The impacts of surface roughness on Indoor aerodynamics of virus-laden particles: The case of contact, deposition, and resuspension

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Abstract. The increasing prevalence and high morbidity of the SARS-CoV-2 virus during the COVID-19 pandemic drew widespread global attention. Surface contact is among the most common ways for the infection to spread within people, especially in buildings and the built environment. The roughness characteristics of finishing materials used in buildings vary, affecting the surface's ability to deposit and resuspend any particles that come into contact with these interfaces. Resuspension of particles indoors may increase the risk of consequent exposure through inhalation. However, little is known about surface roughness characteristics' role in airborne transmission of virus-laden particles in building indoor environments. The study examines the impact of surface roughness characteristics on the airborne transmission of the SARS-CoV-2 virus, considering indoor aerodynamic forces and their influence on particle contact with surfaces, deposition, and resuspension. The study applies Ansys Fluent CFD simulation tools to investigate the effect of volumetric flow rates and air velocity on concentration, deposition, and resuspension. The study also employs an empirical model to estimate surface roughness characteristics' impacts on particle resuspension rate. The results indicate that particle concentration and deposition rates indoors increase with increasing volumetric airflow rates. The particle resuspension rates also decreased with the increasing surface roughness of indoor surface materials. The highest resuspension rate recorded was 3.3 x $10^{-6,}$ and the lowest was 1.6 x 10^{-6} s^{-1}. Therefore, the outcome provides information on the implications of surface material selection and its effects on indoor air quality, health, and virus transmission. The study will offer valuable information for building engineering and design professionals in combating airborne disease transmission due to indoor surface characteristics.

1 Introduction

In the last two decades, pandemic outbreaks, including severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), SARS-CoV-1, Middle east respiratory syndrome coronavirus (MERS-CoV), and Zika virus, are becoming more frequent, causing human morbidity and mortality. The consistent virus outbreaks necessitate researchers from various fields of study to search for possible mitigation measures. The recent episode of the SARS-Cov-2 pandemic has again reignited debates about the potential transmission pathways in building indoor environments and the search for built-environment-oriented solutions. SARS-CoV-2 transmission routes include airborne droplets or contact with surfaces where droplets have been deposited [1]. Previous research outcomes have suggested a high possibility of SARS-CoV-2 airborne transmission in indoor air environments [2]. The disruption of the air-surface boundary layer caused by indoor activities can result in the bulk elevation of inhalable particles in the indoor environment [3]. Thus, researchers and policymakers are becoming more conscious of the impact of indoor surface roughness on indoor air pollution due to the human health dangers posed by small virus-laden particles in building interior settings.

The built-environment-oriented virus transmission mitigation measures mainly focus on reducing the resident time of the virus or any substances harboring the virus indoors. Recent discoveries have indicated that the SARS-CoV-2 virus might survive in aerosols for up to 16 hours [1], [4], [5]. Individuals infected with SARS-CoV-2 have the ability to produce viral bioaerosols that can remain infectious for long periods after production via human shedding and airborne transport [4]. The viability of this virus in the air for long periods raised concerns for occupants of various types of buildings. In healthcare settings, for instance, the increased risk of occupational SARS-CoV-2 exposure for healthcare personnel is particularly alarming [6]. Studies have indicated the presence of remarkable nosocomial COVID-19 transmission among inpatients of hospitals [7]. It is critical to comprehend the role of air particles as vectors for SARS-CoV-2 in such buildings, where conventional infection control strategies may fall short [6].

Moreover, the concern is not limited to the viability of the virus-laden aerosols indoors but the ability of these particles to deposit on indoor surfaces and resuspend later to infect occupants. Particle deposition is the accumulation of discrete particle materials on solid surfaces or other boundaries that contain a liquid or gas flow into which the particles are initially embedded [8]. On the other hand, the physical mechanism that allows the detachment of previously deposited particles from surfaces and re-entrainment into the air is referred to as resuspension [3], [9]. Rolling detachment is the primary mechanism of particle resuspension, and microscopic surface roughness can significantly reduce the adhesive forces. Particle resuspension is a complicated process that is influenced by a variety of factors and their interactions. According to findings, resuspension is the most significant indoor source of particulate matter compared to other indoor sources. Although resuspension estimates vary by order of magnitude, it rises with particle size in walking-induced settings between 0.7 and 10 m [3]. Regardless of the time interval, increased resuspension was associated with increased speed or particle size [10].

Furthermore, indoor particle resuspension increases inhalation exposure to various contaminants (Qian et al., 2014). It poses a significant risk to human health because it reintroduces contaminated particles into the air after deposition on surfaces [11] and subsequently increases the risk of consequent exposure through inhalation and non-dietary ingestion [3]. The most critical factors influencing particle resuspension are particle diameter, surface roughness, and flow acceleration [11], and from grass swards, surface and environmental conditions can significantly impact particle resuspension from natural surfaces [12]. Evidence suggests COVID-19 may be spread through smaller aerosols, such as those produced by speaking [2], [13]–[15]. According to highly sensitive laser light scattering observations, loud speech can emit thousands of oral fluid droplets per second [13]. Due to their ability to enter the lungs more deeply, these smaller particles seriously affect health [6]. A cascade impactor was used in a study [6] to collect size-fractionated particle samples (2.5, 2.5-10, and 10 m) from more than 30 locations in a Kuwaiti hospital. The study discovered that 6% of the samples, 13 out of 210, tested positive for SARS-CoV-2 RNA at concentrations ranging from 3 to 25 copies/m^3. Another more viable method of disease transmission is now believed to be speech droplets produced by SARS-CoV-2 carriers who are asymptomatic.

The influence of surface roughness characteristics on particulate matter deposition and resuspension cannot be over-emphasized. The various surfaces (wall, floor, ceiling, and furniture surfaces) are the principal harbors of airborne contaminants in building indoor environments. These surfaces deposit virus or virus-laden particulate matter and resuspend into the air due to different physical and mechanical conditions within the buildings and the surface textures of the materials. The deposition of particles on indoor surfaces increases the particles' resident time within the environment. It prolongs the dangers posed by the virus-laden particles to building occupants. In some facilities, indoor surfaces are typically chemically treated to prevent staining, protect the surface, and inhibit microbe growth. A treated surface will age, degrade, and sorb onto dust particles, thereby increasing the inhalation exposure to the coating chemicals when the dust particles are resuspended. The treated surfaces can alter indoor surface microbiology by artificially selecting more antibiotic-resistant microbes, resulting in a different collection of inhalable microbes during resuspension events [3]. The ability of the indoor surface to deposit and resuspend particles is mainly dependent on the surface roughness characteristics of the finishing materials and the sizes of the particulate matter. Nicholson [10] applied wind tunnel experiments to study the resuspension of particulate materials with particle sizes greater than 0.1 m, including four different sizes of particulate material (4, 10, 18, and 22 m in diameter) from concrete and grass surfaces. The study found that at moderate wind speeds (less than 5 m/s), resuspension rates averaged over approximately 1 h after the onset of conditions leading to resuspension were in the range of 1×10^{-06} to 5×10^{-06} s^{-1}, with little difference between the grass and concrete surfaces. Several percent of the total surface deposit of 22 diameter particles was removed from the concrete and grass surfaces within 10 seconds of the onset of wind for high wind speeds (greater than 6.5 m/s) wind.

Several studies investigate the ability of various materials to retain deposited particulate matter. According to a study that quantifies the ability of tree branches to retain airborne submicron particles, surface roughness would increase deposition velocity (V_d) as a rougher surface increases turbulence, which is conducive to particle diffusion [16]. The static balance of adhesion and pull-off hydrodynamic forces governs particle resuspension; however, particle motion along the wall surface (once activated) is also an essential aspect of the resuspension phenomenon. Surface roughness is crucial to the resuspension phenomenon [8]. Researchers have used different friction velocities based on wind speeds to study particle depositions and resuspensions indoors. Nicholson [10] used 0.1 to 0.4 m/s friction velocity to test silica spheres, Giess et al. [12] applied 0.3 to 1.4 m/s friction velocity to study silica spheres, and Garland and Pomeroy [17] used 0.2 to 0.8 m/s friction velocity for Tungstic oxide.

Furthermore, friction velocities evaluated from wind speed gradients close to the wind tunnel surface were approximately 0.1, 0.15, and 0.2 m/s for the concrete surface and 0.15, 0.3, and 0.4 m/s for the grass surface [10]. Therefore, this study aims to investigate the impacts of surface roughness on the Indoor aerodynamics of virus-laden particles and their ability to deposit and resuspend on indoor surfaces. The deposition and resuspension of particles indoors are essential subjects due to their ability to increase the particles' residence time indoors. The study outcome will be beneficial for policymakers and built environment professionals.

1.1 Properties of SARS-COV-2

Viruses are frequently spread via respiratory droplets produced by coughing and sneezing. Respiratory droplets are typically classified into two sizes, including large droplets (>5 m in diameter) that fall quickly to the ground that is only transmitted over short distances and small droplets (≤5 in diameter). These Small droplets can evaporate into 'droplet nuclei,' which can linger in the air for long periods, raising the possibility of inhalation [18]. The SARS-CoV-2 virus is classified as a beta coronavirus, which has a round or elliptical shape and is frequently pleomorphic, with a diameter ranging from 60 to 140 nm. SARS-CoV-2 is categorized as enveloped virus with significantly different shapes from one individual virus to another since its lipophilic envelope can integrate varying amounts and types of proteins, allowing for a great deal of flexibility [19]. The SARS-CoV-2 virus is an enveloped virus with a diameter of about 0.1μm [18] and a unique spike morphology measuring about 9 to 12 nm long, projecting from the virus particle's surface and resembling a solar corona [19]. Regarding volume and density, previous SARS--Cov-2 studies used a density of 1 g per mL (1000 kg/m3) [18].
Furthermore, the interaction between the SARS-Cov-2 virus and various materials upon contact has been analyzed. SARS-CoV-2 was found to be more stable on plastic and stainless steel than on copper and cardboard, with a viable virus detected up to 72 hours after application to these surfaces. SARS-CoV-1 stability kinetics were similar after 72 hours on plastic and 48 hours on stainless steel. On copper, there was no viable SARS-CoV-2 after 4 hours and no viable SARS-CoV-1 after 8 hours. On cardboard, no viable SARS-CoV-2 was detected after 24 hours, and no viable SARS-CoV-1 was detected after 8 hours [5]. The SARS-Cov-2 decay rate and half-life were determined, and decay rates ranged from 0.4 to 2.27% per minute, with half-lives ranging from 30 to 177 minutes for the various conditions [1].

2 Methodology

The simulation in this study was carried out using ANSYS CFD Fluent 14.0. The simulation setup used velocity boundary conditions for the inlet and pressure boundary conditions for the outlet. **Table 1** shows the specifics of the boundary conditions and the model parameters used in the simulation. Iteration convergence was attained when the scaled residuals reached 10^{-6} for x, y, and z momentums and 10^{-5} for k and continuity. The particle transport was calculated using the discrete phase model (DPM). This study used the Lagrangian discrete particle model for particle tracking, as used in many studies [20]–[22]. The problem was initially solved as a single-phase flow, and DPM was enabled. The particles used have a density equivalent to dry sand of 2700 kg/m^3. The stochastic tracking and Discrete Random Walk model (DRW) were used to account for the effect of turbulence in particle dispersion. The following assumptions were applied to simplify and reduce computational power: a) Heat and mass transfer between air and particles are neglected; b) No particle rebounds on solid surfaces, such as walls, floors, and ceilings; c) No particle coagulation in the particle deposition process; and d) All particles are in spherical solid shape.

Table 1. Summary of boundary conditions and model parameters.

S/N	Boundary	Settings
1.	Inlet velocity	2.0 m/s
2.	Outlet	Relative static pressure is zero
3.	room size	140 m^2 (12.2 x 11.5m)
4.	Room height	3.3m
5.	Mesh type	Hex-dominant structured grids
6.	Turbulence model	k-ε Realizable
7.	Time	Steady-state simulation
8.	Total number of cells (Average)	2 million
9.	Gravity	-9.81
10.	Air density	1.2 kg/m^3
11.	Air temperature	24^{o}C

The study employed an empirical model developed by [23] for short-time resuspension. The five resuspension parameters used in the model include the friction velocity (u*), the time since the wind flow began (t), the particle diameter (d_p), the particle density (r_p), and the roughness (z_0). The model assumed that the resuspension rate varied in power law or exponential relationships with the parameters. Equation 1 illustrated the empirical models used in this study:

$$\Delta = 0.42 \frac{u_*^{2.13} d_p^{0.17}}{t^{0.92} z_0^{0.32} \rho_p^{0.76}} [s^{-1}] \dots\dots\dots\dots\dots\dots\dots\dots . (1)$$

Where the resuspension rate ∧ has dimensions of s^{-1} and the friction velocity of 0.2 (u*), the particle diameter (d_p) of 0.1 um, time (t) since the wind flow began, was 60 seconds, the particle density (r_p) of 1000 kg/m3 and varying material surface roughness from 0.01 to 0.1 have been set. The model, though empirical, are physically realistic because the resuspension rate increases with u* and particle diameter (within the range of interest) and decreases with time, surface roughness, and particle density. Resuspension increases with the shear force on the surface (characterized by u*). Larger particles (d_p) stick up higher into the boundary layer and thus experience higher removal forces. A rougher surface provides more shielding and acts against resuspension. The usually observed decrease with time is thought to occur because the less tightly adhered particles are removed early, leaving behind a more firmly bound reservoir [23].

3 Results and analysis and discussion

Particle indoor concentration remains the primary factor affecting particle deposition and resuspension, as the deposition rate depends on the total concentration. The volumetric airflow rate naturally or mechanically from the Heating, Ventilation, and Air-Conditioning (HVAC) system influences the particle concentration in the indoor building environment. This study investigated different volumetric airflow rates (0 to 4 m3/s) relating to indoor particle concentrations. The outcome indicates that the indoor particle concentration increases with increasing volumetric airflow rates, as illustrated in **Figure 1**. Assuming the particles are from outdoor sources, this outcome implies that more particles will come into the indoor space with a higher volumetric flow rate, indicating a higher host to trap and carry the virus. Hence, the virus's half-life depends on the particulate matter's chemical and biological properties and physical characteristics.

Furthermore, the influence of volumetric airflow rate on indoor particle deposition is also investigated, indicating similar relation with the concentration rates, as illustrated in Figure 2. The deposition study was carried out for wall, floor, and ceiling surface deposition. The results indicate that the floor surface received the highest deposition rate due to its horizontal orientation, which received most particles drop out of the air. The wall surface received the second highest deposition, and the ceiling surface deposition rate was the lowest, as shown in Figure 2. This outcome is logical because of the orientations of the surfaces, and it is difficult for larger [particles to deposit on both vertical and ceiling surfaces due to disadvantages in gravity compared to horizontal floor surfaces. These outcomes imply that indoor activities resulting in frequent contact with horizontal surfaces (floor, table/desk, etc.) pose a higher risk of contracting virus-laden particles than vertical wall surfaces and ceiling surfaces.

Moreover, it can be observed in **Figure 2** that, with lower volumetric flow rates, the deposition rate in the ceiling was higher than the horizontal flow surfaces. This outcome is not unconnected with the size of the particles, which is very small (0.1 μm) that will effortlessly deposit on the ceiling surface without high airflow rates. However, the possibility of these particles depositing on the ceiling is less upon increasing the airflow rate to a higher level. Besides volumetric airflow rate, air velocity is also an essential factor affecting indoor particulate behavior. The study investigates the influence of average indoor velocity (0 to 0.2 m/s) on particle escape. In this study, particle escape refers to all particles removed from the space via the ventilation outlets, indicating the efficiency of the ventilation system in reducing the particle concentration indoors. The results suggest that the number of particles escaping from space increases as the indoor air velocity increase, as illustrated in **Figure 3**. This outcome implies that improved air distribution is required in the indoor space to remove more particulate matter and reduce the number of particles hosting the virus in indoor environments. The results further indicate that the particle removal rate is slow with lower average indoor air velocity and increases with increasing air velocity (**Figure 3**).

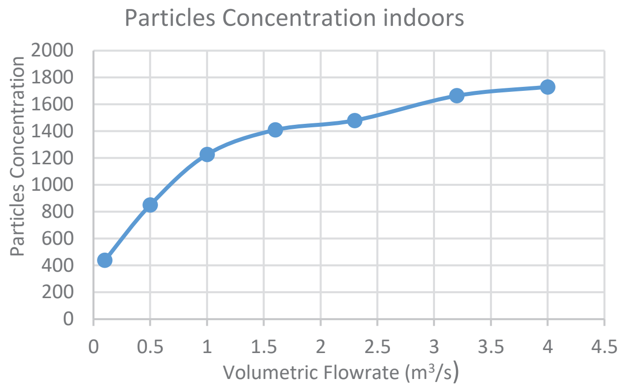

Fig. 1. Particle concentration in building indoor environment.

Moreover, resuspension is the most crucial particulate matter behavior affecting building occupants' health and comfort. Resuspension is the most significant indoor source of particulate matter compared to other indoor sources [3]. Ordinarily, the deposition of particles on indoor surfaces as a sink effect is considered a significant contaminants removal mechanism. However, this removal mechanism needs reconsidering with the possibility of resuspending particles hosting infectious pathogens such as SARS-Cov-2. Any strategy of reducing the deposition on surfaces indoors should be pursued vigorously as the possibility of deposited particles resuspending back to the air is very high. When resuspended, the relationship of the particle with the human body, especially the respiratory system, will be increased, implying a high risk of contracting dust-laden infectious pathogens and viruses. This outcome is supported by recent discoveries indicating that the SARS-CoV-2 virus might survive in aerosols for up to 16 hours [1], [4], [5]. This study investigated the impacts of surface roughness characteristics on particulate matter resuspension rates. The result indicates that the higher the surface roughness of indoor surfaces, the lower the resuspension of particulate mattes indoors, as illustrated in **Figure 4**. The highest resuspension rate recorded was 3.3 x $10^{-6,}$ and the lowest was 1.6 x 10^{-6} s^{-1}. This outcome implies that finishing materials with higher roughness characteristics are preferred compared to smooth finishing materials to reduce the re-entrainment of virus-laden particles into the indoor air. Although these particulate matter will remain on the rough surface, their effects on building occupants will be less than suspended particles. Frequent indoor surface treatment with anti-virus and bacteria chemicals will reduce the concern of virus-active particles deposition on indoor surfaces. Various viruses interact differently with different surface materials depending on material properties. SARS-CoV-2 was found to be more stable on plastic and stainless steel than on copper and cardboard, with a viable virus detected up to 72 hours after application to these surfaces [5].

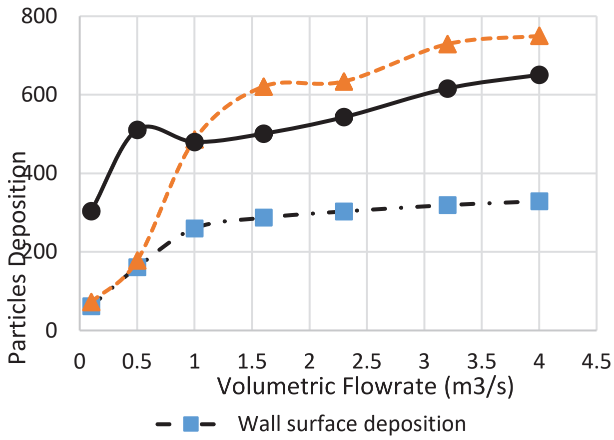

Fig. 2. Particles deposition characteristics in building indoor environment

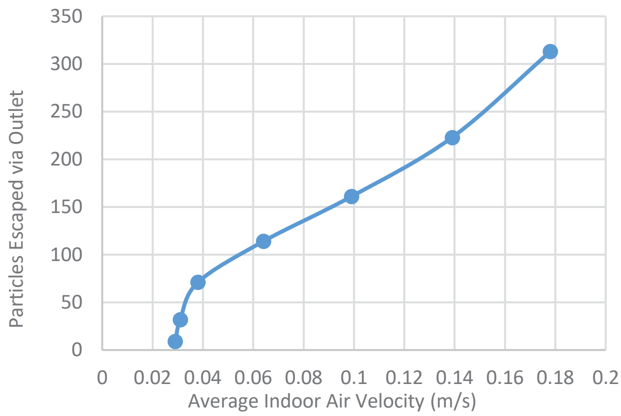

Fig. 3. Particles escape characteristics in building indoor environment

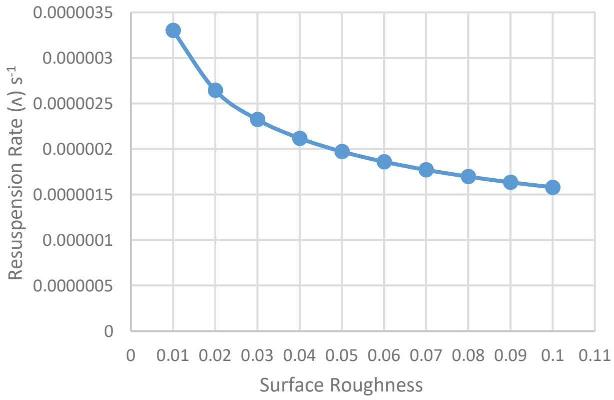

Fig. 4. The relationship between particles resuspension and surface roughness characteristics

4 Conclusion and recommendations

The study's objective is to investigate the impacts of surface roughness on the Indoor aerodynamics of virus-laden particles on indoor particle deposition and resuspension. The study applies Ansys Fluent CFD simulation tools to examine the effect of volumetric flow rates and air velocity on concentration, deposition, and resuspension. In addition, an empirical model is used in the study to estimate the effects of surface roughness characteristics on particle resuspension rate. The results indicate that particle concentration and deposition rates indoors increase with increasing volumetric airflow rates. The particle resuspension rates also decreased with the increasing surface roughness of indoor surface materials. The highest resuspension rate recorded was 3.3 x $10^{-6,}$ and the lowest was 1.6 x 10^{-6} s^{-1}. The outcome of this study provides information on the implications of surface material selection and its effects on indoor air quality, health, and virus transmission. The study will offer valuable information for building engineering and design professionals in combating airborne disease transmission due to indoor surface characteristics. Based on the study's outcome, the following recommendations:

1. The ventilation system should be optimized to reduce particulate matter penetration into the building's indoor environment.
2. The volumetric airflow rate should be increased to remove a significant amount of particulate matter from the indoor environment of the building.
3. Improved air distribution within the building ensures ventilation reaches every indoor space for effective contaminant removal.
4. Select rough indoor surface finishing materials to improve the deposition of virus-laden particles indoors, thereby reducing the amount of suspended particulate matter in the air and, as a result, viral infections.
5. When selecting finishing materials, always choose materials that reduce the stability of viruses and infectious pathogens deposited on their surface. For instance, a study has established that SARS-CoV-2 was more stable on plastic and stainless steel than on copper and cardboard [5].

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