors) at 5-minute intervals. After completing the tracer gas measurements each day, we continuously monitored the differential pressure between the soil pipe and the bathroom using differential pressure sensors (P350, Pace Scientific, Boone, USA) and dataloggers (XR5-SE-M, Pace Scientific, Boone, USA) with a sampling frequency of 1 Hz. The experimental setups are shown in Fig. 2c. The sensor tube was pulled into the branch pipe through the WC in Flats 5C, 7C, 10C, 15C, and 17C to record the differential pressure on the corresponding floors. A positive reading indicated that the pressure inside the drainage stack was higher than that in the bathroom, i.e., air would leak from the drainage stack to the bathroom if leaks existed.

In the Wai Lee Building, we hung an iButton sensor in the drainage pipe through the rooftop to record the temperature and relative humidity inside the drainage pipe at the level of the 23rd floor at 2-minute intervals (Fig. 2b). The same type of sensor with a radiation shield was used to monitor the temperature and relative humidity above the roof and inside the light well near the 14th floor at 2-minute intervals. The differential pressure between the soil pipe and the bathroom in four flats, i.e., Flats 204, 604, 1404, and 2104, was measured. The pressures were measured prior to the tracer gas measurement.

We then analyzed the association between the distribution pattern of flats resided by the infected persons, and the leaked tracer gas under various scenarios. The stack air flow in the drainage pipes was also analyzed using the measured air temperature/humidity and pressure.

3. Results

3.1. Vertical spatial pattern of secondary infections

In Kensington Plaza, 14 residents from 6 flats tested positive for SARS-CoV-2 by RT-PCR (CHP, 2021a). Among them, four -C flats, on the 5th, 6th, 7th, and 17th floors, were affected with 10 cases involved (Table 1). The index case was a 70-year-old male (case K1) who became ill on January 15, 2021, and he was confirmed to be suffering from COVID-19 on January 16, 2021. He lived in Flat 5C and was an employee of a cleaning company with a recent cluster of 11 staff diagnosed with recent COVID-19. The incubation period of the 12 cases within the affected building overlapped with the period of communicability of the index case (2 days prior to symptom onset). A 14-year-old male (Flat 7 C) developed symptomatic COVID-19 in the quarantine camp on February 1, 2021. The later onset implied that it was acquired through household contact with his mother, who was confirmed to be infected with SARS-CoV-2 on January 22, 2021. Details of the other cases are provided in Table 1.

SARS-CoV-2 whole-genome sequencing was performed on three patient samples from three -C flats in the Kensington Plaza cluster. Sequence analysis confirmed that the viral genome sequences were identical in these three cases [cases K1 (Flat 5C), K8 (Flat 7C), and K10 (Flat 17C)], suggestive of a point source in these three cases from -C flats in the cluster.

In the Wai Lee Building, nine residents from five flats were confirmed to have COVID-19. Three were from – 04 flats, which are vertically aligned and connected by the same drainage stack. The index case was an 18-year-old male college student who lived in Flat 1404 (14th floor, Flat 04, case W2). The incubation period of the other eight cases all overlapped with the period of communicability of the index case. Details of the cases are summarized in Table 1.

SARS-CoV-2 whole-genome sequencing was performed on seven patient samples from the Wai Lee Building cluster. The maximum likelihood phylogenetic tree of the SARS-CoV-2 genome sequence is shown in Fig. 3. Sequence analysis confirmed that the viral genome sequences were essentially identical in five cases (cases W1, W3, W4, W6, and W9), whereas sequences from the remaining two cases (cases W7 and W8) contained one and three additional nucleotide substitutions, respectively. Overall, these results support a point source in these three cases from -C flats in the cluster.

Among the 27 environmental samples taken from three flats (5 C, 7 C, and 17 C) in Kensington Plaza, 8 tested positive for SARS-CoV-2, including 1 out of 7 samples from Flat 17 C (interior side of the sink drain in the bathroom), 0 out of 9 samples from Flat 7 C, and 7 out of 11
samples from Flat 5 C (in the kitchen: window frame, floor drain, sink, and interior side of the sink drain; in the bathroom: floor drain, floor drain of the shower area, and exhaust fan). However, no WC samples tested positive in this outbreak. For the 04 flats in the Wai Lee Building, 14 environmental samples were collected, all of which were negative.

The spatial distribution of the flats with infected residents indicated a vertical pattern associated with the same drainage stack. The same vertical pattern for SARS-CoV-2 infection was first reported in a Block X outbreak in Guangzhou (Kang et al., 2020). Here, we demonstrated a similar association between the drainage stack and the vertical spatial distribution of the infected flats, and also revealed the importance of the chimney effect within the drainage stack on virus spread.

3.2. Tracer gas concentration in bathrooms, along facades, or in the light well

Significant tracer gas concentrations were found on the upper floors in both buildings, e.g., Flat 17 C of Kensington Plaza (0.2 ppm) and Flat 2104 of the Wai Lee Building (40.0 ppm) (Fig. 5a and b). The release rate of the tracer gas was similar in the two buildings. The significantly higher concentration observed in the Wai Lee Building compared with that in Kensington Plaza could be explained by the absence of a floor drain U-trap in the former building. Low concentrations were detected in non-infected or lower-floor flats, e.g., Flat 7 C (0.02 ppm) and Flat 10 C of Kensington Plaza (0.03 ppm). However, leaked tracer gas was also detected in Flat 7 C (0.1 ppm) and Flat 10 C (0.4 ppm) in a separate test when the exhaust fans in Flat 7 C and Flat 10 C were switched on (Fig. S2).

We monitored the vertical distribution of the tracer gas concentration along the facades when the windows of the bathroom of the index case were opened during tracer gas release, i.e., Flat 5 C of Kensington Plaza and Flat 1404 of the Wai Lee Building (Fig. 5c–f). In Kensington Plaza, a steep concentration gradient was observed along the façade, with a peak concentration of 3.4 ppm on the 7th floor compared to 0.5 ppm on the 17th floor. In contrast, in the Wai Lee Building, the concentrations in the light well were generally homogeneous with height away from the source, e.g., the 14th floor (near the source: 4.4 ppm), 18th floor (2.0 ppm), and 21st floor (1.8 ppm). The light well is an enclosure with only two openings on the roof and the ground floor, which encourages tracer gas accumulation. The average purging time for the SF6 from the drainage pipes is estimated to be 5–9 min. The above-ambient air temperature inside the semi-open or enclosed light wells also induces upward air movement (Fig. 5e and f).

3.3. Concentration variation near roof vents in the Wai Lee Building

The Wai Lee Building has fully enclosed light wells (Fig. 1b). Every two flats share a light well, which houses the drainage pipes of the two flats. As we released the tracer gas into the WC of the index case, we also monitored the concentration of the tracer gas in the roof vents of other flats, i.e., – 05, – 06, and – 11 flats, to determine the possibility of tracer gas transport in the drainage system because the vertical drainage

Fig. 3. Maximum likelihood tree of SARS-CoV-2 genome sequences from the Wai Lee Building cluster constructed using IQ-TREE version 2.1.1 under the best-fit HKY+F evolutionary model. The node labels at the base of the branches indicate the branch support calculated using ultrafast bootstrap approximation with up to 5000 replicates. Cases A to D are local cases not related to the present cluster, which are included in the tree for comparison.

Fig. 4. Distribution of the infected flats in (a) Kensington Plaza and (b) the Wai Lee Building. No other infections were identified in the same building. Each flat is shown by a box. The flat with the index case is shown in red, and the flats with secondary infections are shown in yellow. In Kensington Plaza, the flats are labeled Flats A–F, where Flat 5 C denotes a C flat on the 5th floor. In the Wai Lee Building, the flats are numbered 01, 02, etc., where Flat 1404 denotes a – 04 flat on the 14th floor.
Fig. 5. Peak tracer gas concentrations near the floor drain in the bathroom in (a) Kensington Plaza and (b) the Wai Lee Building. The star and explosion symbols represent the locations of secondary infected cases and the index case, respectively. The red and blue values in (a) represent the concentrations in different sets of tests. Peak tracer gas concentration along the facades in the light well of (c) Kensington Plaza and (d) the Wai Lee Building. Variations in the tracer gas concentration and temperature difference between the light well and outdoors in (e) Kensington Plaza and (f) the Wai Lee Building. The orange rectangle indicates the dosing period.
stacks of all of the flats in the building likely share a horizontal discharge pipe before the first manhole (Fig. 2b). When we injected the tracer gas into the drainage pipe connected to the vent pipe of Flats 04, 05, 06, and 11, we observed a significant increase in tracer gas concentration due to tracer gas dispersion and transportation outside the pipe system ruled out by a separate test (Fig. S3). The concentration inside the vent pipe of 05 flats was higher than that outside the vent pipe. The drainage stacks of the flats are connected to each other below ground (Fig. 2b), which could affect the distribution of differential pressures presented in Section 3.5. The pipes also serve as transport paths between different flats.

3.4. Temperature and relative humidity variation

An upward chimney effect occurs when the interior air is lighter than the outdoor air, and a downward chimney effect occurs when the interior air is heavier. In Kensington Plaza, the air temperature in the drainage stack ranged from 18.5 °C to 28.0 °C and the relative humidity ranged from 95.5% to 100.0% (Fig. 7a). Such high humidity in drainage pipes has also been observed by Gormley et al. (2014), and the high humidity is an important factor for virus survival (Casanova et al., 2010). Due to solar radiation heating, there was a sudden increase in air temperature inside the drainage pipe at approximately 15:00. The drainage stack is exposed along the exterior of the semi light well facing west (Fig. 1a). In the Wai Lee Building, the measured stack air temperature ranged from 21.2 °C to 23.7 °C and the relative humidity was approximately 90% throughout the day (Fig. 7b). The warm and wet conditions near the open-end roof vent were similar to the data measured in a hospital drainage system by Gormley et al. (2014).

Comparing the measured temperature and relative humidity in the two buildings, the effect of building design on the chimney effect was noticeable, e.g., the use of a fully enclosed light well or semi-open light well and the facing direction of the drainage stack. The air density inside the pipe and outdoors were estimated from the air temperature and relative humidity in the air as an indicator of the buoyancy effect (Fig. 7c and d).

The temperature difference between the drainage pipe inside and outside strongly affected the concentration variation near the roof. For example, there was a significant increase in tracer gas concentration at approximately 15:10 in Kensington Plaza (Fig. 8a), thereby indicating strong upward airflow during this period. This is easily explained by the observed high temperatures and thus the strong upward chimney effect within the vertical stack.

We also monitored the tracer gas concentration near the roof vent of Flats 04 in the Wai Lee Building for an extended period (Fig. 8b). Comparing the variations in the concentration and the air temperature inside the drainage pipe and outside during a specific period (dashed line), the tracer concentration reached a high level when the air temperature inside the drainage pipe was higher than the outside environment. The high readings persisted after dosing was stopped. The peak concentration was not always consistent with the occurrence of the largest air temperature difference because the continuously injected SF6 would escape through the roof vent due to gas expansion even without additional driving forces of air flow within the stacks.

3.5. Differential pressure between the drainage stack pipe and the bathroom

The analysis of temperature and relative humidity inside the drainage pipe indicated that the chimney effect should be salient during the nighttime due to the large temperature difference. Therefore, we monitored the differential pressure between the inner pipe and the bathroom before and/or after the tracer gas measurement period. Fig. 9a–d shows the variation in differential pressure on different floors in Kensington Plaza and the Wai Lee Building. In Kensington Plaza, negative differential pressure was recorded on the 10th floor and positive differential pressure was recorded on the 5th, 7th, 15th, and 17th floors (Fig. 9a and b). The differential pressure results are consistent with the theory of tracer gas measurements in Kensington Plaza. In this building, flats below the 9th floor shared the same vertical stack and flats above the 9th floor were connected to another vertical stack, although these two vertical stacks share the same vent pipe. This might have caused the existence of two neutral level planes, one between the 9th and 10th floors and another below the 5th floor (Fig. 9d). This complex multiple-neutral plane phenomenon has been found in other analogous systems, such as elevator shafts (Yang et al., 2003; Jo et al., 2009).

In the Wai Lee Building, from 20:00–24:00, small negative pressure differences were recorded at the 14th floor and positive pressure differences were recorded at the 2nd, 6th, and 21st floors, which may have indicated the existence of a stack effect. However, nearly all of the differential pressures among the measured floors were positive, including the 2nd, 6th, 14th, and 21st floors at nighttime (e.g., 00:00–04:00), because the air temperature inside the drainage stack was higher than that outdoors during the period 20:00–08:00 (Fig. 7b). The upper part of the drainage system in the Wai Lee Building can be observed, but we know little about the design of the drainage system below the ground. The variation in the tracer gas concentration near the roof vents (Fig. 6) allowed us to infer that the drainage stacks are connected below ground, which is a common design practice in Hong Kong. The architectural design of the drainage system and the opening (leakage) size and distribution would affect the differential pressure distributions (Yang et al., 2003; Liu et al., 2018; Song et al., 2020).

The existence of multiple neutral levels of pressure in such a high-rise drainage stack is not unexpected, as demonstrated in Otis and Jones (1988), although it is less well known. The air temperatures within the stack and outdoors at heights of 63.3 m for Kensington Plaza and 76.6 m for the Wai Lee Building were likely non-uniform, as shown by the measurements. However, the exact temperature profiles require further study.

4. Discussion and conclusion

4.1. Confirmation of the chimney effect in stack aerosol transmission

In this study, both outbreaks suggested a vertical transmission
pattern, which was supported by the phylogenetic analysis and tracer gas study. The environmental measurement studies of the two outbreaks suggested that the airborne transport of infectious aerosols in the drainage stack may provide an explanation for the vertical distribution of cases in the affected buildings. The affected flats were vertically connected via the drainage stack in each building and were correlated with the leaking of tracer gas through the drainage system in the infected and non-infected flats. This conclusion is consistent with that of an early investigation of the 2003 Amoy Gardens SARS-CoV-1 outbreak in which the infection cluster in the column of flats including the index case was mainly due to the drainage pipe system (Yu et al., 2004). The same conclusion was drawn in a study of the SARS-CoV-2 Block X outbreak in Guangzhou (Kang et al., 2020).

This study confirms the hypothesis first proposed by Kang et al. (2020) whereby chimney effect-induced air flows transport the stack aerosols. Following the 2003 SARS-CoV-1 outbreak, Swaffield and Jack (2004) presented one of the first simulation studies on possible contamination routes established due to trap seal loss and/or dried-out traps. However, their study wrongly attributed the cause to pressure fluctuations during or immediately after flushing. The flow and transport of wastewater, solids, and air in a building drainage system are governed by the basic principles of negative pressure transients during flushing, positive pressure transients when the wastewater reaches the horizontal bottom pipe, and two-phase flows (Swaffield, 2010, 2015). The changes in air pressure in building drainage and vent systems were studied by Swaffield and Campbell (1995). Both negative and positive transients were observed during the wastewater discharge flow. The airflow pressure distribution in the drainage stack has been studied using a theoretical approach (Swaffield and Campbell, 1995), measurements (Cheng et al., 2010), and an empirical approach (Cheng et al., 2005). During toilet flushing, wastewater moves in both the inclined horizontal branch pipe and the vertical stack due to gravity causing air entrainment, thereby leading to pressure variations in the stack with upper floors experiencing negative pressure and the bottom 1–2 floors experiencing positive pressure (back pressure). During non-flushing periods, both the positive and negative chimney effect are possible in the stack.

In natural ventilation, a neutral level occurs when the inside and outside pressures are equal. When warm wastewater is discharged from the kitchen/bathroom, the stack walls and air can be heated, and the warmed walls can later heat the stack air. Because the stack is generally poorly ventilated, the stack air remains warmer and more humid. It is expected that drain/vent flows dominated by natural ventilation are possible most of the time, particularly at night when few people use their bathroom/kitchen. The moist and slightly warm foul air rises along the drainage stack with air flowing in through the manhole. If some flats have pipe leaks, the foul air enters them. In addition to the chimney effect, the wind at both the manhole and roof top and exhaust fans in the associated bathrooms can affect the driving pressure of natural ventilation.

The leakage of stack aerosols into the flats is much less likely to occur.

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**Fig. 7.** Temporal variation in air temperature and relative humidity inside the drainage pipe and on the roofs of (a) Kensington Plaza and (b) the Wai Lee Building. Estimated air density for (c) Kensington Plaza and (d) the Wai Lee Building.
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Fig. 8. Tracer gas concentration near the roof vent of the – 04 flats, interior air temperature, and outdoor air temperature for (a) Kensington Plaza and (b) the Wai Lee Building. The orange rectangles represent the dosing period.

during flushing periods than during non-flushing periods. When the wastewater is discharged into the branch pipe and plunged into the vertical stack, the drainage stack on the upper floors first experiences significant negative pressure (maximum of ~1000 Pa; Wong et al., 2013) (Fig. 10a). When the wastewater reaches the bottom of the drainage pipe, there is a short period when positive back pressure (maximum of 500 Pa) is formed (Fig. 10a) and then immediately vanishes. If the pipe has any leaks or loss of the water seal, the air should flow into the lower-floor drainage stack. If this were true, then the infected flats should be on lower floors rather than on mostly upper floors, as was observed. Our measured air temperature and humidity data within the drainage stack revealed a warm, humid environment most of the time due to the discharge of warm water from bathing and other activities. Therefore, a drainage stack can be described as a leaky vertical chimney from the first manhole to the roof vent (Fig. 10b and c). For moist air at 23 °C, an increase in relative humidity from 50% to 90% leads to a stack pressure of 6.84 Pa for a chimney height of 50 m, which is sufficient to drive upward flow. At 50% relative humidity, an increase in temperature from 23.0 °C to 25.5 °C induces a similar stack pressure. In Hong Kong, the warm chimney effect is expected to dominate during winter. If water seal losses or pipe leaks are present, the suspended aerosols should be able to escape into the flats during “calm” periods via natural ventilation of the drainage stacks. The negative pressure in bathrooms due to exhaust fans adds additional driving force for the leakage in upper floors. This agrees with the observation that all vertical outbreaks, except for one, in Hong Kong occurred during the 2020–2021 winter.

The existence of a chimney effect in high-rise buildings is known (Yu et al., 2017); however, to the best of our knowledge, this is the first detailed study of chimney effects on waste stack air flows during non-flushing periods in high-rise housing, and a similar study was reported for a hospital (Gormley et al., 2014).

4.2. Possible roles of washbasin aerosols

The chimney effect only explained the transport of stack aerosols. The generation of stack aerosols is a complicated process. A significant number of aerosols are generated during WC flushing, and more than 99.5% of aerosols are less than 5 μm in size (Gormley et al., 2021). Several studies, including a review by (Berna et al., 2014), have examined droplet generation in annular flow, in which the drops are dislodged by forming either a ligament-like (rolling) or bag-like (undercut) protrusion in liquid, as shown by numerical simulations (Kumar et al., 2016). Most of these annular two-phase studies cannot be directly applied to the generation of stack aerosols because of entrained gas phase flows rather than imposed flows, as described in typical two-phase flow studies. The atomization process may be described by an air vortex generation theory with energy transfer from vortices to droplets. The liquid film on pipe walls is periodically pushed by the air vortex, which sweeps some of the water to form a droplet (Zhang et al., 2015).

Wastewater discharge can originate from the WC (feces, urine, and nasal/oral secretions) and washbasin (nasal/oral secretions). Fecal aerosols, i.e., atomization of feces-containing wastewater, were first hypothesized by Yu et al. (2004) for SARS-CoV-1 and Kang et al. (2020) for SARS-CoV-2. The absence of the detection of viable SARS-CoV-2 in wastewater has cast doubt on the infectivity of fecal aerosols in building drainage systems. Moreover, the low attack rate in the 13 observed COVID-19 vertical outbreaks suggested that the amount of infectious aerosols in building drainage systems is not very high or the leaked amount of infectious aerosols is low. Unlike feces, nasal mucus, saliva, and sputum of infected individuals are known to contain viable SARS-CoV-2 (e.g., Rao et al., 2020; To et al., 2020; Wyllie et al., 2020; Herrera et al., 2021). Nasopharyngeal or oropharyngeal swabs (Caulley et al., 2021) and early morning posterior oropharyngeal saliva collection (Bastos et al., 2021) are used as diagnostic specimen type for SARS-CoV-2. Bastos et al. (2021) found in their latest systematic review of 37 studies with 7169 participants that there was no statistically significant difference between saliva samples and nasopharyngeal swabs for SARS-CoV-2 detection. While there are few data on washbasin usage behavior in private bathrooms, one study reported that 26.4% of people in Hong Kong spit into WCs in public toilets (Wu et al., 2019). We postulate that a higher proportion of people would blow their nose into the sink or spit into the washbasin in bathrooms at home, especially in the morning. If the washbasin is used by a SARS-CoV-2 infected individual, the washbasin is highly likely to be contaminated with SARS-CoV-2. Moreover, women generally spend more time in the bathroom or kitchen than men (Marston, 1999; Baillie et al., 2009), which may explain why 33% more women were infected in the first 10 vertical COVID-19 outbreaks in Hong Kong. Note that these vertical outbreaks have only been observed in Guangdong and Hong Kong, but not elsewhere. Our suggested possible role by bathroom spitting is speculative. By January 25, 2021, 10 high-rise vertical outbreaks of COVID-19 were identified in Hong Kong involving 79 confirmed cases (including 10 index cases), or 0.8% of the 10,158 confirmed cases by the CHP of the Hong Kong SAR government (CHP, 2021d). The 79 confirmed cases included 46 females and 33 males. The hypothesis of stack aerosol origin from nasal mucus, saliva, and sputum of the index case is supported by the high number of positive samples in the kitchen and bathroom of the index cases, including the washbasin in Kensington Plaza before our test dates, but none from WCs. However, no samples were found to be positive in the Wai Lee Building. Multiple studies have detected the RNA of SARS-CoV-2 on washbasin surfaces in hospitals, e.
g., Ding et al. (2021). Boone and Gerba (2005) also detected influenza A virus in sinks and drains of households and day care centers. The amount of wastewater per discharge for a washbasin is generally much less than that of a WC or shower. It is suspected without evidence that such a small amount of discharged water might be fully aerosolized in the vertical drainage stack. The bioaerosols generated after washbasin discharge spread via the drainage stacks and vents with minimum dilution, as with WC flushing (Kang et al., 2021). However, the amount of expectorated mucus is small compared with that of feces, which may explain relatively small-scale COVID-19 outbreaks in these high-rise vertical outbreaks in contrast to the large SARS-CoV-1 outbreak in Amoy Garden in 2003. However, the difference in magnitude of vertical transmission could also be explained by the early recognition of the vertical transmission pattern by the Department of Health of Hong Kong, followed by a joint discipline field investigation with prompt and aggressive measures implemented to terminate the transmission chain in affected buildings. If our hypothesis is confirmed in future studies, then the transmission of SARS-CoV-2 in these vertical outbreaks could be reconciled with the commonly observed predominance of respiratory transmission by expired droplets.

4.3. Implications for infection control

Although vertical transmission in high-rise housing contributed to less than 1% of the total local transmission, prompt identification and high vigilance of vertical transmission patterns coupled with an MDRT field investigation, extensive RT-PCR testing of all residents, and the rapid evacuation/quarantine of residents in the involved stack were the
The full mechanism of vertical transmission in the two high-rise buildings remains to be resolved because the exact source of infectious stack aerosols was not determined.

The finding of airborne transport by the drainage stacks clearly demonstrates that airborne transmission of SARS-CoV-2 by vertical drainage stacks is possible, and phylogenetic analysis of the available virus genome sequences demonstrated clonal spread from a point source in households along the same vertical column. The most effective control for leakage of stack aerosols should be implemented at the source, i.e., avoiding any potential gas leaks from the drainage system into indoor spaces. For example, drainage traps, such as U-shaped water traps, should not be allowed to dry out, and drainage pipes and joints should not have any air leaks. New leak detection methods for drainage pipes have not been widely used in Hong Kong. For example, Kelly et al. (2008) used a reflected wave method to detect lost water seals. Reliance on the visual detection of leaks is not effective. Various pipe leak detection methods have been developed in the piping industry. This may be considered a fault detection and diagnosis problem (i.e., diagnostics identifies the root cause and location of detected faults), which has been addressed for air-conditioning systems, such as via the use of artificial neural networks for fault diagnosis (e.g., Lee et al., 1996a) and for comparison of the normal/expected operation data with measured, possibly abnormal data using residuals (Lee et al., 1996b). It is also necessary for infected individuals, and everyone due to the existence of asymptomatic individuals, to minimize the discharge of nasal or oral secretions into the washbasin (using tissue paper instead). However, this may not be practical as people generally spit into the washbasin while brushing their teeth. This will involve changes in spitting behavior when using private bathrooms and public toilets. It is also important for health authorities to recognize vertical transmission patterns early and to implement appropriate measures to prevent the further propagation of an outbreak through vertical drainage stacks. We cannot rule out the possibility of buoyancy flow transport in fully enclosed or semi-open light wells. Therefore, we recommend that residents close the bathroom windows when turning on the exhaust fan. Opening the toilet door or installing a louver at the toilet door can prevent the buildup of a strong negative pressure in the toilet, thereby minimizing any leaks from the drainage system into a bathroom. Moreover, transmission through contact by common surface touching cannot be ruled out. However, the clear vertical transmission pattern found in this study demonstrates that transmission via chimney effect-induced flows was the most likely route.

4.4. Limitations of this study

There are several major limitations of this study. Only two outbreaks with a total of 23 infected cases were reported. Monitoring of tracer gas concentrations and buoyancy pressure was only conducted in a small number of infected and non-infected flats due to access difficulties. Each building was tested within 1–3 days due to the constraints of the quarantine periods and the need for full disinfection before access by our field test team.

Not all patient specimens were available for sequencing in this study. However, sufficient specimens from relevant flats demonstrated point source transmission along a vertical column. Systematic laboratory or field tests of the chimney effect and its occurrence in different climates and building types are needed.

CRediT authorship contribution statement

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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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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2021.126799.

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