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On male urination and related environmental disease transmission in restrooms: From the perspectives of fluid dynamics

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\textbf{ABSTRACT}

Indoor transmission of COVID-19 is highly probable. Multiple sources have verified that the SARS-CoV-2 can be detected within toilets, and people can be infected in restrooms. There is a huge gap in the coronavirus transmission mechanism in restrooms. Understanding it can help to flatten the curve of the infected cases as well as prevent other viruses transmitted through the sewage or human body fluid. Previous studies have shown how simple actions in daily life (coughing, sneezing, or toilet flushing) contribute to virus transmission. This paper visually and quantitatively demonstrates that male urination, which is also a daily action, can agitate virus particles within the toilet and raise them, which may be the main promoter of cross-infection of COVID-19 in restrooms. Adopting numerical and experimental methods, we demonstrate that male urination can cause strong turbulent flow with an averaged urine impinging velocity of 2.3 m/s, which can act as an agitator to raise the virus particles. The climbing velocity of the airflow can be 0.75\textendash;1.05 m/s. The observed upwards flow will disturb and spread any lurking virus particles (not limited to SARS-CoV-2). Experiments demonstrated that the concentration of the airborne particle could be tripled during male urination. Corresponding precautions are offered as well to prepare the public to act properly when and after using facilities in restrooms for preventing emerging and re-emerging pandemics not limited to the current COVID-19, contributing to the sustainability of human society.

1. Introduction

At present, the Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) and its variants are still raging across the world (Li et al., 2021). Despite vaccination (Jadidi et al., 2021), the SARS-CoV-2 has still shown its strong infectivity (Chen et al., 2022; Ravindra et al., 2021). Marked by the reopening of many mass gathering events across the world (Zhang et al., 2021) and despite the grave pandemic situation, most governments now tend to encourage citizens to learn to live with the coronavirus disease 2019 (COVID-19) (New York Times, 2021). Learning correct and detailed transmission mechanisms can better protect people from being attacked by the virus in daily life which is beneficial to the “sustainability” of the city. Droplets, aerosols, and direct contacts (CDC, 2020; Ahmadzadeh and Shams, 2021) have been acknowledged to be the primary transmission route for the COVID-19. Therefore, more attention has been paid to sneeze-/cough-/speak-based droplets and aerosol transmissions (Pei et al., 2021) with strict preventive measures in place such as mask-wearing (Bu et al., 2021) and physical distancing (Su et al., 2021) during the reopening of the world. However, results of infected cases are getting worse worldwide with an increasing number of daily confirmed COVID-19 cases up to now (up to 3200,940 new cases (Worldometer, 2022) worldwide on January 12, 2022, which is a record level). What’s worse, there are many cases of unknown sources (Cable News Network, 2021; RTHK News, 2021a) and unexpected cross-infected cases in quarantine (RTHK News, 2021b) where the epidemic prevention measures should be the
Gaps between cognitions and facts in the COVID-19 transmission route need to be narrowed imperatively to flatten the curve of the infected cases and to guide the public to protect themselves during the coexistence with COVID-19. However, the number of infections even in a particular area is relatively large that epidemiologists can hardly identify what specific transmission route causes a new case as patients often put themselves in a very complex environment with multiple risks of infection. Therefore, the authors in this paper take a close look at those infected in countries or areas with excellent epidemic prevention performances. China has become one of the best countries for epidemic prevention as the daily confirmed cases have accounted for less than 0.02% (Our World in Data, 2021) of the total number worldwide for months. Cases in China are more valuable for studying pathogenic causes as the environment around patients during their infection process is relatively simple and thus, certain transmission routes can be identified easily.

Most recently, there were many cross-infection cases within restrooms in Guangdong China caused by the SARS-COV-2 Delta variant. More specifically, the first-generation Delta carrier and a second-generation case entered a restroom one after the other. They spent nearly 90 seconds together in the restroom when cross-infection happened (Breaking Latest News, 2021). Another virus transmission in Guangzhou is even more remarkable. The first-generation case and second-generation case entered a restroom and out where the interval was about 14 seconds. This means that even with no physical contact in a restroom, cross-infection can still occur (Breaking Latest News, 2021). Last year, the Global Times reported that two domestic COVID-19 cases in Beijing were confirmed to have been infected in a public restroom (Global Times, 2020). There are in fact many cases of infection in restrooms reported from outside China. Cable News Network (CNN) reported that one South Korean female might have been infected by an airplane toilet in March 2020 (Cable News Network, 2020). A high concentration of active SARS-CoV-2 RNA was practically measured on the toilet surface (Liu et al., 2020). Wang and Liu (2021c) found that public toilets play an important role in the transmission chain of COVID-19. Dancer et al. (2021) and Vardoulakis et al. (2022) reviewed the risk of acquiring COVID-19 in restrooms in which they concluded that the infection risk in public restrooms cannot be ignored. Three spread mechanisms (Dancer et al., 2021) are identified: (1) inhalation of SARS-CoV-2 from fecal and/or urinary aerosol; (2) airborne transmission of respiratory aerosols among restroom users; (3) fomite transmission routes across floors to demonstrate a probability of restroom-based cross-infection without the fecal-oral transmission of the viruses. (Adapted from Gormley et al. (2017)) (B) Schematic structure and overall size of the focused computational domain with a urine inlet (Unit: m). (C) Photographic view of the urination experiment. (D) An experimental high-speed visualization system. (E) Apparatus of the thermal infrared experiment.
transmission when touching contaminated door handles, sink taps, loja and/or toilet roll dispenser. However, experts around the world have declared the fecal-oral transmission of the SARS-CoV-2 to be extremely weak although SARS-CoV-2 RNA was found in patients’ excreta such as feces (Chen et al., 2020) and urine (Peng et al., 2020). Richard et al. declared that “To date, there is no evidence of fecal-oral transmission of SARS-CoV-2 in humans” (Richard et al., 2020). Jones et al. (2020) concluded that “the possibility of fecal/urine-oral transmission of SARS-CoV-2 is extremely low to negligible except direct person-to-person contact”. It explains that the SARS-CoV-2 in human excreta lacks infectivity (Pedersen et al., 2021). Although there are still controversies concerning the fecal-oral transmission of SARS-CoV-2 (Guo et al., 2021), the mainstream view is that fecal-oral transmission of SARS-CoV-2 has relatively limited infectivity.

Sewage systems have been identified as highly active sources of SARS-CoV-2 cross-infection (Pecchia et al., 2020; Megahed and Ghozein, 2020). Since the sewage pipes and toilets are connected physically, the highly active virus can probably enter into the toilet pipe system. Therefore, the virus that originated in the sewage system can be brought into the indoor environment as toilets are one of the main outputs of the sewage system (Tran et al., 2021) as shown in Fig. 1A. History may also teach us more about this topic. In 2003, a total of 321 people who lived in a high-rise housing building in Hong Kong were confirmed to be infected with SARS. In this major community outbreak of SARS, only very few confirmed cases had direct contact with the first-generation virus carrier. Peiris et al. (2003) found that, as shown in Fig. 1A, the SARS virus, originally from respiratory droplets of patients with COVID-19, can be generated and transmitted across floors via faulty sewage systems. This research has been placed in the spotlight because SARS at that time was known for certain infectivity via fecal-oral transmission (Ding et al., 2004). It is notable that, the virus carrier, as marked by the red dotted circle shown in Fig. 1A, can generate the majority of the active respiratory viral infection in the domestic drainage, which can spread across floors through sewage systems as well. This means cross-infection can also happen in the restroom even though the SARS-CoV-2 is seldom transmitted by the fecal-oral transmission. The authors believe if the mainstream view stands, active SARS-CoV-2 originally in the domestic drainage may still be delivered through sewage pipes. Such reasoning agrees well with past experience and the current facts worldwide (Peiris et al., 2003; Komissaro, 2021). Komissaro et al. (2021) have shown that SARS-CoV-2 can be transmitted among floors might be via sewage systems. Evidence has also shown that the SARS-CoV-2 can survive on environmental surfaces for hours or even days, contributing to the spread of COVID-19 through environmentally contaminated surfaces (van Doremalen et al., 2020).

Even with zero possibility of fecal-oral transmission for the COVID-19, cross-infection within the restroom may still be of high probability considering the high mobility of the virus in the sewage system where highly infectious respiratory SARS-CoV-2 from patients with COVID-19 may enter into neighboring toilet areas. Once these viruses rise, they may cause massive indoor cross-infections. Previous studies have shown that toilet flushing not only causes massive virus spread within an indoor environment (Li et al., 2020; Wang et al., 2021a) but also practically promotes SARS-CoV-2 transmission across floors of a building (Liu et al., 2021) due to the flushing-induced turbulence. In Li’s work (Li et al., 2020), the volume-of-fluid (VOF) was used to simulate the flushing process where the air-liquid interface can be tracked decently. Therefore, WHO reports (World Health Organization, 2020), as well as government all over the world, encourage people to close the toilet lid before flushing.

Turbulence is a common phenomenon shared by human sneeze/cough-induced droplet transmissions, known for “violent respiratory events” (Bourouiba et al., 2014). Toilet flushing can cause viruses to spread indoors, which can also be attributed to the turbulence (Li et al., 2020). Previous publications have demonstrated how turbulence contributes to violent virus movement and transmission (Bourouiba, 2021; Bourouiba, 2020). However, there may still be more common daily actions that may cause disease transmission which remain unknown. They may have caused or are causing mass cross-infection of diseases not limited to the current COVID-19. Therefore, these “dangerous” actions should be uncovered imperatively to make the public aware of them. Here, we quantitatively and visually demonstrate that male standing urination is such an action that can also generate violent fluid flow that may cause large-scale movement of virus particles within and out of toilets. A combined method of computational fluid dynamics and family bathroom-based experiments, as shown in Fig. 1B-E, is adopted to explore the fluid dynamic characteristics during male standing urination. It helps to demonstrate how the urine flow and surrounding airflow contribute to the spread of viruses within the toilet. In the simulation, considering the urination process involves the interaction between air and liquid, two-phase turbulence and phase tracking models using the Euler-Lagrangian method (Srivastava et al., 2021) were adopted to simulate the flow dynamics and virus particle movements. In the experiment, the microscopic view of the urine flow dynamics and urine-water collision behavior were analyzed using a high-speed visualization imaging system, and macroscopic imaging was conducted using an infrared camera. A smoke generator was used to visualize the flow dynamic distribution during and after real male urination experimentally. A hotwire velocimetry and particle counter were used to measure the airflow velocity and particle movement during the experiment. Results in this paper reveal a probable transmission path of the SARS-CoV-2 that may be caused by common human behavior. It also provides new clues to rethink those cases of unknown sources of COVID-19 cases worldwide. Precautions according to the results were raised and they will help human society to prevent emerging and re-emerging pandemics that are transmitted via the sewage system or human body fluid, not limited to the current COVID-19.

2. Methods

2.1. Numerical simulation method

Fig. 1B shows the computational area, which consisted of a common siphon toilet and the air area above it. The model had one inlet (urine inlet) and two outlets (outlet 1, outlet 2). Outlet 1 was located at the bottom of the sewage pipe, and outlet 2 included the surrounding boundaries of the air area. The blue part was set to be the air phase and the purple was the water phase for initializing the model. Supplementary Fig. S1A (See Supplementary Materials) displays the geometric size of components in the computational area. A urine inlet was set at the right side of the air area above the toilet where the distance between the urine inlet and the ground was 0.815 m. The diameter of the urine inlet was 0.007 m which was determined by our experimental study (Fig. 3A). To observe how the urine jet affected the adjacent airflow, the adjacent air area above and inside the toilet was studied. The distance between the top air area and the ground was 1.70 m which is a typical male height and the air area was 0.520 m wide. In addition, the height and width of the toilet seat were 0.445 m and 0.490 m, respectively. The software of Ansys ICEM 2019 was adopted to realize domain discretization. The total number of the structured grid in the computational model was 141,374 (it passed the mesh independence test which is presented in Fig. S2 in the Supplementary Materials), in which an encryption method near the wall and at the urine inlet was adopted as shown in Fig. S1B.

The transient Reynolds-averaged Navier-Stokes equation with a realizable k-ε model (Mathai et al., 2021; Wang et al., 2021c) was selected as the momentum conservation equation. Mass and energy conservation equations were also considered (Wu et al., 2021; Yao and Liu, 2021). Specializing in dealing with dynamics of free boundaries such as droplet spreading (Wang et al., 2020b), gas-liquid jetting (Wang et al., 2021b), and droplet detachment (Wang et al., 2020a), the VOF
The pressure outlet condition was 20 \degree C and the temperature of the inlet urine was 36 \degree C. Please refer to Table S1 in Supplementary Materials for detailed boundary conditions. The initial condition of the aerosol particle distribution in the domain is shown in the form of concentration and discrete particles, respectively in Figs. SIC and S1D (in Supplementary Materials). The total number of lurking virus particles was 3000. The average diameter of virus particles was 8.6 \mu m and the density was 1100 kg/m\(^3\) (Gupta et al., 2009; Wong et al., 2015). The pressure-implicit with splitting operator solution was adopted for the solution of the coupling between pressure and velocity. Spatial discretization of the gradient, pressure, momentum, volume fraction, were selected to be least-squares cell-based, PRESTO, second-order upwind, and geo-reconstruct, respectively. Spatial discretization of other variables such as turbulent kinetic energy, turbulent dissipation rate second-order upwind, and energy were second-order upwind. The time step size was 0.001 s, which proved to have a relatively rapid convergence.

2.2. Experimental section

As shown in Fig. 1B, a hot-wire velocimetry (Smart Sensor, AR866A) with an uncertainty of \pm 1\% was used to measure the air velocity in a certain area. During the experiment, the initial velocity of the generated smoke was maintained to be nearly still before a practical male urination experiment. In addition, a high-speed camera (Photron Fastcam SA2) with a telecentric lens (Navitar 1–50,487) was adopted to capture the urine jet dynamics and urine-water impingement process. It recorded the fluid flow process at frame rates of 3010 frames per second with a resolution of 1024 \times 768 pixels. The recorded image sequence was analyzed by the digital particle image velocimetry (DPIV) method (Sarno et al., 2018). It specializes in high-speed imaging analysis with an error smaller than 0.02 pixels/frame (Thielicke, 2014). To study the urine jet in the air, only light source II (Fig. 1C) was used. Light source I and two reflectors were used to capture the urine-water impingement dynamics. Besides the experiments above, a smoke generator was used to visualize the flow distribution during and after the male urination, captured by a Nikon camera (D7100). Besides, airborne particle concentration was measured by a handheld particle counter (Fluke 985). This technology has been validated by Somsen et al. with a high experimental reproducibility (uncertainty of \pm 1\%) (Somsen et al., 2020). Fluid dynamics of macroscopic visualization using a thermal infrared camera (NEC TH9260) were also organized (shown in Fig. 1E) as the high-speed visualization only captured the microscopic images. Detailed experimental procedures of the smoke-assisted fluid flow visualization are described in the Supplementary Materials.

Since flow distribution experiment using smoke is relatively complicated, experimental procedures are described in the following: (1) Install a camera in a proper position, put a circular band light on the toilet inner wall, and power them on; (2) Use a polyethylene film to semi-cover the toilet; (3) Power on the smoke generator to charge the smoke into the uncovered area of the semi-covered toilet; (4) Cover the toilet completely when the internal area of the toilet is full of the injected smoke, shown in Fig. 2A; (5) Wait for at least 5 min to obtain a quasi-static image inside the toilet; (6) Tear off the film gently to ensure no major disturbance to the smoke flow (Fig. 2B shows a gentle smoke flow after the film was taken off); (7) Conduct the urination experiment; (8) Power off the apparatus when the experiment is finished.

3. Results

3.1. Flow dynamics

The dynamics of the violent excretory event (urine jet dynamics and urine-water-seal impingement process) is demonstrated in Fig. 3 using high-speed visualization technology. Fig. 3A shows a section of the urine jet where a seemingly continuous urine jet is composed of discrete urine droplets, which is caused by the Rayleigh-Plateau Instability (Driessen et al., 2013). It is the main cause for the liquid column breaking into droplets under the interfacial tension. Therefore, as shown in Fig. 3B, the urine-water impact upon the water seal is droplet impingement where continuous splashed droplets can be observed on the impact site. Fig. 3C–3F presents the time-sequencing high-frequency pictures of droplet group impacting the water seal where quantitative analysis was acquired. Adopting the PIVlab code, corresponding velocity distribution maps are presented, showing the highest impact velocity can be \sim 3 m/s.

A probability study of the droplet velocity was conducted. Fig. 4 presents the velocity probability distribution of the discrete urine droplets where an approximate normal distribution can be observed. The average velocity of the urine droplets in the air was calculated to be \sim 1.7 m/s which is adopted in the following numerical study. Due to the gravitational acceleration, the average velocity of the impinging urine droplets was lifted to \sim 2.2 m/s. The average velocity of splashed droplets was \sim 0.4 m/s, lower than that of the impinging ones, but the maximum velocity approached 1 m/s. Previous studies have proved that splashes can transfer pathogens from water to air (Bourouiba, 2021). Therefore, male urination has a great probability of causing disease transmission, especially the transmission of COVID-19. For a full 5 s urine jet dynamics and a full 2 s urine-water impingement, please see Video S1 and S2, respectively.

Flow dynamics during male urination was investigated numerically. Two urine exit angles were selected for this paper. Fig. 5 illustrates the simulation results of urination-caused flow dynamics when the \theta = 55\degree at 5 s where the urine flow directly strikes in the middle of the water seal, causing direct water splash upon the water seal and large area vorticity magnitude within the bowl (Fig. 5A). The maximum vorticity magnitude in the bowl was 816.1 s\(^{-1}\), located directly above the inlet of

Fig. 2. (A) Initial state before the smoke-assisted flow visualization experiment where the film can smooth the smoke inside the toilet, and (B) A gentle smoke flow demonstration after tearing off the film.
the sewage pipe where urine and water are encountered. Fig. 5B shows that two large vertical vortices, rotating in opposite directions, were generated on both sides of the urine jet, carrying the surrounding air rotating at a high speed under centrifugal force and resulting in large velocity gradients. Additionally, the left larger vortex moved constantly to the upper area under the action of inertia force, causing the vortex to splash above the toilet seat. The right vortex was relatively smaller due to the space restriction between the urine jet and the toilet bowl. However, the right vortex tended to move upward constantly along the inner edge of the right toilet bowl with a climbing velocity of 0.02 m/s (Fig. 5E–5F). With the turbulence up-movement effect, another small air vortex was generated on the right side of the urine jet near the human side, highlighted by the orange dotted line. Y-component velocity is demonstrated in Fig. 5D where the positive area can be observed except the urine jet and its adjacent area. Quantitatively, the maximum Y-component velocity in the left of the urine jet was 2.86 m/s, and that in the right was 1.07 m/s, the former of which was located in the area adjacent to the urine jet while the latter was located in the area close to the right wall of the bowl. In addition, it implies that the urination process lifts the virus particle within the toilet. Fig. 5C also confirms such a probability where the upper area within the bowl is a negative-pressure area where both airflow and particles climb up due to the pressure difference. Please refer to the Supplementary Materials (Section S2) for an analysis of the numerical results of the flow dynamics when \( \theta \) equals 80°.

Several similarities can be observed in the cases of two urine exit angles: (i) Urine jet at both angles can cause violent turbulence with the liquid-solid-air interactions. (ii) Spiral flow can be generated in both cases under a combined effect of inertia and centrifugal forces. (iii)
Airflow close to both edges of the toilet bowl can have large upwards Y-component velocities. Differences can also be spotted: (i) Maximum vorticity appeared above the sewage pipe for the first case while that located in the right narrow area for the latter case was due to the difference in the direct impact area of the urine jet. (ii) Positive Y-component velocity area in the latter case was much larger than that in the former case. (iii) Airflow vortices were formed on both sides area of the urine jet for the first case while no vortex was formed on the left side area for the latter one.

Smoke flow visualization during and after urination is displayed in Fig. 6A–6C. Fig. 6A demonstrates an oblique ascendant flow at the beginning of the urination process. The upwards flow is caused by the strong urine jet at the beginning, which can tear apart the smoke and generate two primary vortices which have also been verified in the numerical study (Fig. 5B). Vertical upwards smoke flows can be spotted in both Fig. 6B and C, which represents the end of the urination and after the urination. Two reasons could explain: (i) The velocity of the urine jet became smaller at those late-phase moments, causing a weak downward impact on the smoke. (ii) A consistent and strong upwards smoke flow was formed during the early stage of urination, which can resist the downward flow adjacent to the urine jet. Even after urination, the vertical upwards flow can also be observed, showing a great inertia force, which may cause large-scale virus spread indoors if virus microorganisms are involved in the climbing flow. Please refer to Video S3 for a full experiment process of the smoke-assisted flow dynamics visualization during and after male urination.

Fig. 6D shows the air velocity at one observation point from both experimental and numerical studies. It can be verified that the air climbed at the focused point. During urination, the velocity obtained from the numerical study is commonly larger than that from the
experimental study. The largest velocity in the numerical study during urination reached 1.05 m/s and that in the experimental study reached 0.75 m/s. In contrast, the detected velocity shortly after the urination from the experiment was larger than that from the numerical one where the post-urination velocity of air was maintained above 0.5 m/s for approximately 5 s and above 0.4 m/s for 8 s after the urination stopped and then experienced a slow descent while that in the numerical study drops quickly. Reasons for such deviations are as follows: (i) Velocity detection using hot-wire velocimetry is an intrusive measurement where its detector (shown in Fig. 1B) could shrink velocity. (ii) Boundary conditions of the experimental and numerical methods are different. For example, the velocity of the urine droplet is subject to a certain probability distribution (shown in Fig. 4), and the velocity changes with the time while that in the numerical method was set to be a constant. Moreover, the urine exit angles for both studies were different.

Fig. 6E–6H present fluid dynamics of both urine flow impacting the water seal and intensive splash of liquid droplets rebounding upon the inner wall of the bowl and flying outside the toilet. Fig. 6E shows a clean toilet before the urination experiment. Fig. 6F displays the urine flow impacting the inner wall of the toilet bowl at the early stage of the urination process, causing a massive splash. The splashed droplet can reach the upper surface of the toilet edge wall. Urine flow impinging the water seal is displayed in Fig. 6G where strong mixtures between the urine and water within the water seal can be observed. Such significant vortices and the mixing process will certainly cause a further diffused contamination as there is a certain concentration of SARS-Cov-2 in Covid-19 patients’ excrement ($10^2$–$10^7$ gc/ml (Gormley, 2020)). Furthermore, in Fig. 6G, large amounts of urine droplets are splashed on the inner wall of the toilet bowl, indicating virus particles can float in the air area above the water seal. Carried by the uprising airflow, there is a large probability that these tiny droplets can be lifted above the toilet demonstrated by Fig. 6G. Fig. 6H shows that even in the late stage of the urination, a new contaminated area can emerge because of the constant climbing trend of the airflow. Please refer to Video S4 for a detailed macroscopic infrared flow dynamic of the urination process.
3.2. Virus particle movement simulation and experiment

Particle movements are analyzed in this section. Fig. 7 presents phase fraction dynamics and discrete particle movement during male urination. As shown in Fig. 7 the urine jet is also composed of discrete droplets, which is in agreement with the experimental study (Fig. 4A). As shown in Fig. 7A, the virus-laden particles floating above the water seal moved upward along the two side walls of the bowl with a Y-component velocity of 0.43 m/s, carried by the airflow vortices. The particles tended to move centrifugally under the airflow on both sides of the urine jet. Fig. 7B illustrates that numerous particles were driven to the area near the urine inlet along with the urine jet where centrifugal movement can also be spotted (blue dotted line in Fig. 7B). When the time reached 10 s, only a few particles remained in the toilet (Fig. 7C), with approximately 83% of particles having escaped from the bowl to the upper air area. For the θ of 55°, most escaped particles primarily moved towards the standing man, and the maximum height of these upwards particles was 1.14 m from the ground. This means that these particles can be attached to below the waist or chest of the standing man during urination. For the θ of 80°, nearly 86% of particles had spread out through the toilet seat when the time approaches 10 s. Most of the particles moved towards the position where the man was standing, and the rest diffused into the higher air level (marked by the red dotted circle in Fig. 7D). The maximum reach height during urination can be up to 1.55 m, which is the height of a man’s facial area. Please refer to Video S5 and Video S6 for the full processes of the virus particle movement and phase distribution in these two cases.

Particle concentration measurement results of a certain location (middle of the toilet seat surface), marked by the red dot in Fig. 7D, using Fluke 985 are analyzed. It can be observed that before the urination, the concentration of the 2–10 μm airborne particle remains to be around 100 particles/L. When the urination experiment begins, the concentration climbs rapidly to the maximum of 299 particles/L within 8 s. Instantly the urination ends, the concentration decreases gradually. About 20 seconds after the end of the urination, the concentration goes back to the initial condition. The experimental data verifies the simulation results that male urination can cause a large scale of particle movement. It is also recommended that when the previous toilet user finishes using it, the current toilet user should wait for 10–20 s before using it in the public restrooms.

4. Discussions

Although the fecal-oral transmission of the COVID-19 seldom happens, this article points out the cross-infection of the COVID-19 in restrooms is highly likely because of the high mobility of the SARS-COV-2 in the sewage system. Regarding detailed transmission mechanisms in the restroom, the authors find that male standing urination can be a “dangerous” behavior that may disturb virus particles hiding within the toilet and which may cause further spread indoors. Experimental and numerical results support that the downwards impinging urine will cause opposite-direction climbing flows, caused by strong turbulence. The large lifting spread phenomenon (climbing speed: 0.75–1 m/s) within restrooms may promote the potential recurrence and persistent transmission of viruses not limited to the current COVID-19 virus. The particle concentration experiment demonstrates the concentration could

![Fig. 7. Virus particle movement simulation and experiment. (A-C) θ is 55° and flow dynamics at three moments (1 s, 3 s, and 10 s, respectively). (D) θ is 80° and flow dynamics at the moment of 10 s. (E) Experimental results of airborne 2–10 μm (diameter) particle concentration versus time measured by the particle counter. The orange dotted line is a guide to the eye.](image-url)
be tripled during male urination, which will enhance the infection rate if the toilet had been contaminated by certain viruses.

According to the results, a male-urination-induced virus transmission is a high-probable event in the restrooms. Scientists, decoration designers, and policymakers should reexamine the restrooms, which may be a promoter of mass cross-infection of global pandemics in its early stage. The design of the restroom facility (Wu et al., 2020) and people’s common habits in restrooms are encouraged to make changes. As shown in Fig. 8, towels are placed in the upper place of the toilet, which is a very “dangerous” design under the current background of COVID-19 pandemics as not only toilet flushing and urination may cause the virus particles to attach to these towels. Cross-infections may happen when people use these towels. Such design should be avoided in future decoration design of restrooms. Besides, people often put towels, toothbrushes, and cosmetics in bathrooms, which is also very “dangerous” nowadays. People should be encouraged to transfer personal stuff outside of the bathroom.

Other toxic viruses that can survive in sewage systems and human body fluid such as SARS virus, Ebola, Middle-East Respiratory Syndrome Coronavirus, norovirus, coxsackie B virus, poliovirus can also be spread during violent urination turbulence once a toilet has been contaminated. Especially, diseases that can be transmitted by fecal-oral transmission are more likely to be spread through the male urination process. The community outbreak of SARS in 2003, involving 321 patients in a high-rise housing building in Hong Kong, was primarily caused by the turbulence-induced rising virus with a faulty sewage system, polluted by SARS-CoV-contaminated excreta (Peiris et al., 2003; Yu et al., 2004). Part of the turbulence may come from the urination process. The findings in this paper will encourage people to be more aware of virus transmission when in restrooms, and prepare them for emerging and reemerging pandemics, especially for those viruses able to survive in sewage systems or human body fluid.

5. Perspectives, implications and conclusions

The violent turbulence in daily life is identified as a main cause of the massive transmission of viruses. Although fecal-oral transmission of COVID-19 is a small probability event, evidence has shown that viruses in the sewage system do spread out into the indoor environment via turbulences in restrooms, causing cross-infection through outputs such as toilets and drainage systems.

This paper experimentally and numerically demonstrates how male urination leads to an upwards flow and the implications for disease environmental transmission. Experimental study shows that the continuous urine jet as seen by the human naked eye is composed of discrete droplets. Therefore, the droplet-water impingement will occur when the urine jet impacts the water seal with an impinging velocity up to 3.3 m/s and the velocity of the splashed droplet can be as high as 1.1 m/s. Such high-energy impact will cause turbulence and upwards airflow (verified by the experiment in this paper), exposing a standing man to a great probability of cross-infection from diseases.

The numerical study illustrates that alarming vortices will be generated during male standing urination with maximum vorticity of 746.4–816.1 s⁻¹. The observed Y-component velocity in the computational domain ranged from ~1 to ~3 m/s, indicating an aggressive upwards trend. Experimental visualization also captured two main lifting vortices on both sides of the urine jet. Results from hot-wiring velocimetry also show the same tendency with approximately 0.75–1.05 m/s. Such aggressive climbing tendency will be maintained for a long period (8 s) after a 10 s urination process due to the inertia force. The upwards flow will disturb and spread any lurking virus particles (not limited to SARS-CoV-2). Besides, the infrared thermography experiment clearly shows that the urine droplets can rebound from the toilet inner wall and lift out of the toilet easily.

Unexpectedly, the uprising flow will lift the virus particles (not limited to SARS-CoV-2) out of the toilet bowl and cause a massive spread. Numerical study shows that the particle will also have an upward rotational trend with a Y-component velocity of 0.35–0.43 m/s. Nearly 83%–86% of the virus particles can be lifted out of the toilet bowl. More alarmingly, the majority of the lifting particles will attach to the standing man’s clothes and the rest of them will float in the air. The height that the upward particle can approach will be certainly above 1 m. The maximum height observed in this paper was 1.55 m, the height of a man’s facial area.

Although female urination is not the focus of this paper, similar virus lift phenomena should be anticipated. More likely, these particles will attach to the female buttocks. The investigation presented here urges people to use the toilet properly in both family and public restrooms. Wearing masks during urination and washing hands afterward are always strongly recommended. Specifically, spraying a certain amount of anti-virus liquid such as alcohol solution to the front clothes after using the toilet is highly suggested. Physical distancing and time intervals (10–20 s) between two toilet users should be especially emphasized in public restrooms. Another feasible option is to use a disinfectant-contained solution as the flushing liquid to kill the possible virus timely and maintain a clean facility for users.

The practical implications of this paper are outlined in the following. (i) Using visualization technology, this paper guides people to maintain their guard again when in restrooms, protect themselves and others more consciously when and after using the toilet. (ii) Evidence of a probable environmental transmission mechanism of COVID-19 in restrooms is provided, which may contribute to reexamining virus transmission tracking and reanalyzing the cases of unknown sources or unexpected cross-infected cases in quarantine areas for medical workers, epidemiologists, biologists, and governments around the world. (iii) This paper demonstrates that dangerous microbial bacteria can float in the restroom and may cause cross-infection. This should encourage the government and the public to construct well-ventilated restrooms since ventilation has been proved to suppress cross-infection.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.
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