INTRODUCTION

The outbreak of COVID-19 disease at superspreading events intensifies the scientific discussion on the airborne infection transfer mechanism responsible for the global spread of this disease; most of all for combating strategies and then to the issue of rebooting economic activity. Limited information is available on the formation of virus-laden droplets/aerosols, dispersion, and evaporation of expiratory droplet cloud in the indoor environment. Furthermore, there is a wide variation in the input parameters such as droplet size distribution, concentration, volume of expiratory fluid, release conditions, etc. Accordingly, a considerable amount of uncertainty is associated with modeling practices used for inhalation exposure assessment. Although there are few methods of exposure assessment available in the literature, it is necessary to address larger scientific questions which form the basis of these calculations. In this study, we wish to focus on the issue of residence time of cough droplet and droplet nuclei, ejected from the expiratory activity of infected subjects as localized puff to start with, in an indoor space. The residence times are not only important for exposure assessment, but are also important for assessing the performance of air cleaners, or for deciding the minimum level of Clean Air Delivery Rate (CADR) expected of...
them, as effective intervention technologies for minimizing the infection transfer risks in confined environments.

Generally, the mean residence time is derived from the reciprocal of the removal rate, which is a concept based on uniformly mixed chamber models\textsuperscript{10}. This concept is best suited for fine aerosol particles of about 1 μm or less, predominantly occurring in the context of indoor pollution. On the other extreme is the models of residence time for falling-evaporating droplets, as described by Wells\textsuperscript{11} long ago and revisited with considerable mathematical precision by Xie et al.\textsuperscript{12}, which are best suited to describe the fate of droplets of 20 μm or more. There is a wide gap in modeling the residence time for droplets in the intervening size range (say, 5–20 μm), which due to natural convective mixing in a room, will be undergoing dispersal in the air currents during their fall under gravity, and cannot be described by either of the above models. With increasing concern expressed over the yet to be understood role of aerosol route of infection spread in the COVID-19 scenario, the assessment of the impact of size range is of considerable urgency. The first motivating factor for this paper is to formulate a model that smoothly transits from the falling droplet to a uniformly mixed chamber model (Falling-to-Mixing-Plate-out) across the entire size range of polydisperse droplets released in a cough.

A second and more important motivation for this study stems from the following consideration. In a recent paper\textsuperscript{13}, we pointed out that the size distribution metrics of corona virus-laden polydisperse droplets expired from infected subjects, could be very different from the original droplet distributions, due to the well-known Poissonian fluctuations\textsuperscript{13–17} in virus incorporation propensities into droplets at the time of their formation. To focus on this viral load-dependent distinctiveness, a terminology “virusol” was proposed for the ensemble of virus-laden droplets. From both exposure evaluation and control technology point of view, the residence time of the virusolized fraction is a matter of concern, and not that of the entire droplet population. The Poissonian theory shifts focus on larger size fraction effectively rendering the residence times sensitive to the viral load in the ejecta of subjects. Examining this dependence is an important aspect of this study.

Size distribution of expiratory droplets is one of the basic input parameters required to determine the lifetime of the virus-laden droplets in the ambient environment. There are several experimental studies on the size distribution and concentration of expiratory droplets \textsuperscript{7,18–20}. These studies show a large variation in the size distribution parameters of the droplets ejected from the infected subjects. Equally important is the data on viral load among patients and the variability across several findings have been summarized by Anand and Mayya\textsuperscript{13}. The combined effect of size dispersity and viral load has a complex influence on the lifetime of the virus-laden droplets as we will see in this paper.

Computational fluid dynamics (CFD) is an increasingly adopted approach to address the transport of droplets along with their evaporative dynamic, from the point of emission to their settling on surfaces \textsuperscript{21–24}. In a strictly theoretical sense, this would be most accurate for modeling residence time distributions. However, a large number of parameters are required for carrying out simulation using fluid dynamics. Therefore, CFD approaches are highly input parameter intensive. For example, to handle turbulence in a room it would be necessary to specify all the processes responsible for creating turbulence. It should then include both mechanical and thermal sources, and this would make the CFD models quite useful in specific contexts, but lack generic predictive power. To have generality, CFD would require averaging over a large number of scenarios before arriving at the reasonable estimates of a representative droplet residence time. On the other hand, phenomenological model based on turbulent diffusion as the governing transport mechanism in addition to gravitational settling addresses the dispersive mechanisms directly through an assumed diffusion coefficient and hence will be more robust in providing generic estimates of the residence time distributions. Besides, treating droplet transport within the framework of an assumed bulk diffusion process obviates the need to examine the origin of its occurrence for the purposes of describing the migration dynamics of the droplets. Equally important, turbulent bulk diffusion models are amenable to analytical solutions for falling droplets which is useful for comparison purposes for providing insights into the role of individual processes.

In the phenomenological approach, the emitted droplet begins to disperse in bulk space as it settles under gravity simultaneously evaporating and undergoing wall removal processes. The removal rates are matched with the boundary conditions using Lai and Nazaroff model\textsuperscript{10}. This phenomenological model integrates smoothly the wall removal as well as air exchange removal without having to concern about the points of air entry and exit for various realistic emission scenarios. We term it as a residence time distribution problem since the released droplets are not uniformly mixed in the indoor environment, and the inverse of the mean residence time is equivalent to the removal rate of uniformly mixed model. The dynamics of these evaporating and settling virusol puff is studied under different conditions by varying the important input parameters such as relative humidity, differential temperature between the droplet and ambient atmosphere, release height, bulk turbulent coefficient, friction

**Practical Implications**

A recent study points out that due to Poissonian fluctuations, only a small fraction of droplets expired from COVID-19-infected subjects would contain viruses. As a result, the size distribution metrics and residence time of those virus-laden droplets, called virusols, could be very different from those of total droplet populations. By constructing a comprehensive model, this study demonstrates that the mean residence times of virusols, which are of relevance for disease control in indoor air and risk assessment, vary by nearly an order of magnitude depending upon the viral load in the biological fluid ejected from patients.
velocity, initial droplet size distribution, multi-component nature of the droplets, and viral load in the biological fluid. The issue of the dependence of the mean residence time of virus-laden droplets (virusols) on the viral load forms a key component of our analysis.

2 | MATERIALS AND METHODS

Let us consider an expiratory event in which droplets of initial concentration \(N_0\) are released from an infected person at a height \(z_0\) in a closed environment (Figure 1). The convective diffusive expansion of the puff containing airborne droplets is modeled using the mixing transition model, which combines homogeneous mixed room model with falling droplet model seamlessly. Many researchers \(^6\),\(^25\),\(^26\) argue that the cut-off diameter for the aerosol definition in the present context should be a single discrete number (e.g., <5 \(\mu m\) or <20 \(\mu m\)). However, in the present study, a higher cut-off diameter (100 \(\mu m\)) is considered so that the transition to inhalable aerosol size from the evaporation of continuous size spectrum of ejected droplets can be modeled seamlessly.

2.1 | Falling-to-mixing-plate-out model

Preliminary comparative analysis of the proposed 3-D model with 1-D version reveals that the differences in their results are very small for particles >0.1 \(\mu m\). The detailed derivation of analytical solution and comparison of 1-D and 3-D models are presented in Supplementary Material. Significant differences are observed in the case of ~10 nm particles, which is of least interest in the present study. Hence, for all large droplet (>0.1 \(\mu m\)) simulations with air mixing condition, 1-D model (along the direction of gravity) will be good enough and it yields results very close to 3-D model. In the case of 1-D model, the rate of change of droplet concentration \(C\) in the vertical direction \(z\) due to turbulence, gravitational settling, and inactivation of viruses in the droplets is given by

\[
\frac{dC(z, t)}{dt} = D \frac{d^2C(z, t)}{dz^2} + V_g \frac{dC(z, t)}{dz} - \lambda C(z, t)
\]

where \(D\) is the bulk diffusion coefficient along \(z\)-direction due to turbulence, \(V_g\) is the gravitational settling velocity from Equation (6), and \(\lambda\) is the virus decay rate \((0.63 h^{-1})\)^27. In the given coordinate system, ground and roof levels of the indoor environment are represented by \(z = 0\) and \(z = H\) respectively. The initial and boundary conditions (IC, BC) are,

(a) IC: \(C(z, 0) = N_0 \delta (z - z_0)\)

(b) BC1: \(D \frac{dC(0, t)}{dz} + V_g C(0, t) = (V_0 + 0.5 \lambda v H) C(0, t)\)

(c) BC2: \(D \frac{dC(H, t)}{dz} + V_g C(H, t) = -(V_0 + 0.5 \lambda v H) C(H, t)\)

**FIGURE 1** Schematic diagram capturing various physical processes during a typical expiratory event in the indoor environment
where $V_D^f$ and $V_D^r$ are the deposition velocities on floor and roof respectively, obtained from boundary layer models. These deposition velocities depend on the bulk diffusion coefficient, $D$. $\dot{\zeta}$ is the ventilation or air-exchange rate (AER) of the indoor environment, an empirical expression relating AER and bulk diffusion coefficient is given by

$$D = (0.52 \times 8.61 \times 10^{-3}) \; V^1,$$

where $V$ is the room volume ($m^3$). Equations (2b and 2c) accounts for the loss of droplets/particles due to surface deposition on the floor ($z = 0$) and roof ($z = H$) of the indoor environment respectively, gravitational settling, and ventilation removal. The ventilation removal from the enclosure is handled through similar boundary conditions (Equation 2b & 2c) at each of the surfaces.

### 2.2 Mean residence time (MRT)

The integration of solution of Equations (1-2) over the spatial domain gives the droplet/aerosol volume concentration survive in air at any time $t$. If $N_0$ is the total number of particles released at time $t = 0$, then the mean residence time of the expiratory droplets in air is prescribed as,

$$T = \frac{1}{N_0} \int_{t=0}^{\infty} \int_0^H C(z,t) \, dz \, dt$$

(3)

The definition of residence time is more general compared to the lifetime definition used in single exponential decay expressions. In the latter case, the mean residence time refers to time required to decrease $1/e^{0.5}$ of original concentration, equivalent to ~63% removal in the single exponential decay process. Equation (3) is a measure of multi-exponential decay due to various processes acting on the removal/survival of the expiratory droplets.

### 2.3 Vertical motion of evaporating and settling droplets

The equations of evaporation, vertical motion, and temperature of individual droplets are solved independently, and they are coupled together with the solution of mixing transition model through gravitational settling velocity ($V_s$). The governing equations that describe the vertical motion of the evaporating and settling droplets are given by

$$\frac{dN_w}{dt} = -2\pi d_d^3(t) \, Sh(t) \, D_{H_2O} \left\{ \frac{N_w(t)}{N_T(t)} \, p_a(t) \, k_g \, T_d(t) \frac{p_a(t) - p_\text{amb}}{k_g \, T_\text{amb}} \right\}$$

(4)

$$\frac{d}{dt} \frac{T_d}{12 \; k_g \; \left[ T_\text{amb} - T_d(t) \right] \; Nu(t) \; \frac{L_{H_2O} \, M_{H_2O}}{c_{H_2O} \; \rho_{\text{eff}}^2(t) \; p_d(t) \; T_d(t)}} + \frac{\rho_{\text{eff}} \, M_{H_2O}}{c_{H_2O} \; \rho_d \; m(t)} \; \frac{dN_w}{dt}$$

(5)

$$\frac{dV_s}{dt} = g - \frac{V_s(t) \; Stk(t) \; \text{Drag}(t) - m(t)}{m(t)}$$

(6)

where $N_w$ is the number of water molecules in the airborne droplets, $d_d(t)$ is the droplet diameter, $Sh(t)$ is the Sherwood number (ratio of convective mass transfer to the mass diffusivity), given by

$$Sh(t) = 1 + 0.3 \; \sqrt{\text{Re}(t)} \left( \frac{\rho_a}{\rho_d} \right)^{1/3} \; \text{Re}(t) = \frac{V_d(t) \; d_d(t) \; \nu_k}{k_g}$$

(7)

is the Reynolds number, $\nu_k$ is kinematic viscosity of air, $D_{H_2O}$ is diffusion coefficient of water molecules in air at 25°C, $k_g$ is Boltzmann constant, $N_d(t)$ is the total number of molecules (non-volatiles/residue + water) in the droplet, and $p_d(t)$ is the equilibrium vapor pressure of water in the droplet at temperature $T_d(t)$. $k_g$ is the thermal conductivity of air, $c_{H_2O}$ is specific heat of water. $L_{H_2O}$ is latent heat of water $M_{H_2O}$ is mass of water molecule, $m(t)$ is the droplet mass as a function of time, $\rho_{\text{eff}}(t)$ is effective droplet density, $Nu(t)$ is the Nusselt number used to correct the convective heat transfer rate, given by

$$Nu(t) = 1 + 0.3 \; \sqrt{\text{Re}(t)} \left( \frac{\rho_a}{\rho_d} \right)^{1/3} \; Stk(t) = 3 \; \pi \; g \; d_d(t)$$

(8)

is the drag correction factor, $m(t)$ is the rate of change of droplet mass with respect to time due to evaporation, and $g$ is the acceleration due to gravity. The water vapor pressure at a given temperature (Antoine equation) is given by

$$\log_{10} p_d/\text{amb}(t) = A - \frac{B}{T_d/\text{amb}(t) + C}$$

(9)

where $A$, $B$, and $C$ are constants and $T$ is the temperature in °C, suffixes $d$ and $\text{amb}$ refer to droplet and ambient respectively.

The droplets undergo evaporation in a homogeneous temperature $T_\text{amb}$ with a constant ambient water vapor pressure $p_\text{amb}$ at a given relative humidity, till they reach equilibrium conditions. The evaporation model neglects the effect of Stefan flow on heat and mass transfer between the droplet and the surrounding gas since this effect leads to less than 0.5% change in the model variables. The airborne droplets in the puff are assumed to be spherical particles consist of non-volatile components such as Na+, K+, Cl- ions, and lactate and glycoproteins (about 0.71% mole fraction) with water as a major constituent.

### 2.4 Virusol system

The total volume (number) and size distribution of droplets per unit volume of exhaled gas largely depend on the expiratory activities and it is an important input parameter to this model. The droplet size distribution functions are generally obtained by fitting the measurement data using two-parameter lognormal distribution characterized by median diameter and its corresponding geometric standard deviation. In the present study, the lognormal distribution of droplet number concentration is given by

$$\frac{dC}{dd_p} = \frac{N_0}{\sqrt{2\pi} \; d_p \; \log \sigma} \exp \left\{ -\frac{1}{2} \left( \frac{\log d_p - \log \text{CMD}}{\log \sigma} \right)^2 \right\}$$

(10)
where \( N_0 \) is the total number of droplets ejected, CMD is count median diameter, and \( \sigma_g \) is the geometric standard deviation (GSD).

Since atomization is the method of droplet ejection from the infected subject, the probability of viral load in each droplet will depend on the virus concentration \( (v_c) \) in the biological fluid and droplet size\(^{14,28} \). To distinguish the virus-laden droplets from the complete airborne droplet size distribution, the term “virusol” is coined for the aerosol studies related to virus infected diseases\(^{13} \). Many studies show that the presence of viral copies in the smaller size droplets is negligible for virus concentration \( v_c < 10^6 \) RNA copies/ml using the Poisson probability theory\(^{13,14,16,17} \), and thus, the probability of a droplet of diameter \( d_p \) carrying at least one virus (RNA) copy is given by

\[
P = 1 - \exp\left(-\frac{\pi d_p^3}{6} v_c\right)
\]

The virusol droplet number distribution is then obtained by multiplying the number-size distribution \( \left( \frac{dC}{dd} \right) \) with \( P \) at any instant of time \( t \). It is observed that the variation of virus concentration in the biological fluid is very wide \((10^{-2}–10^{11} \text{ RNA copies/ml})\), and studies indicate that there is a possible linkage of viral load with the severity of disease\(^{29} \). Based on data, we approximately classify viral load into two categories, i.e., (i) mild-to-moderate cases – <10^6 RNA copies/ml and (ii) severe cases – >10^6 RNA copies/ml.

### Table 1: Input parameters and constants

| Parameter                             | Typical value | Range        |
|---------------------------------------|---------------|--------------|
| Release height (\( z_0 \))            | 1.5 m         | (0.3, 1.5) m |
| Air exchange rate (\( \lambda_v \))   | 1.0 h\(^{-1} \) | (0–5) h\(^{-1} \) |
| Relative humidity (RH)                | 50%           | (10–90) %    |
| Eddy diffusion coefficients (D)       | 0.003 m\(^2\) s\(^{-1} \) | (0.001–0.03) m\(^2\) s\(^{-1} \) |
| Kinematic viscosity of air (\( \nu_\text{k} \)) | 0.15 cm\(^2\) s\(^{-1} \) | – |
| Diffusion coefficient of water molecules in air at \( 25^\circ\text{C} \) (\( D_{H_2O} \)) | 0.219 cm\(^2\)/s | – |
| Boltzmann constant (\( k_B \))        | 1.38 \times 10^{-23} m\(^2\) kg\(^{-1}\) K\(^{-1} \) | – |
| Thermal conductivity of air (\( k_\text{a} \)) | 0.024 W m\(^{-1}\) K\(^{-1} \) | – |
| Specific heat of water (\( c_{H_2O} \)) | 4184 J kg\(^{-1}\) K\(^{-1} \) | – |
| Latent heat of water (\( L_{H_2O} \)) | 2.26 \times 10^6 J kg\(^{-1} \) | – |
| Specific heat of air (\( c_{air} \))  | 993 J kg\(^{-1}\) K\(^{-1} \) | – |
| Air viscosity (\( \eta \))            | 1.85 \times 10^{-5} Pa.s | – |
| Acceleration due to gravity (g)       | 9.8 m.s\(^{-2} \) | – |
| Viral decay rate (\( \lambda \))      | 0.63 h\(^{-1} \) | – |
| Droplet temperature (\( T_d \))       | 35°C          | – |
| Ambient temperature (\( T_{\text{amb}} \)) | 25°C          | (10–40)°C |
| Viral load (\( v_c \))                | 10^8 RNA copies/ml | (10^7–10^{12}) RNA copies/ml |

**TABLE 1 Input parameters and constants**

3 | RESULTS AND DISCUSSION

The dispersion of a puff containing virus-laden droplets and aerosols exhaled during a cough expiratory event by an infected subject is analyzed using 1-D model described in the Materials and Methods section.

3.1 | Input parameters and initial conditions

The puff is released at a height of 1.5 m (represents the elevation of infected subject’s standing position) in an indoor environment of volume 48 m\(^3\) (height of the room = 3 m) having an air-exchange rate of 1.0 h\(^{-1} \), representing a typical office environment. We consider the puff of cough droplets with a temperature of 35°C is released into an environment at the ambient temperature of 25°C at 50% RH, ideal condition for comfort working environment. A total number of 5000 droplets with lognormal number-size distribution (CMD = 14 μm and GSD = 2.6) is considered in this study. These expiratory droplets contain residues\(^7 \), settle by gravity while evaporating in ambient air. Other important input parameters/constant and their range are given in Table 1. All the governing equations are numerically solved together in the Mathematica\(^{30} \).
Comparison of Falling-to-Mixing-Plate-out model results with falling droplet and uniformly mixed models

Early works of Wells and other studies highlight the dependence of lifetime of the droplets on ambient parameters such as temperature, relative humidity, air speed, and droplet properties such as its size, constituents, and temperature. The falling droplet evaporation model considers the droplet evolution processes in a localized space without considering the boundary wall deposition and ventilation effects. Also, some of these models do not consider detailed droplet composition, and hence, large variation in the final droplet diameters (~20%-50% of the initial values) which will lead to considerable error in the modeling of airborne droplet concentration. On the other hand, homogeneously mixed model assumes uniform mixing of expiratory droplets/aerosols in the indoor volume immediately. This model lacks the handling of spatial variation of the aerosol concentration that affects other accompanied processes. A study is carried out to compare these two models with the present formulation for non-evaporating rigid droplets released at a height of 0.3 m in an indoor room environment with a ventilation rate of 0.5 h⁻¹. The results are presented in Figure 2. From Figure 2, it is quickly apparent that neither falling droplet model nor homogeneously mixed chamber model could adequately describe all the effects if we include coarse as well as submicron particles for assessing risks.

The present model (Equations (1–9)) results show smooth transition of residence time from the falling evaporating model to uniform mixing model as illustrated in Figure 2. These results confirm that the present approach seamlessly integrates all the important processes that governs the residence time of virus-laden droplets and aerosols in a typical indoor environment.

Temporal evolution of droplet diameter of individual droplets undergoing evaporation

The rate of evaporation of droplets and its composition determines the final size of airborne droplets/aerosols (virusols) which play a key role in governing their residence time in the indoor atmosphere. To study these effects, the virusols residence time is estimated at different RH, and compared with that of droplets without solute. The temporal evolution of single droplet diameter (14 μm is chosen since its CMD of the cough droplets considered in this study) at different RH and composition is shown in Figure 3A. At a lower RH (10%), the water vapor content in the atmosphere is less and hence the rate of evaporation is highest. So, the droplet quickly evaporates and reaches a steady size value (~6 μm) in a time period of 0.12 s and 0.3 s for an RH value of 10% and 50% respectively. At higher RH values (90%), the evaporation rate is least due to the saturated water vapor pressure in the indoor environment and hence, it takes more time (> 1 s) to reach the final size. Thus, the results (time scale) clearly show that it is important to integrate the evaporation process with other processes described in the governing equations.

Apart from the atmospheric conditions, the composition of the droplet also plays an important role in determining the rate of evaporation and final size of the droplet. The presence of salt (residue) content reduces the vapor pressure of water thereby leading to lower rate of evaporation and larger final size of the droplet. The comparison of variation of droplet size as a function of time for RH = 50% clearly indicates this fact as the final size reaches to 6.1 μm in the presence of solute while the pure water droplet evaporates completely in ~0.3 s (Figure 3A). The rate of evaporation of droplet thus depends on the volatile content of the droplet along with the ambient conditions.

Furthermore, the final size of all the droplets as a function of initial droplet size is presented in Figure 3B. The overall reduction in the final size is about ~55% for all particle sizes (i.e., droplet with a size of 100 μm reduces to ~45 μm) in the case of RH = 50% and for the given residue composition. This size reduction is more pronounced if solute content in the saliva is reduced as discussed above. It is to be noted that the initial droplet may be large enough to settle down under the force of gravity but simultaneous evaporation will reduce the size significantly (depending upon the atmospheric conditions), thereby reducing the gravitational effects and leading to higher residence time in the air.

Effect of AER on virusol mean residence time

The effect of AER on virusol mean residence time is studied with two different relationships of AER vs D: (i) D as a function of AER given by, and (ii) D is independent of AER, is shown in Figure 4. The bulk diffusion coefficient varies from ~10⁻³ m²/s to 1.1 × 10⁻² m²/s for AER of 0 to 5 h⁻¹ in a room volume of 48 m³. The virusol mean residence time decreases from 960 s to 410 s as the AER increases from 0 h⁻¹ to 5 h⁻¹, in the case of D ≠ AER. For the constant D case, the variation of mean residence time is from 1040 s (0 h⁻¹) to 500 s (5 h⁻¹). These results show that the virusol mean residence time decreases monotonically when the AER increases; however, the reduction is only 0.43 times when the AER is increased from 0 h⁻¹ to 5 h⁻¹. Hence, a large AER is required to reduce the virusol exposure significantly.

Effect of release height and ventilation rate on MRT

The virusol mean residence time of droplets as a function of initial droplet size is compared for different heights of release (z₀ = 0.3 m or 1.5 m) during an expiratory event. The lower value of release height (0.3 m) is chosen to illustrate that the cough cloud does not settle immediately on the ground and buoyancy helps to lift the puff and droplets survives for reasonable time compared to higher release height in the indoors. The mean residence time of the
3.6 Effect of viral load on number-size distribution and MRT of virusol system

Viral concentration in the biological fluid and the process of incorporation of virus in the expiratory droplets/aerosols plays a crucial role in determining the total residence time of virus-laden airborne particles, which is addressed through the concept of virusols. Most of the studies consider virus load in the airborne droplet as linearly proportional to the droplet volume. However, the atomized droplets during the expiratory activity show that the presence of virus in the expiratory droplets/aerosols is a function of viral concentration and droplet size, and it is governed by the Poisson distribution as given by Equation (9).

The initial and final (at \( t = 100 \) s) number-size distribution of virusols are compared with initial complete droplet size spectrum in Figure 6. The complete droplet spectrum which has a CMD of 14 \( \mu m \) contains the droplets/aerosols starting from \(-0.3 \mu m\) onwards with viral load proportional to their volume without considering the Poisson distribution of virions in the droplets. On the other hand, it is very clear from Figure 6 that the introduction of Poisson probability limits the lower particle size of virusols, and the probability of the droplet being virus-laden (virusol) increases with its size. For example, the initial viral number-size distribution (at \( t = 0 \)) shows that the lower cut-off virusol diameter is \(~5 \mu m~\) and \(~1 \mu m~\) for viral load of \(10^6~\) and \(10^{11}~\) RNA copies/ml (corresponding to severe cases) respectively. This shows that there is very low probability that smaller droplets will contain any virus in the case of low viral load (mild-to-moderate cases) in biological fluid (e.g., saliva). It is interesting to note that there is a larger difference in the concentrations at the lower size spectra shows that most of the particles greater than \(~70 \mu m~\) are removed from the system mainly due to gravitational settling; also, the evaporation process plays an important role in shifting the droplet spectrum in the range of \((22\text{–}70) \mu m~\) significantly (Figure 6).

We further study the effect of virus concentration on the residence time and exposure for a wide range of concentration from \(10^3~\) to \(10^{12}~\) RNA copies/ml, and the results are presented in Figure 7 for various RH. The virusol residence time varies from \(~100~s~(RH = 90\%)~\) for viral load \(<10^6~\) RNA copies/ml to \(~1200~s~(RH = 10\%)~\) and viral load \(>10^{11}~\) RNA copies/ml. The results further show that MRT of virusols in the severe cases (viral load \(>10^{11}~\) RNA copies/ml) is eight times to that of mild-to-moderate cases \(<10^6~\) RNA copies/ml) for RH = 50\%, and this ratio increases with RH. As RH increases from 10\% to 90\%, the evaporation rate reduces which leads to larger final size of droplet; hence faster settling and smaller residence time. The study results show that the MRT of virusols increase with viral load and saturates to a constant value beyond \(10^{11}~\) RNA copies/ml for the given conditions, which clearly show larger dependence of virusol residence time on virus load.

The exposure to these virusols can be obtained from the mean residence time using the relationship, \(\frac{T_{BR} \cdot C_v}{V}~\), which is defined as the number of virions breathed in during MRT of virusols \(T_{BR}\) where \(BR\) is the breathing rate \((\sim 10 ~\text{lpm})\), \(V\) is the room volume, and \(C_v\) is the total virions released during the expiratory event. For example, if we consider a viral load of \(10^6~\) RNA copies/ml (RH = 50\%), then the mean
residence time is 150 s (Figure 7) and corresponding exposure is 0.23 virions considering room volume of 48 m³. This result shows that exposure to a single virion is possible only if the viral load in the biological fluid is more than 10⁶ RNA copies/ml. However, if the viral load is 10¹⁰ RNA copies/ml (severe case), then the mean residence time is 1050 s (Figure 7) and the corresponding exposure is 1.6 × 10⁴ virions. These study results show that higher residence time and survival fraction would lead to higher exposure of person contracting the virus, beyond a certain cut-off viral load in the biological fluid. The residence time of the droplets thus plays a significant role in estimating the viral exposure.
exposure to an individual, and it depends on many parameters such as particle size, viral load, process of incorporation of viral copies in the droplet, height of release, turbulent diffusion coefficient, AER, and RH.

4 | CONCLUSIONS

The present conjoined model, “Falling-to-Mixing-Plate-out”, smoothly transits from evaporating and falling droplet model by considering all the important processes that govern the virusol residence time and exposure in an indoor environment. The residence time estimates from the conjoined model lie between that obtained by pure gravitational settling and classical surface-plate out model. The present 1-D model is good enough to quickly estimate virusol residence time and exposure to the individual as their results are closer to 3-D system, particularly for droplets >0.1 µm. The present work thus provides a comprehensive theoretical study from

**FIGURE 4** Mean residence time of virusol as a function of diffusion coefficient and AER.

**FIGURE 5** Variation of mean residence time with respect to droplet diameter for different on ventilation rate and release height.
the droplet emission to inhalation exposure using residence time estimates.

Study results indicate that virusol system residence times could be far less than that for the complete droplet cloud system, and smaller droplets (<20 μm) are more likely to be blanks in mild-to-moderate cases. Virusol system will settle down faster than the complete droplet system and hence less likely to be airborne when the biological viral load is <10^8 RNA copies/ml. However, greater viral load in the biological fluid leads to longer residence time of virusol system. This has important implications from an air cleaning perspective aimed at COVID-19 risk mitigation in enclosed spaces. It may not be necessary to capture ultrafine particles as these would be generally harmless; one may relax filtration efficiency criteria limiting them to essentially larger particles, thereby opting for coarser filters and reducing pressure.
drops and increasing air circulation rates. This has far reaching implications in adopting intervention technologies in indoor spaces.

Also, there is a significant shift in the geometric mean diameter of viruses as compared to that of the complete size spectrum and it has practical implication to risk assessment. On the whole, we have effectively demonstrated that virusol size distribution and residence times are distinctly different from the ensemble of total droplets and will be a critically useful concept both for intervention technologies and lung deposition modeling. These implications are under investigation.

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CONFLICT OF INTEREST
The authors declare no competing interests.

AUTHOR CONTRIBUTIONS
Y.S.M. and A.S. initiated the study and suggested the research method; S.A. and S.B. collected and analyzed data for the research method; J.K., Y.S.M., and A.S. performed numerical calculations and prepared figures; A.S. and Y.S.M. wrote the manuscript; S.B. and J.K. helped in preparation of the manuscript. All the authors reviewed the manuscript.

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SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section.

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