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Enlightenment of re-entry airflow: The path of the airflow and the airborne pollutants transmission in buildings

C.W. Tung, C.M. Mak, J.L. Niu, K. Hung, Yan Wu, Nam Tung, H.M. Wong

Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, China
School of Mechanical Engineering, Tongji University, China
Faculty of Dentistry, The University of Hong Kong, Pok Fu Lam, Hong Kong Island, Hong Kong, China

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ABSTRACT

Viable aerosols in the airflow may increase the risk of occupants contracting diseases. Natural ventilation is common in buildings and is accompanied by re-entry airflow during the ventilation process. If the re-entry airflow contains toxic or infectious species, it may cause potential harm to residents. One of the Covid-19 outbreaks occurred in a public residential building at Luk Chuen House (LC-House) in Hong Kong. It is highly suspected that the outbreak of the disease is related to the re-entry airflow. The study attempts to explain and discuss possible causes of the outbreak. In order to understand the impact of airflow on the outbreak, a public residential building similar to LC-House was used in the study. Two measurements M_I and M_II with the same settings were conducted for a sampling unit in the corridor under low and strong wind conditions respectively. The sampling unit and the tracer gas carbon dioxide (CO\textsubscript{2}) were used to simulate the index unit and infectious contaminated airflow respectively. The CO\textsubscript{2} concentrations of the unit and corridor were measured simultaneously. Two models of Traditional Single-zone model (TSZ-model) and New Dual-zone model (NDZ-model) were used in the analysis. By comparing the ACH values obtained from the two models, it is indicated that the re-entry airflow of the unit is related to the corridor wind speeds and this provides a reasonable explanation for the outbreak in LC-House, and believes that the results can help understand the recent frequent cluster outbreaks in other residential buildings.

1. Introduction

Owing to the limitation of non-renewable energy, the utilization of natural ventilation for good indoor air quality is widely adopted in residential building design [1,2]. Airflow is driven by buoyancy and wind, which affects natural ventilation. Li and Delsante reported that the effects of wind and buoyancy drive usually complement or oppose each other in terms of building ventilation [3]. Allocca and his colleague based on their study came to the same conclusion [4]. However, the airflow contaminated with bio-substance may increase the risk of spreading diseases in the building. During the SARS attack in 2003, the Hong Kong Health, Welfare and Food Bureau (HWFB) conducted environmental sample swab tests on SARS index buildings. The bureau reported that some abnormal samples collected from the Wing Shui House (index building) found SARS bio-substance in the lower index unit and the vertical upper non-index unit [5], among which the residents of the upper unit did not have SARS symptoms. Niu and Tung suspected that the vertical transmission of bio-substance in these two units is related to the open mode of the windows and low wind speeds. They conducted tracer gas measurement and revealed the trick of virus transmission by studying the coupling of mass fraction and wind effects [6]. Their research shows that low wind speeds are conducive to the vertical spread of pollutants. The studies of Ai and Mak [7–10] support this result. Gao and his colleagues studied single-sided ventilation and re-entry airflow in high-rise residential buildings. Their simulation results show that the strong wind speed can suppress the re-entry airflow from the lower unit opening window to the upper unit opening window [12]. Doremalen and his colleagues focused on the aerosol and surface stability of Covid-19 on different media [13] because pathogenic biological substances has longer retention time in the air, which means to increase the risk developing the disease. They reported that the half-life of Covid-19 in the air is estimated to be 1–1.1 h. Based on the study of Doremalen, Riediker and Tsai simulated a given Covid-19 patient in a well-mixed room to observe the effect of ventilation on virus growth in the room [14]. Their report shows that if the number of index

* Corresponding author.
E-mail address: cheuk-ming.mak@polyu.edu.hk (C.M. Mak).

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resident is specified, the stable concentration of Covid-19 in the room mainly depends on the room’s ACH. Even if the ventilation rate of the room is 1 ACH, it will reach a stable concentration within 3 h. According to the studies of Doremalen [13] and Riediker [14], it can be understood that pathogens have a long half-life in the air, and poor ventilation in buildings may cause the disease to spread rapidly in a short time. Moreover, in terms of ventilation, the urban microclimate also plays a major role in the built environment [9,11].

2. Site description

LC-House is a slab-type public residential building. In the study, another long-slab public residential building similar in structure to LC-House was selected for measurement. These two buildings are buildings with poor airtightness. Each floor of the sampling building provides a semi-open internal corridor, and the units are arranged on both sides of the corridor. The corridor extends in the east-west direction, and the width and height of the corridor are 1.75 m and 2.45 m, respectively. After the incoming wind passes through the entrance of the corridor, the wind will be guided along the corridor. However, the wind direction and intensity in the corridor depends on the wind conditions at the two entrances. The sampling unit is with the dimension of 3.38 m × 6.80 m × 2.45 m (WxLxH). Each unit is equipped with a louvre window on the wall of the corridor. The standard width and height of the louvre window are 0.38 m and 0.57 m, respectively. The layout of the sampling site is shown in Fig. 1, where the sampling units are squared by red line. The}

Fig. 1. Layout of the sampling site.
trend also follow the change of the tracer gas of the sampling unit. Unfortunately, there is no definable control volume in the semi-open corridor area, and the combination of control volume and mass balance principle cannot be applied. It makes difficult to express the change of tracer gas concentration in the corridor. However, according to the influence of the wind on the concentration of the tracer gas in the corridor, the form of the concentration of the tracer gas can be obtained. Therefore, it is allowed to simply create an appropriate alternative expression and use it in the modelling, as in Eqn (3).

\[ C_{Cr} = \Omega e^{-\emptyset t} + C_o \]  

\( \Omega \) is an arbitrary constant. It can be determined by on-site measurement, the initial concentration of the tracer gas in the corridor to give Eqn (4).

\[ C_{Cr} = [(C_{Cr})_i - C_o]e^{-\emptyset t} + C_o \]  

The notation \( \emptyset \) is defined as the corridor fade-out index, which is used to describe the attenuation of the tracer gas concentration in the corridor. In the zone of the sampling unit, the rate of change of the tracer gas concentration at time \( t \) is determined by Eqn (5).

\[ \frac{dC}{dt} = q_{cr}C_{cr} - q_aC \]  

By the flow conservation as Eqn (2) \( (q_{cr} = q_a = q) \), and, Eqn (4) was substituted into Eqn (5) and rearranged to obtain Eqn (6) as:

\[ \frac{dC}{dt} + q \frac{C}{V} = \frac{q}{V}[(C_{Cr})_i - C_o]e^{-\emptyset t} \]  

Consider the following equations Eqn (7) and Eqn (8):

\[ \frac{dC_1}{dt} + q \frac{C_1}{V} = \frac{q}{V}C_o \]  

\[ \frac{dC_2}{dt} + q \frac{C_2}{V} = \frac{q}{V}[(C_{Cr})_i - C_o]e^{-\emptyset t} \]  

The solution for Eqn (7) is represented by Eqn (9).
\[ C_i = S e^{-\alpha t} + C_o \]  
(9)

Where, \( S \) is an arbitrary constant.

The particular solution for Eqn (8) is represented by Eqn (10), if the air changes per hour of the sampling unit \( \frac{q}{V} \) is not equal to the corridor fade-out index, then we have:

\[ C_i = e^{-\alpha t} \int_{0}^{t} \left[ (C_{i_0}) - C_o \right] e^{\left( \frac{q}{V} \alpha \right)t} dt \]  
(10)

Or

\[ C_i = \frac{q}{V} \frac{\left[ (C_{i_0}) - C_o \right]}{\left( \frac{q}{V} - \alpha \right)} \]  
(11)

The general solution of Eqn (6) is equal to the sum of Eqn (9) and Eqn (11).

That is \( C = C_1 + C_2 \)

\[ C = \left( S e^{-\alpha t} + C_o \right) + \left( \frac{q}{V} \frac{\left[ (C_{i_0}) - C_o \right]}{\left( \frac{q}{V} - \alpha \right)} \right) e^{-\alpha t} \]  
(12)

If the initial concentration of the unit was \( C_{in} \), selected for a decay time slot of interest, then \( S \) could be determined as shown in Eqn (13).

\[ S = (C_{in}) - \left\{ C_o + \left[ \frac{q}{V} \frac{\left[ (C_{i_0}) - C_o \right]}{\left( \frac{q}{V} - \alpha \right)} \right] \right\} e^{-\alpha t} \]  
(13)

Substitute Eqn (13) into Eqn (12) to get Eqn (14).

\[ C = \left\{ (C_{in}) - \left\{ C_o + \left[ \frac{q}{V} \frac{\left[ (C_{i_0}) - C_o \right]}{\left( \frac{q}{V} - \alpha \right)} \right] \right\} \right\} e^{-\alpha t} + \left\{ \frac{q}{V} \frac{\left[ (C_{i_0}) - C_o \right]}{\left( \frac{q}{V} - \alpha \right)} \right\} e^{-\alpha t} + C_o \]  
(14)

Eqn (14) is essential in quantifying the re-entry airflow of the sampling unit under the configuration of single-sided natural ventilation mode that will be illustrated in section 5.1.

When the air changes per hour of the sampling unit \( \frac{q}{V} \) is equal to the corridor \( \alpha \), the particular solution for Eqn (8) is represented by Eqn (15).

\[ C_i = e^{-\alpha t} \int_{0}^{t} \left[ (C_{i_0}) - C_o \right] dt \]  
(15)

Or

\[ C_i = e^{-\alpha t} \frac{q}{V} \left[ (C_{i_0}) - C_o \right] t \]  
(16)

The general solution of Eqn (6) is represented by Eqn (17),

\[ C = M' e^{-\alpha t} + C_o + e^{-\alpha t} \frac{q}{V} \left[ (C_{i_0}) - C_o \right] t \]  
(17)

From the initial condition of the sampling unit, we have:

\[ M' = \left[ (C_{in}) - C_o \right] \]  
(18)

The sampling unit tracer gas concentration at time \( t \),

Under the condition of \( \left( \frac{q}{V} - \alpha \right) = 0 \) could be represented by Eqn (19) when Eqn (18) is substituted into Eqn (17).

\[ C = \left\{ (C_{in}) - C_o \right\} e^{-\alpha t} + \left( \frac{q}{V} \frac{\left[ (C_{i_0}) - C_o \right]}{\left( \frac{q}{V} - \alpha \right)} \right) \left( e^{-\alpha t} \right) + C_o \]  
(19)

Note that Eqn (19) is very different from Eqn (14), because Eqn (19) is only applied \( \alpha \) is equal to \( \frac{q}{V} \).

In order to identify the air changes per hour from the previous \( AACH \), the title of \( ACH \) was not changed. It is worth noting that \( AACH \) was obtained from the TSZ-model and did not consider the changes in the tracer gas in the corridor. However, \( ACH \) comes from the NDZ-model which considers the variation and coupling of the tracer gas in the sampling unit and corridor. The air changes per hour \( \frac{q}{V} \) represented by Eqn (14) cannot be simply transformed into a linear form for simple regression. However, it can be obtained using the curve fitting method suggested by Tung et al. [18].

4. Instrumentation and setup

In the measurement, the following procedures should be performed: (i) Activate all instrument at the sampling points; (ii) Close all openings and check the gap sealing of the facade windows; (iii) Dose CO₂ gas to the expected level of 3000 ppm; (iv) Remove the tracer gas source before evacuating from the sampling unit; and (v) Open the blades of the louvre.
at the desired angle. The concentration of the tracer gas was monitored using two calibrated CO₂ Monitor-A and -B, TSI Q-Trak Model 8551. Monitor-A was placed at the centre of the unit and Monitor-B was set at a position 0.3 m perpendicular from the centre of the louvre at the corridor. The corridor wind speed was recorded using a low wind velocity flow analyser (Dantec Model 54N50). The flow anemometer was placed at the same height as Monitor-B, but the distance from the louvre window was 0.5 m. The recording interval of the two CO₂ monitors and flow anemometer was 30 s per data set. Before the measurement, a correlation test has been performed on CO₂ Monitor-A and Monitor-B, and the correlation factor and $R^2$ are 1.00 and 0.97, respectively. The correlation uncertainty is less than 3%.

5. Results and discussion

5.1. AACH and ACH values and re-entry airflow of the sampling unit

This section reports the results of two measurements performed under two different wind speed conditions in the corridor. M – I was conducted at the mean wind speed of 0.4 ms⁻¹ with a standard deviation of 0.26 ms⁻¹. M – II was performed at 1.1 ms⁻¹ with a standard deviation of 0.4 ms⁻¹. Data analysis is mainly focused on the time slot of the tracer gas concentration in the sampling unit/corridor attenuation informative duration. These time slots are so-called as the tracer gas decay significant duration.

In M – I, the unit air changes per hour value derived from the TSZ-model is 3.36 h⁻¹ ($AACH = 3.36$ h⁻¹). However, the NDZ-model using the fade out index ($\phi_{(15.5,h)}=15.5$ h⁻¹) gives an $ACH$ value of 4.03 h⁻¹. The value $\phi_{(15.5,h)}$ is obtained from the upper envelope of the corridor tracer gas concentration within the significant decay duration (15:39–15:52). The values of $AACH$ (3.36 h⁻¹) and $ACH$ (4.03 h⁻¹) are calculated from same data set. The $ACH$ value derived from NDZ-model is found greater than the $AACH$ value given by TSZ-model. The scenario of upper envelope of the measurement and prediction curves are sketched in Fig. 3. From the figure, the sampling unit tracer gas concentration curves obtained by measurement, predictions of TSZ-model
and NDZ-model were found to overlap with each other, even if two ventilation index values of the models are in difference.

Referring to Fig. 4 which used the same measured data set as in Fig. 3, the lowest instant concentrations of the corridor tracer gas is highlighted by the lower envelope, and the $Q_{70/h}$ was 70 h$^{-1}$ in use. Applying this value to the NDZ-model, an $ACH$ of 3.44 h$^{-1}$ was obtained, and the ventilation rate of the unit was found to have greater than the value of $AACH$ (3.36 h$^{-1}$) estimated by using the TSZ-model. However, three tracer gas concentration decay curves still overlapped with each other.

The two $ACH$ values obtained from the upper and lower envelopes are meaningful, which indicates that an effective $\phi_{\text{eff}}$ value should be limited within the range of 15.5–70 h$^{-1}$ during this attenuated period. Through moving average, optimization and convergence operations, the value of $\phi_{\text{eff}}$ is 21.74 h$^{-1}$, and the effective $ACH_{\text{eff}}$ value of the sampling unit is 3.81 h$^{-1}$ through the NDZ-model. When the effective $ACH_{\text{eff}}$ value is compared with the $AACH$ value obtained by the NDZ-model. It is found that the estimated value of $AACH$ is 11.81% lower than $ACH$. The detailed derivation of the effective fade-out index is shown in Appendix A. Dramatically, the difference between $ACH_{\text{eff}}$ and $AACH$ proposes a method to determine the mean re-entry airflow of the unit, as shown in Eqn (20).

$$ R_f = \frac{ACH_{\text{eff}} - AACH}{V} $$

(20)

where.

$R_f$ was the mean re-entry airflow of the sampling unit [m$^3$/h$^{-1}$];

$V$ was the control volume of the sampling unit equal to $[3.38 \times 6.8 \times 2.45 \times (1-g)]$ m$^3$ after considering the g factor, where g was the furniture occupancy factor estimated to be 0.15 for the sampling unit. Thus, the mean re-entry flow was 21.54 m$^3$/h$^{-1}$.

$M - II$ was a repeat of the previous operation as $M - I$, but under different wind speed conditions. In the time slot of the unit tracer gas significant decay duration (10:40–11:30), the tracer gas concentration profile recorded at the corridor is very different from the $M - I$ previously recorded. No upper or lower envelopes were observed obviously. The curve was flattened to the background level; however, the tracer gas concentration in the unit still maintained its original profile, see Fig. 5.

It can be seen from Fig. 5 that the $ACH$ value obtained by the NDZ-model is 4.186 h$^{-1}$, and the effective fade-out index 125 h$^{-1}$ is
recommended during operation. The AACH value obtained by the TSZ-model is 4.185 h⁻¹, which is lower the value obtained by the NDZ-model with 0.02%.

5.2. Error analysis

The error of the result relates to the defect of the applied model, the correlation of the two CO₂ monitors, and the variations of the environmental factors. Theoretically, a plot of predicted data and measured data will give a straight line and then pass through the origin. Practically, the measured data is often scattered along the regression curve. The scattering comes from the uncertainty including the model defects, data quality and unknown issues. It is recommended to combine these errors to form a result error, which is denoted by (Error)ᵣ and suggested by Tung et al. [19]. The error is estimated by Eqn (21).

\[
(Error)ᵣ = (1 - ms \cdot R^2) \cdot 100\% \tag{21}
\]

If the slope of the regression line ms is less than or equal to 1, then Eqn (21) gives (Error)ᵣ, otherwise, Eqn (22) is used.

\[
(Error)ᵣ = [1 - (2 - ms) \cdot R^2] \cdot 100\% \tag{22}
\]

When ms and R² are not in the range of 0.5–1.5 and 0.5–1, respectively, curve fitting is considered to be less predictive and therefore will not be accepted in the study.

Table 1

| Measurement | Model       | Air changes per hour (h⁻¹) | (Error)ᵣ (%) |
|-------------|-------------|----------------------------|---------------|
| M – I Corridor in low wind speed conditions | TSZ-model | 3.36 | 25.22 |
| Mean wind speed: 0.4 ms⁻¹ | NDZ-model | 3.81 | 23.30*** |
| M – II Corridor in strong wind conditions | TSZ-model | 4.185 | 0.34 |
| Mean wind speed: 1.1 ms⁻¹ | NDZ-model | 4.186 | 0.32** |

Remark: #: Effective tracer gas concentration fade-out index φₐ₋ is applied in the calculation.
According to the error analysis method, in the scenario of M I, the same set of measurement data is used to separately plot the data predicted by the TSZ-model and the NDZ-model as shown in Fig. 6 and Fig. 7, respectively. By Eqn (22), the resulting errors (Error) of the prediction data generated by the TSZ-model and the NDZ-model are 25.22% and 23.30%, respectively.

In the M II scenario, error analysis is performed, and the measurement was carried out under strong wind conditions in the corridor. Similarly, plot the predicted data of the TSZ-model and the NDZ-model with the measured data to give Fig. 8 and Fig. 9 respectively. The fitting errors corresponding to the TSZ-model and the NDZ-model are 0.34% and 0.32%, respectively. Table 1 summarizes the air changes per hour of the sampling unit and the errors of M I and M II scenarios.

5.3. Further analysis and discussion

5.3.1. Corridor tracer gas concentration and incoming wind flow

By comparing the results of M I and M II, it can be understood...
that the change in the concentration of tracer gas in the corridor (above the background level) is greatly affected by the incoming wind. As shown in Figs. 4 and 5, at low wind speeds, the M – I tracer gas concentration curve is displayed in a sawtooth decay pattern. The measurement results show that the mixing effect of the semi-open corridor is not ideal due to the random change of wind. The pulsation of the wind will only reduce the concentration of the tracer gas in the corridor to a lower envelope level, but the intensity is not enough to remove it all. At the same time, the corridor still receives tracer gas from the sampling unit, which will only reduce the concentration of the tracer gas in the corridor to a value of the concentration from the sampling unit increases, the concentration level should decrease.

As shown in Fig. 6, under strong wind conditions, the average wind speed of M – II is 2.75 times that of M – I scenario, and the tracer gas concentration curve in the corridor becomes flat. This means that the tracer gas contributed by the sampling unit cannot be further accumulated in the corridor due to the strong wind. Eqn (4) also supports the above inference during the corridor at strong wind conditions, where the value of the $\varnothing$ is much greater than 1 as illustrated as the followings:

$$\{ (C_{r}), - C_{r} \} \cdot e^{-\varnothing} \rightarrow 0 \quad (as \ \varnothing \gg 1)$$

Therefore, Eqn (4) degenerates into the following expression.

$$C_{r} \approx C_{o}$$

For the sampling unit, both sub-terms with $\varnothing$ in Eqn (14) will also go to zero, see the followings:

$$\frac{q}{V} \left\{ \frac{(C_{r1}), - C_{r}}{(\frac{1}{\varnothing} - \varnothing)} \right\} \rightarrow 0 \quad (as \ \varnothing \gg 1)$$

$$\frac{q}{V} \left\{ \frac{(C_{r1}), - C_{r}}{(\frac{1}{\varnothing} - \varnothing)} \right\} \cdot e^{-\varnothing} \rightarrow 0 \quad (as \ \varnothing \gg 1)$$

Thus, Eqn (14) will be reduced to the expression of the TSZ-model of Eqn (2).

$$C = \{(C_{i0}), - C_{r} \} \cdot e^{\varnothing} + C_{o}$$

and, $\frac{q}{V} = ACH \approx AACH$

These are the rationales why the re-entry airflow is not obvious under strong wind conditions.

5.3.2. The outbreak of LC-House building and re-entry airflow enlightenment

In the 16 days before the LC-House outbreak on May 30, 2020, Hong Kong did not find any confirmed local cases during this period [20]. The onset dates of cluster residents infected with Covid-19 in LC-House are scattered between May 22, 2020 and June 4, 2020 [21], but there is no official authoritative report indicating the path of this outbreak horizontally [22]. However, this article suspects that the LC-House attack by Covid-19 occurred at night under low wind conditions on May 27, 2020, as described below. Suspicious inferences are based on the history of the index residents, the date of onset of the infected residents, weather information, building orientation, topography, and the results of related research.

There were dominanted index residents living in R812 were not sent to the hospital until May 30, 2020. It is believed that the level of Covid-19 is increasing as the other two members of the unit were found onset dates from May 26 to 31, 2020. The onset dates of the other infected residents as well as unit positions are shown in Fig. 10.

By looking at Fig. 10, the vertical and horizontal infected units are linked by red and blue arrows from the index unit, respectively. The vertical façade infection units R710, R810, R1012 and R1112 are located on the same façade and are restricted by the unit numbered R (floor)10/12. This seems to be a vertically transmitted infection, caused by the up and down movement of contaminated air. The contaminated airflow is a mixture of fresh airflow and virus airflow from the index unit. The studies on re-entry propagation conducted by Niu and Tung [6] and Ai, Mak and colleagues [7-11] can explain this. For horizontal infection, previous vertical re-entry studies cannot provide an acceptable explanation, but due to the occurrence of re-entry airflow and the spread of residues in the corridor, the current horizontal re-entry study can be used to describe horizontal cluster unit infections. In theory, perfect single-sided natural ventilation only allows bilateral ventilation at the same side opening, which means that if single-sided natural ventilation depends on the façade opening, the polluted airflow from the index unit will not reach the corridor. Therefore, no infection will occur on R811 and R813. Based on the locations of the index unit and the infected units and the possible window opening options of the index unit, it is expected that the three members of the index unit will choose to open the unit’s façade and corridor openings to maximize ventilation and reduce indoor virus levels. In this case, the virus-carrying airflow can escape from the openings on both sides of the index unit, the direction of which depends on the instantaneous wind effect around the building and the two entrances of the corridor. The inference of horizontal transmission is based on cross-infection measurements conducted in a similar public flat residential building by Wu and her colleagues [23]. Therefore, it can be inferred that the outbreak of infection may be caused by dual-airflow infection. On the other hand, units that have not yet been infected with the disease are marked as “12” at 7/F, and units marked as “10, 12” at 9/F may be in a closed mode with low ventilation. Although there is no direct information showing that LC-House encountered low wind speeds during the spread of the disease, yet the daily wind speeds of Waglan Island at the Hong Kong offshore weather station provided suggestions. The island is located to the southeast of LC-House [24], and the direct distance from LC-House is 25.54 km as shown in Fig. 11. Mean daily wind speed of Waglan Island [25] in May is shown in Fig. 12. The mean wind speed on May 27, 2020 (1.58 ms⁻¹) was greater than the strong wind speed (1.1 ms⁻¹) collected at M-II. In theory, re-entry airflow should not be the main cause of the outbreak. However, the mean wind speed around the building on May 27, 2020 is
expected less than 0.5 ms$^{-1}$. Low wind speed estimation is shown in Appendix B. It is based on the following rationales: First, the location of LC-House is 3.52 km from the coast near the estuary (measured along the prevailing wind direction on that date), not based on Waglan Island. Irregular terrain and high-rise buildings will weaken the propagation of sea breeze before reaching LC-House. Second, the prevailing wind direction on May 27 was 50° (northeast), and LC-House runs northwest to southeast. Prevailing wind could be not well coupled with the corridor vent walls of LC-House, because the prevailing wind direction and building’s placement perpendicular to each other that impacted to the corridor wind speed; finally, under the destruction of huge obstacles, the destroyed wind profile needs a longer travel distance to be reconstructed again [26]. However, it is not allowed in high-density construction city. In fact, after May 31, 2020, the onset date of infected residents does not exceed June 4, 2020. Based on the above inferences, and further considering that nocturnal inversion will enhance the accumulation of pollutants [27], it is suspected that this disease was spread through the two-way attack on the opposite side and via the index unit openings in the corridor and facade during the long night of May 27, 2020.

6. Conclusion

It has been found that the re-entry airflow of the sampling unit mainly depends on the nearby wind speed conditions. Two new parameters $\phi$ and AACH have been introduced, which are essential for studying and understanding the influence of wind effects on the natural ventilation of buildings. The traditional single-zone model (TSZ-model) or the newly introduced dual-zone model (NDZ-model) cannot quantify the re-entry airflow of single-sided natural ventilation alone. In ideal single-sided ventilation, the average re-entry air flow can be obtained by comparing the ACH and AACH values from the new model and the traditional model. In analyzing the spread of Covid-19 in the LC-House, the NDZ-model will be used as a qualitative guide, rather than quantitatively determining the re-entry airflow, because it is expected that the windows on both sides of the index unit will be open. The concept of re-entry airflow is suggested to apply to other types of residential buildings, because the contaminated airflow escaping from the index unit will linger around, especially at low wind speeds. Ignoring the phenomenon of re-entry airflow may become one of the loopholes in disease transmission. A better understanding of airflow mechanism in buildings can help develop strategies and take measures to minimize the risk of residents being exposed to air pollutants in buildings. It is recommended to use high-performance air purifiers to reduce the release of diseases in asymptomatic patients indoors.

Declaration of competing interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Appendix A

In order to calculate the appropriate value $\phi_{off}$, a moving average method is proposed, which is mainly controlled by repeated operations of isochronous time increments on the upper and lower envelopes. Each time the isometric incremental increase operation is performed, a different envelope trajectory will appear, and a pair of extreme envelopes $\phi$ values can be obtained. In each operation, the larger the time interval, the closer the upper and lower envelopes, which means that the pair of $\phi$ values are closer, and a common $\phi$ convergence value is finally obtained. According to the results of the moving average and the trend of the $\phi$ value, it is recommended to use Eqn (A1) and Eqn (A2) to quickly derive the convergence value.
Among them, $T$ is not less than 0.5 min, otherwise Eqn (A1) and Eqn (A2) become invalid.

$$\phi_{\text{Up}} = W[1 - e^{-(T-f)}] + F$$

(A1)

$$\phi_{\text{Low}} = (M - N)e^{-(T-f)} + N$$

(A2)

where.

$\phi_{\text{Up}}$ is the upper envelope fade-out index [h$^{-1}$]; $\phi_{\text{Low}}$ was the lower envelope fade-out index [h$^{-1}$]; $T$ was the interest time range selected for moving average [min]; $f$ was time shift of 0.5 min; $W, F, M, N$ were the arbitrary constants [h$^{-1}$]; $\eta$ was the tendency index for $\phi_{\text{Up}}$ [min$^{-1}$], and $\mu$ was the tendency index for $\phi_{\text{Low}}$ [min$^{-1}$]. By curve fitting technique, the fade-out index convergence value to be 21.74 h$^{-1}$. The moving average trends of $\phi_{\text{Up}}$ and $\phi_{\text{Low}}$ over increment are plotted in Fig A1.

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**Appendix B. Wind speed ratio between Shatin and Waglan Island**

In order to enrich wind speed information to analyze the spread of LC-House disease, wind speed information was captured from the Hong Kong Observatory [28]. Information was captured from January 20, 2021 to February 04, 2021. Each data set was a 10-min average collected at the beginning of each hour. Since the wind speed during the day (06:00–19:00) affected by sunlight was different from the wind speed at night (19:00–06:00), the data set was analyzed separately according to its time period. The total number of valid data was 347 sets, of which 173 were daytime sets and 174 were night-time sets. It was found that the wind speed ratios (Shatin/Waglan Island) were a right-skewed distribution, as shown in Fig B1. Since the wind speeds on Waglan Island and nocturnal inversion at Shatin were, the cut size of the wind speed ratio was set to 0.3. In the day-night separation analysis, it was found that the relative cumulative wind speed frequency ratios during the day and night were 37.4% and 79.9%, respectively. Therefore, the mean wind speed at Shatin on May 27, 2020 was estimated to be 0.48 ms$^{-1}$ (1.58 × 0.3 ms$^{-1}$).
Fig. B1. Day-night wind speed ratio (Shatin/Waglan Island) and relative frequency.

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