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Exploring the effects of ventilation and air-conditioned environments, on droplet and airborne transmission of SARS-COV-2

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Abstract

To assess the implications of air conditioning and ventilation on droplet and airborne transmission of SARS-COV-2, several scientific research databases were searched and cross-referenced. Then, an analysis was conducted on the findings pertinent to interaction between several environmental variables affected by HVAC systems and their effect on Virus transmission. The results suggest that airflow velocity may interfere with the trajectories of large respiratory droplets and aerosols. Lower relative humidity provided suitable conditions for virus survival whereas higher temperatures increased aerosol formation, but were detrimental to virus survival. Suboptimal temperatures and humidity can compromise pathogen filtration functions in the nose, while proper use of HVAC functions can help preserve them. Transmission of SARS-COV-2 is not affected solely by the virus's internal properties. Ambient conditions, whether natural or modified by HVAC systems can have a significant effect on the transmissibility and virulence of both the virus and virus-related sickness. The current infection prevention measures, such as social distancing, need to be revised in certain scenarios where natural ventilation or HVAC systems are involved. This will offer, hopefully, higher protection from infections with SARS-COV-2 and similar pathogens.

Keywords: Aerosols, Airborne, COVID-19, Droplet, HVAC, Ventilation.

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1. Introduction

The emergence of the novel severe acute respiratory syndrome coronavirus 2 (SARS-COV-2) virus has captured global attention. The rate and magnitude of infection spread has pushed the scientific community into a race against time to understand the mechanisms by which the virus spreads and infects healthy individuals. Initially, the world health organization announced that the virus can be passed between people via direct contact, or droplet transmission [1]. As a result, a set of precautionary measures has been put in place to help protect the public and curb the spread of the virus. In particular, the rule of 1-2 meter (or1.83 m or 6 feet in some regions) social distancing was implemented, requiring individuals to maintain a distance of 1 to 2 meters from other individuals to avoid contracting the virus-laden droplets.

However, as the pandemic progressed, so did our understanding of the virus's pathogenicity and transmissibility. A growing body of evidence suggests that respiratory transmission follows a more dynamic pathway than what was initially imagined, and that several external factors may affect how long and how far can the virus travel and remain infectious, casting doubt on the applicability of the 1-2 meter rule. Here, air conditioning or HVAC systems become important effectors as they can alter several physical parameters in an indoor environment, which can impact how respiratory droplets and airborne particles propagate and evaporate.

Those effects are of greater importance in certain regions and enclosed environments such as work, transportation, or shopping venues. We already know that some populations rely more on social distancing than on face masking as a protective measure [2, 3]. Apart from that, many nations and individuals invest heavily in Heating, Ventilation, and Air Conditioning (HVAC) systems, creating artificial indoor climates in many cases. Taking all that into consideration, it is crucial to review and analyze how these man-made conditions impact the course of the current pandemic.

Droplet and aerosol interactions with each other and with the environment are very complex, and these complexities cannot always be traced bit by bit through direct experimental studies. This is where Computational Fluid Dynamics Modeling (CFD), or its subset, Computational Particle Fluid Dynamics (CPFD) comes in handy. It is a cost effective, and reasonably accurate tool that can plot droplets and pathogens as finite set of particles and later solve the numerical equations that describe their spatial and temporal evolution, providing a good insight into the inner workings of the physical world that dominate infection spread and transmission. However, it is not common for such simulations to be incorporated in clinical scenarios and epidemiological models. This paper provides an overview about used models and attempts to bridge this gap.

2. Methods

PubMed, Google scholar, Mendeley were searched using a combination of the following terms – the terms were used individually and cross-referenced: SARS-COV-2, COVID-19, respiratory droplet, aerosol, airborne, ventilation, air conditioning, ambient airflow, air velocity, humidity, and temperature. The search results were then combined with authors' own selection of relevant studies mostly published from 2000 to 2020.

The backbone of the manuscript was based on papers that provided quantitative analysis of the interaction of three ambient environment elements (air velocity, relative humidity, temperature) with travel range and evaporation curves of respiratory droplets. Papers that met the selection criteria were stratified, and their results for each of the elements were compared back-to-back. The final conclusions were segregated into two scenarios: transmission via large droplets and via aerosols.

The search was later expanded to include secondary findings, which included literature discussing the relationship between HVAC and virus survival, host defense, contamination clearance, and reaerosolization. Databases were also explored for case reports on the spread of the SARS-COV-2 virus, including articles that discussed this transmission in conditions pertaining to improper air conditioning or ventilation setups. Additional searches were conducted for regional or global COVID-19 public health policies, as well as a brief historical background on the development of droplet and aerosol concepts.

3. Discussion

3.1. Basics of Droplet and Airborne Transmission

Respiratory transmission occurs when viruses are expelled from an infected person's mouth or nose through actions such as coughing, sneezing, talking, or exhaling, and then traveling through the air to enter the healthy person's mucosae (mouth, nose, conjunctiva). When viruses are released from the body, they are carried in larger "containers" called droplets, made out of saliva or mucus, and mixed with other inclusions like, epithelial cells, cells of the immune system, and physiological electrolytes (e.g., $Na+$, $K+$, $Cl-$).

The categorization of respiratory droplets versus aerosols depends on environmental conditions such humidity, temperature, and air flow, and there is no clear consensus on the cutoff between droplets and aerosols [4]. It can be seen that some authors go up to 100 μm with what they consider a border-line between droplets and aerosols, on the other hand, the World Health Organization (WHO) defines "droplets" as those with an aerodynamic diameter ≥ 5 μm, while smaller droplets of aerodynamic diameter ≤ 5 μm and dried out droplets (droplet nuclei) are usually named "aerosols" and are the vectors of the so called "airborne transmission"[5].

In the WHO model, droplets larger than 5 μm are heavy enough to fall onto the floor after crossing a distance of 1-2 meters, on the other hand, aerosols – which, by definition can be solid or liquid particles – are capable of remaining suspended in the air/gas for an indefinite period of time, which as a result can carry pathogens to longer distances and for much longer periods of time [6, 7].

The works on droplet and airborne infections were pioneered in the beginnings of the 20th century by Wells [8] who conceptualized the Wells curve Figure 1, which described the relationship between a droplet's size, and it's falling/evaporation gradient.

While Wells acknowledged that other environmental factors do affect a droplet's behavior and fate, he considered size the major determinant of a droplet's propensity to either settle or completely evaporate while traversing the standardized 1-2-meter distance, he concluded that "droplets less than 0.1 mm diameter ejected from the mouth may be assumed to dry before reaching the ground"[8].

Wells' works have been subject to further revisions and critiques over the years, and recently, the 1-2 m /6 feet rule has been heavily criticized by many researchers, all of whom have pointed out that droplets are able to travel farther than what he had speculated [9-11]. Yet, the static "large vs small" droplet dichotomy has barely changed, outlining up till now how infection control protocols and public health policies are constructed.

3.2. Corona Virus and Risk of Airborne Transmission

As stated earlier, the World health Organization declared that SARS-COV-2 can be transmitted mainly through droplets, but not aerosols, except in medical facilities during aerosol generating procedures (AGP). The international organization had built its conclusion on a preliminary series of evidence at the time [12-16].

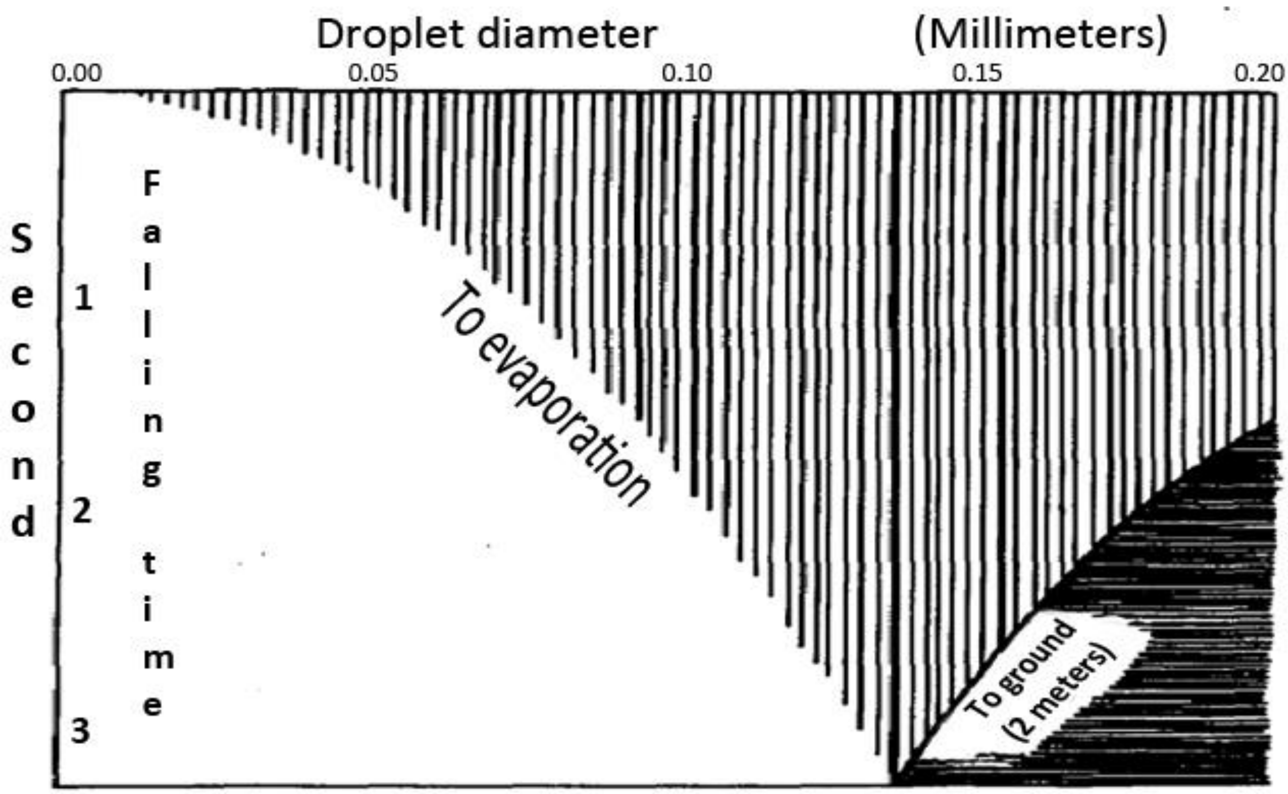

Figure 1.
Wells curve, falling times and evaporation times of droplets of varying diameter.
Note: Wells [8].

However, discussions on the possibility that SARS-COV-2 being airborne began as early as February 2020 [17]. It wasn't long before evidence of airborne transmission started to surface. Between February and March, a team of researchers found SARS-CoV-2 ribonucleic acid (RNA) in suspended aerosol samples taken from 2 Wuhan hospitals [18]. Then another team of researchers were able to retrieve viable virus samples from artificially generated aerosols up to 3 hours after generation, as reported by Van Doremalen, et al. [19]. The result was later surpassed by a newer version of the experiment, where viable samples of the virus could be retrieved 16 hours after aerosol generation. According to Fears, et al. [20]. Subsequently, viable cultures of the virus were isolated from aerosols samples taken from hospital wards, providing evidence that SARS-COV-2 can remain infectious in suspended aerosols in real-world settings [21, 22].

Several studies have provided data supporting the possibility of airborne transmission of SARS-COV-2, including Bahl, et al. [11]; Morawska and Cao [23]; Shen, et al. [24]; Miller, et al. [25]; Chia, et al. [26]. As a result, the Centers for Disease Control and Prevention (CDC) has finally acknowledged that COVID-19 can be airborne. However, the CDC has stated that this mode of transmission is not very efficient, and that certain conditions must be met before it becomes a significant threat. Interestingly, inadequate ventilation and indoor air handling system can contribute to the buildup of infectious viral load indoors, making efficient airborne transmission more likely [27]. This puts ventilation overall, as well as our review on HVAC systems at the center of the efforts to maintain a healthy and virus-free indoor environment.

3.3. HVAC Systems

Air conditioning systems, or as the nomenclature of their bigger family was coined: HVAC (Heating, ventilation, and air conditioning), are currently an integral part of many of modern living environments. They are heavily used in parts of the world where seasonal or perennial temperatures tend to drop or rise significantly.

In order to maintain a comfortable and healthy environment, HVAC systems perform seven key functions: heating, cooling, humidifying, dehumidifying, cleaning, ventilating, and air movement. These functions involve direct cooling or heating of the air, adding or removing water vapor (moisture) from the conditioned air, adjusting air velocity, and diluting indoor air contaminants by mixing it with the influx of fresh outdoor air [28].

Whilst most of the evidence regarding the role of HVAC systems in the spread of the SARS- COV-2 virus is still under review, a further look into the past indicates that indoor ventilation has played a significant role in previous outbreaks and spread of other pathogens such as tuberculosis, measles, chickenpox, influenza, and SARS-COV-1, which was the predecessor of SARS-COV-2 [29, 30]. Therefore, it is reasonable to assume that HVAC systems may also contribute to the spread of the novel virus as well.

HVAC systems usually maintain a wide range of temperature, humidity, and airflow levels, depending on their designation, climatic needs, and size of the target area. The heterogeneity of these systems makes it impractical to choose and study one particular setup as representative of the entire range. Therefore, in this context, climatic factors such as air flow, humidity, and temperature are discussed here irrespective of how they are produced.

Although droplets and aerosols overlap considerably, there are still differences in their behaviors under ambient conditions. To better highlight these differences, we tried to study those behaviors on larger droplets and aerosols separately.

It is also important to note that, in real life situations, droplets and aerosols are produced simultaneously, meaning that a single respiratory event can generate both.

3.4. Droplet Transmission

Here we are referring to droplets that are large and stable long enough to avoid complete evaporation while in the air. These droplets follow a traditional ballistic trajectory and are eventually pulled down by gravity depositing onto the floor or other surfaces.

3.4.1. Effect of Ambient Air Flow

Although droplet size (aerodynamic diameter) is a major determinant of its distance traveled [8, 10], it is not the only factor at play. In a laboratory setting droplets may follow the trajectories predicted by the Wells curve. However, real life environments are more dynamic. Ambient air flows can create turbulent jets that carry these droplets away from their anticipated path.

Computational fluid-particle dynamics (CFPD) models have revealed that ambient air flow fields can significantly alter the behavior of droplets in a respiratory event through the following mechanisms:

1. The dispersion timeline of a cough cloud is affected by the relative positioning of the HVAC device and the direction of the airflow it generates. Models where air stream is not blowing in the same direction as the emitted cough cloud, but rather intercepting or perpendicular, have accelerated the dilution of droplets inside the cloud over time [31].

Conversely, airflow blowing in accordance with a cough jet would restrict the dispersion of cough droplets, and keep them more concentrated as they travel in the air [32].

2. Ambient airflow can extend the distance that emitted droplets can travel beyond 1-2m (6 feet). Generally, at lower airflow velocities, only smaller droplets are affected, while larger droplet respond primarily to gravity, inertia, and their specific evaporation time [33]. However, for higher ambient airflow velocities, larger droplets (within the diameter range of 100 μm) [34, 35] become involved and gain momentum, leading to more complex deposition patterns and transport over longer distances before settling Figure 2. Various studies have reported different airflow speeds V_{in} at which advection range is extended. For instance Feng, et al. [32] found that $V_{\mathrm{in}\geq 19.8\ km/h\ (5.5\ m/s)}$ can extend travel distance up to 3m (10 feet), Li, et al. [36] reported that $V_{\mathrm{in}\geq 7.2\ km/h\ (2\ m/s)}$ can extend travel distance to 6.6 m (22 feet), and Dbouk and Drikakis [37] found $V_{in\geq 4\ km/h\ (1.1\ m/s)}$ causes extension up to 6m (20 feet). The apparent inconsistency in these results may be due in part to variations in the definition of “large droplets” within each study, the characteristics of modeled respiratory event, and initial conditions.

3.4.2. Effect of Relative Humidity (RH)

Higher Relative Humidity (RH) slows down evaporation and helps respiratory droplets maintain or even increase their diameter as they travel in the air. In contrast, lower RH facilitates droplet evaporation at faster rates. Depending on the level of relative humidity, even relatively large droplets can evaporate into airborne particles [32, 38]. These findings are consistent with another numerical simulation, which found that the lifetime of droplets suspended in expiratory clouds is extended by as much as 60-200 times for ambient RH values between 50-90%, when compared to Well’s classical, single -droplet model [39].

3.4.3. Effect of Ambient Temperature

Although higher temperature can theoretically accelerate droplet evaporation, their effect is relatively negligible on large droplets with an initial diameter ($D_{d,o} \geq 100\ \mu m$) [34, 38].

3.5. Airborne Transmission

We are referring here to very small droplets or droplet nuclei, which could have been of any initial size, but due to their nature and the environment conditions evaporated and became aerosols. They have the inclination to be more profoundly affected by HVAC conditions.

3.5.1. Effect of Airflow

As stated earlier, aerosols differ from droplets in that they can remain suspended in the air for much longer duration, and can react to ambient conditions differently. In a quiescent environment, an aerosol's horizontal speed decelerates rapidly after release until it reaches full stagnation, but with ambient air movement, aerosols get carried away farther by air streams. Additionally, ambient airflow can further extend their suspension for even much longer periods [31, 40]. For example, one study found that in an aircraft cabin, higher airflow rates can enhance the distances and dispersion of aerosols, increasing the risk of infection even when accounting for the dilution effect of the supplied fresh air [40].

Furthermore, current social distancing standards assume that deposition of droplets is a final, non-reversible process. However, this may not be the case from an airborne transmission perspective.

One known phenomenon that maybe of importance is the reaerosolization of settled particles. Settled, dried up bacterial spores for example, can respond to airflow by getting detached from the surface and resuspended into the air once more, under certain conditions pertaining to particle, surface, and airflow characteristics [41, 42]. It is plausible that settled droplet nuclei might exhibit a similar behavior especially when higher velocity air conditioners are used. This could significantly increase virus concentration within the indoor spaces, and may therefore contribute to the increased infective behavior the virus has manifested within indoor environments.

3.5.2. Effect of Humidity

As with larger droplets, relative humidity affects the speed of droplet-to-aerosol conversion. Lower RH increases evaporation rates which is more pronounced in smaller droplets. In general, smaller droplets have faster evaporation rates under similar conditions compared to larger ones due to increased surface area available for energy and mass transfer [38, 43].

One study found that under similar conditions, reduced RH alone led to considerable elongation in horizontal travel distances of smaller droplets with size range 35 – 80 μm, as well as a "wider" dispersion profile [44].

3.5.3. Effect of Temperature

The effect of temperature on the evaporation of droplets is more pronounced on smaller droplets. Higher temperatures lead to significant increase in droplet evaporation and aerosol generation [38].

It is important to note here that, as the last two factors (lower RH, higher temperature) can drive an accelerated evaporation of droplets into droplet nuclei. The concentration of inhalable pathogens transmissible by airborne particles, intuitively, grows as well, but surprisingly at disproportionately much faster rates as shown in a study [38]. A reasonable conclusion here is that airborne transmission favors warmer and drier ambient conditions.

3.6. Effect on Virus Survival

Aside from the mechanistic effects of environmental factors on droplets and aerosols as pathogen carriers, these factors exert effects on the survivability and infectivity of the virus itself. A recent systematic review of 517 articles has concluded that higher temperatures and humidity levels played a detrimental role in the spread of the SARS-COV-2 pandemic [45]. Supporting this hypothesis, another study found that a decrease of 1 % in climatic RH leads to an approximately 7-8 % increase in case counts [46]. Moreover, in another study, SARS-COV-2 viability was retained for longer period at RH =40~50 % than that at RH>95%, indicating that coronavirus strains thrive better at RH values at the lower end [47]. Artificial climates created by HVAC systems can mimic these conditions and would therefore lead to similar outcomes.

3.7. Effects on Host Response

In a normal individual with no underlying respiratory condition, and during a typical respiratory cycle, inhaled air undergoes three main processes while passing through the nasal cavity:

1. Humidification, 2. Heat exchange, 3. Filtration.

The latter process is directly related to the defensive functions of the nose. Filtration happens when intranasal turbulent airflow causes the inhaled noxious particles to be deposited onto the mucosal membrane, where a mucus layer traps the particles. Once trapped, the mucociliary apparatus gets rid of them either by sneezing or coughing, or through elimination by immune cells and mucosal enzymes. The degradation products are then transported within the mucus by cilia strokes towards the nasopharynx and then swallowed.

The efficiency of this apparatus depends largely on the viscoelastic characteristics of the bi-layer mucus blanket as well as the motility of mucosal cilia.

Extreme climatic conditions such as dry air with temperatures T $\geq 45\,^{\circ}c$ (113F) *or* $\leq 10\,^{\circ}c$ (50F) can halt ciliary movement [48]. Extremely low relative humidity values $RH \leq 10$ % alone can lead to a significant elongation in measured saccharin clearance time in room temperature [49]. Fortunately, operational standards advise HVAC manufacturers to maintain an optimal room RH range between 30-60 % and room temperature between 20 °C *to* 23 °C (68 *F to* 74*F)* (winter), and 22 °C *to* 26 °C (72 *F to* 80 *F)* (summer). If applied properly, HVAC systems can help maintain a healthy environment for the nose to perform the necessary physiological and immunological functions against pathogens.

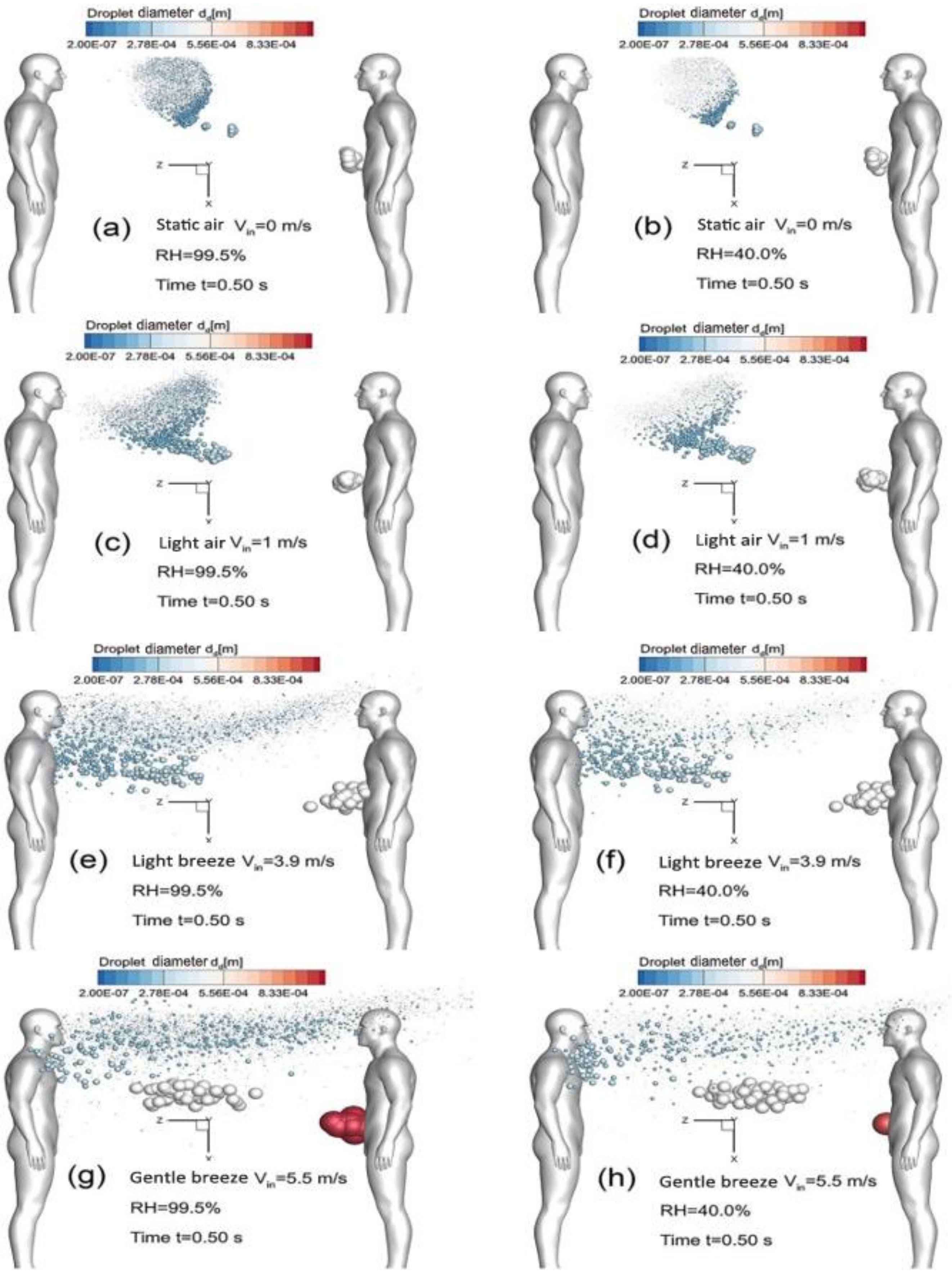

Figure 2.
Wind velocity (Vin) and RH effects on the droplet transmission patterns at t = 0.5 s: (a) Vin = 0 m/s and RH = 99.5%, (b) Vin = 0 m/s and RH = 40.0%, (c) Vin = 1 m/s and RH = 99.5%, (d) Vin = 1 m/s and RH = 40.0%, (e) Vin = 3.9 m/s and RH = 99.5%, (f) Vin = 3.9 m/s and RH = 40.0%, (g) Vin = 5.5 m/s and RH = 99.5%, and (h) Vin = 5.5 m/s and RH = 40.0%. droplet size legend: blue(small), white (medium), red: (large). Distance between mannequins L= 6 Feet (1.8m), flow direction: mannequin 1 (left) to mannequin 2 (right).Respiratory airflow: mannequin 1 (left) to mannequin 2 (right).
Note: Feng, et al. [32].

3.8. Effect of Ventilation Configuration

There is a significant effect on the risk of exposure to airborne pathogens depending on how HVAC systems distribute air within the ventilated space Thatiparti, et al. [50]. A multidisciplinary systematic review has concluded that air flow patterns in buildings can affect the risk of infection spread, which is particularly important when addressing airborne infections [31].

When a ventilation system provides a specific airflow to counteract an incoming virus-laden respiratory cloud, as in the case with personal ventilation (PV) sources, it may impede cloud's flow and stop it from entering into the breathable zone of a healthy person, thus helping protect against disease transmission [51].

Air replacement or mixing models also affect transmission risk. For example, when compared, displacement ventilation (DV) is thought to outperform mixing ventilation (MV) at reducing human exposure to airborne pathogens [52-54]. But these findings are not yet conclusive [55-57]. Displacement ventilation may create a special climatic phenomenon where exhaled droplets do not fall freely but rather become "locked-up" in thermally stratified air layers, leading to slower droplet evaporation and dispersion, and prolonged exposure to pathogens trapped at breathing height, particularly when exhaust outlets are not properly configured [43, 58]. Further research is needed to get a better understanding of the predominant mechanisms in this domain.

3.9. HVAC Systems and COVID-19 Cases

There have been several incidents where HVAC systems, or their absence thereof, were speculated to have been involved in super spreading events. The COVID-19 outbreak at a Dutch nursing home was linked partially to the newly installed HVAC system which did more air recirculation than replacement, leading to the formation of airborne transmission [59]. The role of air quality in the virus spread can be seen in an outbreak in a South Korean fitness dance school, where the incident was attributed, in part, to poor ventilation and humidity conditions in the classrooms [60].

The most interesting case was an outbreak that took place in a restaurant in Guangzhou, China, between January and February 2020, involving three family clusters. Out of 91 people that were at the restaurant at the time the index case was present. The only infected individuals belonged to two families that were seated near the family of index case along the AC air stream. The fact that none of the other staff were infected and culture samples from AC outlet and inlet were negative makes airborne transmission unlikely, and droplet transmission is assumed instead. Since tables were more than 1 meter apart, and considering the three families seating arrangement along the AC's air stream. It can be assumed that the strong airflow from the AC has affected the droplets trajectory and enabled them to travel longer distances [61].

4. Areas for Future Research

Computational fluid-particle dynamics modeling is a valuable tool when studying the response of virus-laden respiratory particles to changes in the physical parameters of the surrounding. However, they lack the ability to describe the simultaneous effect of those parameters on the biological processes that govern infection spread. Future hybrid models which take both physical, microbiological and epidemiological dynamics into account would provide a more accurate prediction on how infections spread in the real world.

We know that large droplets which harbor the majority of pathogens are quickly deposited and dried up, but the possibility that strong air flow generated by HVAC may reaerosolize those dried up nuclei would therefore be of great importance. Further research in this domain would be of great help.

Relative humidity affects both large and small droplets. When airborne transmission is a concern, lower temperatures and higher RH at certain ranges help reduce its occurrence. However, it is still not clear whether such conditions can be achieved without compromising the thermal comfort of the conditioned space. Further research is necessary to address this issue.

5. Conclusion

Ambient conditions can significantly affect the way SARS-COV-2 is carried and transmitted in indoor environments. Through their ability to control these conditions, HVAC systems can be directly involved in the transmission and infectivity dynamics of pathogens including the novel virus.

Contrary to the common understanding that only airborne particles are subject to change by airflow, we have found evidence that some flow is strong enough to carry large droplet further beyond the limits of social distancing. The ability of various HVAC systems to generate such velocities still needs to be elucidated. Airflow significantly increases the dispersion and spread distance of airborne particles, and it can even interfere with the dilution function of ventilating airflow. This effect is more noticeable when ventilation or air conditioning systems vigorously recirculates indoor air, such as when mixing ventilation is used.

We believe that current social distancing guidelines may be over simplistic and require re-evaluation in certain scenarios, particularly in heavily air-conditioned places where high velocity air flow is expected. Until more information is available, we recommend placing greater emphasis on the use of masks.

References

[1] World Health Organization, "Modes of transmission of virus causing COVID-19: Implications for IPC precaution recommendations," Retrieved: https://www.who.int/news-room/commentaries/detail/modes-of-transmission-of-virus-causing-covid-19-implications-for-ipc-precaution-recommendations. [Accessed January 11, 2022], 2020.

[2] E. K. J. Dzisi and O. A. Dei, "Adherence to social distancing and wearing of masks within public transportation during the COVID 19 pandemic," *Transportation Research Interdisciplinary Perspectives,* vol. 7, p. 100191, 2020. https://doi.org/10.1016/j.trip.2020.100191

[3] V. E. F. De Moura, R. V. M. Lopez, and A. P. S. E. A. Sato, "COVID-19 outbreak in Brazil: Adherence to national preventive measures and impact on people's lives. 2020, an online survey," *BMC Public Health,* vol. 21, no. 1, pp. 1-10, 2021. https://doi.org/10.1186/s12889-021-10222-z

[4] J. Gralton, E. Tovey, M.-L. McLaws, and W. D. Rawlinson, "The role of particle size in aerosolised pathogen transmission: A review," *Journal of Infection,* vol. 62, no. 1, pp. 1-13, 2011. https://doi.org/10.1016/j.jinf.2010.11.010

[5] J. Atkinson, Y. Chartier, C. L. Pessoa-Silva, P. Jensen, Y. Li, and W. H. Seto, "Natural ventilation for infection control in health-care settings." Geneva, Switzerland: World Health Organization, 2009, pp. 77-81.

[6] R. Tellier, Y. Li, B. J. Cowling, and J. W. Tang, "Recognition of aerosol transmission of infectious agents: a commentary," *BMC Infectious Diseases,* vol. 19, no. 1, pp. 1-9, 2019. https://doi.org/10.1186/s12879-019-3707-y

[7] R. Tellier, "Aerosol transmission of influenza A virus: A review of new studies," *Journal of the Royal Society Interface,* vol. 6, no. suppl_6, pp. S783-S790, 2009. https://doi.org/10.1098/rsif.2009.0302.focus

[8] W. F. Wells, "On air-borne infection: Study II. droplets and droplet nuclei," *American Journal of Epidemiology,* vol. 20, no. 3, pp. 611-618, 1934. https://doi.org/10.1017/s0022172400019288

[9] L. Bourouiba, "Turbulent gas clouds and respiratory pathogen emissions: Potential implications for reducing transmission of COVID-19," *Jama,* vol. 323, no. 18, pp. 1837-1838, 2020.

[10] X. Xie, Y. Li, A. Chwang, P. Ho, and W. Seto, "How far droplets can move in indoor environments--revisiting the Wells evaporation-falling curve," *Indoor Air,* vol. 17, no. 3, pp. 211-225, 2007. https://doi.org/10.1111/j.1600-0668.2007.00469.x

[11] P. Bahl, C. Doolan, C. De Silva, A. A. Chughtai, L. Bourouiba, and C. R. MacIntyre, "Airborne or droplet precautions for health workers treating coronavirus disease 2019?," *The Journal of Infectious Diseases,* vol. 225, no. 9, pp. 1561-1568, 2022. https://doi.org/10.1093/infdis/jiaa189

[12] J. Liu *et al.*, "Community transmission of severe acute respiratory syndrome coronavirus 2, Shenzhen, China, 2020," *Emerging Infectious Diseases,* vol. 26, no. 6, p. 1320, 2020. https://doi.org/10.3201/eid2606.200239

[13] J. F.-W. Chan *et al.*, "A familial cluster of pneumonia associated with the 2019 novel coronavirus indicating person-to-person transmission: A study of a family cluster," *The lancet,* vol. 395, no. 10223, pp. 514-523, 2020. https://doi.org/10.1016/s0140-6736(20)30154-9

[14] Q. Li *et al.*, "Early transmission dynamics in Wuhan, China, of novel coronavirus-infected pneumonia," *The New England Journal of Medicine,* vol. 382, no. 13, pp. 1199-1207, 2020.

[15] C. Huang *et al.*, "Clinical features of patients infected with 2019 novel coronavirus in Wuhan, China," *The Lancet,* vol. 395, no. 10223, pp. 497-506, 2020.

[16] R. M. Burke *et al.*, "Active monitoring of persons exposed to patients with confirmed COVID-19—United States, January–February 2020," *Morbidity and Mortality Weekly Report,* vol. 69, no. 9, pp. 245-246, 2020. https://doi.org/10.15585/mmwr.mm6909e1

[17] C. Offord, "How COVID-19 is spread," Retrieved: https://www.the-scientist.com/news-opinion/how-covid-19-is-spread-67143. [Accessed February 2], 2021.

[18] Y. Liu *et al.*, "Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals," *Nature,* vol. 582, no. 7813, pp. 557-560, 2020. https://doi.org/10.1038/s41586-020-2271-3

[19] N. Van Doremalen *et al.*, "Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1," *New England Journal of Medicine,* vol. 382, no. 16, pp. 1564-1567, 2020.

[20] A. C. Fears *et al.*, "Persistence of severe acute respiratory syndrome coronavirus 2 in aerosol suspensions," *Emerging Infectious Diseases,* vol. 26, no. 9, p. 2168, 2020.

[21] J. A. Lednicky *et al.*, "Viable SARS-CoV-2 in the air of a hospital room with COVID-19 patients," *International Journal of Infectious Diseases,* vol. 100, pp. 476-482, 2020.

[22] J. L. Santarpia *et al.*, "Aerosol and surface contamination of SARS-CoV-2 observed in quarantine and isolation care," *Scientific reports,* vol. 10, no. 1, p. 12732, 2020. https://doi.org/10.1038/s41598-020-69286-3

[23] L. Morawska and J. Cao, "Airborne transmission of SARS-CoV-2: The world should face the reality," *Environment International,* vol. 139, p. 105730, 2020. https://doi.org/10.1016/j.envint.2020.105730

[24] Y. Shen, C. Li, and H. e. a. Dong, "Community outbreak investigation of SARS-CoV-2 transmission among bus riders in Eastern China," *JAMA Internal Medicine,* vol. 180, pp. 1665-1671, 2020.

[25] S. L. Miller *et al.*, "Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley chorale superspreading event," *Indoor Air,* vol. 31, no. 2, pp. 314-323, 2021.

[26] P. Y. Chia *et al.*, "Detection of air and surface contamination by SARS-CoV-2 in hospital rooms of infected patients," *Nature Communications,* vol. 11, no. 1, p. 2800, 2020.

[27] New York Times, "The virus is an airborne threat, the C.D.C. acknowledges," Retrieved: https://www.nytimes.com/2021/05/07/health/coronavirus-airborne-threat.html. [Accessed June 23], 2022.

[28] R. McDowall, *Fundamentals of HVAC systems (IP)*, 1st ed. Cambridge: Academic Press, 2006.

[29] J. C. Luongo, K. P. Fennelly, J. A. Keen, Z. J. Zhai, B. W. Jones, and S. L. Miller, "Role of mechanical ventilation in the airborne transmission of infectious agents in buildings," *Indoor Air,* vol. 26, no. 5, pp. 666-678, 2016. https://doi.org/10.1111/ina.12267

[30] Y. Li *et al.*, "Role of ventilation in airborne transmission of infectious agents in the built environment-a multidisciplinary systematic review," *Indoor Air,* vol. 17, no. 1, pp. 2-18, 2007. https://doi.org/10.1111/j.1600-0668.2006.00445.x

[31] V. Vuorinen *et al.*, "Modelling aerosol transport and virus exposure with numerical simulations in relation to SARS-CoV-2 transmission by inhalation indoors," *Safety Science,* vol. 130, p. 104866, 2020. https://doi.org/10.1016/j.ssci.2020.104866

[32] Y. Feng, T. Marchal, T. Sperry, and H. Yi, "Influence of wind and relative humidity on the social distancing effectiveness to prevent COVID-19 airborne transmission: A numerical study," *Journal of Aerosol Science,* vol. 147, p. 105585, 2020.

[33] R. Mittal, R. Ni, and J.-H. Seo, "The flow physics of COVID-19," *Journal of Fluid Mechanics,* vol. 894, no. F2, pp. 1-14, 2020. https://doi.org/10.1017/jfm.2020.330

[34] C. Chen and B. Zhao, "Some questions on dispersion of human exhaled droplets in ventilation room: Answers from numerical investigation," *Indoor Air,* vol. 20, no. 2, pp. 95-111, 2010. https://doi.org/10.1111/j.1600-0668.2009.00626.x

[35] L. Borro, L. Mazzei, M. Raponi, P. Piscitelli, A. Miani, and A. Secinaro, "The role of air conditioning in the diffusion of Sars-CoV-2 in indoor environments: a first computational fluid dynamic model, based on investigations performed at the Vatican State Children's hospital," *Environmental Research,* vol. 193, p. 110343, 2021. https://doi.org/10.1016/j.envres.2020.110343

[36] H. Li, F. Y. Leong, G. Xu, Z. Ge, C. W. Kang, and K. H. Lim, "Dispersion of evaporating cough droplets in tropical outdoor environment," *Physics of Fluids,* vol. 32, no. 11, p. 113301, 2020. https://doi.org/10.1063/5.0026360

[37] T. Dbouk and D. Drikakis, "On coughing and airborne droplet transmission to humans," *Physics of Fluids,* vol. 32, no. 5, p. 053310, 2020. https://doi.org/10.1063/5.0011960

[38] X. Li, Y. Shang, Y. Yan, L. Yang, and J. Tu, "Modelling of evaporation of cough droplets in inhomogeneous humidity fields using the multi-component Eulerian-Lagrangian approach," *Building and Environment,* vol. 128, pp. 68-76, 2018. https://doi.org/10.1016/j.buildenv.2017.11.025

[39] K. L. Chong, C. S. Ng, N. Hori, R. Yang, R. Verzicco, and D. Lohse, "Extended lifetime of respiratory droplets in a turbulent vapor puff and its implications on airborne disease transmission," *Physical Review Letters,* vol. 126, no. 3, p. 034502, 2021. https://doi.org/10.1103/physrevlett.126.034502

[40] G. N. Sze To, M. P. Wan, C. Y. H. Chao, L. Fang, and A. Melikov, "Experimental study of dispersion and deposition of expiratory aerosols in aircraft cabins and impact on infectious disease transmission," *Aerosol Science and Technology,* vol. 43, no. 5, pp. 466-485, 2009. https://doi.org/10.1080/02786820902736658

[41] P. Krauter and A. Biermann, "Reaerosolization of fluidized spores in ventilation systems," *Applied and Environmental Microbiology,* vol. 73, no. 7, pp. 2165-2172, 2007. https://doi.org/10.1128/aem.02289-06

[42] J. S. Kesavan, P. D. Humphreys, J. R. Bottiger, E. R. Valdes, V. K. Rastogi, and C. K. Knox, "Deposition method, relative humidity, and surface property effects of bacterial spore reaerosolization via pulsed air jet," *Aerosol Science and Technology,* vol. 51, no. 9, pp. 1027-1034, 2017. https://doi.org/10.1080/02786826.2017.1335389

[43] F. Liu, H. Qian, X. Zheng, J. Song, G. Cao, and Z. Liu, "Evaporation and dispersion of exhaled droplets in stratified environment. In IOP Conference Series: Materials Science and Engineering. IOP Publishing," 2019, vol. 609, no. 4, p. 042059.

[44] L. Liu, J. Wei, Y. Li, and A. Ooi, "Evaporation and dispersion of respiratory droplets from coughing," *Indoor Air,* vol. 27, no. 1, pp. 179-190, 2017. https://doi.org/10.1111/ina.12297

[45] P. Mecenas, R. T. d. R. M. Bastos, A. C. R. Vallinoto, and D. Normando, "Effects of temperature and humidity on the spread of COVID-19: A systematic review," *PLoS One,* vol. 15, no. 9, p. e0238339, 2020. https://doi.org/10.1371/journal.pone.0238339

[46] M. P. Ward, S. Xiao, and Z. Zhang, "Humidity is a consistent climatic factor contributing to SARS-CoV-2 transmission," *Transboundary and Emerging Diseases,* vol. 67, no. 6, pp. 3069-3074, 2020. https://doi.org/10.1111/tbed.13766

[47] K. Chan, J. Peiris, S. Lam, L. Poon, K. Yuen, and W. Seto, "The effects of temperature and relative humidity on the viability of the SARS coronavirus," *Advances in Virology,* vol. 2011, pp. 734690-734690, 2011. https://doi.org/10.1155/2011/734690

[48] J. C. Watkinson and R. W. Clarke, "Physiology of the nose and paranasal sinuses. In: Galm T, Ahmed SK. Scott-Brown's otorhinolaryngology head and neck surgery," vol. 1, 8th ed. Boca Raton, FL: CRC Press, 2018, p. 985.

[49] Y. Sunwoo, C. Chou, J. Takeshita, M. Murakami, and Y. Tochihara, "Physiological and subjective responses to low relative humidity in young and elderly men," *Journal of Physiological Anthropology,* vol. 25, no. 3, pp. 229-238, 2006. https://doi.org/10.2114/jpa2.25.229

[50] D. S. Thatiparti, U. Ghia, and K. R. Mead, "Computational fluid dynamics study on the influence of an alternate ventilation configuration on the possible flow path of infectious cough aerosols in a mock airborne infection isolation room," *Science and Technology for the Built Environment,* vol. 23, no. 2, pp. 355-366, 2017. https://doi.org/10.1080/23744731.2016.1222212

[51] J. Pantelic, G. N. Sze-To, K. W. Tham, C. Y. Chao, and Y. C. M. Khoo, "Personalized ventilation as a control measure for airborne transmissible disease spread," *Journal of the Royal Society Interface,* vol. 6, no. suppl_6, pp. S715-S726, 2009. https://doi.org/10.1098/rsif.2009.0311.focus

[52] Q. He, J. Niu, N. Gao, T. Zhu, and J. Wu, "CFD study of exhaled droplet transmission between occupants under different ventilation strategies in a typical office room," *Building and Environment,* vol. 46, no. 2, pp. 397-408, 2011. https://doi.org/10.1016/j.buildenv.2010.08.003

[53] Y. Zhang, G. Feng, Y. Bi, Y. Cai, Z. Zhang, and G. Cao, "Distribution of droplet aerosols generated by mouth coughing and nose breathing in an air-conditioned room," *Sustainable Cities and Society,* vol. 51, p. 101721, 2019. https://doi.org/10.1016/j.scs.2019.101721

[54] R. K. Bhagat, M. D. Wykes, S. B. Dalziel, and P. Linden, "Effects of ventilation on the indoor spread of COVID-19," *Journal of Fluid Mechanics,* vol. 903, pp. 1-18, 2020. https://doi.org/10.1017/jfm.2020.720

[55] J. M. Villafruela, I. Olmedo, F. A. Berlanga, and M. Ruiz de Adana, "Assessment of displacement ventilation systems in airborne infection risk in hospital rooms," *Plos One,* vol. 14, no. 1, p. e0211390, 2019. https://doi.org/10.1371/journal.pone.0211390

[56] Y. Yin *et al.*, "Experimental study on displacement and mixing ventilation systems for a patient ward," *HVAC&R Research,* vol. 15, no. 6, pp. 1175-1191, 2009. https://doi.org/10.1080/10789669.2009.10390885

[57] A. Jurelionis *et al.*, "The impact of the air distribution method in ventilated rooms on the aerosol particle dispersion and removal: The experimental approach," *Energy and Buildings,* vol. 86, pp. 305-313, 2015. https://doi.org/10.1016/j.enbuild.2014.10.014

[58] Q. Zhou, H. Qian, H. Ren, Y. Li, and P. V. Nielsen, "The lock-up phenomenon of exhaled flow in a stable thermally-stratified indoor environment," *Building and Environment,* vol. 116, pp. 246-256, 2017. https://doi.org/10.1016/j.buildenv.2017.02.010

[59] De Man P, S. Paltansing, D. Ong, N. Vaessen, G. Van Nielen, and J. G. M. Koeleman, "Outbreak of COVID-19 in a nursing home associated with aerosol transmission because of inadequate ventilation," *Clinical Infectious Diseases,* vol. 17, pp. 365-366, 2020.

[60] S. Jang, S. H. Han, and J.-Y. Rhee, "Cluster of coronavirus disease associated with fitness dance classes, South Korea," *Emerging Infectious Diseases,* vol. 26, no. 8, p. 1917, 2020. https://doi.org/10.3201/eid2608.200633

[61] J. Lu *et al.*, "COVID-19 outbreak associated with air conditioning in restaurant, Guangzhou, China, 2020," *Emerging Infectious Diseases,* vol. 26, no. 7, p. 1628, 2020. https://doi.org/10.3201/eid2611.202948