

THE INFLUENCE OF COVID RELATED VENTILATION RATE CHANGES ON THE ENERGY CONSUMPTION AND INFECTION PROBABILITY OF THE BUILDINGS: UNDERFLOOR AND OVERHEAD AIR DISTRIBUTION SYSTEMS

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ABSTRACT

The COVID-19 pandemic has urged the need to reconsider how our built environments influence our health conditions. The new guidelines have highlighted the importance of environmental settings in the virus transmission process. Given that external air ventilation is a major element of a building's energy performance, it is necessary to investigate the influence of the new settings on the building's energy consumption. This study aims to determine the energy performance and infection risk of underfloor air distribution UFAD and overhead systems OH when exposed to varying levels of external air ventilation. The findings indicate that raising the rate of outside ventilation increases a building's energy usage in all climates. It is also shown that the UFAD system shows its energy-saving potential the most in cold climates and higher ventilation rates. These findings suggest that it is critical to consider distinct ventilation techniques to prevent rising energy consumption rates while lowering the risk of viral transmission.

Keywords: building energy consumption, EnergyPlus, ventilation rate, outdoor air, virus transmission

1 INTRODUCTION

The COVID-19 pandemic has urged the need to reconsider how our built environments influence our health conditions. As of March 7, 2022, approximately 220 nations and territories have reported an epidemic of coronavirus illness (COVID-19). The virus has infected about 447 million people globally and claimed six million lives ("WHO Coronavirus (COVID-19) Dashboard | WHO Coronavirus (COVID-19) Dashboard With Vaccination Data" n.d.). According to the World Health Organization (WHO), the United States is one of the most seriously affected nations. ASHRAE, along with many other organizations such as the

Federation of European Heating, Ventilation, and Air-conditioning Associations (REHVA), and the Society of Heating, Air-Conditioning, and Sanitary Engineering in Japan (SHASE), issued guidelines on the transmission of SARS-CoV-2 and the operation of HVAC systems. These documents have highlighted the importance of enclosed spaces in their environmental setting in the virus transmission process. ASHRAE has published several updated epidemic task forces to help building owners, managers, and engineers with recommendations for controlling buildings' HVAC systems. These epidemic taskforces have listed seven basic approaches to reduce the infection risk in commercial buildings. The elimination of the virus, defined as physically removing the hazard, is the most prioritized task in this report. Other features are listed as substitution (replacing the risk), engineering controls (isolating people from the hazard), administrative controls (changing the way of work), and personal protective equipment. According to WHO, the ventilation rate is one of the most critical factors, which considerably influences the building's energy performance. The influence of the new COVID-19 related regulation on energy consumption is of great importance, especially with regard to the building sector. Buildings account for about 35 percent of total energy consumption and 38 percent of total global energy-related CO₂ emissions. In the United States, this amount is approximately 76 percent of total electricity consumption and 40 percent of total energy consumption (Hamilton and Rapf 2020). HVAC systems are responsible for most of a building's energy consumption, making it critical to investigate how these new restrictions will affect HVAC energy usage. This research aims to evaluate the energy performance and infection probability of underfloor air distribution and overhead systems when subjected to varying degrees of outdoor air ventilation. We created a model and simulated an actual office building in Phoenix, Arizona, employing ten different outdoor air ventilation rates. Additionally, the energy performance of the same facility throughout seven different climatic zones is examined and compared.

2 BACKGROUND

The ASHRAE position document on infectious aerosols refers to ventilation as the primary strategy for removing contagious agents and disease control. Increasing outdoor air ventilation, using MERV-13 filters, and running the system for long hours are their top three suggestions for non-healthcare buildings (Circle et al. 2020). In addition, the ASHRAE epidemic task force for COVID19 has suggested building managers comply with the minimum outdoor ventilation amount defined by ASHRAE Standard 62 while using MERV 13 filters and continue the operation of all systems during the occupied hours (ASHRAE 2021). The Federation of European Heating, Ventilation, and Air Conditioning (REHVA) also states that all the recirculation dampers need to be closed at the time of the COVID-19 pandemic. If this results in reduced cooling or heating performance, this must be accepted since preventing pollution and protecting public health is much more essential than saving energy (J. Kurnitski, Franchimon, and Hogeling 2020). This document argues that even the use of air filters does not justify opening the return air dampers since they may be ineffective at preventing viruses. In an updated version in 2021, REHVA states that building managers should ensure that the required number of air exchanges in each hour is met since increasing air exchanges per hour reduce transmission risk in enclosed settings. Depending on the space, natural or mechanical ventilation may be used (Jarek Kurnitski, Boerstra, and Franchimon 2021). Studies have started to investigate the new ventilation guidelines and their possible influence on both building occupants and its energy performance. While most of the recommendations in the studied guidelines are mostly similar, the precise ventilation rate required to limit the spread of an airborne virus, such as SARS-CoV-2, is not specified and requires more investigation (Awada et al. 2021). Although there is still no fixed suggested number for the building's ventilation in a pandemic or post-pandemic time, it is necessary to study the performance of different ventilation approaches on the infection risk. In addition to onsite CO₂ measurements, the risk assessment simulation models make it possible to calculate the influence of the ventilation rate on the infection risk based on the exposure time of the individuals (Li and Tang 2021). Using the well-known Wells-Riley model, researchers have calculated the infection risk based on the average fresh air and human density, which were gathered by experimental measurements. Riley, Murphy, and Riley (1978) used data from a measles epidemic in 1974 to develop this model, which is the most well-known model to quantitatively quantify the risk of airborne infection. Numerous research on the spread of airborne infectious diseases

have widely used the Wells-Riley model. For instance, Escombe et al. (Escombe et al. 2007) showed using the Wells-Riley model that several building elements, including the ventilation rate, are significant removal mechanisms for airborne infectious pathogens.

Computational Fluid Dynamic (CFD)-based studies have also compared different types of ventilation strategies, including mixing ventilation, zone ventilation, stratum ventilation, and displacement ventilation, regarding their ventilation performance and infection risk. The relative distance between the infected occupant and the outlet in an interior setting was shown to be a significant factor in the infection probability (Ren, Zhu, and Cao 2022). The notable influence of ventilation strategies on the distribution of aerosols and individuals' exposure to viruses has been highlighted more in the presence of an infected individual. The results indicate that displacement ventilation under the ASHRAE minimum required air-change rate can bring more exposure risk with a small air change rate, which can be even greater than mixed ventilation exposure risk. However, increasing the air change rate in this setting may effectively limit human exposure to exhaled aerosols by providing additional clean air and changing the airflow characteristics (Pei, Rim, and Taylor 2021; Yang et al. 2021). Recent research in this area has shown the improved air quality when the ACH is increased displacement ventilation setting up to ACH 7 (Yang et al. 2021). Other research set the reasonable required ventilation rate from ACH5 to ACH 10 to ensure a healthy environment (Bhagat and Linden 2020). More in detail, previous studies on the influence of ACH on the percentage of inlet concentration argue that increasing the ventilation rate up to ACH10 can improve the environment in the occupied zone. However, increasing the ACH more than ACH10 had not shown much improvement in the air quality. Researchers are also investigating the influence of the new COVID-19-related guidelines on the energy consumption of the buildings. Some studies highlight the critical role of the building's climatic environment on the changes in energy consumption behavior. As they argue, in a typical high-rise office building, these regulations will increase the energy consumption in climate zones above the mixed-humid type. While this can decrease the energy use in climate zones below that (Cortiços and Duarte 2021).

Several recent and previous studies have shown the effectiveness of underfloor air distribution systems (UFAD) on the ventilation performance of the room. The UFAD system offers various potential benefits, including greater thermal comfort, improved indoor air quality (IAQ), and increased energy efficiency compared to traditional overhead systems (OH) and mixed ventilation approaches (Webster et al. 2012; Ashrafi et al. 2019). The energy performance of HVAC system including the UFAD are highly dependent on the climatic condition (Ashrafi et al. 2019; Pease, Chhabra, and Zolfaghari 2021). With regard to the infection risk, the UFAD system mixes the air on a local level while preventing toxins from spreading across the room. The local diffusers mix the air upward into a stratified layer, which is subsequently expelled from the area through a return diffuser in the ceiling, making this system more effective in removing aerosols than mixing ventilation (Burkett 2021). As the research shows, the infection prevention performance of UFAD systems is highly dependent on the system setting, including the rate. Therefore, relying on an underfloor air distribution setting does not guarantee the viability of outdoor air exchange in decreasing the virus exposure. In addition, this is of much importance to learning about the influence of these new UFAD system settings on the energy performance of the building. In this study, we look into the impact of different ventilation rates on the energy performance of UFAD systems. In addition, we compare the energy consumption increase with overhead systems in the same climatic conditions. Finally, we have looked into the energy-saving potential of UFAD in comparison to OH as we increase the ACH. Based on the provided literature, the ACH is increased up to ACH10 for both systems.

3 METHODOLOGY

This research aims to assess the energy performance of the UFAD and OH systems under different outdoor air ventilation rates. To that end, we examined the yearly energy usage of an office building in a hot and dry climate in detail. We chose seven major cities from different climatic zones based on ASHRAE Standard 169-2013 (Crawley et al. 2013). Table 1 lists the chosen cities, each representing a distinct climatic zone selected for model simulation. This simulation was conducted utilizing meteorological data files for

the original building climate, Phoenix, and six other cities, including Miami, Los Angeles, New York, Chicago, Minneapolis, and Duluth.

Table 1: Selected Cities

CITY	ZONE	ZONE NAME	CITY	ZONE	ZONE NAME
Miami	1	Very Hot- Humid	Chicago	5	Cool- Humid
Phoenix	2	Hot- Humid	Minneapolis	6	Cold- Humid
Los Angeles	3	Warm-Dry	Duluth	7	Very Cold
New York	4	Mixed-Humid			

3.1 Modeled Building Description

The studied space is the middle floor of a three-story office building in Phoenix, Arizona, with 4544 sq. meters. The perimeter and interior zones are defined by the effective area of the windows and diffusers connected to the building’s exterior wall, which results in a five-foot-wide perimeter zone. As displayed in Figure 1, the interior zone is divided into three sub-zones based on the air handling unit’s effective area. The supply and return plenums have been modeled as individual thermal zones with 60 cm heights. Additional details about each zone are included in Table 2. The building’s construction method is based on the required standards for climate zone two. The lighting, occupancy, and equipment schedules are based on the real-world schedule of the building, which is typically inhabited from 6 a.m. to 6 p.m., and the equipment is operational from 4 a.m. to 10 p.m.

Table 2: Building Model Properties

Walls	Construction	Metal Frame, 2*6, 16 in. O.c.
	Ext Finish/Color	Wood/Plywood ‘Medium’ (abs= 0.6)
	Exterior Insulation	½ in. fiberboard sheathing (R-13)
	Additional Insulation	R-19 batt
Ground Floor	Construction	4 in. Concrete
	Exterior Insulation	3 in. polyurethane (R-18)

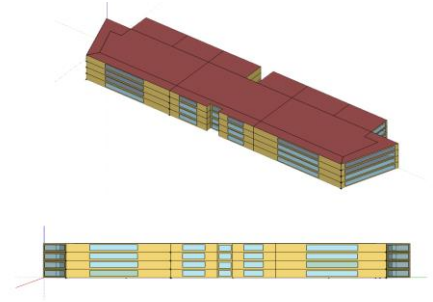


Figure 1: Simulated Building Model

3.2 Building Conditioning System

We utilized the Energy Plus modeling program, which is presently the most suitable for modeling the UFAD due to its ability to account for room stratification and simultaneous stimulation of zones, systems, and plants (Schiavon et al. 2010). The simulation include detailed information about lighting, equipment, occupants, and schedules of the existing building due to their importance in final energy consumption (Zolfaghari et al. 2020). The UFAD system used in this project is a variable air volume (VAV) design with electric reheat in the perimeter zone. The system’s supply air temperature is determined by the building’s information system, which is 15°C. The supply plenums are ducted using a fabric duct system, which minimizes thermal decay and increases fan energy savings. The cooling supply air temperature for the OH system is 11°C, and the static fan pressure is increased to 1000 Pa. Our first scenario is the baseline simulation with 1 Air Change per Hour (ACH) based on the existing building. In the baseline scenario, the minimum outdoor air amount is defined as slightly higher than the requirement of ASHRAE 62.1-2019 for

an office environment, which is 17 CFM/person (ASHRAE 2019). We have run the simulations for both UFAD and OH, starting with a 1ACH for each city and raising it to a 10ACH in separate simulations.

3.3 Simulation Validation

The EnergyPlus version we have used for this simulation is V9.5.0. Its ability to simulate UFAD systems was validated by Webster et al. (2008) in detailed laboratory tests (Raftery et al., 2012; Schiavon et al., 2011). In addition, this is essential to validate the energy model simulation for making sure of having a reliable presentation of building's energy performance (Mostafavi et al. 2018). We decided on two business weeks in the winter (January) and summer (August) to validate the simulation in heating and cooling modes. In addition, to validate our simulations, we compared the interior air temperature collected by data loggers in the Phoenix building's perimeter zones to the zone air temperature outputs from the simulations. The north perimeter zone was chosen for comparison, and the average room temperature was compared throughout the day and during occupied hours. Table 3 shows the observed and simulated average zone temperatures during the occupied hours. As seen in Table 4, the simulation results match the temperature data for cooling and heating days, with respective zone set point temperatures of 24 °C and 21 °C. The Error column represents the allowed simulation error, which is less than 4% on all the selected days.

Table 3: Simulation Validation

Design Day	Measure	Model	Error (%)	Design Day	Measure	Model	Error (%)
8/15/2016	25.20	24.97	0.009	1/18/2016	19.98	20.47	-0.02478
8/16/2016	25.22	24.55	0.026	1/19/2016	20.31	20.50	-0.00925
8/17/2016	25.46	24.52	0.036	1/20/2016	20.60	20.56	0.002119
8/18/2016	25.00	24.51	0.019	1/21/2016	20.51	20.50	0.00015
8/19/2016	24.92	24.47	0.018	1/22/2016	20.43	20.48	-0.00251

3.4 Infection Probability

The concept of a "quantum of infection" serves as the foundation for the Wells-Riley equation. The quantity of infectious airborne particles necessary to infect a person is referred to as a quantum. This model is widely used for quantitative risk assessment of infectious illnesses in indoor environments since it is fast and does not need interspecies extrapolation of infectivity. Assumptions made by the Wells-Riley model were based on a number of basic ones. Therefore, the chance of infection is uniform inside a restricted area, the ventilation and infector numbers are constant, and the biological decay of airborne infectious pathogens, as well as infectious particle removal induced by filtration and deposition, are negligible, all at the same time.

$$P = \frac{C}{S} = 1 - \exp\left(-\frac{Iqpt}{Q}\right) \quad (1)$$

P stands for probability of infection, C for infection cases, S for susceptibles, and I for infectors. q stands for quanta generation rate (quanta/h), p stands for pulmonary ventilation rate for a person (m³/h), t stands for exposure time interval (h), and Q stands for room outdoor ventilation rate (m³/h).

4 RESULTS

We ran ten simulations with varying ventilation rates on the same building model in each of the seven specified climates and two different systems totaling 140 runs. The results are investigated by looking into total annual energy consumption and annual energy usage by different fan, cooling, and heating energy categories.

4.1 Total Energy Consumption

We included the final data for ten ventilation rates since each simulation's overall HVAC energy consumption is noteworthy. The energy consumption increase of the building's HVAC system per conditioned space is shown in Table 4 and 5. As shown, increased outdoor air ventilation results in increased energy usage in most scenarios. However, the pattern of energy consumption change varies across climatic zones at higher and lower latitudes. While Miami (zone 1, very hot-humid) and Phoenix (zone 2, hot-humid) see an immediate rise in energy consumption due to increased ventilation levels, climates in lower latitudes display an initial drop followed by a final increase in energy consumption. The energy consumption of all higher latitude cities, including New York (zone 4, mixed-humid), Chicago (zone 5, cool-humid), Minneapolis (zone 6, cold-humid), and Duluth (zone 7, extremely cold), was initially reduced by increasing the ventilation rate, which can be achieved by introducing fresh air with the desired temperature into the building during the summertime. However, the high temperature of the outside air in lower latitude areas necessitates conditioning it before mixing it with the building's air system. For cities with milder climates, such as Los Angeles (zone 4, warm-dry), energy consumption stays constant in the first four simulations, with an increase in ventilation rate (reaching ACH4) followed by a decrease in energy consumption rate. There is also an increase in energy consumption for the OH system as we increase the ACH. However, the increase rate is lower than in the UFAD system. As can be observed in the comparison of final numbers with ACH10 in all the climates, the UFAD system needs to increase the energy consumption much more than the OH system to provide the same ventilation rate. These results can be justified due to the low airflow rates in the UFAD system, which is one of the main reasons for energy saving in this setting.

Table 4: HVAC Energy Consumption Increase Percentage (MJ/m2) for UFAD

City \ ACH	2	3	4	5	6	7	8	9	10
Miami	11.09	29.02	48.31	68.72	91.29	114.8	140.33	166.6	193.39
Phoenix	6.29	16.14	30.33	47.64	67.85	91.67	118.13	146.5	177.33
New York	-5.91	0.46	14.81	51.16	73.57	98.13	126.11	157.0	187.60
Los Angeles	0.07	0.00	2.06	7.39	17.55	30.75	49.49	70.7	98.26
Chicago	-9.29	-8.59	-0.02	12.47	44.98	46.00	64.40	86.5	109.81
Minneapolis	-11.31	-8.56	3.94	20.79	38.82	59.56	82.11	106.1	133.13
Duluth	-16.08	-17.94	-12.43	-3.71	7.66	23.60	41.99	62.8	86.86

Table5: HVAC Energy Consumption Increase Percentage (MJ/m2) for OH

City \ ACH	2	3	4	5	6	7	8	9	10
Miami	14.81	33.59	52.98	71.42	90.39	110.87	132.53	154.61	179.18
Phoenix	7.49	18.44	31.40	43.99	57.89	74.37	92.33	111.10	132.60
New York	5.25	6.00	14.21	24.68	36.19	49.61	64.05	79.08	97.35
Los Angeles	5.87	14.38	25.14	33.68	41.97	53.13	66.45	80.74	98.99
Chicago	1.28	0.56	5.46	11.33	18.90	28.05	38.42	49.13	62.19
Minneapolis	-1.68	-3.25	3.55	9.50	16.62	26.01	36.35	47.10	59.70
Duluth	-1	-4	-1	3	7	13	20	28	39

Furthermore, we have looked into the difference in energy consumption for our lowest and highest ventilation rate simulations, shown in Figure 2(below). The graph displays the annual HVAC energy usage per condition when the air change per hour increases from 1 ACH to 10 ACH in all the selected cities. In addition, the final energy consumption difference between the lowest and highest ventilation rate scenarios

is displayed by the yellow dotted line. As Figure 3 shows, HVAC energy consumption increases exponentially in all climates. The slope of increase varies according to the city’s climatic conditions.

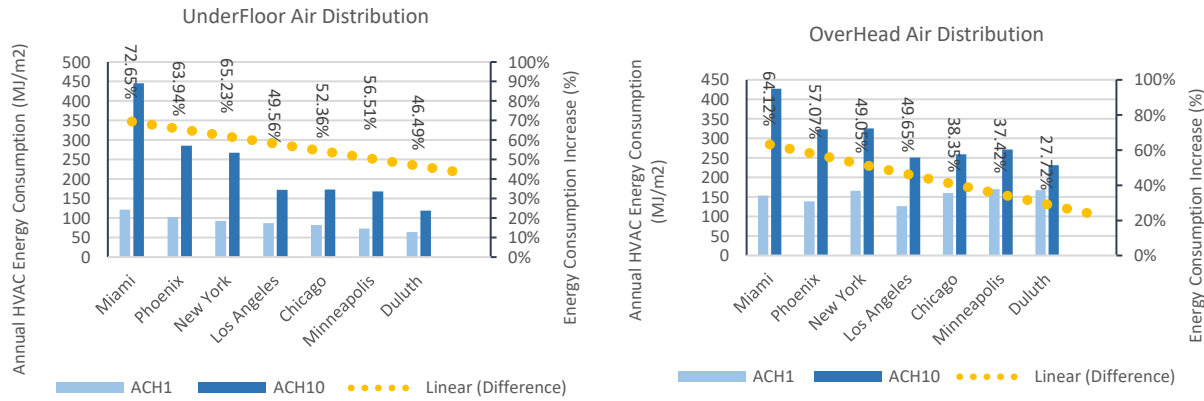


Figure 2: Annual Energy Consumption in the First and Last Scenarios

In the colder climates of Duluth, Minneapolis, New York, and Chicago, the UFAD energy consumption decreases from ACH 1 to ACH 2 and ACH 3. This pattern is the same in the OH system for those climatic conditions. The rate of the energy consumption increase is relatively low as we increase the ACH to 4. In a milder climate such as Los Angeles, the OH system shows an immediate rise in energy consumption as we increase the ACH; however, in the UFAD system, the initial increase in ACH does not result in an energy consumption increase. The hotter climates show higher increase rates. This behavior is extreme for Miami in very hot and humid conditions, and the energy consumption increase is not affected by the air distribution system setting.

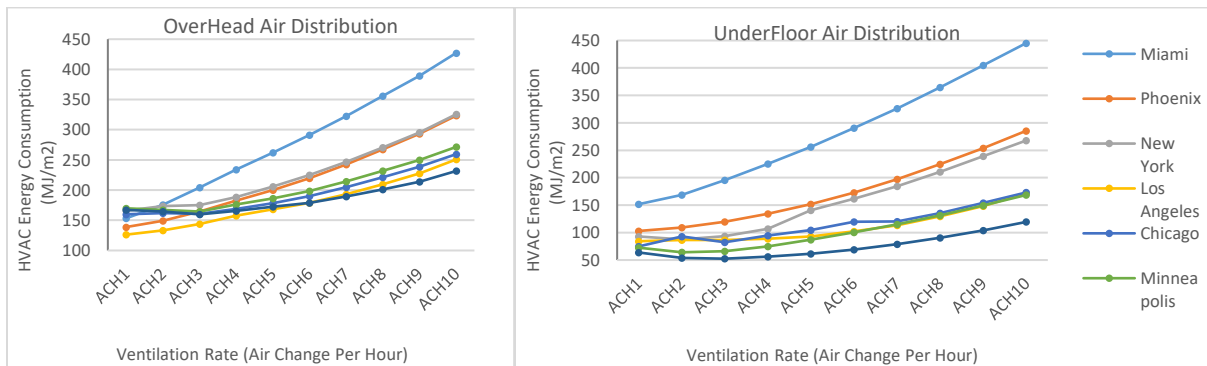


Figure 3: HVAC Energy Consumption in Different Ventilation Rates

4.2 Fan Energy Consumption

Outdoor air ventilation directly affects fan energy consumption. Therefore, it will not be affected by the climatic conditions and will consistently increase as the outdoor ventilation rate increases. A complete demonstration of the simulation results for fan energy consumption is shown in Figure 4 by displaying all ten ventilation rate scenarios for the selected cities. By looking at the numbers in Table 6, we can see that for both systems, the lowest fan energy consumption is at Duluth, at 23.67 MJ/m², and the highest fan energy consumption is at Miami, at 28.89 MJ/m². In Figure 5, we observe a consistent increase in the fan energy consumption for all the climates. These numbers are in line with the literature and indicate that the increase in fan energy consumption is independent of the climatic conditions. It can also be observed that the fan energy consumption of the UFAD system is lower than the OH system in all the scenarios, which is expected as the UFAD system deliver the supply air with lower velocity to the occupied zone.

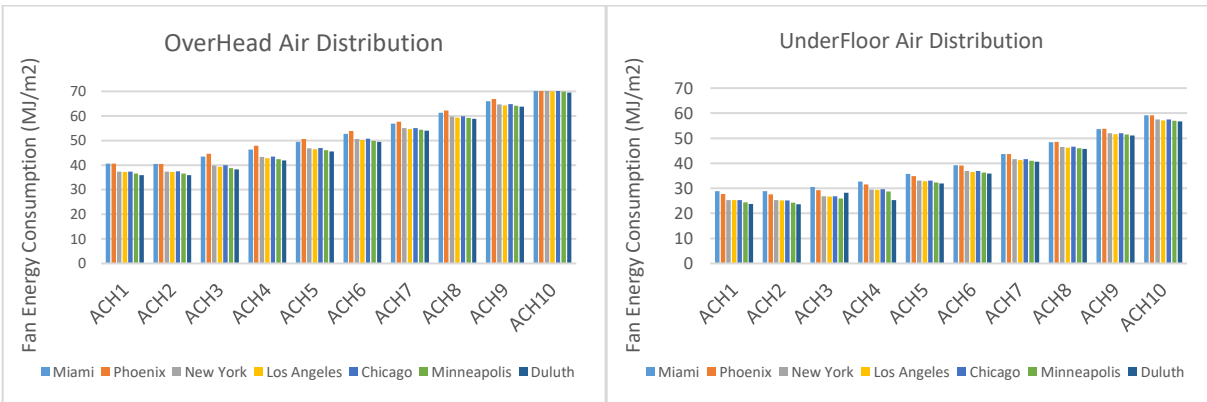


Figure 4 : Fan Energy Consumption in All Different Ventilation Rates

4.3 Cooling and Heating

The annual energy consumption through cooling and heating coils is extracted for all twenty scenarios in each city, as shown in Figure 5. As it is expected, the cooling energy in the hot and humid climate of Miami increases immediately. This behavior is due to introducing additional unconditioned outdoor air, which will result in increased heating load, especially in the summertime. Additionally, in humid areas such as Miami, dehumidification often accounts for up to half of the cooling ventilation load, resulting in considerable supply air temperature decrease and overcooling. In all other climates, the cooling energy is decreased initially due to increased outdoor air ventilation rate. The cooling energy consumption is due to introducing fresh air with the desired temperature in the cooling mode, which continuously decreases the cooling energy up to a specific ventilation rate for each city. The cooling load increases after the ventilation rate reaches 4ACH for Phoenix and New York, 5ACH for Chicago, and 6ACH for Los Angeles. Increased ventilation rates result in a significant increase in energy consumption to support the heating or cooling of incoming air to maintain a desired degree of comfort. The Heating load is most prominent in the cold climates of Minneapolis and Duluth, which will result in an initial decrease in heating energy, followed by increasing heating energy consumption from the 6th simulation run in both cities (6). We believe that this decrease in energy consumption is a result of the building room air model, which is underfloor air distribution. As mentioned before, this air conditioning approach provides the conditioned air directly to the occupied level with a lower supply air temperature in the heating mode (18°C). As the conditioned warm air travel upwards, it will enter the return air plenum. This approach makes the underfloor air distribution systems work more efficiently than the overhead systems in the heating mode. The efficient strategy makes it possible to use additional airflow rates throughout the day for space heating.

4.1 Energy Saving Potential

The UFAD system shows its energy-saving potential the most in cold climates. This behavior can also be observed in Figure 6, which presents the energy-saving potential of the UFAD system in understudied climates. This energy-saving ability increases in most climates as we increase the ACH up to ACH 6, which is an acceptable ventilation rate for minimizing the infection risk. This shows for having a healthy indoor environment with the ability to dilute the viruses and pollutants the UFAD systems offer better energy performance. We can conclude that although the energy consumption increases by increasing the ACH, using proper air distribution systems such as UFAD can result in a better performance in comparison with other systems.

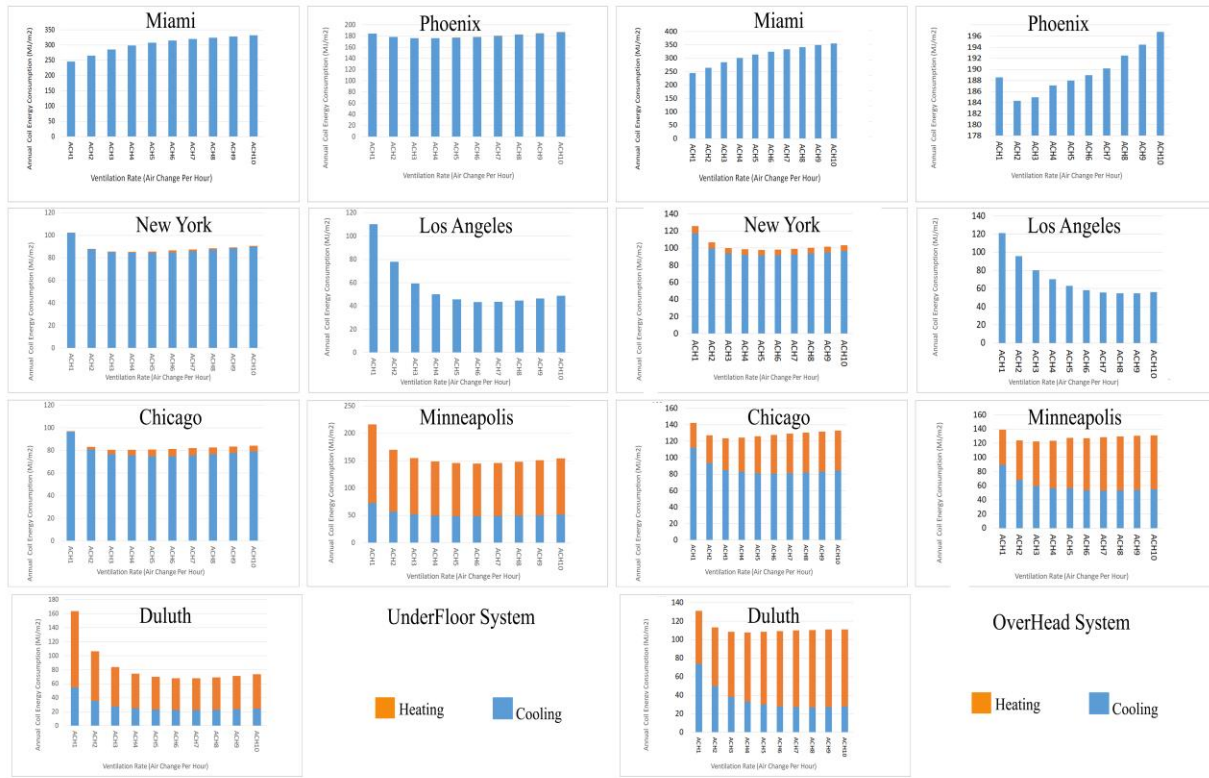


Figure 5: Energy Saving in UFAD compare to OH

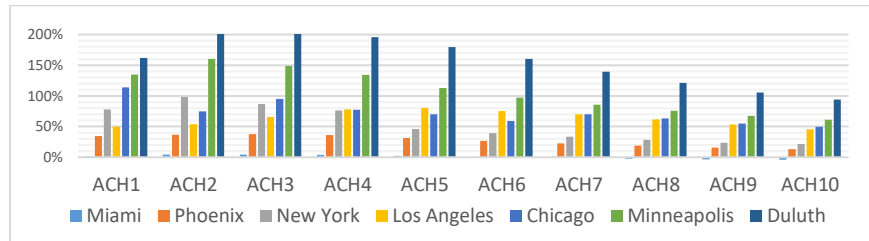


Figure 6: Heating and Cooling Coil Energy Consumption for All Cities

4.2 Infection Probability

Moreover, we demonstrate how the probability changes with ventilation rate for a defined office space. We take into account 430 total occupants based on the energy plus model and the absence of masks in order to standardize the findings. We have repeated the calculations for 1 to 10 infectors. We choose the quanta generation rates based on two usual levels of talking and breathing, which are 100 m³/h and 10 m³/h, respectively. The infectious quanta dosage that was received in each space may be computed as a function of the overall ventilation rate using Equation 1. Figure 7 displays these results. The predicted infection rate varies considerably among different ventilation rates and climates.

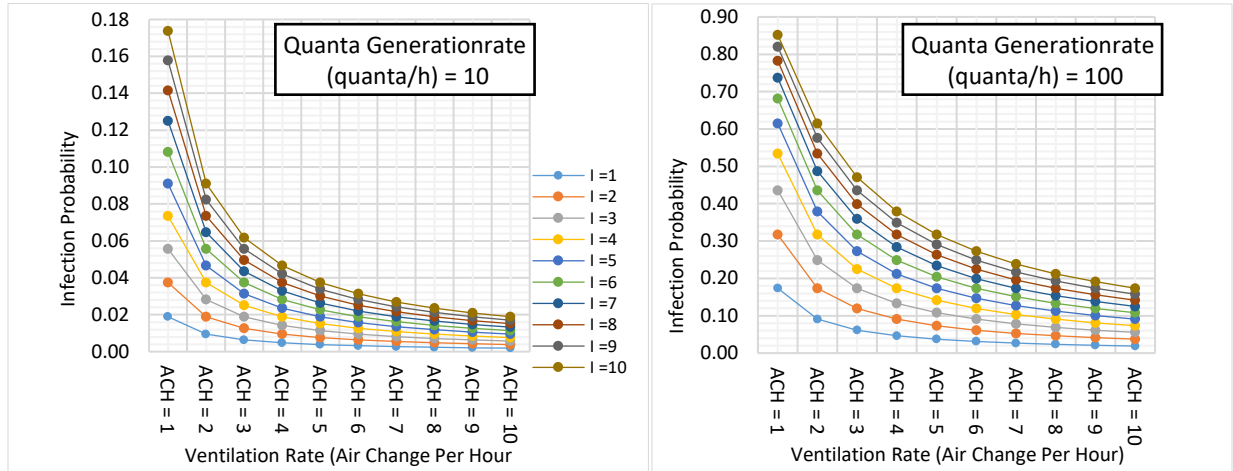


Figure 7: Infection Probability Based of Different Ventilation Rates

Figure 8 presents the changes in energy consumption based on different infection probabilities, which vary by changing the outdoor air ventilation rate. It is important to mention that the Wells-Riley model assumes that the air in the space is well-mixed and the concentration of particles is uniform in all the room, which doesn't let us vary the UFAD and OH system in this regard.

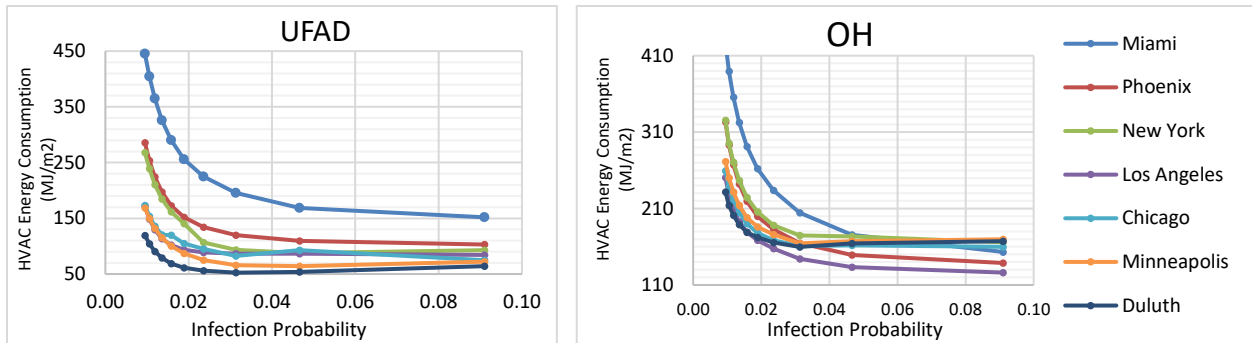


Figure 8: Infection Probability and Energy Consumption Tradeoff

5 CONCLUSION

Due to plenty of scientific evidence about the airborne viruses' transmission behaviors, it is absolutely necessary to reevaluate our building control system at the air conditioning level. The ventilation rate and outdoor air percentage in the mixed supply air temperature are two of the most important factors that need to be increased to reduce the infection risk in a building. While most of the recommendations in the studied guidelines are mostly similar, the precise ventilation rates required to limit the spread of an airborne virus such as SARS-CoV-2 are not specified and require more investigation. This study has investigated the changes in building energy consumption and infection probability as the ventilation rate increases across a wide range. We have learned that the energy consumption increase is primarily due to the additional fan energy usage. In addition, the hot and humid climates have shown higher energy consumption increases in comparison to climates at higher latitudes. The infection probability was shown to decrease immediately by changing the ventilation rate, especially in the initial increased levels. Therefore, it is important to find a balance between the energy and ventilation performance based on the air distribution system and the climatic conditions. This result indicates that it is essential to consider other possible approaches for outdoor air ventilation, including natural ventilation.

This study only looked into the influence of outdoor air ventilation on building energy consumption as one of the most critical post-COVID building control strategies. Other suggested approaches, including adding

MERV13 filters, running the HVAC system for additional hours before and after occupancy, and decreasing the number of occupants, will be investigated in future studies. Moreover, this study uses an analytical approach for calculating the infection probability in the room, which does not allow us to change the air system strategy (UFAD or OH). We need additional CFD based analysis to look into the impact of different ventilation strategies on the infection probability.

REFERENCES

- ASHRAE. 2019. "ANSI/ASHRAE 62.1-2019 Ventilation For Acceptable Indoor Air Quality." ASHRAE. 2019. <https://webstore.ansi.org/Standards/ASHRAE/ANSIASHRAE622019>. Accessed Jan. 5, 2022
- . 2021. "Ashrae Epidemic Task Force. Healthcare." *Ashrae*, 2021. https://www.ashrae.org/file_library/technical_resources/covid-19/ashrae-filtration_disinfection-c19-guidance.pdf. Accessed Jan. 5, 2022
- Ashrafi, R., M. Azarbayjani, R. Cox, B. Futrell, J. Glass, A. Zarrabi, and A. Amirazar. 2019. "Assessing the Performance of UFAD System in an Office Building Located In Various Climate Zones." <https://doi.org/10.5555/3390098.3390127>. Accessed Jan. 5, 2022
- Awada, M., B. Becerik-Gerber, S. Hoque, Z. O'Neill, G. Pedrielli, J. Wen, and T. Wu. 2021. "Ten Questions Concerning Occupant Health in Buildings during Normal Operations and Extreme Events Including the COVID-19 Pandemic." *Building and Environment* 188 (September 2020): 107480. <https://doi.org/10.1016/j.buildenv.2020.107480>.
- Bhagat, R. K., and P. Linden. 2020. "Displacement Ventilation: Available Ventilation Strategy for Makeshift Hospitals and Public Buildings to Contain Covid-19 and Other Airborne Diseases." *MedRxiv*, 2020.04.22.20075648. <https://doi.org/10.1101/2020.04.22.20075648>.
- Burkett, B Y J. 2021. "Airborne Transmission And Distribution," no. April. https://www.ashrae.org/file_library/technical_resources/ashrae_journal/2021journaldocuments/april2021_10-17_burkett-pt2.pdf. Accessed Jan. 5, 2022
- Circle, T., N E Atlanta, S. Fisher, T. M Rainey, W. P Bahnfleth, S. Campbell, A. K Persily, G.M Dobbs, D. L Herron, and D. S Marciniak. 2020. "ASHRAE Position Document on Infectious Aerosols." https://www.ashrae.org/file_library/about/position_documents/pd_infectiousaerosols_2020.pdf. Accessed Jan. 5, 2022
- Cortiços, N. D., and C. C. Duarte. 2021. "COVID-19: The Impact in US High-Rise Office Buildings Energy Efficiency." *Energy and Buildings* 249. <https://doi.org/10.1016/j.enbuild.2021.111180>.
- Crawley, D. B, D. B Shirey, S. M Cornick, P. L Jarrett, J.N Lott, R. J Morris, I. S Walker, et al. 2013. "ANSI/ASHRAE Standard 169-2013 Climatic Data for Building Design Standards." Accessed Jan. 5, 2022
- Escombe, A. R., C. C. Oeser, R. H. Gilman, M. Navincopa, E. Ticona, W. Pan, C. Martínez, et al. 2007. "Natural Ventilation for the Prevention of Airborne Contagion." *PLoS Medicine* vol. 4 (2), pp.0309–0317. <https://doi.org/10.1371/journal.pmed.0040068>.
- Hamilton, I., and O. Rapf. 2020. "Executive Summary of the 2020 Global Status Report for Buildings and Construction." *Global Alliance for Buildings and Construction*, 1–7.
- Kurnitski, J., F. Franchimon, and J. Hogeling. 2020. "How to Operate and Use Building Services in Order to Prevent the Spread of the Coronavirus Disease (COVID-19) in Workplaces." *Rehva* 2020 (i): 8. <https://www.rehva.eu/activities/covid-19-guidance>. Accessed Jan. 5, 2022
- Kurnitski, J., A. Boerstra, and F. Franchimon. 2021. "COVID19 HVAC Guidance Version 4.1." *Rehva*, 41. <https://www.rehva.eu/activities/covid-19-guidance/rehva-covid-19-guidance>. Accessed Jan. 5, 2022
- Li, C., and H. Tang. 2021. "Study on Ventilation Rates and Assessment of Infection Risks of COVID-19 in an Outpatient Building." *Journal of Building Engineering* 42 (August): 103090. <https://doi.org/10.1016/j.jobe.2021.103090>.

- Mostafavi, S., R. Cox, B. Futrell, and R. Ashafari. 2018. "Calibration of White-Box Whole-Building Energy Models Using a Systems-Identification Approach." *Proceedings: IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society*, December, 795–800. <https://doi.org/10.1109/IECON.2018.8591845>.
- Pease, P., J. Chhabra, and Z. Zolfaghari. 2021. "Planning for Net Zero by 2050, What HVAC System Interventions Will Today's Code Minimum Commercial Buildings Require?" 2050. <https://arxiv.org/abs/2111.03899v1>.
- Pei, G., D. Rim, and M. Isabella Taylor. 2021. "Effects of Indoor Airflow and Ventilation Strategy on the Airborne Virus Transmission" vol. 127 (2010), pp. 206–216.
- Ren, C., H. Zhu, and S. Cao. 2022. "Ventilation Strategies for Mitigation of Infection Disease Transmission in an Indoor Environment : A Case Study in Office." *Buildings*, vol. 12(2), art. 180.
- Schiavon, S., K. H. Lee, F. Bauman, and T. Webster. 2010. "Influence of Raised Floor on Zone Design Cooling Load in Commercial Buildings." *Energy and Buildings* vol. 42 (8), pp. 1182–1191. <https://doi.org/10.1016/j.enbuild.2010.02.009>.
- Webster, T., T. Hoyt, E. Lee, A. Daly, D. Feng, F. Bauman, S. Schiavon, K. Ho Lee, W. Pasut, and D. Fisher. 2012. "Influence of Design and Operating Conditions on Underfloor Air Distribution (UFAD) System Performance" <https://escholarship.org/uc/item/2082b3gt> Accessed March 11, 2022
- "WHO Coronavirus (COVID-19) Dashboard | WHO Coronavirus (COVID-19) Dashboard With Vaccination Data." <https://covid19.who.int/>. Accessed March 11, 2022
- Yang, R., C. Shen Ng, K. Leong Chong, R. Verzicco, and D. Lohse. 2021. "Optimal Ventilation Rate for Effective Displacement Ventilation." *JFM RAPIDS*, April, 1–10. <http://arxiv.org/abs/2104.03363>.
- Zolfaghari, Z., J. Jones, R. Gibbons, and R. Schubert. 2020. "Study of the Effect of Light Emitting Diode (LED) on the Optimum Window-to-Wall Ratio and Whole-Building Energy Consumption in Open Offices," no. January. <https://doi.org/10.13140/RG.2.2.24398.18245>.

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