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Numerical investigation on the transmission and dispersion of aerosols in a 7-stories building drainage system

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ABSTRACT

In previous reports, the positive SARS-CoV-2 nucleic acid was detected in the fecal samples from confirmed pneumonia patients, suggesting a high probability of the fecal-oral transmission. To date, however, the role played by the drainage system of a high-rise building in the virus transmission is not clear and especially studies on the dynamics mechanism behind is scarce. From this point of view, the present work carries out a computational fluid dynamics (CFD) modeling to investigate the effects of the water seal effectiveness of the floor drain, the negative/positive pressures at the cowl and the negative pressure at the cowl on the transmission of the virus-laden aerosol particles in a drainage system of a typical 7-stores residential building. The CFD models are first validated by the previous experiments in literature. Numerical results imply that the drainage system might play an essential role to the virus transmission. Then, results indicate that, the leakage risk of the aerosol particles via the floor drain with inefficient water-seal (UFD) mainly exists at the upper floors above the neutral pressure level (NPL). Besides, the negative and positive pressures at the bathroom can enhance and reduce the exposure risk of aerosol particles from the corresponding UFD, respectively. The ΔT increasing does not modify the location of the NPL. Moreover, the exposure risk of aerosol particles can be effectively avoided by the well water-sealed floor drains and/or the presence of a proper negative pressure at the cowl on the top floor. Finally, based on the CFD results, several protection suggestions on the drainage system and human activities are provided.

1. Introduction

The outbreak of the new coronavirus pneumonia, i.e., COVID-19 [1], is caused by a highly infectious novel coronavirus, which has been identified as a severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) [2-4]. In Jan 2020, evidence has been affirmed for human-to-human transmissibility of the COVID-19, which rapidly causes the worldwide concerns. Due to its rapid spreading and increasing threat to human health, the COVID-19 outbreak has been recognized by the world health organization (WHO) as a pandemic and public health emergency of international concern [5]. Globally as of May 13, 2021, the COVID-19 outbreak has resulted in 161,725,739 confirmed cases including with over 3,353,760 deaths within over 200 countries [6]. To prevent us from being infected, it is important to study the possible transmission routes of SARS-CoV-2.

For SARS-CoV-2, three main routes of the transmission have been identified in the [7], including i) short-distance inhalation of the virus carried by the liquid droplets, ii) close contacting with the infected people, and iii) touching with virus-contaminated surfaces. Nevertheless, it was also reported that the positive SARS-CoV-2 nucleic acid was detected in the fecal samples from some confirmed pneumonia patients, suggesting a high probability of the live virus in feces [8,9]. Moreover, in the past two decades or so, several coronaviruses, including the severe acute respiratory syndrome coronavirus (SARS-CoV) in 2003 [10-14] and the Middle East respiratory syndrome coronavirus (MERS-CoV) in 2012 [15,16], also spread internationally and result in a major epidemic. A typical feature of these coronaviruses is that they potentially associated with fecal-oral transmission [17,18]. In addition, the SARS-CoV-2 has been recognized as a sister to the SARS-CoV [1,19]. It is thus inferred that the SARS-CoV-2 might be also characterized by the fecal transmission [8,9], blocking which is favorable to suppress the spread of those emerging and re-emerging viruses.

On the other hand, since the outbreak of SARS in 2003, the role played by the drainage system in the virus transmission has been paid growing attention. Note that, in modern cities, the drainage system is important and connects each floor of the high-rise building. During
SARS epidemic, the Amoy garden incident attracted great concern and 18% of all confirmed cases in Hong Kong was reported here [10,11]. The following epidemiological investigation by the WHO found that about one third of the SARS patients at Amoy garden came from the Block E. One of the possible reasons deduced for this high infection rate was the spread of the virus-laden aerosol particles via the drainage system of the building. More specifically, the WHO hypothesis [10,11] stated that a large number of virus-laden aerosol particles were produced and suspended when the fecal containing viruses from a confirmed patient was flushed into the drainage system via a toilet. If the pipe wall breaks or the water seal, i.e., U-trap, of a floor drain loses its sealing function, the virus-laden aerosol particles in the drainage system have chance to escape into other floors, causing a cross-infection [10,11,20]. This risk can be exacerbated by the natural airflows within the drainage system and the negative pressure resulted from the exhaust fan of the bathroom [21]. From this point of view, the drainage system in this situation can be regarded as an infection source. As a result, when a confirmed or asymptomatic infection case stays home, a high risk of virus transmission via the drainage system to the high-rise residential building might exist even him/her does not contact other people directly. However, a fundamental and comprehensive understanding on this aspect has not been clearly given to the public. For this reason, investigations on the aerosol particles movement and dispersion inside the drainage system are imperative to the further epidemic prevention. Unfortunately, to date, there is little mechanistic dynamics studies on this.

Motivated by the research gap in the above discussion, the objectives of the present study includes three aspects: (1) To numerically explore whether the drainage system of a high-rise building can promote the virus transmission from the view of fluid mechanics; (2) To investigate the dynamic characteristics of the transmission and dispersion of aerosols in a 7-stories building drainage system; (3) To systematically investigate the influence of the water seal effectiveness of the floor drain, the negative/positive pressures in the bathroom, temperature differential, outside wind velocity, the piping fittings and the negative pressure at the cowl. The finding of this work can provide some suggestions to epidemic prevention during home quarantine and so reduce the exposure and infection risk of indoor people.

2. Details of the drainage system

The focus of this paper is a drainage system of a typical 7-storeys residential building, which is located in Guangba Road of Wuhan. Fig. 1 shows the external appearance of a common 7-storeys building and the structure diagram of the drainage system. The drainage system is a 7-storeys pipe network, which is consist of one vertical riser pipe and seven horizontal pipes. The vertical riser pipe has a cowl at its top and a sewage outfall at the bottom. The height between every two floors is 2.9 m and so the riser pipe has a height of 20.8 m. The length of the horizontal pipe on every floor is 1.8 m. A toilet sewer, floor drain and washbasin are arranged on every horizontal pipe. According to the

Fig. 1. The external appearance of a common 7-storeys building (a) and the structure diagram of the drainage system (b).
standard for design of building water supply and drainage [22], the slope between the horizontal and riser pipes is set as 0.026 (=1°) to ensure sewage can flow into the riser pipe naturally due to the gravity. The diameter of the vertical riser pipe, horizontal pipe and other branch pipe are 200 mm, 100 mm, and 50 mm, respectively.

In the present work, the drainage system is placed in an outside space, whose dimension is 20 m × 20 m × 30.8 m. Thus, the main driving force of the airflow and the possible airborne particle transmission inside the pipes might be the pressure differential, which is resulting from the combination of the chimney effect, wind or mechanical system. According to the ASHRAE Handbook [23], the chimney effect in the pipe system is mainly determined by the temperature differential (ΔT) of air inside and outside the drainage system and the height of the vertical riser pipe [24]. For the ventilation, a NPL exists and is that height in the building envelope where, at that particular instant, there is no indoor-to-outdoor pressure differential. If only the chimney effect is considered, the NPL is typically located at the mid-height [23], i.e., the height between the 4th and 5th floors for the present work. Moreover, the NPL does not vary with the ΔT and can rise when the wind pressure is superposed [23,25], as being discussed later in Section 5.3 and 5.4. Since SARS and SARS-CoV-2 both outbreak at the beginning of the year, 2003/2 and 2020/1, so the present work mainly considers the scenarios in Winter, i.e., the temperature inside the pipe system is higher than the temperature outside. Driven by the chimney effect and wind pressure, the direction of the airflow inside the vertical pipe is typically from the bottom to the top and eventually the air exhausts through the cowl on the top floor.

3. Numerical method and solution strategies

3.1. Models for airflow

In the present work, air inside the drainage system is assumed to abide the continuum medium model. The governing equations, including continuity, momentum and energy are resolved. According to the literature [26–28], the Reynolds stress model (RSM) is adopted to predict the turbulent airflow in the three-dimensional pipe. Compared with other turbulent model, e.g., the k-ε or k-ω models, the RSM model was proven to predict the airborne particle dispersion more accurately because it offers an opportunity to consider turbulent anisotropy. The variable near wall was treated by the Enhanced wall treatment model. More details about the RSM model are referred in the [29].

3.2. Models for aerosol particle dispersion

The Lagrangian method is used to predict the trajectory of particles by coupling the discrete phase model (DPM) and the RSM models. In DPM model, the different particle forces are considered in the present simulation, including the drag force, the gravity force, the buoyancy force, the Brownian force and the Saffman’s lift force, as those used in the previous studies [26,27,30,31] on the prediction of the particle dispersion. The discrete random walk (DRW) model is adopted to predict interaction between turbulence and particle dispersion.

3.3. Mesh generation and independence analysis

To predict the natural flow, the drainage system is placed into the atmosphere environment, as shown in Fig. 2(a). The dimension of the outside space is 20 m × 20 m × 30.8 m. Here, two other dimensions, i.e., 10 m × 10 m × 30.8 m and 40 m × 40 m × 60 m, are also considered to check the effect of the outside space size. It is revealed that the particle dispersion are nearly identical when operated at the same boundary conditions (Fig. S1). As a result, the size with 20 m × 20 m × 30.8 m is adopted in the following discussion. The vertical pipe is 0.5 m always from one side of the outside space. Other details can be found in Figs. 1 and 2. ANSYS ICEM is used to generate the highly orthogonal hexahedral structured grid for the 7-storeys drainage system and the outside space, as shown in Fig. 2(b). For the accuracy of modeling, the local grid refinement is implemented near the wall and the region where a high velocity gradient exists. The centroid of the first grid is 0.005 m away from the wall with the y’ being about 1.3. After the grid-independency of the results by using a finer grid, the final grid for the drainage system and the outside space have about 650, 000 and 1, 600, 000 cells, respectively.

3.4. Boundary conditions and solution strategies

No-slip velocity boundary condition is adopted on the inner and outside surfaces of the drainage system. The temperature of the inner surface of the drainage system is set as 25 °C, 30 °C, and 40 °C, so the air inside can be heated. Side boundaries of the outside space are set as the velocity, no-slip velocity wall, and the pressure outlet conditions. The temperatures at the sides of the outside space are all 20 °C. Thus, the temperature differential (ΔT) inside and outside of the drainage system could be 5 °C, 10 °C and 20 °C.

During every drainage process in the vertical riser pipe, the fecal-sewage from the toilet flushing generates a certain amount of virus-laden aerosol particles. According to Lai et al. [32] and Johnston et al. [33], the particle size of the aerosol particles generated during a flushing in the modern flush toilets are mainly ranged from 0.3 to 10 μm. In their experiments, the total number of the particles are 80,200, 145,000, and 287,000 during a toilet flushing at different water supply pressures, i.e., 200 kPa, 350 kPa, and 400 kPa, respectively. Therefore, the present work is mainly focused on the transmission and dispersion of aerosols with a diameter being 1 μm. The number of particles is selected as 170, 000, e.g., approximating the average of the measured particle numbers from the three experiment [32,33]. The aerosol particles are released at the converging point of the vertical riser pipe and the horizontal pipe on the 2nd floor, as shown in Fig. 1. The density of the particle is 1, 000 kg/m³. Since the DRW model is used, a particle number independence test is conducted in order to ensure that the number of the injected particles is sufficient for obtaining statistically meaningful results. Four particle numbers, i.e., 2 000, 20,000, 170,000 and 300, 000 are selected for the independence test. The numerical results indicate that the deposition and dispersion characteristics of the particles is nearly identical for the cases with particle numbers being 20,000, 170,000 and 300, 000, as shown in Fig. S2. Therefore, 170,000 particles are sufficiently enough for the present investigation.

Several assumptions are considered in this paper. (1) The virus-laden aerosol is assumed as an airborne particle and water sphere. (2) There is no heat and mass transfer between the particles and air. (3) Evaporation of the particle is ignored. (4) The size and other physical properties of the particles remain constant. (5) The coalescence between different particles is ignored. (6) According the numerical data and as shown in Fig. S3, the volume rate of the sewage during a toilet flushing is relatively small and the sewage has little impact on the airflow inside the vertical riser pipe. Thus, the piston-effect caused by the toilet flushing can be not considered and the vertical riser pipe is assumed to be filled by air. (7) Since the particle size is too small, i.e., 1 μm, and the particle is mainly made of water, the rebound of the particles from the wall surface is ignored. Thus, the particles are captured by the wall once they hit the wall surface. Moreover, it is assumed that the particles escape from the computational domain once they have reached the pressure-outlet boundary.

In this paper, ANSYS FLUENT v16.0 [29] is used to solve all the transport equations (continuity, momentum, turbulence kinetic energy, RSM, ε). The RSM turbulence model is used to predict the gas flow. The DPM is used to predict the gas-particle interaction. The Lagrange method is used to track the trajectories of the particles. The semi-implicit method for pressure linked (SIMPLE) algorithm is utilized to solve the pressure-velocity coupling. The pressure staggering option (PRESTO) scheme is selected to solve the pressure equation. The
Fig. 2. Computational domain (a) and grids (b) of the drainage system and outside space.
Runge-Kutta method and the DRW model are used to track the path of the particles. The second-order upwind scheme is employed for discretizing the equations in order to improve the accuracy of the simulations. The solution convergence criteria include two, i.e., (i) the numerical residuals are less than $10^{-6}$ for all the variables; (ii) the variations between consecutive iterations of velocity are kept within $\pm 0.1$ m/s at the cowl outlet of the computational domain.

3.5. Test cases

The present work then conducts a series of cases to study the dispersion of the aerosol particles inside the drainage system. As summarized in Table 1, 11 cases are carried out to check the effects of the water seal effectiveness, the negative pressure ($P_1$) and positive pressure ($P_2$) at the UFD, the temperature differential ($\Delta T$) between inside and outside the drainage system, the outside wind velocity ($v$), the fittings of the pipe system, and the negative pressure ($P_3$) at the cowl.

4. Modeling validation

In this section, the numerical models mentioned above are validated. Since there is no related experimental data on the dispersion of particles in a drainage system, the measurements on the particle deposition and dispersion in an enclosed room [34] and a typical ventilation duct [35] are adopted here for the modeling validation. In the validation case, the numerical methods, including models and solution strategies, are the same as those listed in Sections 3.1-3.2.

4.1. Validation of the particle dispersion

For the experiment of Chen et al. [34], the enclosed room geometry is length ($x$) × width ($y$) × height ($z$) = 0.8 m × 0.4 m × 0.4 m, whose inlet and outlet area are of the same size, 0.04 m × 0.04 m. After a grid-independency, a highly orthogonal hexahedral structured grid with about 1,500,000 cells, as shown in Fig. S4, is used for the enclosed room [34]. Particles enter the room together with the inlet air. The velocity at the inlet is 0.225 m/s and the density of the particle is 1,400 kg/m$^3$. Measurements of the air velocity and particle concentration along the $z$ direction at $x = 0.2$ m, 0.4 m, and 0.6 m of the $x$-$z$ plane are conducted. More details are referred to the literature [34]. Particle concentration is normalized by the inlet concentration and the concentration at the inlet is thus $C_{in} = 1$. As shown in Fig. 3, the results indicate that the predicted spatial distributions of the $x$ direction velocities ($V_x$) and normalized concentration ($C^*$) agree well with the measurement. Thus, the aforementioned numerical methods are appropriate to calculate the air-flow field and the particle dispersion in a ventilated chamber.

4.2. Validation of the particle deposition

For the experiment of Sippola and Nazaroff [35], the ventilation duct is smooth and contains one inlet and one outlet. It has a square cross-section of $152$ mm × $152$ mm and a length of 3 m. The density of the particle is $1.520$ kg/m$^3$ and the air velocity is $5.2$ m/s. Measurements of the particle deposition in both vertical and horizontal ducts are conducted. More details are referred to the literature [35]. For this duct, a highly orthogonal hexahedral structured grid with 1,200,000 cells is used for the validation simulation after a grid-independency, as shown in Fig. S5.

Fig. 4 plots the experimental and numerical dimensionless particle deposition velocity ($V_d^*$) against the dimensionless relaxation time ($\tau^*$) in the vertical and horizontal ducts. For comparison, the previous numerical data by Tian and Ahmadi [36] and empirical formula by Wood [37] are also included in this figure. Here, the relationship between $V_d^*$ and $\tau^*$ is a useful index to evaluate the characteristics of the particle deposition. $V_d^*$ is calculated via the method proposed by Matida [38],

$$V_d^* = \frac{U_{mean} A_{in} \sqrt{N_w}}{\Delta T} \frac{N_w}{N_{out}}$$

(1)

$$\tau^* = \frac{t u^*}{\nu}$$

(2)

$$u^* = \sqrt{\frac{\tau^*}{\rho}} = U_{mean} \frac{\sqrt{f/2}}$$

(3)

where $U_{mean}$ is the mean velocity of the air in the ventilation duct, $A$ is the cross-sectional area of the duct, $P$ is the wet cycle of duct, $L$ is the length of duct, $N_{in}$ and $N_{out}$ are the number of particles at the inlet and outlet of the duct, $u^*$ is the friction velocity, $\nu$ is the dynamic viscosity and $f$ is the friction factor, respectively.

Although slightly higher than that predicted by Tian and Ahmadi [36], the present prediction of the particle deposition data agrees well with the experimental data and the empirical formula by Wood [37] in both the vertical and horizontal ducts. More specially, as shown in Fig. 1, the drainage system is also consisted of several vertical and horizontal pipes. Consequently, based on the comparison made in Figs. 3 and 4, it can be concluded the present numerical models are valid to predict the particle dispersion and deposition behaviors and so can be utilized for the numerical simulations in the following section.

Table 1: A summary of the 11 test conditions.

| Case | Water seal effectiveness of the floor drains | Temperature differential | Wind velocity | Fittings | Cowl |
|------|---------------------------------------------|--------------------------|--------------|---------|------|
| 1    | + + + +                                    | $\Delta T = 5$ °C        | $v = 0.001$ m/s | remain  | /    |
| 2    | - - - -                                    | $\Delta T = 5$ °C        | $v = 0.001$ m/s | /       | /    |
| 3    | - - $P_1 = -1.7$Pa                         | $\Delta T = 5$ °C        | $v = 0.001$ m/s | /       | /    |
| 4    | - - $P_1 = -5$Pa                           | $\Delta T = 5$ °C        | $v = 0.001$ m/s | /       | /    |
| 5    | - - - -                                    | $\Delta T = 5$ °C        | $v = 0.001$ m/s | /       | /    |
| 6    | - - - -                                    | $\Delta T = 20$ °C       | $v = 0.001$ m/s | /       | /    |
| 7    | - - $P_1 = -1.7$Pa                         | $\Delta T = 5$ °C        | $v = 1$ m/s    | /       | /    |
| 8    | - - - -                                    | $\Delta T = 5$ °C        | $v = 2$ m/s    | /       | /    |
| 9    | - - - -                                    | $\Delta T = 5$ °C        | $v = 0.001$ m/s | remove  | /    |
| 10   | - - - -                                    | $\Delta T = 5$ °C        | $v = 0.001$ m/s | remain  | $P_3 = -15$Pa |

* + and – mean the water seals are effective and ineffective, respectively. $P_1$ and $P_2$ denote the negative pressure and positive pressure above the UFD. $P_3$ denotes the negative pressure above the cowl. $\Delta T$ denotes the temperature differential between inside and outside the drainage system. $v$ denotes the outside wind velocity.
5. Results

5.1. Effect of the water seal effectiveness

In the high-rise buildings, a well water-sealed floor drain is a barrier to isolate the indoor environment and the drainage system, so preventing virus-laden aerosol leaking into the residential house. However, if the water seal of the floor drain is dried and the U-trap loses its effectiveness, the aerosol particles inside the drainage riser pipe might enter the indoor room via the floor drain. In this regard, this subsection investigates the effect of the water seal effectiveness on the particle transmission.

Fig. 3. Comparison of measured and predicted $x$ direction velocities ($V_x$, a1–a3) and normalized concentration ($C^*$, b1–b3) at three different locations of $x = 0.2$, 0.4, and 0.6 m. In this figure, the symbols are the measurements and the solid lines are the numerical data.

Fig. 4. Modeling validation of the dimensionless particle deposition velocity ($V^+_d$) and the dimensionless relaxation time ($\tau^+$) in the vertical (a) and horizontal (b) ducts.
Airflow is essential for the transport of the fine particles [36,37,39,40]. Fig. 5 illustrates the airflow velocity distribution of the plane at \( y = 0 \) mm in the drainage system from Cases 1–2. It is clearly shown that, driven by the thermal pressure, the main airflow direction in the drainage system is from the sewage outfall at the bottom to the cowl on the top. In Case 1, if the water seals of the floor drains are all effective, the airflow velocity in the horizontal pipe of each floor is always kept at nearly 0 m/s, as shown in Fig. 5(a). This means the air inside the riser pipe cannot enter into any horizontal pipe. However, in Case 2, if the water seals of the floor drains are all ineffective, there is a strong airflow inside the horizontal branch pipe. More specially, since \( \Delta P = P_{\text{out}} - P_{\text{in}} \) is positive at the 1st to 4th floors below the NPL, the airflow direction is from the branch pipe to the main riser pipe, as shown in Fig. 5(b). Here, \( P_{\text{out}} \) and \( P_{\text{in}} \) represent the air pressure outside and inside of the drainage system, respectively. In contrast, \( \Delta P \) becomes negative at the 5th to 7th floors above the NPL, so the airflow direction is reversed, i.e., from the main riser pipe to the branch pipe. As a result, the air inside the drainage system might be leaked to outside from the UFD at the upper floors, while no air could be leaked at the lower floors.

Fig. 6 illustrates the transmission process of aerosol particles in the drainage system from Cases 1 and 2. It is clearly shown that, as the time proceeds, the aerosol particles in the airflow move upwards gradually after being released at \( t = 1s \), and most of them escape from the cowl eventually. This process both last 100s for the two cases. During this process, some of the particles are deposited onto the inner surface of the pipe wall. The most important impact of the water seal effectiveness is on the particle movement behavior inside the horizontal branch pipes. As seen Fig. 6(a), for the case with the water seals of the floor drains all being effective, nearly no aerosol particles can move horizontally and so cannot escape via any floor drain. The reason behind is that no air can flow into the branch pipes and be discharged via any well water sealed floor drain, as indicated by Fig. 5(a). However, in Case 2 with ineffective water seals, Fig. 6(b) demonstrates that no particles can move horizontally into the branch pipes at the lower floors below the NPL. In contrast, at the upper floors, i.e., the 5th to the 7th floors, above the NPL, when the aerosol particles stride across these floors, some of them can enter the horizontal pipe and eventually escape from the UFD. The particle movements at different floors in Case 2 are consistent with the airflow field, as shown in Fig. 5(b). That is, the outside air is inhaled into the main pipe via the floor drain at the lower floors, while the air inside the drainage system leaks to outside via the floor drain at the upper floors above the NPL.

Fig. 7 shows the deposition ratio (\( \lambda_d \)), the escape ratio (\( \xi_c \)) of the particles via the cowl and the escape ratio (\( \xi_f \)) of the particles via the floor drain on each floor in Cases 1–2. Here, \( \lambda_d \) is defined as the ratio between the number of the particles deposited onto the pipe wall and that of the initial released particles. Similarly, \( \xi_c \) is the ratio between the number of particles escaped from the cowl and the initial released particles, where the subscript \( i \) ranges from 1 to 7. It can be observed from Fig. 7 that less than 25% of the released particles can deposit onto the inner wall surface of the drainage system, while more than 60% of them escape from the cowl. For Case 1, the escape ratios via the floor drains (\( \xi_f \)) are all equal to 0%, which means no particle can escape through any floor drain with an effective water seal, consistent with the particle movement behavior shown in Fig. 6(a). For Case 2, the escape ratios (\( \xi_f1, \xi_f2, \xi_f3, \xi_f4 \)) are all kept at 0%. That is, no aerosol particles can escape via the UFD on the lower floors, i.e., 1st to 4th floors, below the NPL. Conversely, the escape ratios (\( \xi_f5, \xi_f6, \xi_f7 \)) are higher than 0%, suggesting the aerosol particles can escape via the UFD on the upper floors, i.e., 5th to 7th floors, above the NPL. Moreover, it is of interest to find that the non-zero

\[
\xi_f5 = \xi_f6 = \xi_f7 > 0
\]

Fig. 5. Airflow velocity distribution of the plane at \( y = 0 \) mm in the drainage system in Cases 1–2.
escape ratios (ξf5, ξf6, and ξf7) becomes higher at an upper floor, where ΔP is greater.

In summary, when all water seals of the floor drains are effective, no virus-laden aerosol particles can escape via any floor drain. However, if a water seal loses its sealing function, the aerosol particles can escape via the corresponding ineffective floor drain at the upper floors above the NPL, otherwise, they cannot. Moreover, the leakage risk of the virus-laden aerosol particles via the UFD is higher at an upper floor.

5.2. Effect of the pressure at the UFD

In the above analysis, it is known that whether the aerosol particles can be leaked via a floor drain with an ineffective water seal depends on the ΔP (= Pout - Pin), i.e., ΔP > 0 below the NPL and ΔP < 0 above the NPL. However, if there is a negative pressure, i.e., caused by an indoor exhaust fan, the vicinity of the UFD, ΔP decreases and might become negative even at the floors below the NPL. If the bathroom has natural ventilation with the window at the windward facade, ΔP increases and might become positive even at the floors above the NPL. These variations of ΔP might cause the reverse of the airflow direction, i.e., issuing out or entering into the drainage system, and so the change of the leakage risk of the particles. Consequently, this subsection discusses the dependence of the particle transmission on the pressure at the UFD, i.e., Cases 2–4. The negative pressure (P1) above the UFD on the 3rd floor is set as −1.7Pa and −5Pa, less than 10% of the total pressure (50Pa) of a typical exhaust fan, to emulate the scenario of the bathroom equipped an opened exhaust fan. The positive pressure (P2) above the UFD on the 3rd floor is set as 0.8Pa and 5Pa to emulate the scenario of the bathroom with its window being placed at the windward facade.

Fig. 8 shows the airflow velocity distribution of the plane at y = 0 mm in the drainage system in Cases 2–4. As seen in Fig. 8(a), since no extra pressure exists above the UFD on the 3rd floor, the ΔP is positive.
and so air is inhaled into the branch pipe. When $P_1$ at the 3rd floor is reduced from 0 Pa to -1.7 Pa, it can be found that the air inside the branch pipe becomes nearly static, see Fig. 8(b). When $P_1$ is further reduced to -5 Pa, it is clear from Fig. 8(c) that the air in the vertical pipe flows into the branch pipe and so might be discharged outside via the UFD at the 3rd floor. Similarly, when $P_2$ is increased from 0 Pa to 0.8 Pa and then 5 Pa, the airflow direction in the branch pipe at the 5th floor is gradually reversed, as shown in Fig. 8(a)–(c). To summarize, the indoor negative pressure, i.e., caused by an indoor exhaust fan, above the UFD can reduce $\Delta P$, while the positive pressure, i.e., caused by the natural ventilation, can increase $\Delta P$. That is, the indoor negative pressure can increase the possibility of air to discharge outside via the UFD even at the floors below the NPL, while the positive pressure can reduce the possibility of air to discharge outside via the UFD even at the floors below the NPL.
above the NPL. Moreover, it can be deduced that there is a critical indoor negative pressure for the floors below the NPL and positive pressure for the floors above the NPL to make $\Delta P = 0$. For the present work, the critical pressures are $-1.7$ Pa and $0.8$ Pa for the 3rd and 5th floors, respectively, as shown in Fig. 8.

Fig. 9 shows the $\xi_1$, $\xi_2$, and $\xi_3$ as pressures above the UFD at the 3rd and 5th floors are varied. It is clearly that, $\xi_3$ is equal to $0\%$ when there is no extra negative pressure or the extra negative pressure ($P_2$) is not less than $-1.7$ Pa. That is, although the water seal is effectiveness, no aerosol particles can escape via the UFD at the 3rd floor. However, if $P_2$ is sufficient, e.g., $P_2 = -5$ Pa, the corresponding airflow velocity direction is reversed, i.e., from the pipe network to outside. As a result, some aerosol particles have opportunities to escape from the floor drain. More specially, Fig. 9 indicates that when $P_2$ is reduced from $0$ Pa to $-1.7$ Pa and $-5$ Pa, $\xi_3$ is finally increased from $0\%$ to $18.6\%$. As for the 5th floor, the aerosol particles will escape via the UFD when there is no extra positive pressure ($P_2$), i.e., $\xi_5 = 1.43\%$. However, if $P_2$ is higher than $0.8$ Pa, i.e., $P_1 = 0.8$ Pa or $5$ Pa, $\xi_5$ is equal to $0\%$. That is, although the water seal loses its effectiveness, no aerosol particles can escape from the UFD on the 5th floor once the positive pressure ($P_2$) is higher than the critical value, i.e., $0.8$ Pa.

Overall, it can be concluded that the indoor negative pressure can increase the possibility of the virus-laden aerosol particles to escape via the UFD. Moreover, with a sufficient indoor negative pressure, the particles can leak via the UFD even it is located below the NPL. The positive pressure caused by the natural ventilation is beneficial for the suppression of the particle leakage via the UFD. With the help of a sufficient positive pressure, no particle can leak via the UFD even it is located above the NPL.

5.3. Effect of the temperature differential inside and outside the drainage system

The chimney effect is determined by the $\Delta T$ of air inside and outside the drainage system. This section discusses the effect of $\Delta T$, i.e., $5^\circ$C, $10^\circ$C and $20^\circ$C, on the airflow and aerosol dispersion in the drainage system, i.e., Cases 2, and 5–6. Fig. 10 illustrates the airflow distribution in the drainage system at different $\Delta T$. It is clearly shown that the airflow velocity inside the riser pipe is gradually increased from $0.8$ m/s to $1.6$ m/s as $\Delta T$ is increased from $5^\circ$C to $20^\circ$C. This is because with the increase of the $\Delta T$, the chimney effect is strengthened. Despite of this, NPL is identical with $\Delta T$ and so the airflow direction of the horizontal branch pipes is not changed.

Fig. 11 shows the $\lambda_1$, $\xi_2$, and $\xi_3$, $\xi_4$, $\xi_5$, $\xi_6$, $\xi_7$ in Cases 2, 5 and 6 at different $\Delta T$. As $\Delta T$ increases, $\lambda_4$ gradually increases. This is caused by the larger airflow velocity in the riser pipe [26]. At different $\Delta T$, $\xi_1$, $\xi_2$, $\xi_3$, and $\xi_7$ below the NPL are always kept at $0\%$. At each $\Delta T$, $\xi_5$, $\xi_6$, and $\xi_7$ are increased with the height, as discussed in Section 5.1. However, at a higher $\Delta T$, the growth rate of $\xi_5$, $\xi_6$, and $\xi_7$ decreases gradually.

In Section 5.2, it is found that there is a critical indoor negative pressure for the floors below the NPL and positive pressure for the floors above the NPL to make $\Delta P = 0$. As a result, the following work discusses the dependence of those critical values on the $\Delta T$. Fig. 12 illustrates the airflow distribution in the drainage system from Cases 3 and 7. It can be seen in Fig. 12(a) that air is nearly static in the horizontal branch pipes at both 3rd and 5th floors, because the critical pressures are used for Case 3 with $\Delta T = 5^\circ$C, as discussed before. However, at $\Delta T = 20^\circ$C, it can be found from Fig. 12(b) that, the air in the branch pipes at 3rd floor flows into the rises pipe, while the air in the rises pipe issues into the branch pipes at 5th floor. This indicates the critical pressures in Case 3 are not sufficient. Thus, it can be deduced that larger critical negative pressures below the NPL and positive pressure above the NPL are needed to establish the pressure environment with $\Delta P = 0$.

5.4. Effect of the outside wind velocity

For natural ventilation in a high-rise building, the wind effect is also important. Thus, this subsection checks the effect of the outside wind velocity, i.e., Cases 2, 8, and 9. The monitored velocity in Wuhan [41] is used as a reference for the selection of wind velocity. Since the mean monitored velocity in Wuhan is around $2$ m/s and the wind might further weaken by the blocking of other urban buildings, three velocities, i.e., $0.001$ m/s, $1$ m/s, and $2$ m/s, are selected for investigation.

Fig. 13 illustrates the airflow velocity distribution of the plane at $y = 0$ mm in the drainage system from Cases 2, 8 and 9. It is clear that the NPL rises gradually as the wind velocity is increased, i.e., located between the 4th and 5th floors for the case with $0.001$ m/s and between the 6th and 7th floors for the case with $2$ m/s. As a result, relative to Case 2, the airflow directions in the branch pipes on the 5th and 6th floors are reversed for Cases 8 and 9, respectively. Thus, no particle can be escaped via the UFD on the 1st to 6th floors for Case 9 with $2$ m/s, while the corresponding floors can only be lower than the 4th floor for Case 2 with $0.001$ m/s. In other words, when the wind velocity is increased, the particle leakage via the UFD on more high-floors might be avoided, since the location of the NPL becomes higher. However, it should be point out
that, the vertical transport of the contaminant along the building facade could be enhanced at a higher wind [25, 42]. This aspect is also worthy more concern.

5.5. Effect of the pipe and fittings in the pipe system

In the actual drainage system, there are many fittings, which may influence the airflow and aerosol dispersion of the pipe system. Accordingly, this subsection checks the effect of the fittings and branch pipe on the aerosol dispersion in the drainage system. For comparison, only the vertical riser pipe is remained and other fitting/branch pipes are all removed in the Case10 without any fittings.

Fig. 14 shows $\lambda_d$, $\xi_c$, $\xi_{f1}$, $\xi_{f2}$, $\xi_{f3}$, $\xi_{f4}$, $\xi_{f5}$, $\xi_{f6}$, $\xi_{f7}$ for the cases with and without fittings. It can be observed that, compared to the case 2 with the fittings, the $\xi_{f5}$, $\xi_{f6}$, $\xi_{f7}$ increases greatly in the case 10 without any fittings. The main reason includes two aspects. One is that the flow resistance in the case 10 without any fittings is smaller, so the horizontal velocity becomes much larger, as shown in Fig. S6. The other reason should be the reduction of particle deposition on the horizontal pipes since all the branches are removed in the no fitting case. It hence can be concluded that the fitting in the piping system has a great influence on the airflow and particle dispersion. Worthy point out that, the present work does not consider other fitting, e.g., the cover and body of the floor drain, in the pipe system. Consequently, the predicted particle leakage rate might be reasonable higher than the actual values. However, it might be too complex to investigate all such fittings. Moreover, though
the geometry of the drainage system is facilitated, it is believed that the trends of the particle dispersion would not be change significantly. Therefore, the present work is focused on the structure of Fig. 1.

5.6. Effect of the negative pressure at the cowl

As demonstrated in Fig. 7, when the water seals of floor drains at the floors above the NPL are ineffective, the aerosol particles in the drainage system might be leaked outside. This is mainly caused by the positive pressure environment inside the drainage system. It is expected that if the pressure ($P_{in}$) inside the drainage system is lower than that ($P_{out}$) outside, there will be no leakage of the air inside the pipe and hence no particles escape even if the water seals are ineffective. From this point of view, this subsection discusses the effect of the negative pressure at the cowl on the particle transmission, i.e., Cases 2 and 11 in Table 1. In these cases, all the water seals of the floor drains are assumed ineffective. A negative pressure ($P_3$) of −15Pa at the top surface of the cowl is considered.

Fig. 15 shows the airflow velocity distribution of the plane at $y = 0$ mm in the drainage system in Cases 2 and 11. As stated previously, Fig. 15(a) demonstrates that, in the drainage system with the water seals of the floor drains all being ineffective, air outside is inhaled into the pipe network at the floors below the NPL, while air inside the drainage system flows outside at the floors above the NPL. In contrast, the negative pressure at the cowl, i.e., $P_3 = −15Pa$, leads the pressure inside the drainage system to be wholly lower than that outside. Hence, as shown in Fig. 15(b), the airflow direction in the horizontal branch pipes is always from the outside into the pipes, no matter whether the floor drains are effective and the floors are below the NPL or not. Because of the higher pressure differential between the bottom and the cowl, the airflow velocity in the main riser pipe increased from about 0.8 m/s to about 1.9 m/s.

Fig. 12. Airflow velocity distribution of the plane at $y = 0$ mm in the drainage system in Cases 3 and 7.

(a) Case 3 (b) Case 7

6. Further discussion

6.1. Assessment of the exposure risk via the drainage system

As indicated in Fig. 7, when the water seals of floor drains at the floors above the NPL are ineffective, some aerosol particles can escape from the floor drain at the upper floors, i.e., 5th - 7th floors, above the NPL, while no particles can be leaked from any floor drain at the lower floors, i.e., 1st - 4th floors, below the NPL. It is hence deduced that the exposure risk of aerosol particles mainly exists at the floors above the NPL and is higher at an upper floor. Moreover, if a negative pressure by an exhaust fan exists, aerosol particles might be extracted into the bathroom even if the floor drain is located on the floors above the NPL.

Fig. 16 shows effect of the negative pressure ($P_3$) at the cowl on the $\lambda_{d3}$, $\xi_{c1}$, $\xi_{f1}$, $\xi_{f2}$, $\xi_{f3}$, $\xi_{f4}$, $\xi_{f5}$, $\xi_{f6}$ in Cases 2 and 11. It is clearly indicated that, with respect to Case 2, if there is a negative pressure ($P_3 = −15 Pa$) at the cowl, $\xi_{f5}$, $\xi_{f6}$, and $\xi_{f7}$ is decreased dramatically to 0%. This is consistent with the airflow direction shown in Fig. 15(b), where air is always inhaled into the pipes. It hence suggests that a proper negative pressure, e.g., $P_3 = −15Pa$ in the present work, at the cowl is valid to avoid any aerosol particle leakage via the UFD, even if the floor drain is located on the floors above the NPL.

On the basis of these analysis, Fig. 17 illustrates the exposure/leakage risk of the virus-laden aerosol particle from the drainage system into other floors of a high-rise building. Since the exposure risk is difficult to quantify, only a relative qualitative analysis of the exposure risk is carried out here. In this figure, all the water seals of the floor drain
are assumed ineffective. The shade in Fig. 17 represents the exposure/leakage risk for the occupants. The darker shade means a higher risk, corresponding more leakage of the aerosol particles. Clearly, since $\Delta P = P_{\text{out}} - P_{\text{in}}$ is negative, air is discharged from the pipe to outside and so the exposure risk exists at the floors above the NPL, e.g., 5th - 7th floors. Moreover, the risk becomes higher at an upper floor. At the lower floors below the NPL, e.g., 1st - 4th floors, the risk is low because $\Delta P$ is positive. However, with the help of the negative pressure from an exhaust fan, the risk at the 3rd floor can be greatly increased. In addition, since most particles escape from the cowl, the risk on the roof is the highest.

The risk rank shown in Fig. 17 is indirectly supported by the findings from the epidemiological survey of SARS [10,11] and recently COVID-19 [1,43]. During the outbreak of SARS, in the Block E of Amoy Gardens, almost all the infections occurred at the upper half or 2/3 floors, while infection of SARS occurred rarely at the lower 1/3 or half floors [11,44]. Recently in Hongkong, two similar cases of COVID-19
can be also found. The first case occurs in Heng Tai House at Fu Heng Estate \[45\], where a fifty-nine years old resident living in the 3413 flat of the 34th floor might be probably infected by the confirmed SARS-CoV-2 patient living in the 3213 flat of the 32nd floor. For the second case in Luk Chuen House at Lek Yuen Estate \[46\], the secondary SARS-CoV-2 infections of the residents living in the 710, 810, 1012, 1112 flats of the 7th, 8th, 10th, and 11th floors might be linked to the index patient living in the 812 flat of the 8th floor. Note that second infection in 710 flat is below the 8th floor, which appears abnormal. Three possible reasons can contribute to this. (i) Aerosols might be generated at the lower floors during the falling process of the sewage, as shown in Fig. S3; (ii) A negative pressure might exist in the bathroom in 712, which will greatly increase the exposure/leakage risk, as shown in Fig. 9; (iii) The cross-infection occurred in a public place such as lobby or elevator might also exist. In the outbreaks of the above three cases, the secondary infections all occur at upper floors and are expected to be highly related to the aerosol transmission in the vertical drainage pipe system. Accordingly, from the view of fluid dynamics, the drainage pipe might prompt the virus-laden aerosol transmission due to the chimney effect (buoyancy), as stated in Section 5.1. Moreover, the negative pressure, e.g., caused by an indoor exhaust fan, can increase the infection risk.

Fig. 15. Airflow velocity distribution of the plane at $y = 0$ mm in the drainage system in Cases 2 and 11.

Fig. 16. Deposition ratio ($\lambda_d$) of the particles onto the pipe wall of the drainage system, the escape ratio ($\xi_c$) of the particles via the cowl and the escape ratio ($\xi_{f1}$, $\xi_{f2}$, $\xi_{f3}$, $\xi_{f4}$, $\xi_{f5}$, $\xi_{f6}$, $\xi_{f7}$) of the particles via the floor drain on each floor in Cases 2 and 11.
6.2. Fate of the aerosol particles and protection suggestions

The above discussion illustrate that the large-scale airflow is essential to the transmission of the virus-laden aerosol particles generated during the fecal-sewage flushing. Driven by the chimney effect (buoyancy), the aerosol particles move upward from the initial releasing position to the cowl at the top floor. During the transmission process, the fate of the particles inside a drainage system includes three aspects. Firstly, a small amount of those particles is deposited onto the inner wall of the pipe network. Since these deposited particles might be resuspended again by another fecal-sewage flushing, it is hence necessary to clean the drainage system of a high-rise building regularly; Secondly, many of those aerosol particles can escape from the cowl on the top floor and the escape ratio is higher than 40% for almost all the cases in the present work. Hence, the second infection risk is the highest, as shown in Fig. 17. Accordingly, humans should keep away from the cowl of the drainage system.

Fig. 17. Diagram of the exposure/leakage risk of the virus-laden aerosol particle from the drainage system in a high-rise building. In the figure, $\Delta P = P_{\text{out}} - P_{\text{in}}$, where $P_{\text{out}}$ and $P_{\text{in}}$ represent the pressure outside and inside the pipe. The shade represents the exposure/leakage risk for the occupants and the darker shade means a higher risk. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
drainage system. Besides, a higher position of the cowl is beneficial to dilute the escaped particles and so is recommendable. Thirdly, some of the aerosol particles can escape from the floor drain with ineffective water seals on upper floors above the NPL, while particles cannot escape at the lower floors below the NPL. Despite of this, the presence of a negative pressure above the floor drain with ineffective water seal can cause and enhance the escape of the aerosol particles, seen in Fig. 9. This then might increase the infection risk. In contrast, no particles can escape via any well water sealed floor drain, seen in Figs. 5–7. This suggests that the exposure of the virus-laden aerosol particles in the drainage system to the residents on the other floors can be well avoided by the efficacious water seal of the floor drain. Therefore, the procedures, such as regularly adding water to make the water seal of a floor drain being effective and turning off the exhaust fan when the toilet is not used, are essential to avoid the leakage of virus-laden particles and highly recommended.

7. Conclusion remarks

This paper numerically investigates the dependence of the aerosol particles transmission on the water seal effectiveness of the floor drain, the negative/positive pressures \((P_1, P_2)\) in the bathroom, temperature differential \((\Delta T)\), outside wind velocity \((v)\), the piping fittings and the negative at the cowl \((P_3)\) in the drainage system of a typical 7-stories residential building. Measurements on the particle transport in the typical ventilation room and duct are utilized to validate the numerical models in the present work. The conclusions can be drawn as follows:

1. When all water seals of the floor drains are effective, no aerosol particles can escape through any floor drain and so no exposure risk from the floor drain exists;
2. When the water seals of the floor drains loss their sealing function, the aerosol particles can escape via the UFD on the floors above the NPL, while they cannot escape at the floors below the NPL.

That is, the exposure risk from the UFD mainly exists at the floors above the NPL. Besides, the risk is higher at an upper floor;

3. The presence of a negative pressure \((P_1)\) above the UFD can strengthen the escape of the aerosol particles. Moreover, if \(P_1\) is sufficient and exceeds a critical value, the leakage risk of particles via the UFD exists even the corresponding floor is below the NPL;
4. The presence of a positive pressure \((P_2)\) above the UFD can reduce the escape of the aerosol particles. Moreover, if \(P_2\) is sufficient and exceeds a critical value, the leakage risk of particles via the UFD can be avoided even the corresponding floor is above the NPL;
5. The increment of \(\Delta T\) does not modify the position of the NPL. A higher \(\Delta T\) requires a higher critical \(P_1\) to make the particle leakage via UFD on the floors below the NPL;
6. The increase of the outside wind velocity can rise the NPL and thus make the particle harder to be leaked. It is hence deduced that the positive pressure in the bathroom caused by the outside wind might be beneficial for the suppression of infection via the drainage system;
7. The use of the negative pressure \((P_3)\) at the cowl can reduce the pressure inside the drainage system and so makes air be inhaled into the pipes at all the floors. Consequently, with the help of a proper \(P_3\), no aerosol particle can escape from any floor drain with an ineffective water seal and thus the exposure risk of aerosol particle via the floor drains can be well avoided at all the floors.

Faced with the above conclusions, several safe procedures are recommended herein, i.e., i) keep the water seal of the floor drain always being effective and regularly add water into the floor drain to avoid a dried U-trap; ii) do not turn on the exhaust fan of the bathroom when the toilet is not in use; iii) make sure the floor drain and the bathroom be regularly disinfected; iv) keep away from the cowl of the drainage system on the top floor; v) heighten the height of the cowl to dilute the escaped aerosol particles; and v) create a negative environment at the cowl.

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. Supplementary data

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