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*Research Article*

# CFD Simulations of Small Particle Behavior with Blower-Driven Airflows in Single-Family Residential Buildings

**Yigang Sun, Paul Francisco, Zachary Merrin, and Kiel Gilleade**

*Champaign County Regional Planning Commission, Champaign, IL, USA*

Correspondence should be addressed to Yigang Sun; ysun@ccrpc.org

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Inhaling airborne droplets exhaled from an infected person is the principal mode of COVID-19 transmission. When residential energy efficiency workers conduct blower door tests in occupied residences with a COVID-19-infected occupant potentially present, there is a concern that it could put the workers at risk of infection with massive flows of air being generated by the tests. To minimize this risk, computational fluid dynamics (CFD) simulations were conducted for four prototype houses to develop guidelines for workers to follow during their service visits. The CFD simulations visualized the movements and evaluated the residence time of small particles released at certain locations under a series of scenarios representing situations that are likely to be encountered during in-home energy efficiency services. Guidelines were derived from the simulated tracks of droplets to help to increase the safety of the worker(s).

## 1. Introduction

Inhaling airborne droplets exhaled from an infected person is the principal mode of COVID-19 transmission [1]. Human expiratory activities, including breathing, speaking, coughing, and sneezing, produce thousands of droplets with various sizes. The number and size ranges of droplets exhaled per activity have been reported to be highly variable by different researchers with different measurement methods and different subjects [2–12]. In general, the sizes of the exhaled droplets at the mouth and nose openings range somewhere from submicron up to 2000 $\mu$m with most of the droplets falling in the range of 0.3 to 100 $\mu$m. The original droplets from breathing are under 20 $\mu$m. There are small differences between nose breathing and mouth breathing in terms of the sizes of their produced droplets, but nose breathing may produce a lower number of particles [10]. The presence of viral infections could also change the distribution of droplet sizes [13].

The size of a droplet has a dominant effect on its behavior in an airflow field. Larger droplets ($\geq$100 $\mu$m) fall to the ground quickly, while small water droplets ($\leq$50 $\mu$m) will evaporate completely before they can reach the ground [14, 15]. The evaporation process is mainly affected by ambient air's relative humidity (RH) and droplet's size. With water as their main content, droplets exhaled from humans also contain some nonvolatile contents such as salt, protein, and surfactant [16]. Diameter ratios of the postevaporation to original droplets are typically in the range of 20%–40% (volume ratio range: 0.8%–6.4%) with different assumptions of protein concentration in the droplets [17] or from 19% to 100% (volume ratio range: 0.68%–100%) with different levels of air RH [18]. The concentrations of nonvolatile contents vary between individuals and within individuals over time, and it is likely the concentration will increase with a respiratory infection [16]. Small droplets generated by coughing, sneezing, speaking, and breathing rapidly evaporate into nuclei [11], and most of droplet nuclei generated by coughing are in the size range of 0.74-2.12 $\mu$m [12]. In fact, it is droplet nuclei, around 5 $\mu$m or smaller in diameter, that have been associated with airborne transmission of pathogens [3, 19, 20]. These small particles of droplet nuclei generated by an infected person can float in the air for a long time and can closely follow airflows to anywhere inside and outside the building.

Many home performance entities attempted to resume their residential energy efficiency services in 2021, the second year of the COVID-19 pandemic in the United States, with the goal of a return to normal operation. However, there were concerns about the risk of the virus exposure to the workers during a service, especially blower door testing, in a customer's home with a potentially infected occupant present. This concern triggered the need for additional guidance that the workers should follow to minimize the risks and to decrease the chances of virus transmission in the buildings.

As a diagnostic tool for building energy professionals, blower door testing [21] is widely used to assess a building's airtightness, pinpoint specific leaks, determine the need for additional mechanical ventilation, and estimate space conditioning loss resulting from air leakage. For a typical blower door test in a single-family residential house, all doors and windows are closed and fan is installed within an airtight shroud in an exterior door, often the front door. The fan is turned on and exhausts air from the house until a 50-pascal (Pa) pressure difference is achieved between the house and outdoors. The quantity of airflow this requires is measured in cubic feet per minute (CFM) and recorded as the CFM50 of the home. It is also possible, although less common, to conduct the blower door test in depressurization mode where the fan blows air into the house instead of exhausting it from the house. Blower door testing generates large air flows near the fan and could conceivably allow airborne droplet nuclei to travel further and at a higher concentrations, potentially increasing risk.

To assess the concern and provide scientific bases for the guidance development, it is necessary to examine the transport and the fate of the droplets exhaled by a potentially infected occupant inside a home, which can be studied experimentally and/or numerically. Compared to experimental methods, numerical modeling approaches are more convenient, time-saving, and cost-effective to investigate and visualize the transmission pathways of airborne respiratory droplets. Computational fluid dynamics (CFD), as the most popular numerical modeling tool, has been widely applied to model and investigate the dispersion of airborne particles and infectious agents in confined spaces, such as a hospital ward [22–31], a hospital isolation room [32–36], a hospital clinic room [37], a hospital waiting room [38], a children's recovery room [38], an intensive care room [22, 39], an operating room [40, 41], a classroom [42–53], an office room [54–57], a conference room [58], a dining room [59], a restaurant [60, 61], small flats in a high-rise residential building [62], an elevator cabin [52, 63], an aircraft cabin [49, 64–68], a train cabin [49, 69], a car cabin [70, 71], a bus [72–75], a supermarket [52, 76], and meat and slaughter facilities [77, 78]. Most of the simulation spaces in these studies were small and simplified to a single room, while the size of the air space of the study subjects significantly affects the airflow patterns and the dispersion of respiratory droplets [78]. There have been a few published studies for simulating particle transports in building rooms with a comparable or larger floor area than the focus of this study, single-family residentials. Li et al. [60] tried to understand and explain an actual infection case of COVID-19 among different seats at three neighboring tables in a restaurant, a widely reported incident at the early stage of the COVID-19 pandemic, by conducting CFD simulations combined with an epidemiologic analysis and onsite experimental tracer measurements. The droplet spread pattern predicted with the visualized streamlines and the concentration of predicted infectious droplet nuclei obtained from the simulations was consistent with the actual infection distribution in the case. Another CFD simulation study by Liu et al. [61] on the same infection case as Li et al. [60] provided spatial distribution maps of the airborne virus-laden aerosol in the restaurant, consisting with the reported infection patterns. Ren et al. [57] investigated the impact of physical barrier heights on the spread of aerosol particles in an open office environment. The infection risks at different locations with different virus source positions were evaluated based on the concentration distribution of the gaseous pollutant, representing the exhaled droplets from a virus source, derived from their CFD simulation results. Ren et al. [51] also investigated the impact of window openings and implementation of window-integrated fans on the airflow distributions and infection risk in a naturally ventilated classroom with CFD simulations. Cui et al. [76] studied the transport of virus-laden particles in a supermarket by coupling CFD with Lagrangian particle tracking. They assumed that only the mechanical ventilation induced the indoor airflows, which could significantly enhance the transport of particles. Kumar et al. [78] modeled the airflow patterns and the dispersion of sneeze droplets in a large meat facility with CFD simulations. They found that the location of the asymptomatic sneezer critically affected the droplets' spreading behavior, and the airflow pattern inside the facility dominated the droplet's dispersion pattern. Despite the large number of publications about droplet spreading in an indoor environment, none was found that address single-family residential buildings or a blower door test scenario.

This paper reports on the results of CFD simulations to visualize and evaluate the movements and residence time of small particles under a series of scenarios representing situations that are possible during in-home building diagnostic services using blower doors in typical single-family buildings.

## 2. Methodology

Commercial CFD software ANSYS Fluent 2020R2 was used in this study to develop the CFD model and conduct the simulations with the Lagrangian discrete phase modeling approach being used to track droplet nuclei under different ventilation conditions. The RNG $k$-$\varepsilon$ model was chosen as the turbulence model in the simulations based on our experience and other research for simulating indoor airflow fields in the past [79, 80]. Among all commonly used computational models for turbulent flows, which could be practically handled with a personal computer, the RNG $k$-$\varepsilon$ model generally performs the best, or nearly the best for indoor airflows according to past comparisons.

*2.1. Building's Floor Plans and Their Simulation Physical Domains.* After consulting with the sponsor, four floor plans were selected, which attempted to show a diversity of layouts and replicate common single-family homes in the sponsor's service territory, for the simulations. The floor plans are shown in Supplementary Information S1 (floor plans). Each of the first three houses has about 1500 square feet (~140 $m^2$) of floor area, while house 4, which has split-level construction, has about 1730 square feet (~160 $m^2$). A blower door fan is virtually installed at the front door of each house. To facilitate the CFD simulations, no human body was present and there was no heat source other than the warm droplets inside the physical domain of the simulations. The simulation physical domains contain the air spaces enclosed by the house envelopes, which will be further discussed in the boundary conditions below.

*2.2. Droplet Release.* Considering the size range of the droplets produced from breathing and the fast evaporation of small droplets, we chose droplets in the size range of 1–10 $\mu$m with a Rosin-Rammler distribution [81] and treated them as nuclei without evaporation in the simulations. We used a droplet release source with a virtual cone shape with a diameter of 30 mm (1.2″). In the four houses to be simulated, a droplet release source was set in alignment with or perpendicular to the fan direction and located at the middle point between the front and back walls in the living room at the height of 1.6 meters (5′3″); this represented a person standing in the living room. Another droplet release location was also put in a distant room from the front door; this represented a person who was staying in a distant room to maintain social distancing. The initial speed of the exhaled droplets was set at 0.5 m/s, considering that the range of breathing droplet velocity is normally from 0.1 to 1 m/s [82].

*2.3. Air Condition.* The temperature and relative humidity of infiltration air into each of the houses were set at 23°C (73.4°F) and 50% (vapor mass fraction = 0.86%), respectively.

*2.4. Boundary Conditions.* In the real world, outdoor air infiltrates a building through myriad openings, joints and cracks in walls, floors and ceilings, and around windows and doors during the depressurization process by a blower door fan. For a CFD model, a practical way to account for the overall infiltration flow for a blower door test is to set the boundary surfaces of walls, floors, and ceilings as velocity inlets directly.

To determine the air velocity on each boundary surface as an air inlet in the CFD models, more assumptions are needed. In this study, we assume there is no air penetrating any part of the floors in all the four houses, and the infiltration and exfiltration air can only go through the house's side walls and ceilings. We also explore both depressurization and pressurization blower door tests. During the 50 Pa depressurizing process in a blower door test, the amount of infiltration air through the ceiling would account for 18% of the total infiltration air [83], while the infiltration air through all the side walls would account for the remaining, i.e., 82% of the total regardless of the area ratio of the side walls to the ceiling. The total amount of the infiltration air would be equal to the airflow exhausted through the blower door fan.

For CFD simulations of a 50 Pa pressurization blower door test, the boundary conditions of the exfiltration air velocities on ceiling and wall surfaces would be set at the same magnitudes as the infiltration air velocities in the depressurizing process, but in their opposite directions. Additionally, the same overall leakage value for the home was used in both cases.

*2.5. Simulation Scenarios.* For each of the four houses, six ventilation scenarios were simulated. Scenarios (1) and (2) are the typical cases while running the blower door fan. Scenarios (3)-(6) aim to represent different situations when a home is at its normal condition or the condition with a blower door installed at the front door but without the fan operating. It is very difficult, if not impossible, to accurately simulate the conditions of the homes with fluctuating wind outside and the resulting variable infiltration. However, most of the situations encountered by a residential energy efficiency worker during his/her service visit to a home is likely similar to one of the six scenarios or in a transition state among them. The findings from the simulations of these scenarios can address most situations during a blower door test visit. The six simulation scenarios are listed below:

(1) 50 Pa depressurization case: a blower door fan at the front door is depressurizing each of the houses with a 3000 cubic feet per minute (CFM) flowrate, i.e., CFM50 = 3000 CFM. The infiltration air through the ceiling was set as 540 CFM, while the infiltration flowrate through all the exterior walls was 2460 CFM. All the airflows were in the steady state, and the air velocity was uniformly distributed on each of the surfaces

(2) 50 Pa pressurization case: this case was set the same values as in case (1) except each of the airflows had an opposite direction, and the infiltration in case (1) became exfiltration in this case

The seasonal average air infiltration rate of a residential house at its normal condition would be of the order of one-twentieth of the measured air change rate at 50 Pa [84, 85], which can be assumed to be roughly the calculated infiltration rate at 0.5 Pa from the CFM50, i.e.,

$$\bar{Q}_{\text{inf}} \approx \frac{1}{20}\text{CFM50} \approx \text{CFM50} \times \left(\frac{0.5\ \text{Pa}}{50\ \text{Pa}}\right)^{0.65}. \quad (1)$$

For simplicity's sake, we denote these scenarios with "seasonal average," which is abbreviated as "S.A." in the result figures.

(3) Seasonal average with fan-outlet case: a blower door fan was installed at the front door but not in operation. The fan hole was totally open. It was assumed that the house had an exfiltration of 150 CFM (one-twentieth of 3000 CFM), which was totally flowing

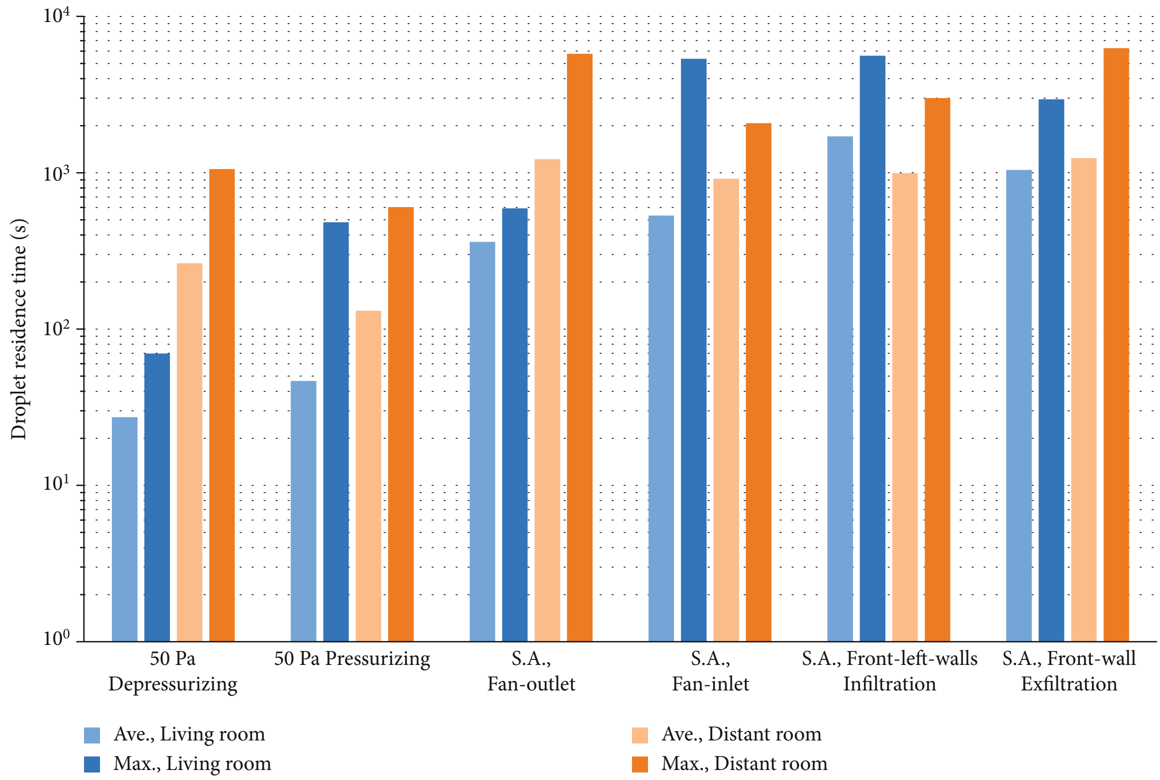


FIGURE 1: Residence time of droplets in house 1.

out of the house through the fan hole. The outside air infiltrated into the house through the rear and the right walls. No air was getting into or out of the houses through the ceilings, the left and the front walls, and the floors

(4) Seasonal average with fan-inlet case: the same as (3) except an infiltration of 150 CFM was flowing into the house through the fan hole; air flowed out of the house through the rear and the right walls and the ceilings; the exfiltration air through the ceilings was set at 27 CFM, while the exfiltration air through the right and the rear walls was 123 CFM. No air was getting into or out of the houses through the left and the front walls and the floors

(5) Seasonal average with front-left-wall-infiltration case: the fan hole was covered and treated as a part of the front wall. An infiltration of 150 CFM was flowing into the houses through the left and the front walls. The same amount of exfiltration air flowed out of the houses through the rear and the right walls and the ceilings. The exfiltration air through the ceilings was also set at 27 CFM, while the total exfiltration air through the right and the rear walls was 123 CFM

(6) Seasonal average with front-wall-exfiltration case: the same as (5) except that the rear walls were the air infiltration surfaces, while the front walls and the ceilings were the air exfiltration surfaces

## 3. Results and Discussions

The average and maximum of the droplet nuclei retention time in the house interior air spaces from the simulation results are shown in Figures 1–4, respectively. The droplet nuclei tracks generated in the simulations for each ventilation scenario are shown in Supplementary Information S2 (droplet nuclei tracks). The simulation animations of the droplet nuclei tracking can be accessed in the following link: https://www.youtube.com/playlist?list=PL8m47d3M-Obxo_H1cZk39_yR9YUJREBVM. From the droplet tracks, we can deduce some guidelines which indicate safer areas for workers to stay during their services in the houses under a variety of scenarios.

From Figures 1–4, it can be seen that running a blower door fan at the front door of the houses, either depressurizing or pressurizing to 50 Pa, shortened the droplet residence time by around an order of magnitude, thus decreasing the average droplet concentrations significantly, compared with the normal situations in the houses. During a depressurizing test, the tracks of the droplets released in the living room were predictable and occupied a relatively small space which a worker could easily avoid. When there was a droplet release source in a distant room, pressurizing could keep the droplets inside the room and make other zones outside the room safe even though the droplet residence time in this case might be longer than the depressurizing operation. Except in house 1 for the case where the droplet release was in a distant room, pressurizing resulted in longer residence times regardless of where the droplet release was from,

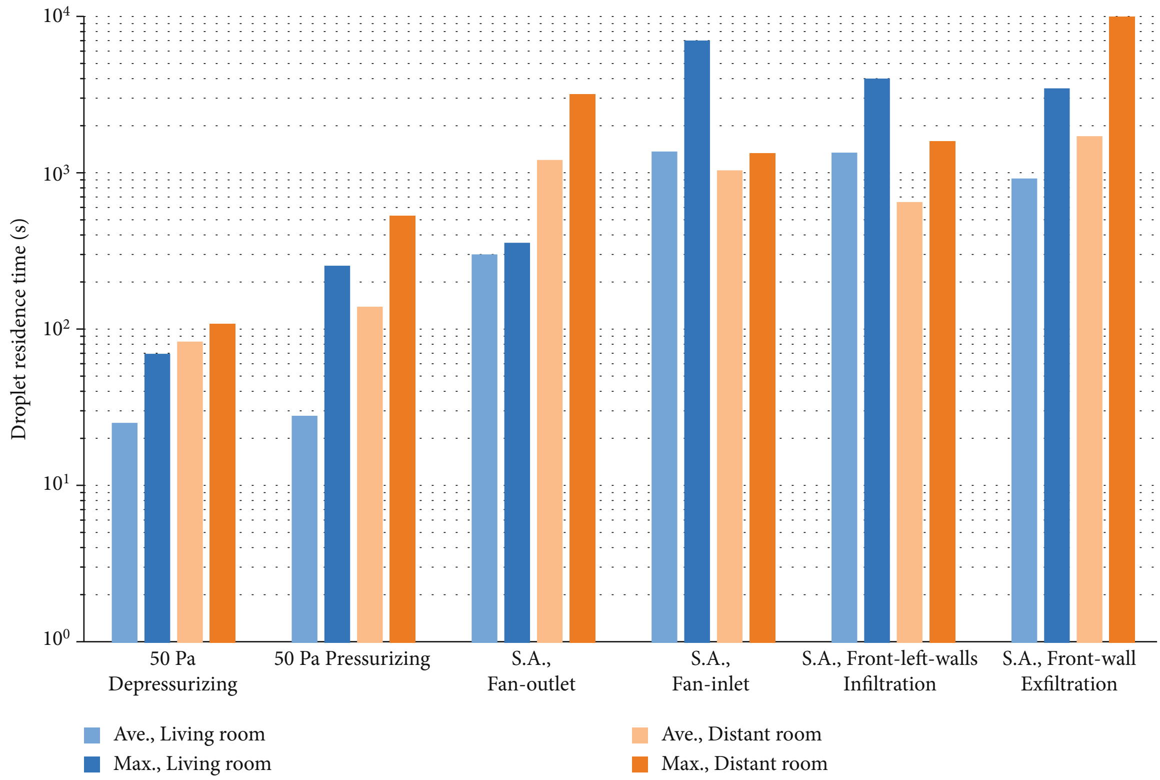


Figure 2: Residence time of droplets in house 2.

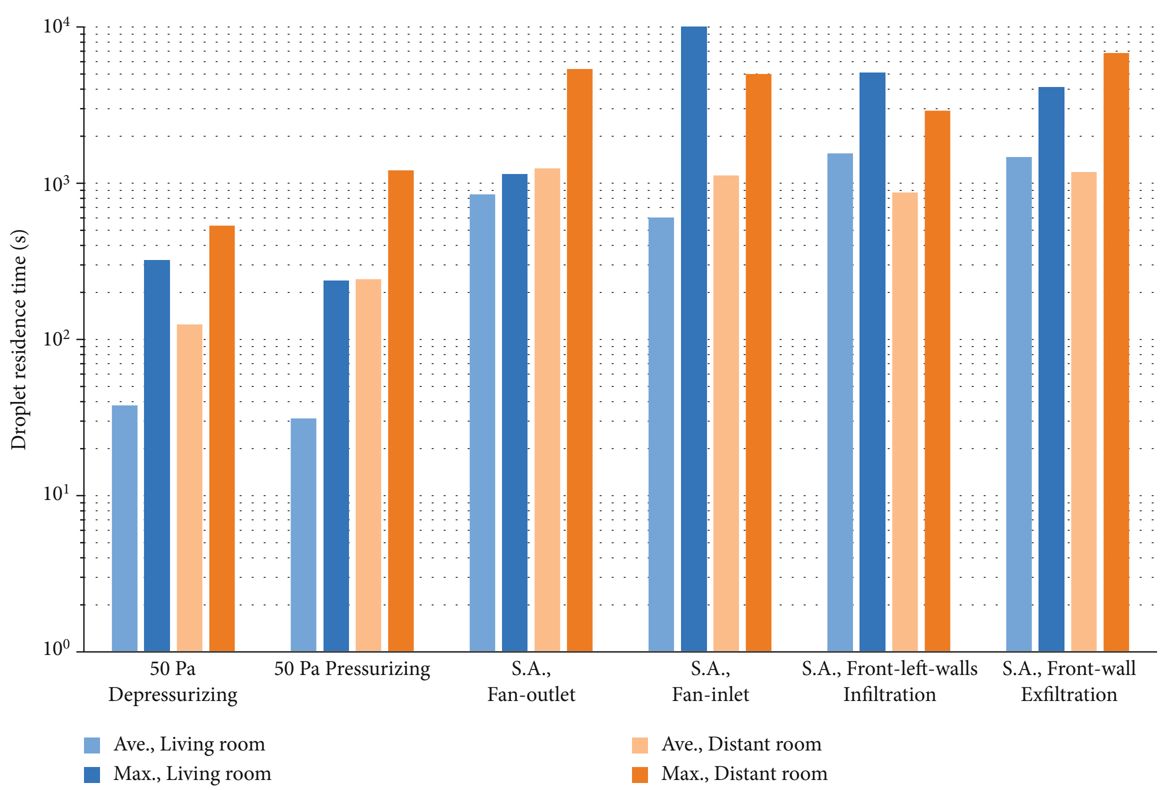


Figure 3: Residence time of droplets in house 3.

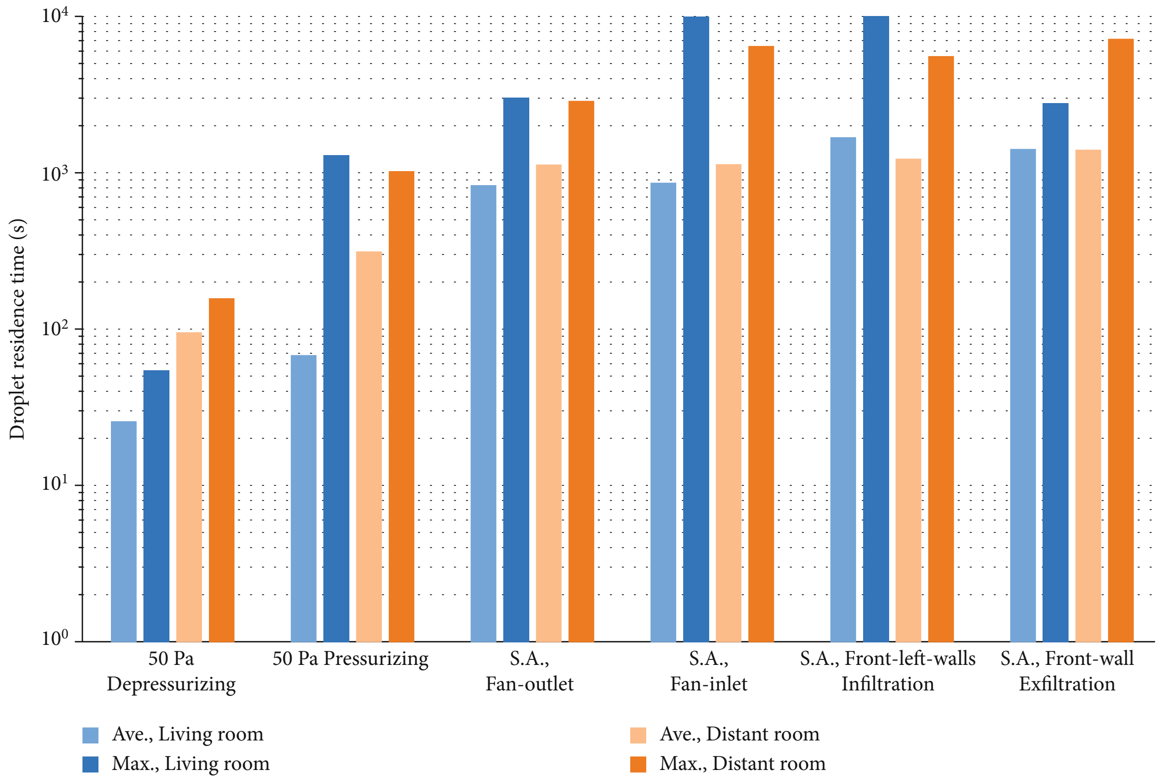


Figure 4: Residence time of droplets in house 4.

suggesting that depressurization blower door tests will generally be preferred over pressurization tests. Additionally, the results show that running a blower door is safer than not doing so, potentially identifying opportunities to improve safety throughout the time in the home by having the fan operating at some level at all times.

*3.1. 50 Pa Depressurizing Case.* When the droplet release source was in the living room, the majority of droplets were exhausted out of the houses through the fan hole, while the rest deposited on surfaces, especially the front door area with the blower fan installed and nearby. The ratio of the exhausted droplet number to the depositing droplet number was mainly related to the entrance space. The ratio would be high when the entry opens into a large room as in houses 3 and 4. The overall average residence time of the droplets was 27.3 seconds in house 1, 25.6 seconds in house 2, 37.4 seconds in house 3, and 26.0 seconds in house 4, respectively. A small number of droplets stayed around in the entrance hallway within about 6 feet from the door panel and suspended in the room air longer than the others before either exiting the houses or depositing on surfaces. Therefore, to maximally limit exposure, workers should stay at least 1.8 meters (6 feet) away from the front wall during the 50 Pa depressurization and have an offset of at least 1.2 meters (4 feet) from the line from the droplet source site to the fan.

When the droplet release source was in a distant room, the droplet residence time would be much longer than in the living room, and the droplet plumes in the living room would be much thicker if the entry opens into a large room as in houses 3 and 4. The ratio of the exhausted droplet number through the fan hole to the depositing droplet number would not be related to the entrance space and became much lower than the cases when the droplets were released in the living room in the houses except house 3. In house 3, the droplet plume from the distant room needed to make two relatively sharp turns on its way to the fan, which left more droplets trapped on wall surfaces and the ratio much smaller in this house than in other three houses. The ratio in house 3 in this case was even lower than that in the seasonal average with fan-outlet case, which was also different from other three houses, because a sharp turn makes droplets at higher speeds be trapped on surfaces more easily.

*3.2. 50 Pa Pressurizing Case.* When droplets were released in the living room, the jet flow generated by the fan to pressurize the houses would disperse the droplets to everywhere in the living room, and some of droplets would also enter other rooms before they deposited on surfaces. It would not be safe for a worker to stay in the living room in this case.

When the droplet release source was in a distant room, which has at least one exterior wall, the droplets would likely be kept in the room and would not travel to other rooms.

*3.3. Seasonal Average with Fan-Outlet Case.* In this case, the fan was not in operation, but the fan hole was open. It was assumed that the air exchanged between the indoor of the houses and the outside was caused by a steady wind. The rear and the right walls were on the windward side, while the front and the left walls were on the leeward side. All the exfiltration air flowed out of each of the houses through the fan hole, and there was no airflow penetrating the front and the left walls and the ceilings.

Although the majority of droplets flowed out of the houses as in the 50 Pa depressurizing cases when the droplet release source was in the living room, the ratio of the exhausted number to the depositing number related to the entrance space in the opposite way from the 50 Pa cases. The ratios were much higher in houses 1 and 2, which have a narrow hallway, than in houses 3 and 4, whose entries open into a large room. Compared with the 50 Pa cases, these seasonal average with fan-outlet cases had much longer droplet residence time. The overall average residence time of the droplets was 6 minutes in house 1 (13.2 times longer), 5.1 minutes in house 2 (12 times longer), 14 minutes in house 3 (22.4 times longer,) and 14 minutes in house 4 (32.3 times longer), respectively. The concentrations of the droplets in the plume of the droplet tracks would increase with the decrease of the droplet movements. If a person stayed in the droplet track plumes, they would have an exposure dose about the times higher as last mentioned in the seasonal average cases than in the 50 Pa depressurizing cases (e.g., 12 times higher in house 2). Therefore, to limit exposure, a worker should avoid the droplet track plume. If a worker needs to go between the droplet source site and the outlet, he or she should face to the front wall and stay at least 4 feet from the center line of the plume.

When droplets were released in a distant room, the ratio of the exhausted number to the depositing number would be smaller than the cases when droplets were released in the living room, but the droplet plumes would be thicker and the safe zone in the living room would become smaller.

Unlike the 50 Pa depressurizing cases, there was little circulation of the droplets in the entrance hallway near the front wall in the seasonal average with the fan-outlet cases. Thus, workers could stay close and face to the fan for setting up the blower door equipment without an even higher chance of exposure to the droplets, though the exposure was already significantly higher in this case than with the blower door running.

*3.4. Seasonal Average with Fan-Inlet Case.* The setup of this case was the same as the seasonal average with fan-outlet case, but the wind direction was the opposite. It was assumed that the rear and the right walls were on the leeward side, while the front and the left walls were on the windward side. All the infiltration air flowed into each of the houses through the fan's open hole, while the exfiltration air got out of the houses through the rear and the right walls and the ceilings. There was no airflow penetrating the front and the left walls.

When droplets were released in the living room, although the average residence time of droplets in each house in this case was comparable to that in the fan-outlet case, the maximum residence time would be hours longer, from over 2 hours to nearly 4 hours. Some of the droplets could travel back to the fan area. The safest place for a worker to stay would be the area near the front wall and beside the fan since that was where the outdoor air was entering, but exposures were still likely to be much higher in this scenario than in the previous cases.

When the droplet source was in a distant room, droplets would be kept in the room and eventually deposit on surfaces.

*3.5. Seasonal Average with Front-Left-Wall-Infiltration Case.* In this case, the fan was not in operation and the fan hole was covered. Again, it was assumed that the air exchange between the indoor of the houses and the outside was caused by a steady wind. The rear and the right walls were on the leeward side, while the front and the left walls were on the windward side. Outdoor air infiltrated into each of the houses through the front and the left walls, while the exfiltration air flows out of the houses through the rear and the right walls and the ceilings.

Although their average residence time was long, droplets mostly floated to the inner parts of the houses and only traveled a very limited distance toward the fan direction. In the situations of houses 1 to 3, it would be safest for a worker to stay 6 feet or farther away from the droplet source location if they needed to be between the droplet source location and the fan. In house 4, in addition to the 6 feet and farther distance, a worker should also stay on the near side of the staircase and keep away from the staircase. Because many droplets would float toward the interior of the home, exposures could be greater during the full assessment than had the blower door been operating.

*3.6. Seasonal Average with Front-Wall-Exfiltration Case.* In this case, the rear walls were on the windward side, while the front walls were on the leeward side. Outdoor air infiltrated into each of the houses through the rear walls, while the exfiltration air got out of the houses through the front walls and the ceilings. No airflow penetrated the left and the right walls.

The droplet plume in each house moved much slower and expanded much more widely than in the 50 Pa cases. When droplets were released in the living room, the volumes of the droplet plumes in this case were roughly 7.9, 61, 19.2, and 9.0 times larger than in the 50 Pa depressurizing case in houses 1 to 4, respectively. The average droplet residence times in this case were about 38.2, 36.6, 38.9, and 55.1 times longer than in the 50 Pa depressurizing case in houses 1 to 4, respectively. If we assume that the droplet number produced each breath and the breath rate of the potentially infected person is consistent, the droplet concentrations within the plumes in this case would be 4.8, 0.6, 2.0, and 6.1 times higher than in the 50 Pa depressurizing case in houses 1 to 4, respectively. All the houses except house 2 had a larger droplet plume and a higher droplet concentration in the plume at the same time. Although the droplet concentration in the droplet plume in house 2 in this case was only 60% of that in the 50 Pa depressurizing case, the plume volume was over 60 times larger in this case. Overall, there was a much higher chance to get a higher dose of exposure for a worker to stay downstream of an infected person in a typical wind infiltration house with its exterior windows and doors being closed than during a blower door test. There was no safe spot near the front door in this situation. In this case, it would be better to ask all the residents to stay in remote rooms far away from any upstream location of the workers.

The simulation results for all the seasonal average cases were based on the assumption that the infiltration was caused by a steady wind and a consistent stack effect. In the real world, wind is always fluctuating with both speed and direction. It is likely that the airflow fields and the droplet movements in the houses in most time are somewhere between these simulation results although the droplet residence time would be longer since they may move back and forth. Still, we can reach some conclusions and create some guidelines based on these simulation results.

## 4. Concluded Guidelines

The simulation results show that running a blower door fan to depressurize a house to 50 Pa will shorten the droplet residence time significantly, thus decreasing the average droplet concentrations significantly, compared with the normal situations in the houses. During the depressurizing period of time, the tracks of the droplets released in the living room are predictable and occupy a small space where a worker could easily avoid. When there is a droplet release source in a distant room, pressurizing can keep the droplets inside the room and make other zones outside the room safer even though the droplet residence time in this case might be longer than the depressurizing operation. According to the simulation results, guidelines for workers to follow during their service visit have been developed.

In general, depressurization blower door tests provide the minimum potential exposure to virus-laden particles of the cases analyzed. Pressurization blower door tests can also be beneficial compared to not performing the test. The results also suggest that operating the blower door throughout the site visit can be beneficial, beyond the time needed to do the blower door test itself.

During the service visit with a depressurizing blower door test, the following tips will help to increase the safety of the worker(s):

(i) A blower door fan depressurizing a room to 50 Pa can effectively shorten the pathways and decrease the residence time of airborne droplets exhaled from an infected person. During the 50 Pa depressurizing process, a worker should ideally stay at least 6 feet away from the front wall and at least 4 feet away from either side of the droplet pathway from the droplet source site to the fan in order to minimize exposure

(ii) When the blower door fan is installed with its hole being open and being not in operation, the safest place for a worker to stay is the area near the front wall, and at least 4 feet away from the line from the droplet source to the fan center. If a worker needs to reach the fan, it would be better to keep his/her face toward the front wall and approach the fan from its either side to avoid being right in front of the fan

(iii) When the exterior windows and doors of a house are all closed without a blower door fan installed, or with a blower door fan installed but with its hole covered, this is the most dangerous situation, especially when outdoor wind fluctuates and changes its direction. It would be better to ask all the residents to stay in remote rooms far away from any upstream location, caused by outside wind, of the workers

The simulations conducted in this paper do not take account of the impact of sneezing or coughing jets on the airflow patterns, thus wearing face masks is highly recommended for the worker(s) and all the occupants, which would weaken the nose or mouth jet flow and make it more similar to a breathing flow. Since the guideline is developed from the six simulation scenarios without considering the fluctuations of the direction and speed of outside wind, this study cannot give guidance on those circumstances. If there is a diagnosed infected occupant in the home, the home service visit should be cancelled. During a service visit, all the occupants, without any of them being knowingly infected, should stay together in the living room if a depressurizing test is selected, or a remote room from the front door if a pressurizing test is selected, or outside if possible.

## Data Availability

The output data for and from the CFD simulations used to support the findings of this study are included within the article or the supplementary files.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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## Supplementary Materials

S1: floor plans. S2: droplet nuclei tracks. S3: animation list. *(Supplementary Materials)*

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