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Quantifying the Effects of HVAC Operation to Mitigate Aerosol Concentration in a Classroom using CFD

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Quantifying the Effects of HVAC Operation to Mitigate Aerosol Concentration in a Classroom using CFD

By

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THESIS ACCEPTANCE PAGE
Scott Deprez

This thesis is approved as a creditable and independent investigation by a candidate for the master's degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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This thesis is dedicated to the pursuit of science in order to explain the effects of nature for the benefit of all human beings.

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NOMENCLATURE

CFM	Cubic Feet per Minute
BTU	British Thermal Unit
W	Watt
C	Celsius
F	Fahrenheit
hr	Hour
A	Area $[m^2]$ $[ft^2]$
u	Velocity in the x direction [m/s] [ft/s]
v	Velocity in the y direction [m/s] [ft/s]
w	Velocity in the z direction [m/s] [ft/s]
x	one of three spatial coordinates [m] [ft]
y	one of three spatial coordinates [m] [ft]
z	one of three spatial coordinates [m] [ft]
t	temporal coordinate [s]
d	differential sign present in a derivative
P	Pressure [Pa] [psi]

Re	Reynolds number
g	gravity [m/s^2] [ft/s^2]
E	Energy [J] [BTU]
Q	Heat Transfer [J] [BTU]
Q	Flow Rate [m^3/s] [ft^3/s]
L	Length [m] [ft]
L_e	Entrance Length [m] [ft]
D	Diameter [m] [ft]
W	Work [J] [BTU]
c	Specific heat capacity [J/(kg*K)] [BTU/lbm*F]
T	Temperature [K] [C] [F]
N	Number of diffusers [-]
R	Gas constant [J/mol*K] [ft^2*F*hr/BTU]
ρ	Density [kg/m^3] [lbm/ft^3]
τ	Shear stress [Pa] [psi]
μ	Dynamic viscosity [Pa*s] [psi*s]
υ	Kinematic viscosity [m^2/s] [ft^2/s]

Δ	Difference between two values [-]

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ABSTRACT

Using CFD to Quantify HVAC Operation to Mitigate Effects of Aerosol Concentration in Classrooms

Scott Deprez

2022

Heating, ventilation, and air conditioning (HVAC) is a complex mechanical system for the transition of air between outdoor and indoor areas. These systems are directly responsible for temperature, humidity, and air flow into any given space, thereby providing a level of comfort to those who live indoors. These systems account for 52 percent of U.S. energy consumption. When designing HVAC systems, indoor air quality (IAQ) is the main focus for achieving safe and clean air, such as in the case of airborne diseases. HVAC systems are responsible for the flow of air in indoor spaces and thereby expand the transmissible pathways of any given airborne virus. As a result, engineering and health organizations such as the World Health Organization (WHO), the Centers for Disease Control (CDC), and the American Society of Heating, Refrigeration, and Air conditioning Engineers (ASHRAE) have issued many guidelines. The focus of this study was to scientifically prove these guidelines and to determine whether the blanket statements provided by these organizations are supported by simulation results of various layouts in a university classroom setting. Computational fluid dynamics (CFD) is used as the foundation for software to determine the effects of mitigation strategies on the transmission of infectious aerosols. In this study, a university classroom located on South Dakota State University (SDSU) campus was modeled in computer-aided design (CAD) software and then imported into CFD software with a set of baseline physics conditions that would be used for various mitigation strategy. The mitigation strategies proposed in this study for the same university classroom are as follows: (1) airflow modification, (2) introduction of an acrylic barrier, (3) room layout adjustments, and (4) air redistribution techniques. Results show that the best and worst results are unique and there is no overlap between heating and cooling simulations sets. For instance, a bad result would be an overall increase in aerosols being distributed throughout the breathing zone of the room, whereas a good result would be a decrease in overall aerosols being distributed. Furthermore, there appears to be no one-size-fits-all solution throughout the calendar year, and each room under the influence of an HVAC system will have a unique strategy to mitigate the transmission of infectious aerosols.

CHAPTER 1 INTRODUCTION

1.1. HVAC Design Systems

Heating Ventilation and Air Conditioning (HVAC) refers to the combination of different systems responsible for the transitioning of air between outdoor and indoor areas [1]. There are five different basic types of systems, (1) traditional split, one system for heating and one for cooling, (2) ductless split, one unit per room depending on if heating or cooling is required, (3) hybrid split, two heating sources to control energy consumption options where one of the heating sources acts as an air conditioner in the summer by pulling heat out of the system, (4) packaged, fits all components for heating and cooling into one small compact system, and (5) geothermal systems, uses the earth to facilitate heating and cooling systems [2]. Going one step further, there are three parameters for each system when considering the design of an HVAC system for specific needs of the building owner such as (1) sizing, (2) ductwork, and (3) ventilation [2]. Sizing the equipment is crucial. If the unit is too big then the temperature in the room will change too quickly, if it is too small then the unit will run extensively trying to reach the desired temperature [2]. The length, path, and size of your ductwork plays a large part in the airflow patterns of the HVAC system and plays a big role in supplying even comfort throughout the building [2]. Without proper ventilation occupants can experience poor indoor air quality (IAQ) leading to illnesses, asthma attacks, and allergy flare-ups. Additionally poor ventilation leads to mold and moisture build up within the building [2].

There is a wide variety of codes compliance manuals available for current commercial and residential HVAC practice so there is no need for an installer to reinvent the wheel when designing an HVAC system [2]. Following the manuals and tools that are made readily available on public sites such as American Society of Heating Refrigeration, and Air-Conditioning Engineers (ASHRAE) and Air Conditioning Contractors of America (ACCA) will allow contractors to make more responsible decisions with regards to human comfort and other various human health concerns [2].

Increasing thermal comfort and reducing HVAC related energy consumption are often viewed as two conflicting goals [3]. Thermal comfort is one the most influential factors that affects indoor environmental quality (IEQ) [3]. The parameters that affect thermal comfort can be divided into two categories, (1) environmental related parameters, such as air temperature and humidity, and (2) occupant related parameters, such as clothing and metabolic rate [3]. ASHRAE Standard 55 and 62.1 are used by building owners to design an HVAC system that can moderate the air quality and thermal comfort requirements for human occupancy environmental conditions [3]. ASHRAE Standard 55 and 62.1 are used by building owners design an HVAC system that can moderate and meet air quality and the thermal comfort requirements for human occupancy environmental conditions [3]. Thermal comfort assess an occupant's thermal comfort satisfaction level based on the environmental and occupant parameters. However, a more conservative approach is taken when considering HVAC operation settings due to the lack of control the HVAC system has over occupant related parameters [3]. This conservative setting stems from the idea that HVAC systems need to be more energy efficient and should not exceed code compliant expectations.

1.2. Time Humans Spend Indoors

Time activity patterns indicators can be categorized into four parameters (1) Season, (2) age, (3) gender, and (4) urban rural status [5]. Time activity patterns can then be described into three separate type of environments (1) indoors, (2) outdoors, and (3) in a vehicle [5]. Of these three categories an overwhelming 89 percent of the time is spent indoors whereas 6 percent and 5 percent is spent outdoors and, in a vehicle, respectively [5].

Personal exposure to environmental substances such as airborne contaminants is determined by time-microenvironment activity (TMA) patterns [6]. For example, TMA patterns can be monitored in the EXPOLIS, which stands for Air Pollution Exposure Distribution Within Adult Urban Populations in Europe, “EXP” stands for Exposure and POLIS is Greek for “a city”, study that included 1,427 individuals ranging from ages 19-60 across seven European cities ranging from the UK to the Czech Republic [6]. The study showed that more the 90 percent of the variance in indoor TMA patterns originated from differences between the individual rather than the cities [6]. The difference among all seven cities were typically work status, unemployment status, living alone, or living with children [6]. The study then assessed the exposure to secondhand tobacco smoke among all seven cities, but the results differed substantially, the consensus to the difference in exposure to airborne contaminants is likely due to selection bias in the sample local populations [6]. It remains to be seen that TMA patterns need to be assessed when considering exposure to airborne contaminants such as SARS-CoV-2 when 89 to 90 percent of an individual’s time is spent indoors [5] [6].

1.3. Balance between Energy Consumed and Well-Conditioned Air supplied by HVAC Systems

Energy consumption through HVAC systems represents a significant portion of the nationwide energy usage in America [7]. According to the U.S. Small Business Administration, the Department of Energy (DOE), and the U.S. Energy Information Administration, HVAC systems account for 52 percent of the total energy usage in the U.S. where commercial buildings account for 40 percent and residential buildings have a nationwide average of 12 percent total energy usage in the U.S. where the amount of greenhouse gasses generated in homes is twice as much when compared to cars and is a contributing factor to climate change [7] [8]. The Efficiency of HVAC systems is the leading cause to the total amount of energy consumed during building operations and is responsible for twice as much greenhouse gas emissions then what is produced by a car, according to the Department of Energy (DOE) [7]. HVAC usage can vary widely from commercial buildings to residential homes but the most effective way to decrease the overall energy consumption is via heating and cooling efficiency [7]. For example, the effectiveness of any HVAC system comes from the installation, maintenance, and usage of the system by replacing equipment such as furnaces, air conditioners and even ductwork [7]. Additionally, designers should aim to use renewable energy systems whenever possible and to take advantage of natural conditions and reusable by-products found in the environment to effectively heat and cool the air [7]. For example, using heat exhaust and utilizing moisture or condensation to heat and cool the air respectively [7].

1.4. Indoor Air Quality

Indoor air quality (IAQ) is the air quality within and around buildings and structures and its relationship to the health and comfort of the occupants inside [9]. Reducing indoor health concerns comes with the understanding of air pollutants such as asthma triggers, secondhand smoke, mold, and radon [9]. The health risk associated with these air pollutants can be experienced both immediate and long term. For example, symptoms of immediate or repetitive exposure to air pollutants include irritation of the eyes, nose, and throat, headaches, dizziness, and fatigue and the likelihood of experiencing immediate reactions depends on age and preexisting medical conditions [9]. The treatment for short term symptoms is often removing the individual from the source of the air pollutant [9]. As a result, it is important to identify the air sources of the pollutant and maintain the supply of outdoor air coming indoors and heating, cooling, or humidity levels that are prevalent for the indoor environment [9]. Long-term symptoms associated with air pollutants may show health effects years after exposure and are leading causes to respiratory disease, heart disease, and even cancer. Therefore, it is important to improve IAQ even if short term symptoms are not immediately observed or experienced [9].

1.5. Airborne Disease

A virus is an intracellular parasite that cannot reproduce on its own but can direct a host cell to produce more viruses, it is essentially Ribonucleic acid (RNA) or Deoxyribonucleic acid (DNA) that is enclosed in a protein coating [10]. The study of viruses is a relatively new area due to the isolation of viruses from individual people, however the invention of the electron microscope enabled researchers to physically visualize a virus [10]. The most famous study on viruses was a 1934 study done by William F. Wells who expressed the relationship between droplet size and evaporation falling rate for airborne diseases such as Severe Acute Respiratory Syndrome (SARS) [10]. The study showed that the probability of infection was directly proportional to the number of infection cases divided by the number of susceptible people prone to infection [10]. The Wells study provides tremendous insight into the mechanisms of infection rates and provides a baseline for engineers and health officials to begin a deeper investigation into SARS related diseases.

SARS is a viral respiratory disease that was first reported in China in February of 2003. It was the first readily transmissible disease in the 21st century. SARS is capable of airborne transmission via small saliva droplets and contact transmission of surfaces that have been touched by an infected person. SARS is most likely to infect individuals that range between ages 25-70 with a 3 percent mortality rate [11]. A variant of SARS called, SARS-CoV-2 more commonly known as the corona virus or COVID-19 was first reported in Wuhan, China, on December 31, 2019. This is the latest variant of the SARS virus and has resulted in approximately 4.4 million deaths worldwide as of August 2021 and continues to grow as well as unprecedented government action for contagion of the virus including but not limited to the shutdown of non-essential businesses [12]. SARS-CoV-2 has had a major impact on the world and how humans socially interact on a global scale, the world pre SARS-CoV-2 is very different from post SARS-CoV-2 due to the need of containing such an easily transmissible disease.

SARS spreads rapidly, specifically within congregated areas such as university classrooms. For example, in August of 2020, as colleges and universities in the United States began to resume in person classes the number of cases in the United States began to rise and by February of 2021, the number of confirmed cases that were directly linked to university operations had already reached over 530,000 individuals [12]. Although in most university environments the demographic is young adults ranging from the age of 18-25, an age group that is much less susceptible to infection then individuals over the age of 65, it is likely the outbreaks occurred due to high density clustering of people in on campus housing such as dorm rooms and tightly packed lecture halls, combined with the need for young adults to socialize with their peers was the perfect environment for a readily transmissible airborne disease to thrive [12].

1.6. Transmission Methods

Exposure to SARS can take place in three primary methods: (1) inhalation of microscopic respiratory droplets and aerosol particles, (2) deposition of respiratory droplets and particles on exposed mucous membranes located in the mouth, nose, or eyes, and (3) touching your mouth, nose, or eyes with hands that have either been directly infected by virus containing fluids or indirectly infected by touching virus containing surfaces [13]. These primary methods of transmission can be simplified down to direct transmission and indirect transmission.

Direct transmission is carried out by direct contact between a susceptible person and an infected person by way of skin-to-skin contact or kissing as well as through short range droplet spread such as coughing, sneezing, or even talking. In some cases, the infected individual could be asymptomatic meaning they are displaying no signs or symptoms of being infected but are still able to directly infect susceptible individuals.

Indirect transmission is more difficult to contain and is often the reason for the spread of SARS from person to person. Indirect transmission can be through food, water, vehicles, or other inanimate objects that can store the virus on the surface for prolonged periods of time [10]. For example, indirect transmission via inanimate objects storing a virus on the surface for prolonged periods of time could be an infected individual sneezing onto the surface of a table. Hours later, a susceptible individual that sits at an infected table is now at a high risk for transmission of an airborne disease, even though this susceptible individual never physically contacted the infected individual. Other methods of indirect transmission are short and long range airborne transmission of liquid particles called aerosols [10].

Aerosols are smaller respiratory particles that can remain suspended in the air and thus disperse over distances that are greater than six feet. Epidemiologic studies show the biological plausibility of long range airborne transmission of SARS and that steps must be taken to mitigate the spread of airborne diseases [14]. Examples of a comprehensive epidemiological study that supports the long range airborne transmission of SARS was taken place in New Zealand where four people were staying in non-adjacent rooms all greater than six feet apart. The study showed that all people were subject to infection of the SARS-CoV-2 virus and that the only way for the disease to become transmissible in this study was by way of long range airborne transmission of infectious aerosols through the air stream of the facility which is controlled by the HVAC system [14].

Another study was done on the effects of virus laden aerosols in a music classroom located at the University of Minnesota in the Twin Cities. The study monitored different levels of injection rates for the virus due to the playing of instruments and singing. The virus is likely to propagate throughout the classroom at a more rapid rate than conventional lecture classrooms where individuals are talking and exhaling air at a more conventional rate. The results of this study showed that musical classrooms are indeed more susceptible to higher transmission rates due to the rate at which the disease propagates through instruments and the higher exit velocity of air from a person's mouth when signing or playing an instrument. To remedy this problem the University of Minnesota elected to implement portable air purifiers help bring the ventilation rates to an acceptable value of at least 288 m^3/hr per person prescribed by health officials from the World Health Organization (WHO) [15]. Nevertheless, it appears that the persistence and rate of propagation of infectious aerosols is in direct relation to the transmission of not only the SARS-CoV-2 virus but most, if not all, airborne related diseases such as SARS-CoV-1 and MERS-CoV [16].

1.7. Long Distance Transmission

Airborne transmission can be further classified into short and long range transmission. Short range transmission occurs when two people are in proximity of less than six feet apart and the aerosols between these individuals is directly inhaled from each other. Long range transmission occurs when droplets evaporate to a size where they can remain suspended in the air stream for extended periods of time. These suspended viral particles are then susceptible to be transported through the air stream by air currents, thermal plumes, and pressure differentials which are all influenced by the HVAC system [17]. As a result, the HVAC system has a direct impact on how long range airborne transmission can affect how a virus spreads from person-to-person.

The WHO supports the theory of contact and droplets as two major routes of transmission for SARS-CoV-2 [18]. In fact, according to the National Health Commission of China (NHC China) infectious aerosols in an enclosed environment are postulated to remain airborne anywhere from a few hours up to as long as a few weeks, assuming the infectious aerosol is less than one micrometer in diameter [18]. Even though the focus as of recent history has been for SARS-CoV-2 the spread of airborne transmission via aerosols is a physical concept that is not confined to any one disease, evidence is supported by the NHC China and WHO that long range transmission of infectious aerosols is also prevalent in SARS-CoV-1 which was first reported back in February of 2003 and MERS-CoV which first appeared in 2012 [18].

Beyond various SARS and MERS viruses, long range airborne transport of porcine reproductive and respiratory syndrome virus (PRRSV) and Mycoplasma hyopnumoniae (M hyo) has been recorded to travel as far as approximately 5 km through the air [19]. This shows that looking into preventing long range transmission is not just a problem for the SARS-CoV-2 outbreak but for other current and future diseases and outbreaks that will inevitably happen with the certainty of virus mutations. It is up to current HVAC engineers to design and modify existing models to manipulate the airstream in a way that can mitigate long range transmission of infectious aerosols.

1.8. Transmission Dependencies

The spread of infectious aerosols within an indoor space is dependent on the thermal plumes, air flow velocity, relative humidity, and pressure differential which can be defined as the indoor air quality (IAQ) or indoor environment quality (IEQ) of the space. The goal of any HVAC system is to directly control the IAQ of an indoor space regardless of the application and operation of the building. Controlling the IAQ in a way that lowers transmission rates is a problem that needs to be solved to combat present and future outbreaks [20].

The focus of the HVAC engineering community pre SARS-CoV-2 has largely been to maintain temperature and humidity comfort levels in a cost effective way with low energy costs [20]. Whereas a focus on responsible IAQ practices would prove to be a useful tool in combating infection rates from airborne disease such as varieties of SARS. Beyond even disease the benefits of responsible IAQ practices exceed even that of lowering transmission rates in that an improvement in IAQ can lead to better performance in schools and work, a reduction in sick building syndrome symptoms, and fewer sick days being taken by employees [21].

1.9. Airflow Patterns

As aerosols are exhaled from an infected individual, it is important to monitor how these aerosols travel throughout the space to analyze the IAQ at various locations in the room. It is possible that certain areas can be safer than other areas depending on the distribution of these infectious aerosols. To accomplish this, the characteristics of the airstream need to be visualized to define what locations in the room are experiencing circulation of old air and what areas are experiencing proper airflow from diffuser inlet to return outlet. To visualize these characteristics studies have been done by connecting a fog machine to the mouth of a mannequin and simulating the exhalation of water droplets so that researchers are able to experimentally track how these water droplets, which is assumed to be an infectious aerosol, travel through the room [22]. By being able to track these water droplets, engineers can adjust HVAC systems and compare the results of how these droplets travel throughout the air stream. Although this can be a useful process to ensure that building owners are taking the correct precautions and adhering to guidelines that make a significant difference in a reduction of transmission rates. The process can be very time consuming and, in some instances, impossible for new buildings that do not yet physically exist, thus running simulations using Computational Fluid Dynamics (CFD) is important due to the cost effectiveness, easy access, and time efficiency of a simulation versus experimental data.

HVAC systems in buildings, enclosed spaces, and public transports play a significant role in limiting the transmission of airborne pathogens such as SARS-CoV-2 at the expense of increased energy consumption and reduced thermal comfort [23]. The use of a liquid desiccant as opposed to traditional air scrubbers is an emerging technology in which the indoor air quality is increased, and the inactivation of pathogens is achieved via temperature and humidity control [23].

1.10. Importance of CFD

The use of CFD in the HVAC industry is an emerging technique for commercial use but is quite common for research purposes. One application of CFD in this field of study would be to analyze ventilation design specifications in buildings. This technique can be quite useful as gathering experimental data for buildings in operational use can be impossible, quite challenging, and extremely time intensive. The results on the analysis of the specifications in ventilated school buildings by use of CFD simulation is found in a study conducted in China where researchers were able to compare four different designs and determine which design would be able to deliver the most thermal comfort [24].

Similar simulations can be run for tracking the distribution of infectious aerosols as many HVAC systems are directly tied to IAQ such as thermal plumes, pressure differentials, and air stream velocities. For instance, take an office space where CFD simulations are ran to compare the effects of mixing ventilation (MV) or displacement ventilation (DV). Results showed that under the MV case particle concentration of infectious aerosols were uniformly distributed throughout the office. Whereas the DV system generated a vertical distribution of concentration. Further analysis showed that an increase in ventilation or the velocity of the air stream entering the space would drastically lower the concentration of infectious aerosols by as much as 60 percent and as low as 10 percent depending on if the ventilation system was MV or DV. However, the overall trend showed a decrease in particle concentration, a conclusion that is scientifically proven by running CFD simulations and zero experimental data [25]. The main takeaway here is that CFD simulations are cost effective, have a short time to solve, and as reliable as gathering physical experimental data, when the models are appropriately created and interpreted. It is important to use the technology that is available to scientifically prove that guidelines recommended by health officials like the CDC and WHO are making a significant improvement in the reduction of infection rates and that these proofs are being presented to the public in a timely manner as pandemics unfold in everyday life to the public.

1.11. Motivation and Goals

In light of the recent SARS-CoV-2 pandemic HVAC engineers have been developing guidelines and solutions to improve IAQ and combat long range transmission of infectious aerosols [20]. The need to improve IAQ is not just a short term goal for the current pandemic but is also a long term goal to prevent future extreme government anti-contagion actions such as shutting down non-essential businesses. If HVAC engineers can modify and develop future HVAC systems that are able to provide high quality and safe IAQ practices that can combat infectious aerosols, then the shutdown of non-essential businesses and extreme government intervention can be avoided for future pandemics.

The goal of this study is to conduct CFD on a university level classroom to monitor the spread of aerosols and long range transmissions to develop a proof of concept for future applications such as various social and commercial environments such as a grocery stores, office spaces, and restaurants. This study will show cost effective ways to reduce the overall concentration of infectious aerosols and while making drastic improvements to IAQ and to double check that guidelines proposed by the CDC, WHO, and ASHRAE are beneficial in all applications of society.

1.12. Organization of Thesis

Chapter 2 will focus on the current guidelines and mitigation strategies already made available by national and global health organizations and engineering societies such as the CDC, WHO, ASHREA, REHVA, and others. This chapter will also entail the capabilities cutting edge technology, such as CFD, has for industry use and the measures people can take to examine the safety of an indoor space with regards to infectious aerosol mitigation strategies. Chapter 3 lays out the fundamental equations used in this case study as well as laying out all the assumptions, set up, and ideas for the simulations. This chapter will also entail the questions this study aims to answer as well as any modeling techniques that are transferable to potential future case studies. Chapter 4 will then transition into the results and how all the different variations in mitigation strategies available for preexisting HVAC design systems, that were developed pre SARS-CoV-2, have an effect on aerosol concentration levels. Chapter 5 will discuss all the data obtained in the simulations ran and which strategies pose as a benefit to human safety versus which strategies can increase the level of aerosol concentration there by posing as an even greater threat to human health concerns. Finally, Chapter 6 summarize the key findings of this research and will provide recommendations for future studies to explore this research topic.

CHAPTER 2 LITERATURE REVIEW

This chapter aims to provide a comprehensive review of the relevant guidance made available by national and global health organizations and engineering societies such as the CDC, WHO, ASHRAE, and REHVA, as well as discuss the potential use of CFD analysis as an industry standard when designing post SARS-CoV-2 HVAC systems. It is important to notice that determining IAQ is a unique problem to solve for every room in every building across the entire globe and that each situation needs to be evaluated on a case by case study before even beginning to determine the best course of aerosol concentration mitigation strategy.

2.1. Current Guidelines of HVAC for Ensuring Indoor Air Quality

2.1.1. Ventilation

Ventilation is a crucial design aspect that needs to be considered when assessing the quality of IAQ and that proper ventilation techniques can lower the risk of person to person transmission of airborne infectious aerosols including SARS-CoV-2 [26]. ASHRAE Standard 62.1 is a minimum ventilation rate standard intended to provide acceptable IAQ to human occupants and minimize adverse health effects such as the spread of infectious aerosols [27]. This standard is updated annually as research develops and knowledge of how HVAC systems effect IAQ unfolds with regards to safety and comfortability as an adequate starting point when analyzing the minimum requirements that building owners are advised to follow to achieve responsible and safe IAQ practices for various building operations and scenarios. Ventilation is typically accomplished by using a mechanical HVAC system to introduce a combination of fresh outdoor air and recirculated indoor air, but it is also quite common to find older buildings in the Northeast and out west to only have natural ventilation [26]. Conversely, natural ventilation is the use of passive outdoor air flow through windows, doors, and other openings [26]. The standard ventilation rate for ASHRAE varies from building to building but for the case of university classrooms, ideal ventilation is 4.3 liters per second (1.136 gallons per second) per person of outdoor air [26]. It is often found that this standard is not physically being met whether it be to malfunctioning HVAC systems, excessive air recirculation, inadequate natural ventilation, or even by design to cut down on energy cost associated with heating and cooling applications throughout the calendar year and varying degrees of climate change depending on the situation or application of the building [26].

With the rise of industrialization in more countries around the world, the focus of purifying outdoor ambient air and lowering outdoor pollutants has been improved dramatically [28]. The consequence of this practice is the proportionate decline in IAQ due to energy conservation, decreases in ventilation, and the introduction of indoor pollutants [28]. IAQ is a main public health concern and is the leading cause of allergic and asthmatic disease and is responsible for absenteeism from work and even school [28]. This decline in IAQ is largely attributed to the combination of increase in energy prices and energy conservation rhetoric [28]. In 2018 buildings where responsible for 40 percent of energy use in Europe and 50 percent in the United States, this high energy consumption cost involves the essential use of ventilation to ensure acceptable IAQ and reduce the risk of person to person transmission of infectious aerosols [29] [30]. This leads to the implication that energy consumption and transmission mitigation are closely related in that an increase in energy consumption will result in the potential for greater ventilation of fresh outdoor air into the HVAC system and subsequently the rooms that are being supplied fresh air from that system to mitigate the spread of disease. Models are then established to assess what is the optimal point to achieve a safe level of IAQ for disease mitigation and minimize cost simultaneously. For example, a zonal model, which strives to explain the motion of air at different specific locations or zones in the room, asses the relationship between the applied ventilation at the location and the risk of infection using CFD [29]. The assumptions of this model are as follows: (1) there are only vertical and horizontal faces for the fluid to interact on, (2) each zone is well mixed in temperature and density, and (3) thermodynamic properties are correlated by the ideal gas law [29].

2.1.2. Filtration

Filtration systems are the most common type of IAQ practice found that is proven to protect individuals from airborne diseases [31]. However, choosing the correct filter size is done on a case by case basis, as every HVAC system will need different size filters based on building operations, cost of replacing the filter, and the size of the particles that are being filtered. Filters are rated by their HVAC filtration efficacy; this is determined by testing the Minimum Efficiency Reporting Value (MERV) which classifies filters according to their efficiency [31]. However, these tests are run for ideal installations only, that is to assume that there is no gap between the filter and the HVAC system, and there is no bypass for the air and particles to travel around the filter. Physically, this is not a good assumption because in most circumstances there are always small and even large gaps found at the edges of these filters [31]. The most significant flaw in these tests is that the rated filter efficiency of MERV 13 is going to be rated higher than the efficiency will physically be due to gaps between the filter and the HVAC system. Therefore, the proposed filter rating provided by ASHRAE, and health officials will not be enough to combat airborne diseases.

When considering filtration systems and their associated performance metrics to make adequate adjustments on any HVAC system three characteristics related to filtration must be called into question: (1) filtration effectiveness, (2) the risk reduction to transmission rates achievable, and (3) the cost of risk reduction [32]. Using a modified version of the Wells-Riley model, a 1934 study done by William F. Wells who expressed the relationship between droplet size and evaporation falling rate for airborne diseases such as severe acute respiratory syndrome (SARS) [10]., researchers can measure the risk associated with airborne infection transmission rates and relate the risk of transmission to the HVAC system design parameters such as filtration and outdoor air ventilation [32]. For example, a case study was done on the airborne transmission of influenza throughout a hypothetical office space at multiple different climates such as time of the year, geographical location on the earth, and heating versus cooling temperature modes. The results showed that for a significant risk reduction in person to person airborne transmission, MERV 13-16 filters were found to be the most effective while also maintaining low operational costs. Additionally, it was found that recirculating the equivalent amount of fresh outdoor air for ventilation to the filters proved to be equivalently effective with a bonus that recirculation is a lower operational cost [32].

Although for this study recirculation appeared to be just as effective as equivalent introduction of fresh outdoor air for the risk reduction in airborne transmission, it is important to note that not all IAQ practices are equivalent for every scenario such as classrooms and commercial buildings which will require further research on safe IAQ practices for the risk reduction in person to person airborne transmissions.

2.1.3. Humidity

Humidity is a natural property of air, like all other properties such as temperature, pressure, and velocity it is directly linked to IAQ and therefore influenced by HVAC system design. Epidemiological studies show that SARS-CoV-2 is more effective in cold and dry climates as opposed to warm and humid climates [10]. The effect of cold and dry climates being more susceptible to the spread of airborne disease is commonly attributed to the indoor crowding of individuals in tight close spaces, but the accurate cause of this phenomenon is the deactivation of the mucosal membrane by dry air in indoor facilities [10]. The mucosal membrane is a permeable barrier that selectively prohibits the passage of bacteria and permits the introduction of water and nutrients [20]. This barrier represents the first line of defense for individuals against pathogens. The effectiveness of this barrier is directly linked to the amount of moisture in a human's body [10]. For example, if an individual is dehydrated, they are more likely to be susceptible to infection and transmission than an individual that is sufficiently hydrated due to the deactivation of the mucosal membrane [10]. Another example of why a cold dry climate is more susceptible to higher infection rates then a warm humid environment would be due to the cold outdoors indoor facilities are typically heated, and current HVAC practice does not adhere to moisturizing the air during operations of heating the air. Additionally, naturally heating the air causes it to become drier, so the result is that the IAQ exhibits a characteristic of extremely dry air which causes moisture to leave the body of building occupants, leading to the deactivation of the mucosal barrier and a crowded area of highly susceptible individuals open to susceptible person to person airborne transmission.

2.1.4. Ultraviolet Germicidal Irradiation (UVGI)

Ultraviolet Germicidal Irradiation (UVGI) is a form of disinfection in which portable units are meant to be supplemental to HVAC system IAQ parameters. Portable UVGI's are placed in a room, similar to space humidifiers, the objective of these units is to use ultraviolet light to deactivate infectious airborne aerosols that are playing host to viral particles within the space of the room prior to returning to the HVAC system. The advantage of these portable units is that it will disinfect the air while it is not under the direct influence of the HVAC system. For example, air that is not directly in the duct work can only be influenced by the HVAC system in terms of the direction and velocity of the flow. Air that remains in the space cannot be disinfected by the HVAC system unless directly influenced by and external unit such as a portable UVGI. In the case of Tuberculosis (TB) upper room UVGI's are used to either kill or inactivate mycobacteria [33]. When conducting this practice, six parameters need to be considered when evaluating the effectiveness of portable UVGI's on airborne infectious aerosols [33]. The six parameters are as follows: (1) irradiance level, (2) UVGI influence levels, (3) effect of air mixing, (4) relationship between mechanical ventilation and UVGI, (5) effects of humidity and photoreactivation, and (6) optimum placement of portable UVGI units [33].

It is important to note that further IAQ practices need to be implemented in addition to what can be made to HVAC design due to the probability of transmission occurring at a time where exhaled air from an infected individual is inhaled by a susceptible host before the infectious aerosol is able to enter the HVAC system and be deactivated/disinfected. Although HVAC systems can affect the characteristics of air travel it cannot physically clean the air until passing through a filter, being ventilated to the outdoors via the duct work, or the use of ionization techniques within the physical unit.

Although the use of ionization in UVGI’s have been around for years in the physical air handling units of an HVAC system as a disinfectant for airborne pathogens, there is one major flaw in that the use of ionization techniques can attribute to an electrical discharge caused by the increase of the electron volt (eV) into the air stream [34]. The eV is the amount of energy gained when the electric potential of an electron increases by one volt [35]. To reduce the increase of eV during ionization, new technologies are being developed such as the needle point bi-polar ionization (NPBI) [34]. Other techniques such as Bi-polar ionization has been used for many years in specific applications where the ventilation of outside air needs to be reduced to accommodate ionization in the process of disinfection and cleaning of odors and other unwanted chemicals [34]. This is counterintuitive as it is already established that an increase in outdoor air ventilation is beneficial when reducing the risk assessment of transmission rates from person to person of airborne infectious aerosols. The problem then arises: What is the best course of action when using ionization techniques in tandem with ventilation requirements? To optimize the buildings air handling system for ventilation and ionization for the risk reduction of airborne aerosols, three questions must be asked when considering the new design:

1. What is the particle size range being targeted?
2. At what rate would over filtering part of the airstream achieve a reduction in particles of the targeted size?
3. What ionization techniques achieve lower levels of ozone and volatile organic compounds (VOC)?

When considering all these parameters it is found that not only a balance between ionization and ventilation can be determined, but rather it is an optimization problem between humidity, filtration systems, ionization, and ventilation techniques that all lead to an improvement in IAQ and a risk reduction in person to person airborne transmission rates.

2.1.5. General Guidance

With corroboration from health officials originating from the CDC to the WHO, it is recognized that the potential from airborne transmission is a certainty [36]. As a result, AHRAE has announced the formal position which states, “Transmission of SARS-CoV-2 through the air is sufficiently likely that airborne exposure to the virus should be controlled. Changes to building operations, including the operation of heating ventilation, and air conditioning systems, can reduce airborne exposures” [36]. Mitigation strategies are then implemented to assess the safety of occupants as a key performance indicator, one example of this in a laboratory setting would be high air change rates and exhaust systems to prevent the entrainment of contaminated indoor air [36]. It was found that using 100 percent of air exhausted to the atmosphere and replaced with fresh outdoor air was a typical use of mitigation strategies, but that several other recommended setting would not be as effective for other building applications such as a laboratory space [36].

General guidelines related to direct HVAC involvement in the transmission of infectious aerosols involve the increase in outdoor air ventilation, disable demand control ventilation (DCV), improve central air filtration to MERV 13, keep systems running 24/7, consider portable air filters, open outdoor air dampers to 100%, eliminating air recirculation, and consider portable UVGI systems [37]. In addition to these HVAC design techniques simple actions such as increasing the disinfection of frequently touched surfaces, installing more hand sanitation dispensers, close water stations, and supervising food preparation when applicable are all critical for building owners and occupants to mitigate the spread of infectious aerosols throughout multiple different building/ room scenarios [37].

Many HVAC design parameters pose a significant factor to the spread of SARS-CoV-2 [38]. Increased ventilation, advanced filtration, humidification, and improved mechanical hygiene are all measures intended to reduce the spread of airborne infectious aerosols [38]. For example, the impact of large diameter (7 ft. diameter) ceiling fans (LDCF) on SARS-CoV-2 exposure in warehouses in the United States were evaluated [39]. LDCF’s are commonly used for comfort cooling and destratification, this tends to result in a more mixed air distribution and continuous dilution of the indoor air [39]. The study of LCDF in American warehouses and the effect it has on person to person transmission of airborne infectious aerosols is applicable to many manufacturing and industrial facilities [39]. Ultimately the guidelines for LCDF's in manufacturing facilities such as warehouses was given four conclusions: (1) running fans at the highest speed with downward flow yielded the best performance, (2) high fan speeds lead to thermal discomfort in occupied zones, (3) reversing the direction at high fan speeds lowered the performance, and (4) reverse direction and low fan speeds caused the overall concentration levels of infectious aerosols to increase throughout the entire warehouse [39].

IEQ refers to the acceptable levels of thermal, visual, and acoustic comfort as well as IAQ, in Florina, Greece, university classroom systemic measurements were included to evaluate the status of IEQ and IAQ such as thermal comfort and levels of concentration from VOC's [40]. During the study surveys were handed out to evaluate the experimental results of thermal comfort and then cross examined to CFD simulation for validation on the assessment of IEQ, similar practices were also executed with the visual and acoustic comfort for an overall IEQ assessment [40]. Prior to the SARS-CoV-2 pandemic, maintaining a high IEQ rating was a goal to achieve high energy efficiency buildings in Europe [40]. For the specific case of a university classroom maintaining the comfort and health of indoor facilities can not only positively impact the health safety but the learning performance and participation of the occupants in the classroom [40]. With the risk for person to person airborne transmission of infectious aerosols, more stringent IAQ control measures should be applied in a post SARS-CoV-2 pandemic world [41]. A systemic review of IAQ practice recommendations such as ventilation and filtration need to be analyzed to assess the intended and unintended consequences of guidelines and recommendations supported by health officials [41]. The fact that an individual can spend more than 90 percent of their time indoors shows the importance of safe quality IAQ and that the recommendations and guidelines proposed by heath officials need to be assessed for there long term/ short term and unintended/ intended consequences [41]. The mitigation of airborne infectious aerosols is the primary short term goal, but the risk and benefits of changing fundamental HVAC design systems must be assessed to establish a strong scientific consensus on mitigation strategies proposed by health officials [41] [42].

2.2. Contaminants Regulated in the US and Internationally

The Clean Air Act (CAA) is a United States federal law implemented in 1970 that allows the federal government to regulate air emissions from stationary or mobile sources, this law authorizes the Environmental Protection Agency (EPA) to establish National Ambient Air Quality Standards (NAAQS) to regulate emissions of hazardous air pollutants for the benefit of public health and welfare [34]. Under the CAA a VOC is defined as photochemically reactive chemicals that produce ozone into the atmosphere and are regulated by the EPA [33]. However, IAQ is not regulated because VOCs that are considered toxic but not photochemically reactive are not regulated under the CAA [33]. This leads to products that are labeled as either “no VOC” or “low VOC” under the CAA and can contain VOCs that are toxic at high levels of concentration which will result in low or even unsafe IAQ [33]. While some VOCs are regulated under the CAA only outdoor air VOCs fall under that category, the EPA nor does any federal agency have the authority to regulate household products or any other aspect of IAQ nor do they have the authority to collect information on the chemical content of products in the marketplace [33]. The only authority the EPA has over IAQ is under Title IV of the Superfund

Amendments and Reauthorization Act (SARA) is to perform research and disseminate the information to the public [33]. Internationally speaking in Canada there is minor regulation of consumer products in deadly VOC concentration levels for just 98 consumer products ranging from personal care, household maintenance, and automotive refinishing [28]. In the European Union (EU) directive 2004/42/EC allows the regulation of VOC levels in just paints varnishes and vehicle refinishing and requires suppliers to label the legal limit value of VOC and maximum content of VOC in the products ready to use form [28].

2.3. Shortcomings Identified in HVAC Design

With significant advances within the past decade of HVAC design, the balance between energy efficiency, indoor air quality, and a comfortable indoor environment has been an ongoing challenge among HVAC engineers [43]. The techniques and approaches for designing HVAC systems have matured over the years and the parameters are primarily concerned with thermal sensation supplied by the systems air handling unit (AHU) and indoor thermal processes [44]. Despite the maturity of these techniques there remain disadvantages and advantages among various HVAC models such as the Black-Box model and the Gray-Box model [44]. The modeling of any HVAC system is a complex matter consisting of mass transfer and heat equipment and can be divided into three categories (1) physics based (White-Box), (2) data driven (Black-Box), and (3) Grey-Box [43]. Physics based models are based on fundamental physical laws like the conservation of energy, mass, and momentum [43]. These fundamental laws are then used to derive a set of equations to predict the performance of an HVAC systems components via simulations at the design stage [43]. Data driven based models are developed using real time data to establish a relationship between the output and input variables of the HVAC system using mathematical techniques and is only a suitable technique for already existing HVAC systems [43]. Grey box models are a combination of physics based and data based models where in some cases a physical process of the HVAC system is not clearly defined by thermodynamic equations and in other cases data is lacking [43].

As far as the Black-Box and Grey-Box models are concerned the shortcomings among both models lie in the simplifications made to reduce the complexity of thermal interactions leading to an uncertainty in thermal properties of structural elements [44]. Along with the uncertainty in thermal characteristics being a primary concern, neither model considers the AHU and the building simultaneously [44]. Additionally, the building models do not include the lag time in cooling load and solar gains for the ceiling, window, and walls whereas the AHU neglects the effectiveness of the air mixing chamber and assumes a cooling coil with no applied precooling [44]. In the process of the design phase, it is important to note that every HVAC model will have advantages and disadvantages that are directly tied to the assumptions made in the model and uncertainties calculated in the system properties [43].

2.4. CFD in Tracking Airborne Disease

When assessing the risk percentages for person-to-person transmission of infectious aerosols, CFD is used to optimize the best strategies for IAQ in terms of filtration, ventilation, humidity levels, temperature distributions, and air flow patterns on a case by case study. To observe the phenomenon of airborne transmission CFD takes advantage of a tool called “Passive Scalar”. A passive scalar is a technique in CFD in which the user introduces a dye to the fluid that originates from a source to be of 100 percent concentration [44]. This dye does not impact the motion of the fluid in any manner and the concentration levels will dissipate over both time and distance from the source. In CFD, the dye can be interpreted as an aerosol originating from and infectious individual that will follow the airflow around the room as time goes on. The source can then be thought of as an individual’s mouth as infectious aerosols are being exhaled. Since this technique does not directly track the viral particles, the analysis only shows the likely hood and not the certainty of person to person transmission for infectious aerosols containing virus laden particles such as SARS-CoV-2.

SARS-CoV-2 has caused unprecedented human and economic loss around the world [46]. While general guidelines such as social distancing and masking have been published as effective means to reduce airborne disease spread, the science behind these measures is still in its infancy [46]. With the knowledge of airborne diseases such as SARS being transported via respiratory aerosols, the characteristics of fluid dynamics fundamentally describes how airborne diseases spread from person to person [46]. The use of CFD is then able to provide tremendous insight in the understanding of any airborne disease such as SARS-CoV-2 [46]. With the powerful insight that CFD provides, engineers can make and implement control measures that reduce mitigation of airborne diseases without having to worry about compliance of the individual to adhere to health guidelines such as mask mandates and social distancing [46].

2.5. CFD in Indoor Air Quality

In CFD, IAQ is analyzed by modeling a typical HVAC system and room layout then visualizing the results such as temperature plumes, overall airflow patterns, horizontal and vertical distribution of cold air versus hot air, and humidity levels [20]. Each room and HVAC layout scenario will be unique based off building operation purpose, occupant status of the room, location on earth, and time of the year with relation to climate of the region. With all these variables to consider when designing an HVAC system that will supply adequate IAQ, it is virtually impossible to apply experimental data from one situation to another with reasonable accuracy that the best practices for one application will translate over to others. As a result, running CFD simulations is the quickest and most cost effective practice when analyzing IAQ and how it can be used to monitor the probability of transmissible airborne diseases from person to person within a confined space on a case by case study. For example, CFD simulations are ran to evaluate the effectiveness of a wall hanging air conditioning unit in the summer, the simulation results show the air speed within the room, temperature distribution throughout the space, and age of the air from entering to leaving the room [47]. The CFD results showed that wall-hanging air conditioning systems can undertake indoor heat load and conduct good indoor thermal comfort. However, in terms of the air speed, areas where people sit, and stand showed moderate levels of wind comfort but for air quality there were localized areas in the room with no ventilation thus toxic gasses did not discharge in time [47]. Even though the average ventilation of the room was considered high enough for adequate IAQ, CFD shows that localized areas could have little to no ventilation resulting in dangerously poor IAQ if toxic gasses are present.

2.6. Applications of CFD beyond State of the Art HVAC Design

Throughout the past two decades, CFD has seen an increase in development in relation to combustor designs, aerodynamic simulation of aerospace flights and shuttles, as well as other aerospace applications and even nuclear engineering technology [31]. For example, CFD plays an important role in reactor design and thermal hydraulic analysis for nuclear engineering [32]. The CFD method is used in high fidelity simulations that ultimately developed the multi-scale and multi-physics coupling platforms used in nuclear engineering [32]. Ultimately it is these platforms that lead to key nuclear power plant equipment such as the Reactor Pressure Valve (RPV), Steam Generator (SG), valves, T-Junctions, and passive residual heat exchangers to be developed [32]. The basis of the CFD method is that the analysis of fluid flow is numerically solved, and the user can analyze complex problems involving fluid to fluid, fluid to gas, or fluid to solid interactions.

2.7. Summary

The safe and responsible practice of high IAQ throughout facilities is fundamentally an optimization problem for engineers to solve. It comes down to energy costs and all the different aspects that make up IAQ such as humidity, ventilation, filtration, and temperature distributions. Even further than conventional characteristics of

IAQ, engineers need to consider the effects of the environment and operational use of the building such as climate change, location of the building on earth, time of the year, and even the building layout such as a university classroom, movie theatre, or a grocery store. Every detail will need to be considered on a case by case study as there tends to be no sign of a one size fits all solution for any building application when it comes to a minimum IAQ requirement for the reduction in the risk percentages for person to person transmission of infectious aerosols. Therefore, the use of software simulations such as CFD will have to lead the way for building owners to establish personal guidelines tailored to the physical real life application their occupants will experience on a day to day basis.

CHAPTER 3 METHODS AND APPROACH

3.1. Research Questions

When considering a standard university classroom setting this research study will aim to answer five questions about potential mitigation strategies on the person-to-person transmission for aerosol spread:

(1) At what point does too much ventilation become detrimental to the mitigation of aerosols, and what is the ideal ventilation rate for minimal propagation of these aerosols?

(2) How does the temperature of incoming indoor air affect the spread of aerosols, specifically with regards to how a flu season is seen in the winter months as opposed to the summer months?

(3) How effective is the introduction of an acrylic barrier in front of a speaker at impeding the flow of aerosols?

(4) Does physically changing the orientation of the room with relation to the direction the speaker is facing significantly affect the propagation of aerosols?

(5) Is it possible to create artificial quarantine zones by modifying the downward flow velocity of incoming air in five of the six diffusers while maintaining the same level of total ventilation rate being supplied by the HVAC system?

3.2. Hypothesis Statement

When considering five different aerosol mitigation strategies it is expected that there will not be a one size fits all solution where one strategy will prove to be significantly more effective than all other strategies at all times of the year. It is likely that depending on the time of the year, speaking arrangement, and classroom setup in terms of desks, chairs, and overall number of people that some strategies will prove to be more effective than others for each circumstance. The most significant example of this will show up when comparing aerosol mitigation strategies for the summer and the winter months due to the significant change in airflow patterns of the temperature differences between the incoming hot and cold air and the respective cold and hot air that is already in the room prior to HVAC use.

3.3. Designs of Computational Experiments

For the purposes of this research study, a classroom at South Dakota State University (SDSU) in Crothers Engineering Hall (CEH) is selected to simulate the likelihood of person to person airborne transmission for SARS-CoV-2. The room is assumed to have 21 individuals consisting of 20 sitting students all six feet apart from each other in a 4x5 grid set up and one standing teacher giving a lecture at the front of the room. The walls of the room are adiabatic except for one exterior wall that exhibits a heat flux value depending on the time of the year, either summer or winter. Located at the ceiling there is six diffusers positioned in a 2x3 grid setup that supply a constant cubic feet per minute (CFM) of air to the room which is specified by the building operator.

All classroom dimensions such as height, width, and length of the entire room, tables, windows, and supply diffusers are measured experimentally then recreated in SOLIDWORKS Computer Aided Design (CAD) modeling software. The CAD model was then imported into Star-CCM+ Computational Fluid Dynamics (CFD) software to establish all initial and boundary conditions such as temperature of supply, indoor and outdoor air, heat flux of the exterior wall, body heat of each individual person, individual CFM being supplied to the six diffusers, and exhalation and inhalation rates of the 21 individuals depending on breathing activity. The assigned value of each initial and boundary condition can then be adjusted depending on time of the year, ventilation rate desired, and speaking activity of the room. The adjustment of the furniture can also be altered via SOLIDWORKS CAD modeling software.

3.4. Model inputs and Predicted Outputs

Five input scenarios will be simulated to determine the best mitigation strategy against the propagation of aerosols. These scenarios and their inputs are listed in the five following applications: (1) the effectiveness of ventilation is to be examined by assessing the propagation of aerosols when altering the incoming flow rate of supply air to 800 CFM (22.65 cubic meter per minute) to explore under ventilated systems that are at the absolute minimum of ASHRAE standards and evaluating that level of IAQ safety, 1100 CFM (31.15 cubic meter per minute) to account for exceeding ASHRAE standards that currently exist by a certain factor of safety to maximize occupant comfort and simultaneously minimize operational cost, and 1600 CFM (45.31 cubic meter per minute) to explore exceeding ASHRAE standards while maximizing occupant comfort and ignoring operational cost. (2) The relationship between temperature and the propagation of aerosols is evaluated by comparing the introduction of hot and cold supply air for the winter and summer months respectively. (3) Among multiple cost effective mitigation strategies, the introduction of an acrylic barrier to impede the flow of aerosols is evaluated by placing a solid barrier directly in front of the mouth of the teacher as is shown in Figure 1 and then simulated in CFD to assess aerosol propagation. (4) The second cost effective mitigation strategy is altering the orientation of the furniture, teacher, and students to potentially shorten the pathway of aerosols, this is accomplished by changing the orientation of all the desks, chairs, and students by 90 degrees clockwise and changing the orientation of the teacher 90 degrees counterclockwise as is shown in Figure 1. (5) The final mitigation strategy is to experiment with the velocity of incoming air while maintaining a constant CFM. This is accomplished by increasing the air in five of the six diffusers and completely turning off the sixth diffuser which is located directly above the teacher.

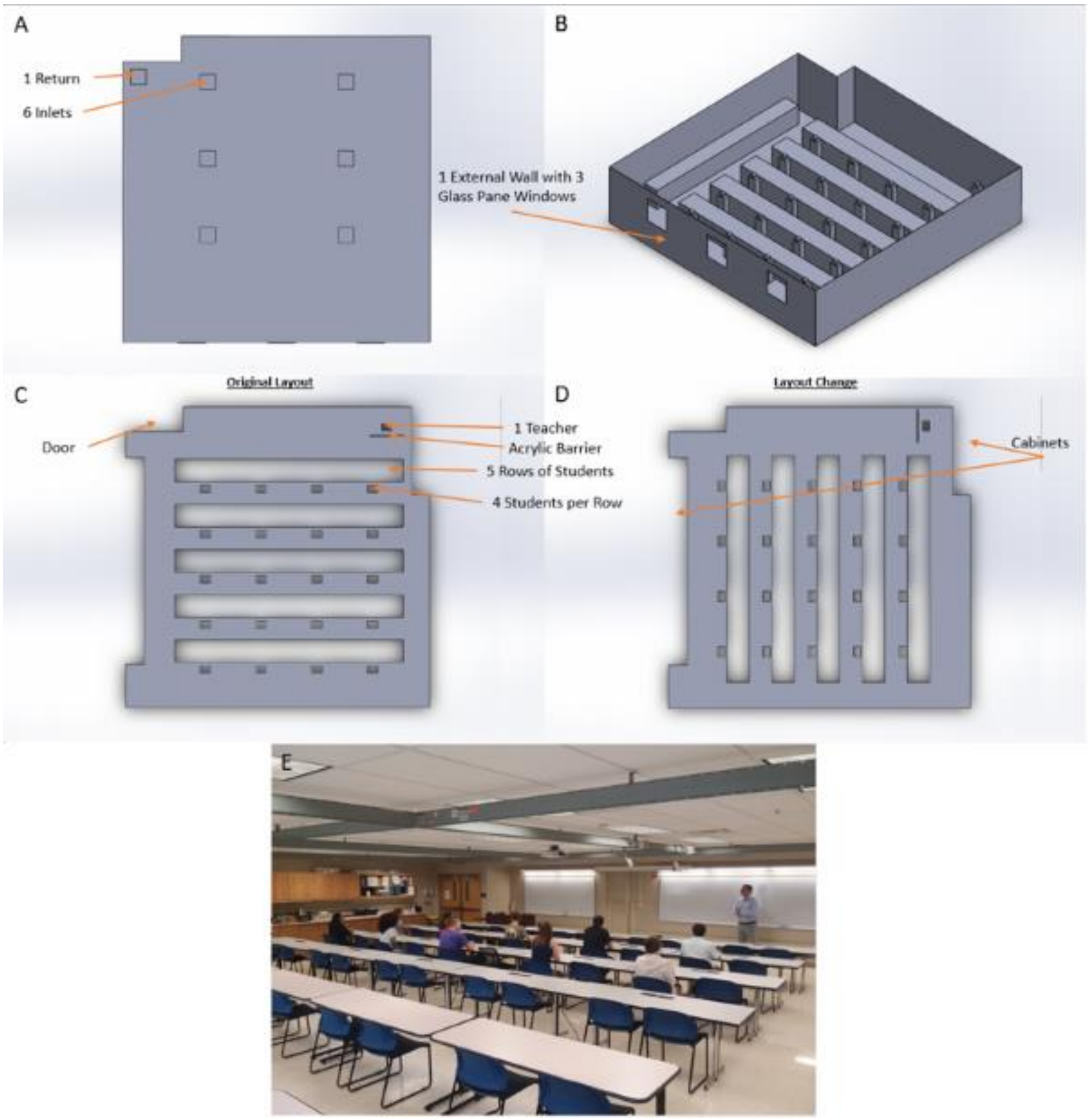


Figure 1: CAD Model of the University Classroom with Change in Layout and an Acrylic Barrier.

What is expected to happen in each of the five respective scenarios is then listed in the following: (1) Higher ventilation rates will lead to a decrease in the propagation of aerosols, regardless of heating or cooling temperature modes for the summer and winter months respectively. (2) Dryer air exhibited in the winter months will create a much larger propagation of aerosols throughout the space making it more likely for person to person transmission of SARS-CoV-2. This will show that disease mitigation strategies are more prevalent in the winter months as individuals tend to be more susceptible to person to person transmission of aerosols. (3) The introduction of an acrylic barrier in front of the teacher, assuming the teacher is infected, will impede the flow of aerosols to the students and result in a more significant decrease in the propagation of aerosols originating from the teacher then if there was no acrylic barrier at all. (4) Changing the furniture around by reorientating the direction an individual is speaking can affect the overall travel of aerosols independent of all other factors and that some orientations are beneficial in that it will decrease the overall propagation of aerosols throughout the space. (5) Re-allocating supply air velocities to other diffusers while maintaining the overall CFM supplied to the room at a constant value will cause the downward flow of air to segregate aerosols to one section of the room and drastically reduce aerosol propagation.

3.5. List of Assumptions and Boundary Conditions

When analyzing aerosol mitigation strategies, a list of assumptions and boundary conditions are made to set up a system of computational experiments and compare each of the five previously described scenarios, in total there are seven combined assumptions and boundary conditions made: (1) one person generates 200 - 250 BTU/hr (60 - 70 W) of body heat, (2) inside temperature of the air for both heating and cooling temperature modes will be set to 72 F (22 C), (3) outside temperature of the air for heating and cooling temperature modes will be set to -15 F (-26 C) and 95 F (35 C) respectively, (4) 21 total people in the room consisting of 20 students and 1 teacher, (5) 1,600 square feet

(148 square meters) of floor space in the room, (6) cross sectional area of the ductwork is 4 square feet (0.37 square meters), and (7) the entrance length of the ductwork is 20 feet (6 meters) to allow for fully developed flow in the simulation, a similar characteristic that is exhibited in physical HVAC design systems.

3.6. Governing Equations

3.6.1. Continuity

The continuity equation is one of many fundamental sets of equations that encompass all applications of fluid dynamics, it states that when a fluid is in motion it must move in such a way that mass is conserved, this is more commonly known as the conservation of mass equation [48]. The Continuity equation is expressed using Equations 1.0, 1.1, and 1.2 where “A” is the cross sectional area with respect to direction of the flow, “ρ” is the density of the fluid, “u”, “v”, “w” is the velocity of the fluid in the respective “x”, “y”, and “z” spatial direction it exists in whereas “t” represents the temporal state in which the fluid can exist in.

$$\boldsymbol{\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0}$$

$$\boldsymbol{Mass_{in} = Mass_{out}}$$

$$\boldsymbol{\rho * A_{in} * V_{in} = \rho * A_{out} * V_{out}}$$

3.6.2. Streamlines

A streamline is a pathway traced out by a massless particle moving with the fluid and the velocity direction of the fluid is tangential to the streamlines [49]. Mass cannot cross any streamlines and the streamlines travel the same pathway as the object [49]. In HVAC streamlines provide critical insight into how air flows throughout a space. Streamlines are calculated using Equation 2.0 where "dx", "dy", and "dz" represent an element of the fluid in any of the three spatial directions and "u", "v", and "w" represent the velocity in the respective spatial direction of the fluid.

$$\frac{dx}{u} = \frac{dy}{v} = \frac{dz}{w}$$

3.6.3. Conservation of Momentum

The differential form of the conservation of momentum, referred to as the Navier-Stokes equations, are a three dimensional set of equations which describe the velocity, pressure, and density, of a fluid in motion and include the effects of viscosity [50]. These equations depend on the time dependent continuity conservation of mass equation as described previously, three time dependent conservation of momentum equations, and a time dependent conservation of energy equation [50]. The equations depend on four independent variables that consist of three spatial coordinates and one temporal coordinate [50]. All Navier Stokes equations are shown below in Equations 3.0, 3.1, and 3.2 where variables that are seen in the continuity equation such as "ρ" the density of the fluid, "u", "v", "w" the velocity of the fluid in the respective "x", "y", and "z" spatial direction it exists and the "t" temporal state in which the fluid can exist in are all expressed in the Navier Stokes equations as well as the continuity equations. Additionally, the Navier stokes equations account for “P” pressure, “Re” Reynolds number, and “g” gravity.

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho u^2)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}+\frac{\partial(\rho uw)}{\partial z}=\rho g_x-\frac{\partial P}{\partial x}+\mu\,(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2})$$

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho v^2)}{\partial y}+\frac{\partial(\rho vw)}{\partial z}=\rho g_y-\frac{\partial P}{\partial y}+\mu\,(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2})$$

$$\frac{\partial(\rho w)}{\partial t}+\frac{\partial(\rho uw)}{\partial x}+\frac{\partial(\rho vw)}{\partial y}+\frac{\partial(\rho w^2)}{\partial z}=\rho g_z-\frac{\partial P}{\partial z}+\mu\,(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2})$$

The fourth equation is the conservation of nergy equation, which accounts for heat transfer and temperature differences between fluids is expressed in Equation 3.3. where all of the parameters in Equations 3.0 – 3.2 are shared but two parameters are added to account for “E” energy, “q” heat transfer, and “τ” shear stress.

$$\begin{aligned}\frac{\partial(E_T)}{\partial t}+\frac{\partial(uE_T)}{\partial x}+\frac{\partial(vE_T)}{\partial y}+\frac{\partial(wE_T)}{\partial z}\\
&=-\frac{\partial(pu)}{\partial x}-\frac{\partial(pv)}{\partial y}-\frac{\partial(pw)}{\partial z}-\frac{1}{Re_T*Pr_T}*(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z})\\
&+\frac{1}{Re_T}\\
&*(\frac{\partial}{\partial x}(u*\tau_{xx}+v*\tau_{xy}+w*\tau_{xz})+\frac{\partial}{\partial y}(u*\tau_{xy}+v*\tau_{yy}+w*\tau_{yz})\\
&+\frac{\partial}{\partial z}(u*\tau_{xz}+v*\tau_{yz}+w*\tau_{zz}))\end{aligned}$$

3.6.4. Reynolds Number

Reynolds number is a similarity parameter that represents the ratio of the inertia and viscous forces of the fluid [51]. The inertial forces are described by the product of density, velocity, and the first velocity gradient. This is more commonly known as acceleration of the fluid [51]. The viscous forces are characterized by the product of dynamic viscosity, and the second velocity gradient with respect to x [51]. The Reynolds number can be expressed below in Equation 4.0 where "ρ" is the density of the fluid, "v" is the velocity of the fluid, "L" is the cross sectional characteristic length with respect to the direction of the flow, and "μ" and "ν" are respectively the material properties of dynamic and kinetic viscosity for the fluid.

$$Re = \frac{\rho * \mathrm{v} * L}{\mu} = \frac{\mathrm{v} * L}{\nu}$$

3.6.5. Entrance Length

Entrance length is the space a fluid needs to fully develop the velocity profile after passing through components such as turns, valves, pumps, and turbines in the pathway of the fluid [52]. In HVAC the fluid is fully developed once entering the space and exposed to the occupants [52]. Entrance length is calculated using Equation 5.0, 5.1, and 5.2 to calculate the entrance length number based off of laminar or turbulent flow and subsequently the length of piping required for fully developed internal flow. The variables "EL" is the dimensionless entrance length number for fully developed flow, "L" is the length of piping, “D” is the diameter of the piping, and “Re” is the Reynolds number.

$$EL = \frac{L}{D}$$

$$EL_{Laminar} = 0.06 * Re$$

$$EL_{Turbulent} = 4.4 * Re^{\frac{1}{6}}$$

3.6.6. First Law of Thermodynamics

Thermodynamics is a branch of physics which deals with the energy and work of a system [53]. The first law of thermodynamics is equivalent to the conservation of energy when referencing heat transfer and work. It defines the change in internal energy from state one to state two and is proportional to the heat transfer into the system and the work done by the system, work done, and heat removed represent negative values for the overall system of equations [53]. The first law of thermodynamics is defined in Equation 6.0 where “E” is energy, “q” is the heat transfer, and “W” is the work done by the system.

$$E_2 - E_1 = q - W$$

3.6.7. Heat Transfer Analysis

Heat transfer is the process of reaching thermodynamic equilibrium in which heat is transferred from a warmer object to a colder object. At equilibrium heat transfer is equal to zero and the temperature of both objects is equivalent [54]. The amount of heat transfer achieved is proportional to the product of the temperature difference and the overall average heat capacity between the two objects [54]. There are three different unique cases in which heat transfer can occur, (1) convection for fluids, (2) conduction for objects in direct contact, and (3) radiation for heat transfer via electromagnetic waves. All three unique equations are expressed in Equation 7.0 where “Δ Q” is the change in heat transfer, “c” is the specific heat capacity of the material/ fluid, and “ΔT” is the temperature difference of the cold material/ fluid and the hot material/ fluid.

$$\Delta Q = C * \Delta T$$

3.7. CAD Modeling

A CAD model of the classroom was generated in SOLIDWORKS modeling software by creating a 40 ft x 40 ft (12.19 m x 12.19 m) room, with a floor to ceiling height of 10 ft (3.05 m). Inside the room there are five rows of tables with four students in each row, located 6 ft (1.8 m) apart from each other to abide by CDC and WHO social distancing guidelines. Each of the twenty student is assumed to have a designated standing height of 72 inches (183 centimeters), this would then result in a sitting height of 48 inches (122 centimeters). The teacher is located at the front of the classroom and is assumed to have the same standing height of 72 inches (183 centimeters) as the students.

The supply diffusers are placed in a 2x3 grid, allowing for the placement of 6 total supply diffusers each with the dimensions of 24 inches x 24 inches (61 centimeters x 61 centimeters). To represent the incoming air deflection through the overhead diffusers, a flat baffle plate was modeled just below the ceiling surface at each diffuser opening. The distance between the ceiling and baffle plate was modified in an isothermal simulation until the horizontal throw from the diffusers matches closely with that of a typical ceiling diffuser.

3.8. CFD Modeling

3.8.1. Mesh Modeling

After the CAD model is created, CFD simulations are used to perform the fluid analysis of the airflow throughout the room and track the distribution of aerosols from the source. To begin these simulations, a mesh is created from the CAD model of the classroom using the surface remesher, automatic surface repair, polyhedral mesher, and advanced layer mesher as the four meshing models. In doing so, a mesh of almost 540,000 cells was generated. The mesh modeling is just one of two critical components of any CFD simulation. The point of the mesh is to establish an array of cells that CFD software Star-CCM+ can use to numerically solve the Navier Stokes equations. The more refined the mesh, the more cells there are to numerically solve, leading to a more detailed explanation about what is physically happening to the fluid dynamics of the system.

3.8.2. Physics Conditions

After meshing is established the second critical component of the CFD simulation is to define a baseline of physics conditions that will be used across each simulation to provide an unbiased comparison between variations in the layout and HVAC system operations. All eight physics conditions are listed in Table 1. A constant density of air was assumed, which was paired with the Boussinesq heating approximation. This approximation simplifies the physics of the fluid dynamics throughout the simulation while providing sufficient accuracy.

Table 1: List of General Assumptions and Physics Conditions for all Simulation Variations.

Physics Conditions	Physics Description
Segregated Flow	CFD Solver that runs fast and is easy to use with the exception of supersonic flow
Segregated Fluid Temperature	Used to establish an initial fluid temperature for the "Segregated Flow" physics condition
Boussinesq Model	Used for Buoyancy driven flow, also known as natural convection and accounts for the change in temperature and heat transfer in the air
Constant Density	No significant change in elevation or pressure and "Bousinesq Model" accounts for the change in temperature or heat transfer in the air
Passive Scalar	Diffusive contaminant in a fluid flow that is present in such low concentration that it has no dynamical effect on the fluid motion
Gravity	The fundamental interaction that attracts all things with mass or energy towards each other
Turbulent	Type of fluid flow in which the fluid undergoes irregular fluctuations, or mixing, in contrast to laminar flow in which the fluid moves in smooth pathways or layers
Reynolds-Averaged Navier Stokes (RANS)	Time averaged equations of motion for fluid flow, used to describe turbulent flows to give approximations of time averaged solutions
K-Omega Turbulence	Two equation turbulence model used in CFD and is used as an approximation of RANS
SST (Menter) K-Omega	Two equation eddy viscosity turbulence model used in CFD that combines the K-Omega nand K-Epsilon turbulence models
Turbulence Suppression	Used to establish the transition between laminar and turbulent flow regimes
Transition Boundary Distance	Establishes the area of critical Reynolds number which represents the transition between laminar and turbulent flow regimes
All y+ Wall Treatment	A treatment that attempts to represent the combination of high wall treatment for coarse meshes and the low y+ wall treatment for fine meshes
Wall Distance	The minimum distance between a given point and any of the other points on the wall boundaries of the CFD model
Implicit Unsteady	Allows the user to run the simulation as a function of time
Gradients	A differential operator applied to a three dimensional vector valued field function such as velocity, temperature, and pressure
Three Dimensional	Accounts for the traditional three dimensional spatial coordinate system
Gas	Air is the main component ran in the simulation and is in its gaseous state

3.9. Breathing Characteristics

The breathing characteristics of an individual can be described as the relationship between flow rate for breathing, tidal volume (TV), respiratory frequency (RF) for inhalation and exhalation, and the minute volume (MV) [55]. The TV is the volume of air expired in a single breath, MV is the volume of air expired in a minute, and the RF is expressed as the number of breathes per minute [55]. Additionally, the MF, TV, and RF differ from person to person based off sex, weight, height, breathing activities such as talking, coughing, and breathing at rest, and the average cross sectional area opening of the human mouth/ nose depending on what is the primary mode of breathing [55]. Due to the exhalation and inhalation of breathing cycles it is expected that any mathematical model that accounts for the flow dynamics of breathing will exhibit characteristics of a sine wave [55]. For the purposes of this research every student will be male, 72 inches (183 centimeters) tall, 200 pounds (91 kilograms), and sitting in a chair at rest listening to the instructor with the primary mode of breathing being a 0.11 square inches (0.71 square centimeters) mouth, the sitting height will be set to 48 inches (122 centimeter) and the mouth will be located 4.745 inches (12 centimeters) below the top of the head in all circumstances. The teacher will have the exact same parameters as the students except he will be standing, and the breathing activity will be talking.

3.10. Additional Parameters

3.10.1. Passive Scalar

A passive scalar is a scalar quantity that is not actively involved in the flow physics of the CFD simulation [45]. The source of the passive scalar must be a fluid present with a low concentration of contaminants getting transported with the fluid flow such as aerosols [45]. The passive scalar then has a negligible effect on the physical properties of the fluid flow [45]. For the purposes of this research SARS-CoV-2 is the contaminant, aerosols in the air stream are the mode of transportation, and the source is the exhalation of a given infected individual such as the teacher. This study will be monitoring the propagation of the passive scalar originating from the teacher at two different specified elevations: (1) the standing breathing zone and (2) the sitting breathing zone. These breathing zones are two dimensional section planes located at an elevation equal to the middle of the mouth opening at the respective standing and sitting heights, because the mouth is assumed to be 4.745 inches (12 centimeters) below the total height and the mouth is 0.4 inches (1 centimeter) tall, the standing and sitting breathing zones will be 4.945 inches (12.56 centimeters) below the total height.

3.10.2. Velocity of Supply Air

The velocity of incoming air is calculated using Equation 8.0 when defining a volumetric flow rate “Q” (a.k.a. ventilation rate) that is typically given in the units of CFM or cubic meter per minute depending on the unit system. For the purposes of this study ventilation rates of 800 CFM (22.65 cubic meter per minute), 1100 CFM (31.15

cubic meter per minute), and 1600 CFM (45.31 cubic meter per minute) total being supplied to the room will be tested. To calculate the velocity “v” of incoming air for one individual diffuser, the velocity calculated in Equation 8.0 needs to be divided by the total number of supply diffusers “n” in the room, in this case the total number of supply diffusers is six. The incoming air velocity is one of two primary parameters that influence the mixing of indoor air and has a direct impact on the propagation of aerosols.

$$Q = \frac{v * A}{n}$$

3.10.3. Heating versus Cooling Modes

Heating and cooling temperature modes are the second primary parameter that influences the mixing of indoor air and the propagation of aerosols. This stems from the ideal gas law as is expressed in Equation 9.0 where indoor air is expressed as a function of pressure “P” and temperature “T”, and density “ρ” and the ideal gas constant “R” is held constant. This relationship then shows the characteristic that hot air reaches higher elevations and cold air is naturally drawn to lower elevations. When considering the mixing of air in heating and cooling temperature modes the temperature distribution would illustrate either a layered or homogeneous distribution to show characteristics of unmixed or mixed air respectively.

$$P = \rho * R * T$$

3.10.4. Orientation of the Room Furniture

Altering the orientation of the furniture in the room is one of the most cost effective mitigation strategies available. By altering the furniture and orientation of the teacher and students as is shown in Figures 1 and 2 the characteristics of the airflow pattern are affected and by extension the spread of the aerosols which originate from an infected individual, such as the teacher located at the front of the room. The goal of this mitigation strategy is to alter the pathway of aerosols by potentially shortening the distance and time it takes to reach the return grill once exhaled by any individual.

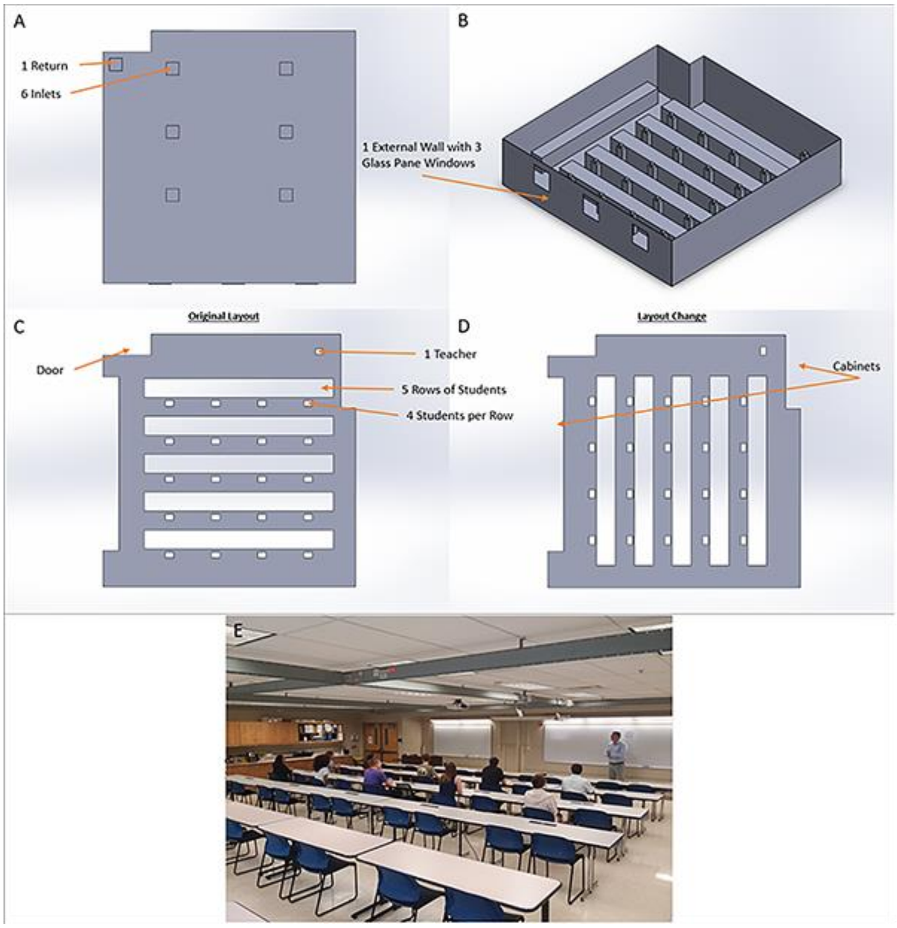


Figure 2: CAD Model of the University Classroom with Change in Layout and no Acrylic Barrier.

3.10.5. Introduction of Physical Obstacles to Impede Airflow

The introduction of an acrylic barrier to impede the airflow of aerosols from an instructor in a university classroom is a mitigation tactic first implemented at the beginning of the SARS-CoV-2 pandemic in 2020 [56]. This research aims to monitor the effectiveness of this tactic and test its validity as a benefit to public health safety. For the purposes of this research a solid barrier is placed in front of the instructor in the CAD model and as is shown in Figure 1.

3.10.6. Supply Diffuser Adjustments

Adjusting the downward velocity of incoming air for five of the six diffusers and eliminating airflow in the sixth diffuser while maintaining an overall constant ventilation rate being supplied to the room is done to monitor the effectiveness of creating artificial quarantine zones throughout the space. In this study the teacher is assumed to be infected and the diffuser directly above the teacher is turned off. To maintain a constant ventilation rate, the downward velocity of the other five diffusers is increased. The goal is to create an environment of extremely mixed fresh clean air and to mitigate the mixture of aerosols from the teacher.

3.11. Outputs

3.11.1. Horizontal and Vertical Temperature Distribution

The horizontal and vertical temperature distribution shows not only the characteristics of unmixed versus mixed air but is also just one of two parameters that determine the thermal comfort of the occupants. While some mitigation strategies such as altering the temperature of incoming air may prove to be effective, side effects such as occupant discomfort could prove to be just as big of an issue as the spread of aerosols during building operations. Therefore, it is important to monitor the temperature distribution throughout the space and assess whether comfortability is being achieved in any mitigation strategy such as temperature control.

3.11.2. Horizontal and Vertical Throw Velocity

The horizontal and vertical throw velocity originating from the supply diffusers is the second aspect of occupant comfortability. When incoming air passes through the supply diffuser air it is deflected at a set velocity and distributed horizontally, it is then vertically distributed by the effects of temperature and gravity. The higher the velocity at the moment of deflection in the supply diffuser the more intense characteristics of mixed air will be apparent throughout the room which has the potential to either be detrimental or beneficial to occupant comfort, depending on the temperature of incoming, external, and initial temperature of the air already present in the room.

3.12. Model Convergence Criteria

In a simulation the residuals are a clear indicator of the stability and quality of the mathematical model. Residuals are defined as what remains after the calculation. Due to the breathing characteristics of the twenty one occupants inside the room, the mathematical model will show characteristics of a sine wave, because of this the residuals revolve around a value of 0.001 with an amplitude of 0.01 and show a very clear sine wave pattern. This is significant because it illustrates that the model is of high quality and stability. In addition, the model is simulated as a function of time where one time step is one second and every second there is five iterations across a total time of 15 minutes, this will end up in a total iteration count of 3000 iterations and one period of the sine wave is 20 iterations.

3.13. Method of Evaluating and Interpretation of Predicted Outputs

To assess the effectiveness of each mitigation strategy a constrained plane was created to surround all twenty students as is shown in Figure 3, this was performed to directly assess the likely hood of contracting an airborne disease from aerosols for the air that is surrounding the primary mode of breathing among each non infected student. Within this constrained plane the value of the passive scalar is quantified as a function of the square area within the constrained plane. The passive scalar values were then taken on a range from 0 – 0.1, this range was then separated into four equal parts and give the following characteristics: (1) 0.0 – 0.025 is safe for occupant use, (2) 0.025 – 0.05 represents a low probability to receive infection, (3) 0.05 – 0.075 represents a moderate likely hood to receive infection, and (4) 0.075 – 0.1 represents a high likelihood to receive infection. Any value that is over 0.1 is severe and occupants should exit the building as soon as possible. These values are represented on a histogram plot and every simulation is compared to quantitatively evaluate which mitigation strategy provides the safest environment for the twenty students inside the room across a 15 minute time period.

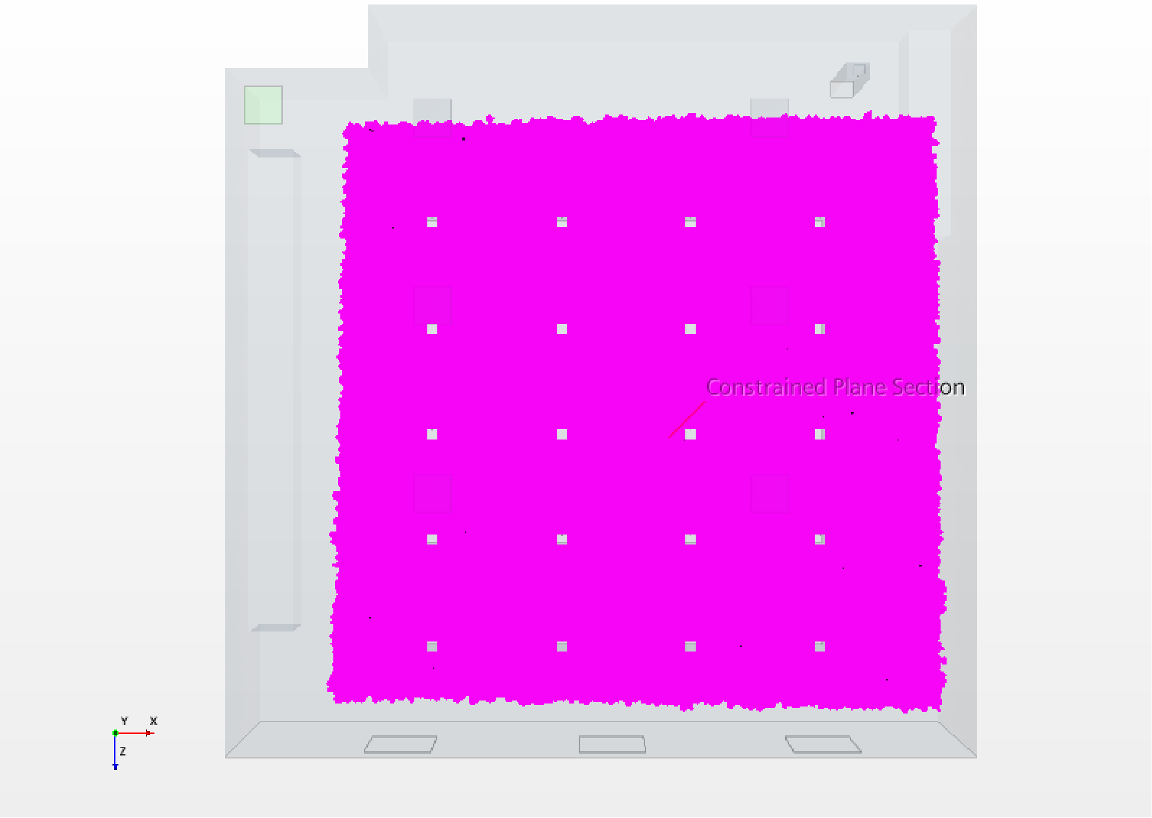


Figure 3: Constrained Horizontal Section Plane where the Aerosol Concentration at the Seated Breathing Zone is calculated for all Subsequent Histogram Plots and is used to determine the Level of Probability of Infection Among the Student Population in the University Classroom.

3.14. Model Verification and Validation Approach

When verifying the results of each mitigation strategy the airflow patterns and the spread of airborne contaminants need to be validated by comparing the comprehensive guidance for proper ventilation of indoor spaces, the impact of HVAC layout with the location and number of supply diffusers, and the indoor airflow patterns with the resulting risk of infection to that of experimental data found in common HVAC design related to indoor commercial spaces (ICS) such as aircraft cabins and office spaces which can be found in two independent research studies.

ICS configurations such as an aircraft cabin was analyzed to monitor the effects of inhaled mass and particle removal dynamics [57]. CFD models were used to characterize the spread of aerosols generated by a coughing or breathing person suffering from a respiratory illness such as SARS-CoV-2 with an aircraft cabin and office spaces of a commercial business [57]. This independent study monitored the differences between steady state and well-mixed conditions as well as compared the CFD results to empirical data from a U.S. Transportation Command (TRANSCOM) study that tracked particles from infectious individuals in an airplane cabin environment [57]. The airplane cabin system is a mixed flow system that results in higher concentrations of infectious aerosols closer to infected individuals and lower concentrations present in seats at greater distances away from the source [57]. Although the airplane cabin is a unique environment compared to other ICS configurations there are some areas in which ICS studies can benefit from the airplane cabin example [57]. In some ICS configurations the lack of high efficiency filtration assists in the spreading of infectious aerosols for person to person transmission [57]. With regards to the airplane cabin study, it was made clear with empirical data from TRASNCOM that the ICS environment is neither steady state or well-mixed and that low masses of particulates are shown to spread from person to person specifically in airplane cabins [57].

Additionally, office spaces were analyzed to assess the comprehensive guidance of proper ventilation [8]. This study specifically shows that even a simple layout of a small office space that the location of the supply diffusers and return grill can significantly impact the risk assessment for person to person transmission of infectious aerosols containing SARS related diseases [51]. For example, the HVAC configuration with a single four way supply diffuser and a single return grill as is shown in the office space example can result in the formation of stagnant air which is a characteristic for pockets of high concentration of contaminants in localized areas of the room [8]. These pockets can then allow contaminated air to travel farther from the source allowing the risk of infection to increase [8]. The solution to this problem in the office example is to create what is called an aerodynamic containment (airflow envelope) which is defined as equal amounts of incoming and outgoing air entering and leaving the room [8]. The results of these CFD analyses demonstrates the necessity of a model that uses large dynamic set of data points to monitor infectious aerosol exposure within any type of ICS configuration such as airplane cabins, commercial office spaces or even university classrooms residing in CEH [57].

CHAPTER 4 RESULTS

This chapter outlines the results from comparisons of the five different simple and cost effective adjustments under investigation for the university classroom in CEH. The following will clearly display how each modification affects the spread of aerosol particles emitted from the instructor at the front of the classroom as has been previously outlined in the CAD Modeling section in Chapter 3 Section 7. To start the study, the room was modeled without any modifications in both heating and cooling temperature modes for the HVAC system. The study illustrates the different airflow patterns representative in the two temperature modes by focusing on the thermal stratification of the air. The study then focuses on the aerosol distribution at the breathing zone of the students located at a height of 46 inches from the floor in a variety of different room setup and operation scenarios. Using passive scalar plots at the horizontal plane of the student breathing zone, these variations are able to be visualized for local hotspots and then quantitatively analyzed to determine if the majority of the room contains high, low, or somewhere in the middle amounts of concentration for aerosols.

4.1. Heating and Cooling Temperature Modes

Heating and cooling temperature modes were simultaneously analyzed for each of the subsequent five modifications that are being simulated in this study to assess the effectiveness of each modification throughout the entire calendar year and will later be used to determine if there is a general solution of best practices to reduce the mitigation of aerosols for the configuration of a university classroom. Figure 4 and Figure 5 show the vertical difference in airflow patterns and temperature distribution of the air respectively for both heating and cooling temperature modes.

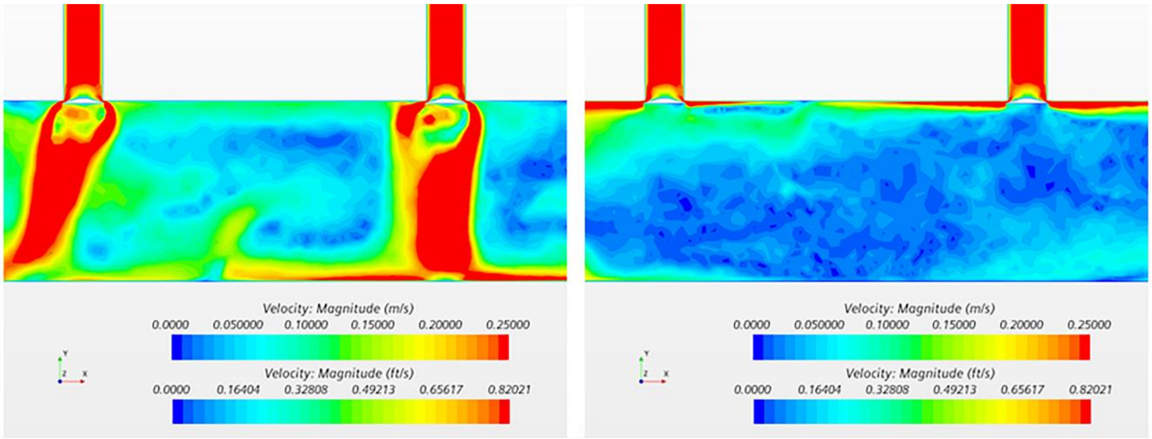


Figure 4: Vertical Temperature Distribution at the First Row of Students with 1100 CFM (31.15 m^3/min) of Supply Air in Both Cooling (left) and Heating (right) Operation.

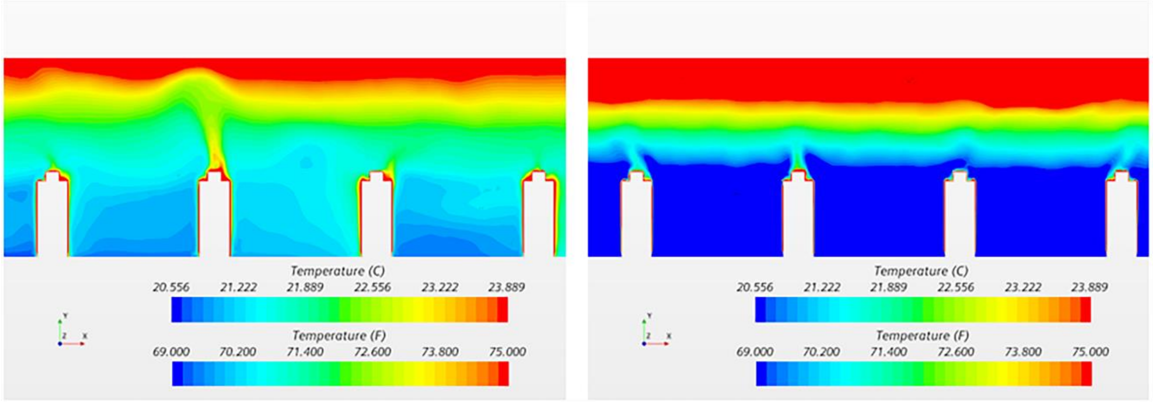
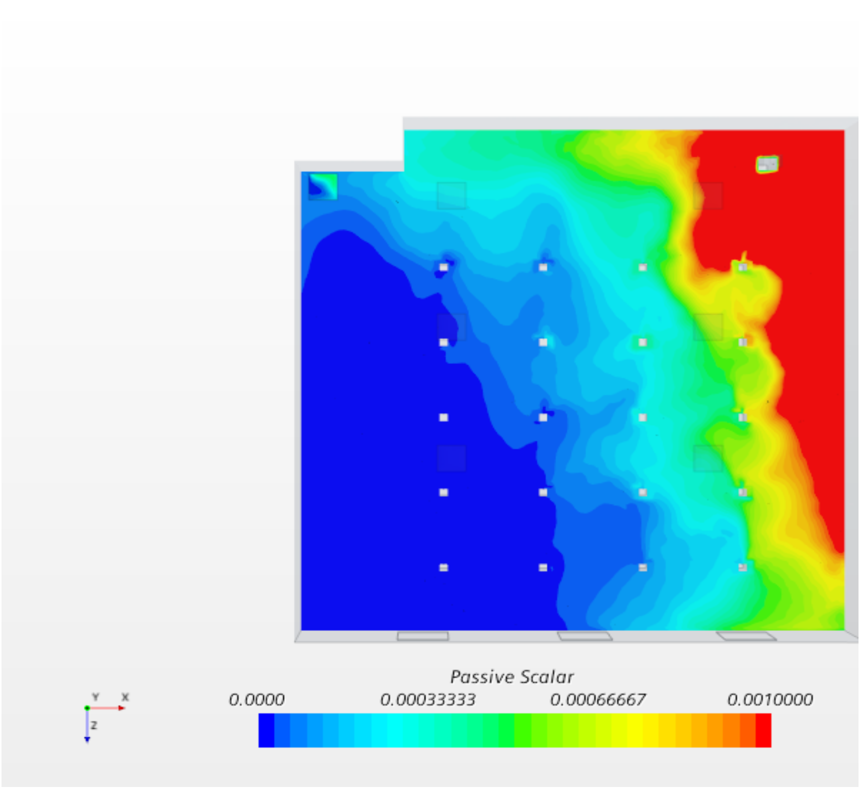


Figure 5: Diffuser Cross-Sectional Airflow Patterns in the University Classroom with 1100 CFM (31.15 m^3/min) of Supply Air in Both Cooling (left) and Heating (right) Operation.

4.2. Control Simulation

The first set of simulations analyzed were the control experiments, these two simulations evaluate the projected aerosol distribution throughout the space with no modifications to existing room layout or the HVAC system. These baseline simulations were conducted under heating and cooling temperature loads to account for variance of airflow throughout the calendar year. These baseline simulations were set to a supply airflow rate of 1100 CFM (31.15 m^3/min). Figure 6 and Figure 7 shows the horizontal cross section of the passive scalar on a range from 0.0 to 0.001 and the quantitative aerosol distribution within the student occupied (constrained plane) zone as a function of the square footage of space that resides in each tier of aerosol concentration for both cooling and heating temperature models.

	Heating Temperature Mode
Control Simulation	

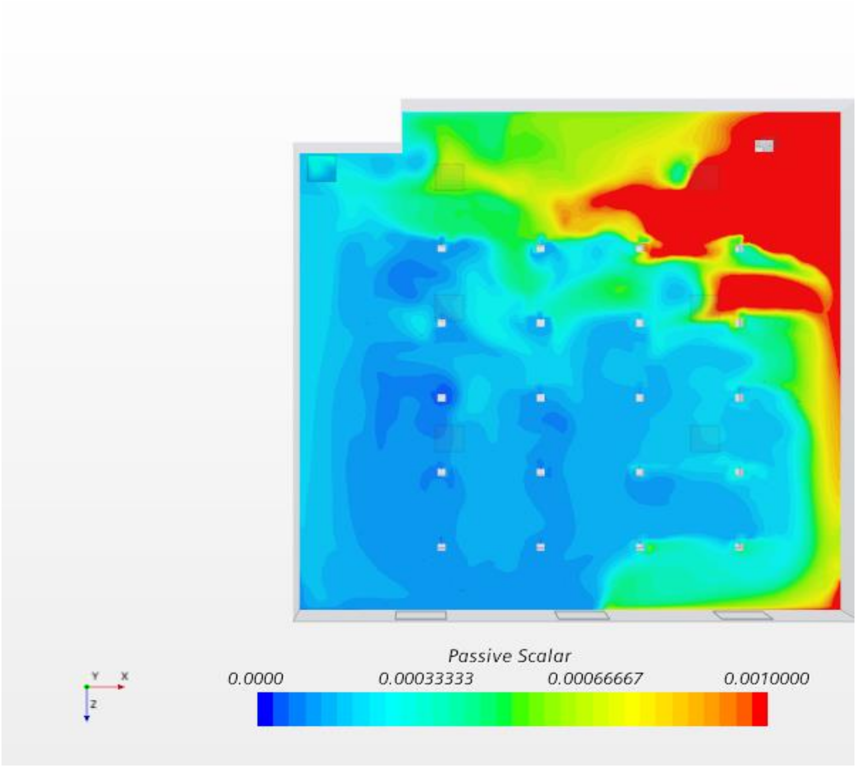
	Cooling Temperature Mode
Control Simulation	

Figure 6: Horizontal Section Plane of the Aerosol Concentration at the Seated Breathing Zone of the Students for the Heating and Cooling Control Simulation.

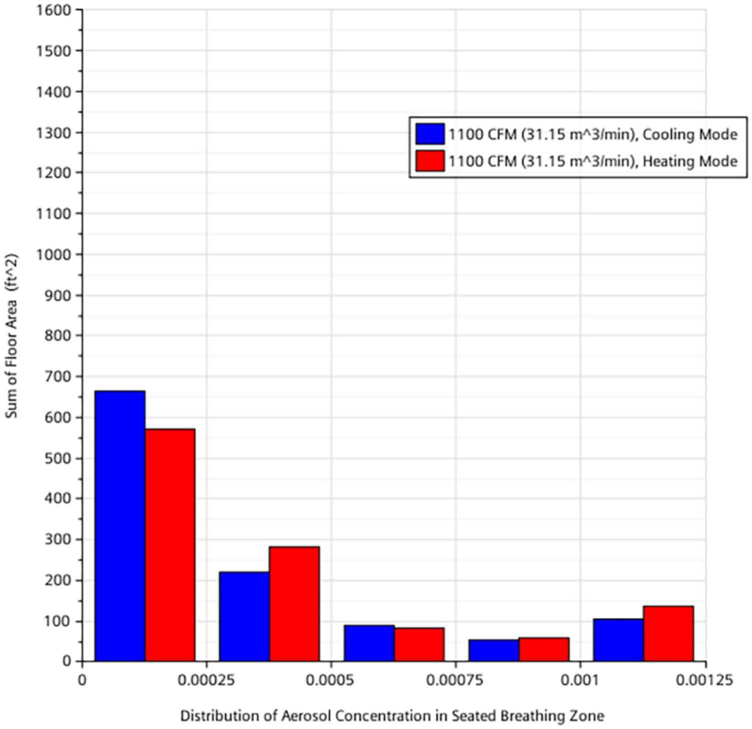
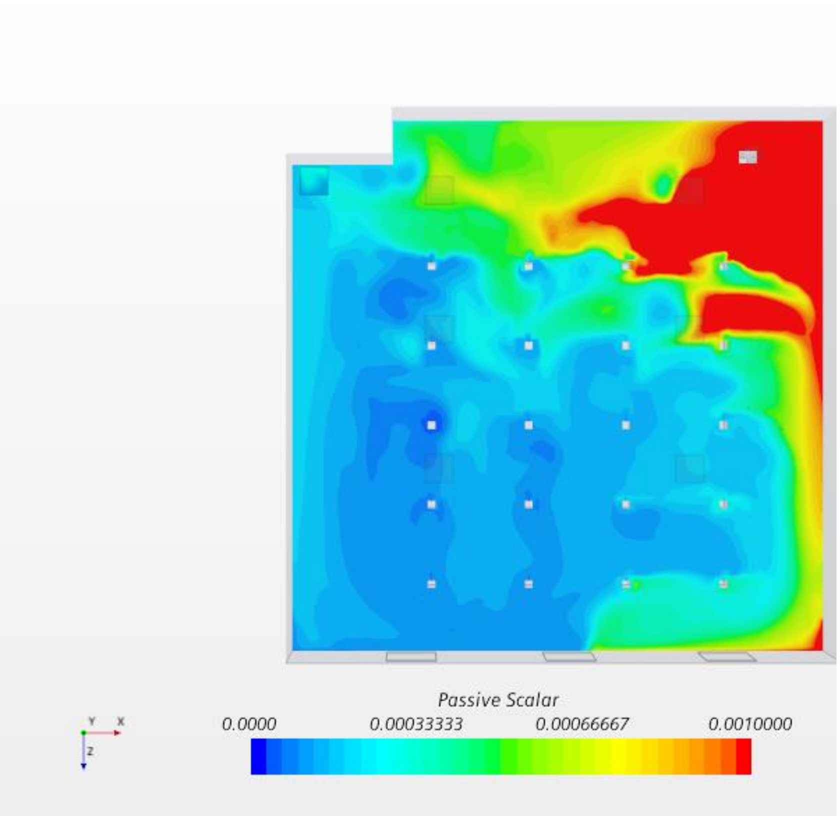
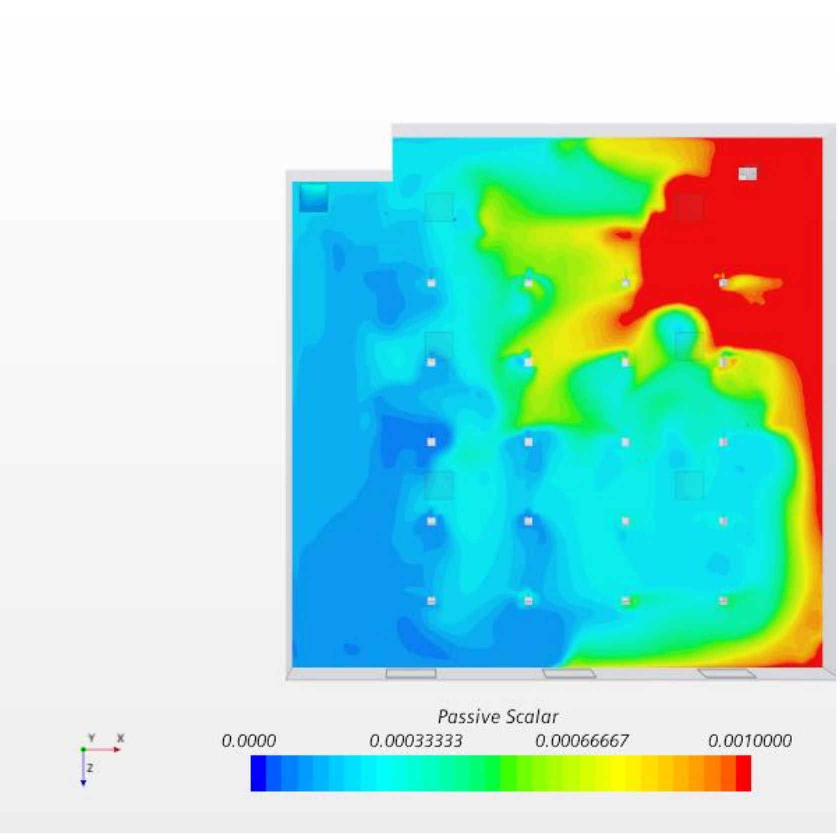
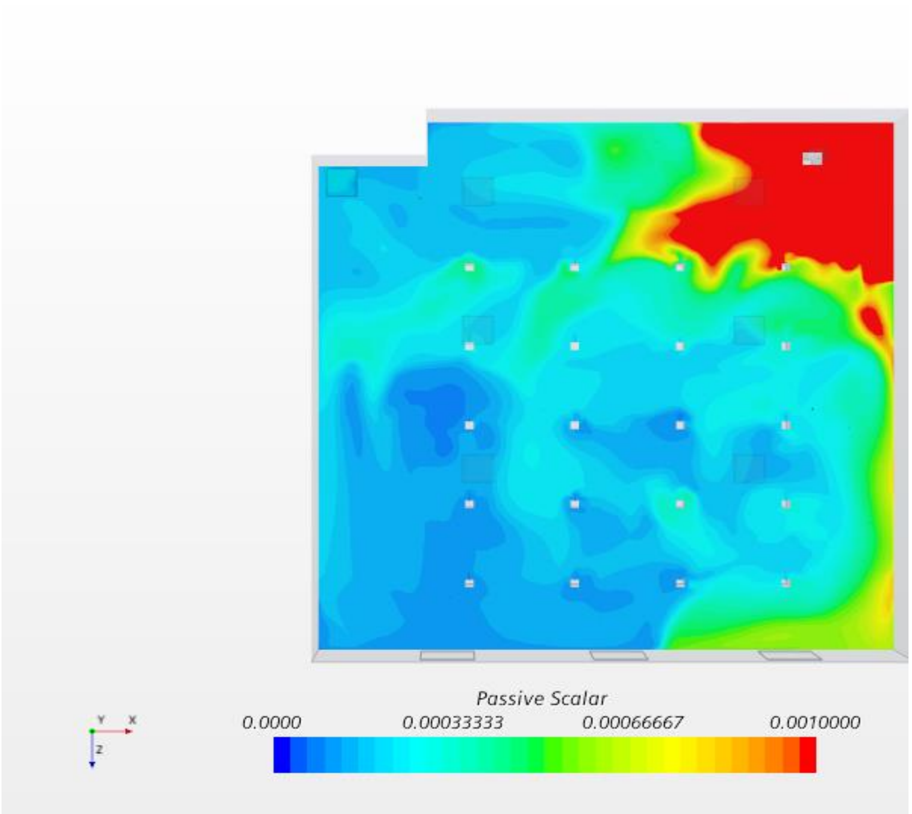


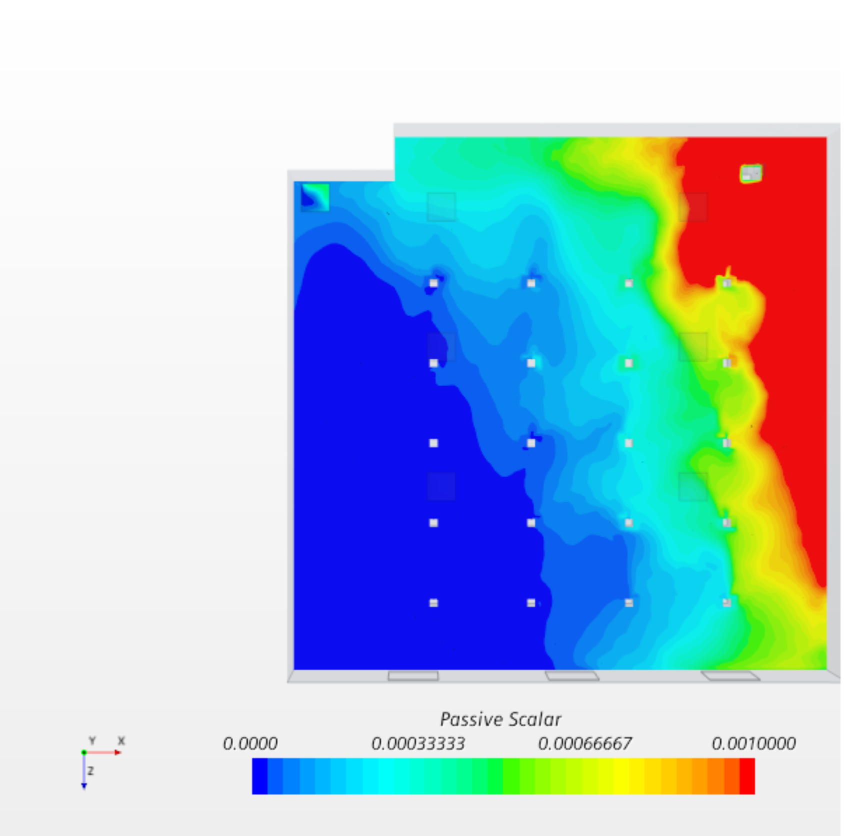
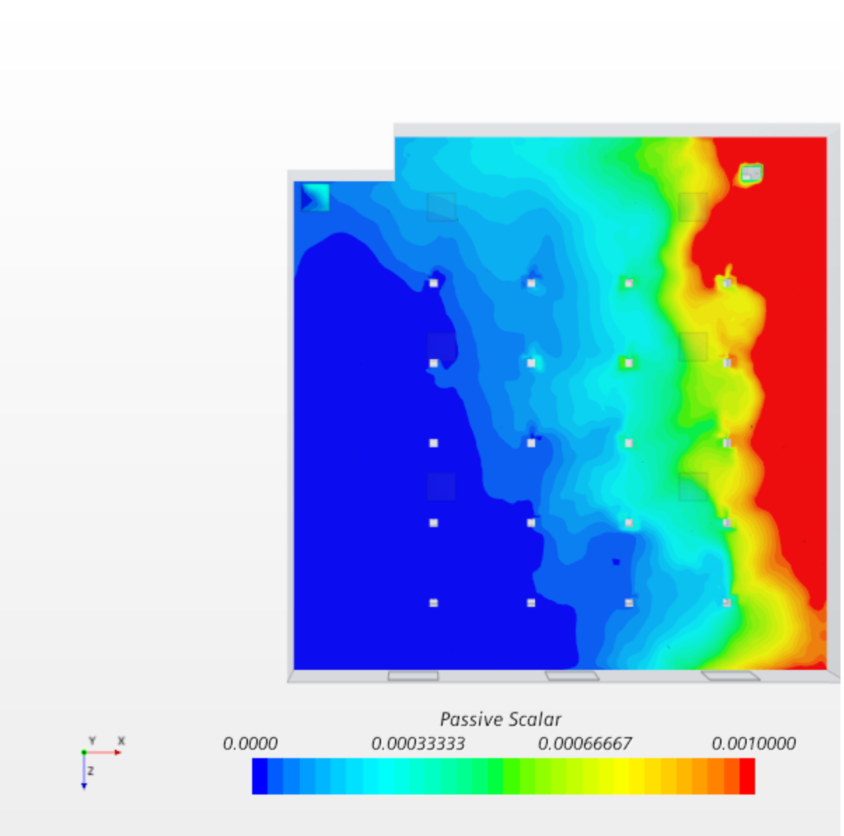
Figure 7: Square Footage Histogram at Various Concentrations of Aerosols in the Seated Breathing Zone of the Student-Occupied Space in Heating and Cooling Operations.

4.3. Airflow Modifications

The second modification is introducing variable airflow amounts being supplied to the room with no alterations made to the room layout. Figure 8 and Figure 9 illustrates the horizontal cross section of the passive scalar on a range from 0.0 to 0.001 and the quantitative aerosol distribution within the student occupied (constrained plane) zone as a function of the square footage of space that resides in each tier of aerosol concentration for both cooling and heating temperature models. The airflow amount values were set to 800 CFM (22.65 m^3/min) and 1600 CFM (45.31 m^3/min) to imitate low and high ventilation rates respectively when compared to the code complaint 1100 CFM (31.15 m^3/min) being supplied in the control simulation.

	Cooling Temperature Mode
Control Simulation	
800 CFM	

	Cooling Temperature Mode
1600 CFM	

	Heating Temperature Mode
Control Simulation	
800 CFM	

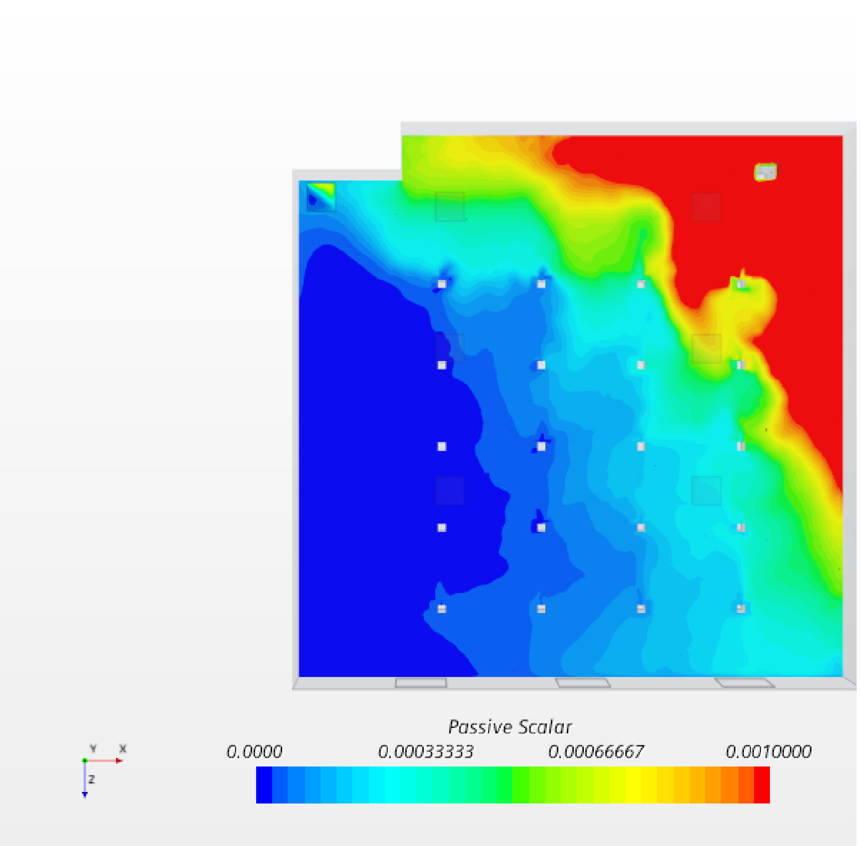
	Heating Temperature Mode
1600 CFM	

Figure 8: Horizontal Section Plane of the Aerosol Concentration at the Seated Breathing Zone of the Students for the Heating and Cooling Operations with Various Airflow Rates.

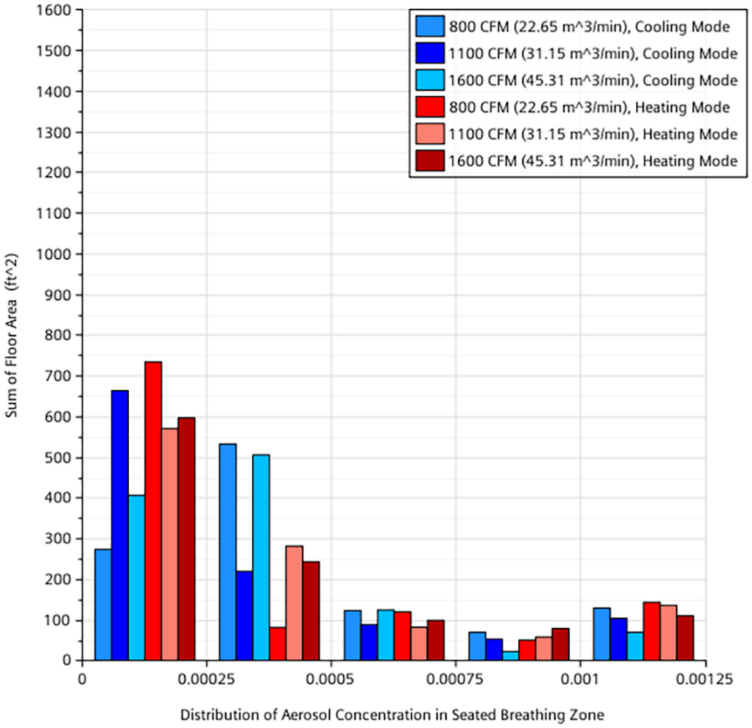
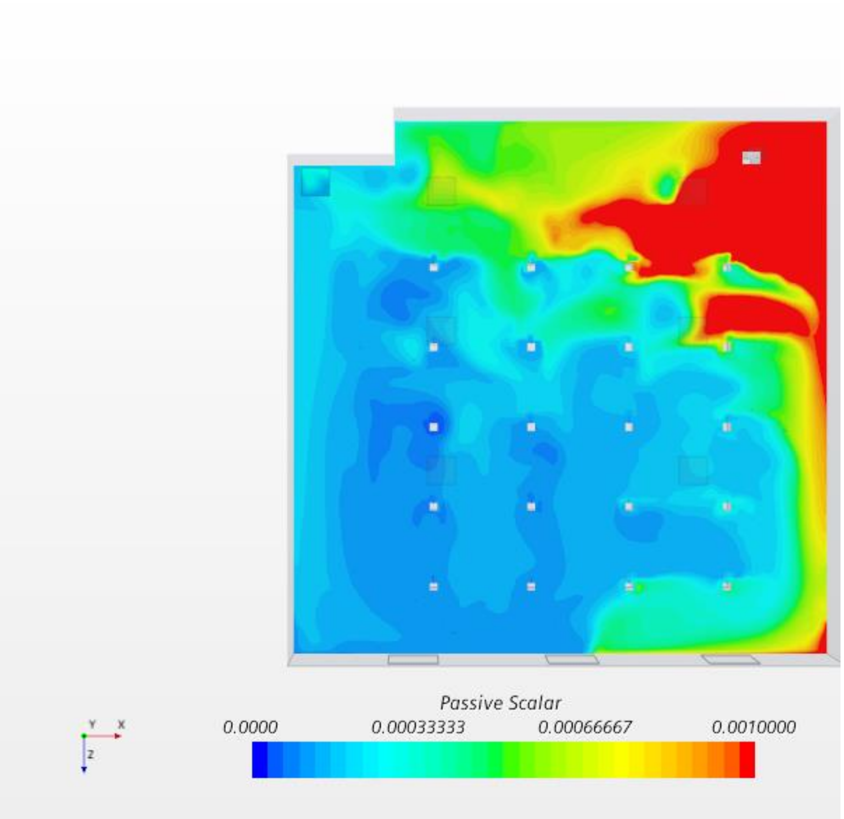
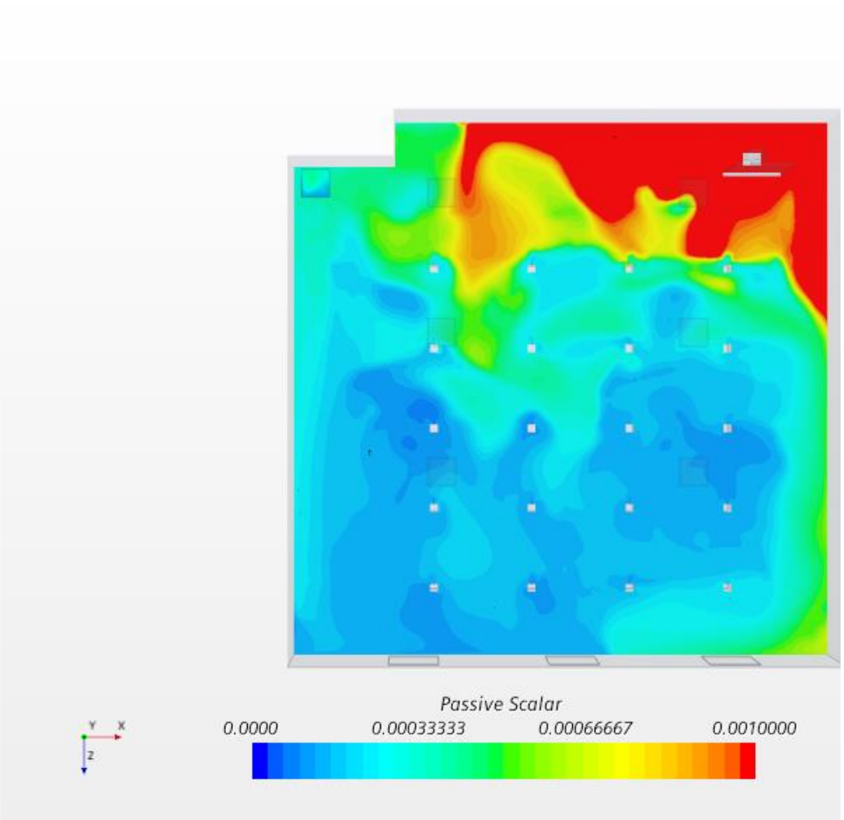


Figure 9: Square Footage Histogram at Various Concentrations of Aerosols in the Seated Breathing Zone of the Student-Occupied Space in Heating and Cooling Operation with Various Airflow Rates.

4.4. Introduction of an Acrylic Barrier

Next the effects of introducing an acrylic barrier directly in front of the infected instructor were analyzed during each cooling and heating phase of the HVAC system. Figure 10 and Figure 11 shows the parametric view of the passive scalar on a range from 0.0 to 0.001 and the quantitative aerosol distribution within the student occupied (constrained plane) zone as a function of the square footage of space that resides in each tier of aerosol concentration for both cooling and heating temperature models. The acrylic barrier is placed in front of the teacher as was outlined in Chapter 3 Section 7.

	Cooling Temperature Mode
Control Simulation	
With an Acrylic Barrier	

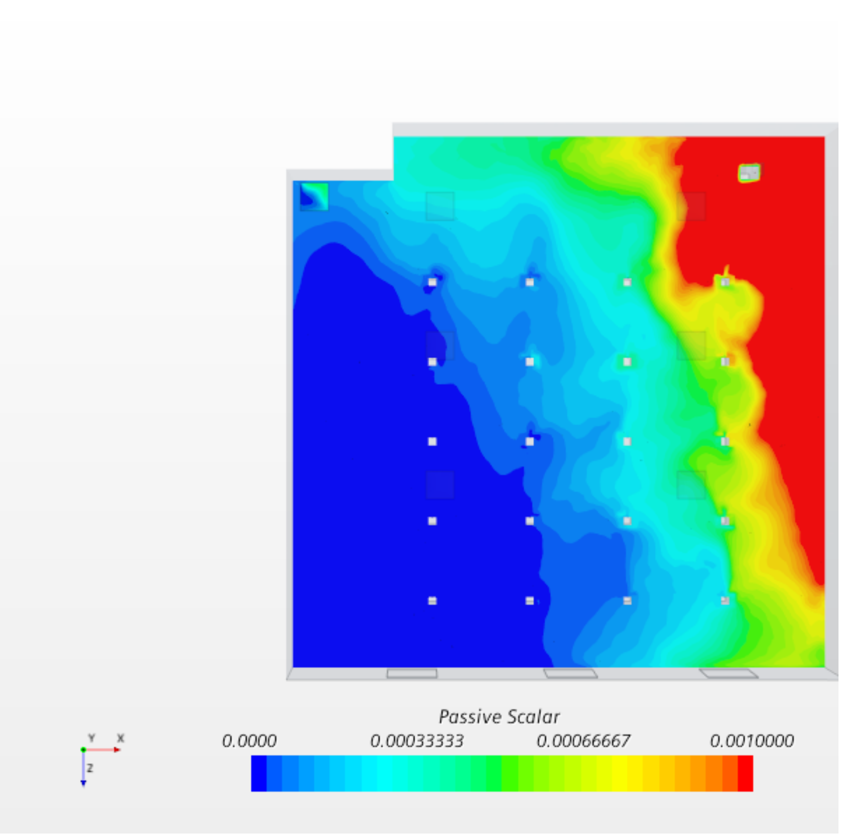
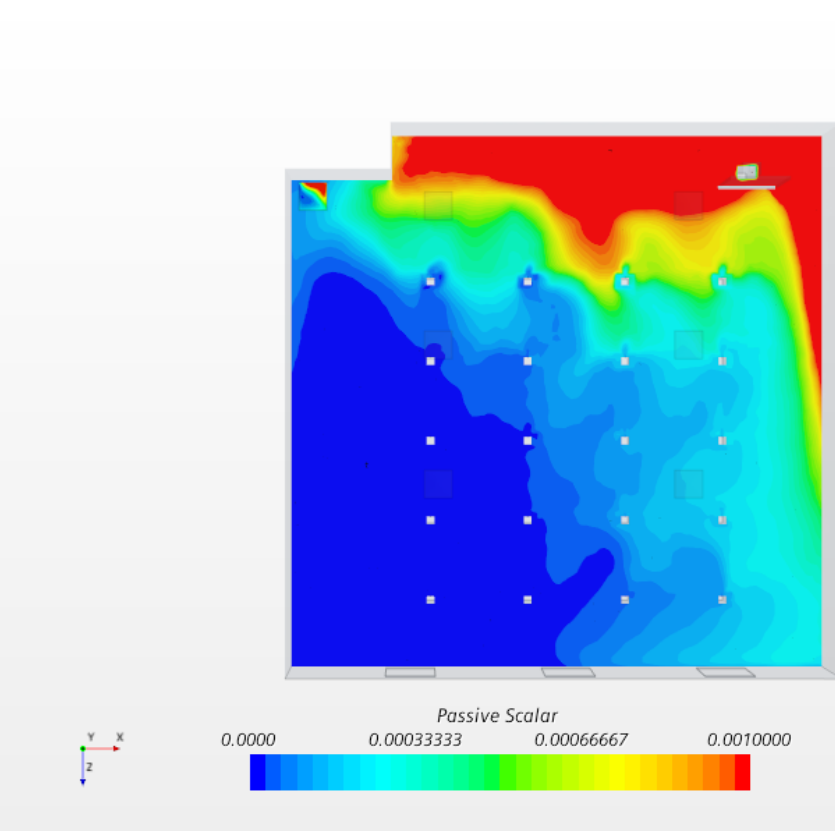
	Heating Temperature Mode
Control Simulation	
With an Acrylic Barrier	

Figure 10: Horizontal Section Plane of the Aerosol Concentration at the Seated Breathing Zone of the Students for the Heating and Cooling Operations with the Inclusion of an Acrylic Barrier in Front of the Instructor.

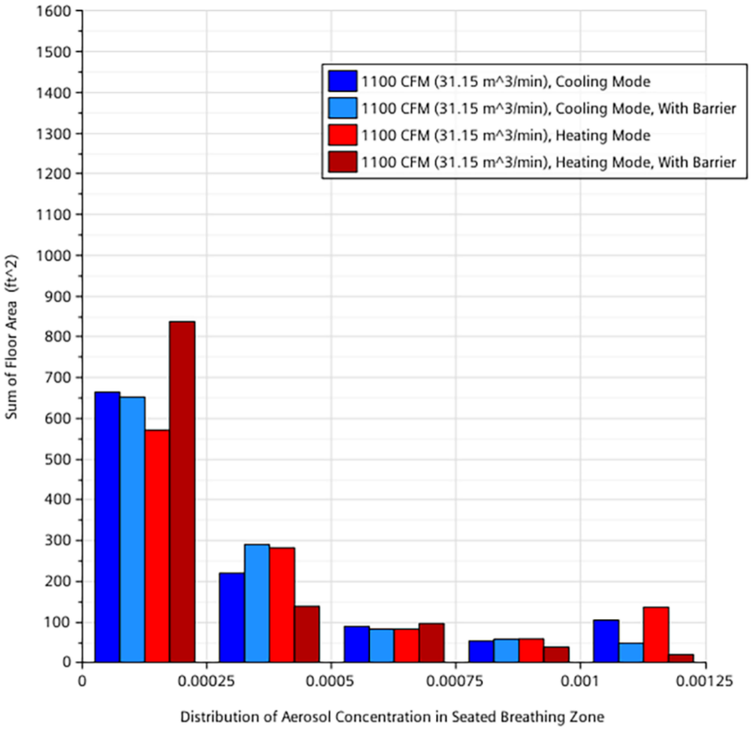
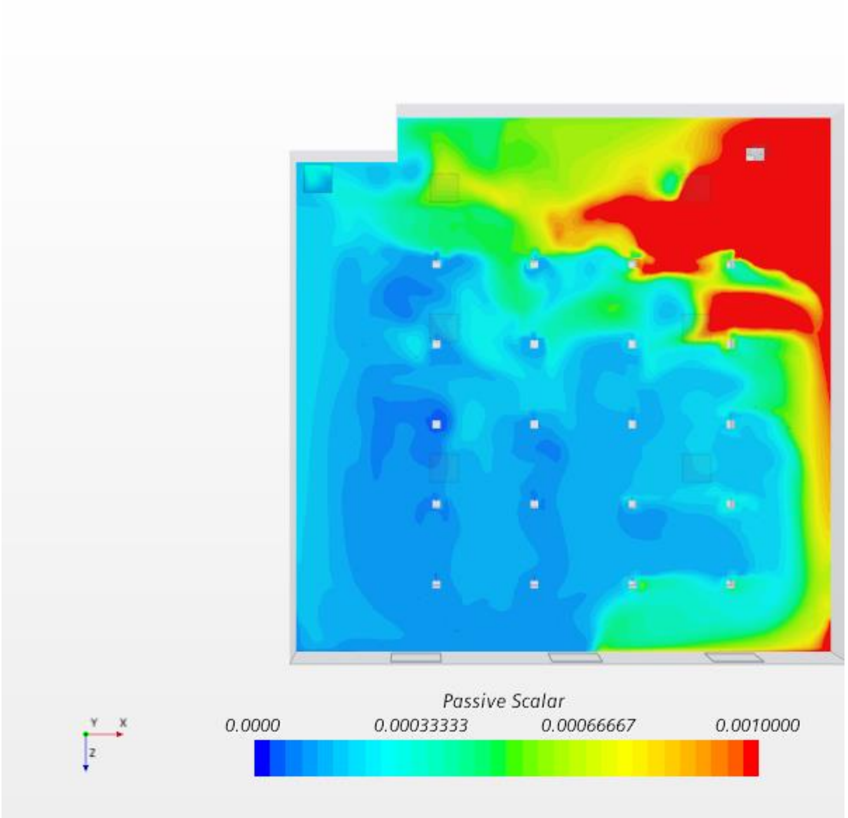
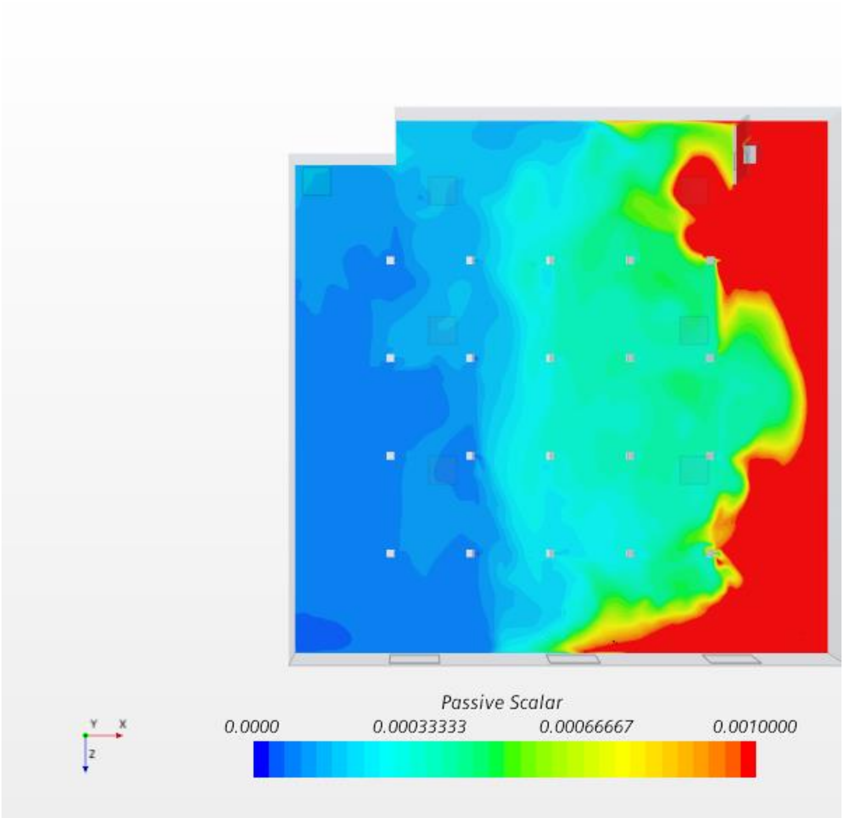
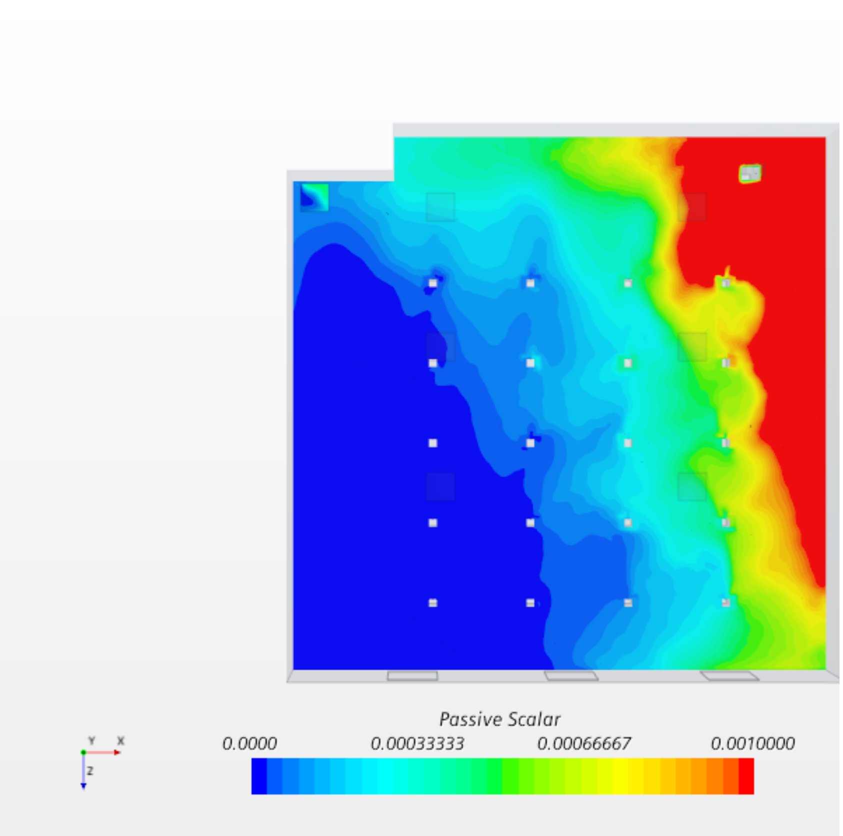
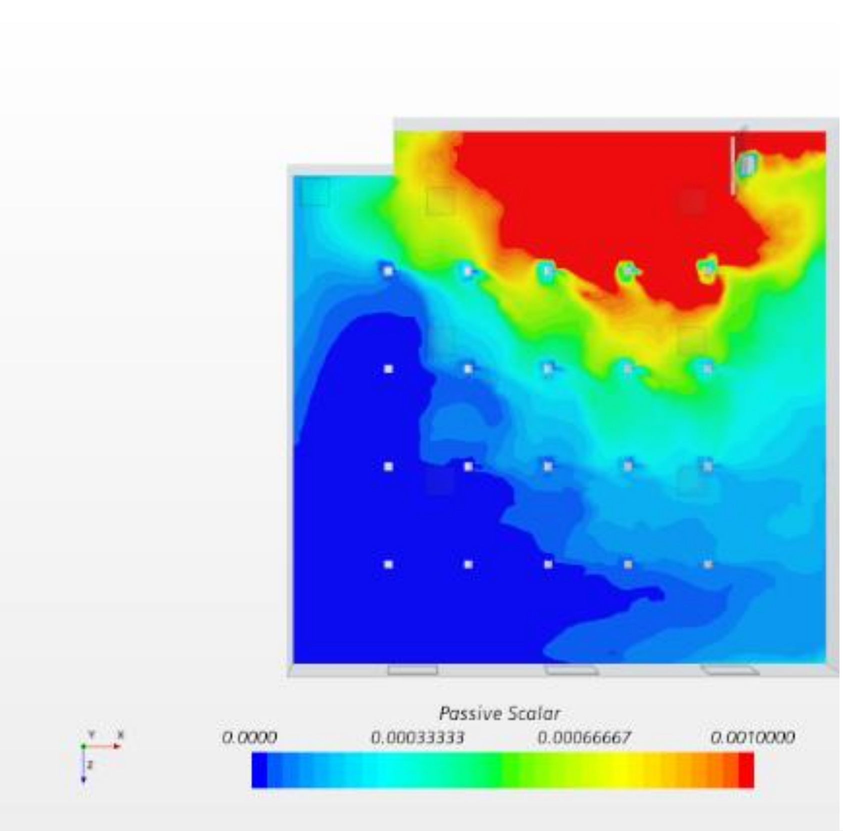


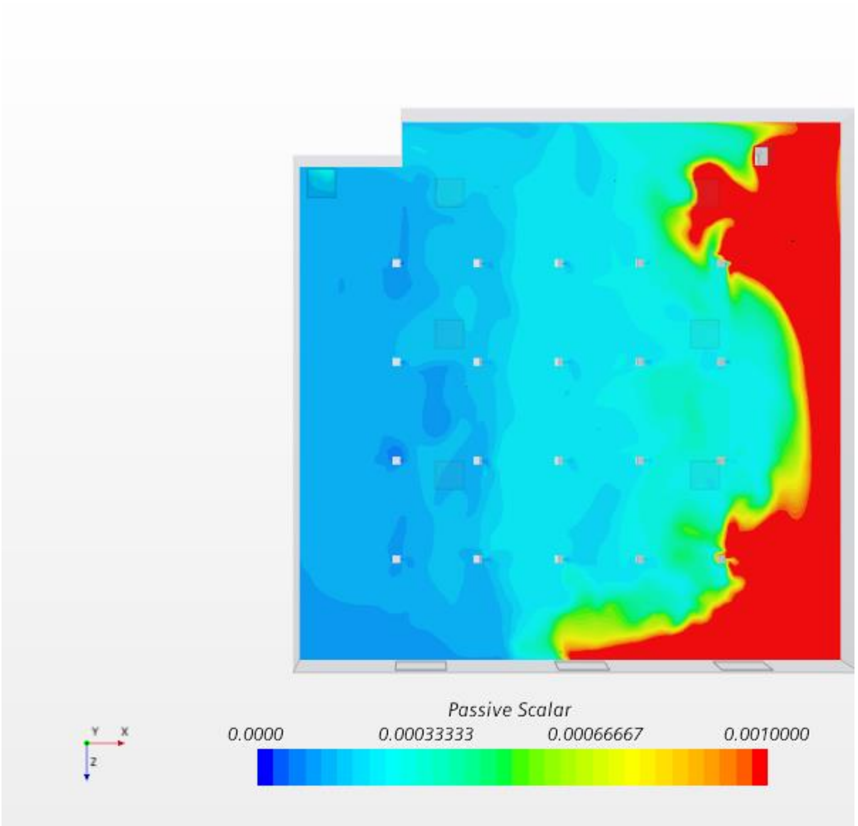
Figure 11: Square Footage Histogram at Various Concentrations of Aerosols in the Seated Breathing Zone of the Student-Occupied Space in Heating and Cooling Operation with the Inclusion of a Barrier in Front of the Instructor.

4.5. Room Layout Adjustments

Additionally, it was investigated how reorienting the furniture of the room would affect the aerosol concentrations near the students. In this analysis the desks and students were all rotated 90 degrees clockwise and the teacher was rotated 90 degrees counterclockwise to still be facing the students in this new orientation as was described in Chapter 3 Section 7 Figure 12 and Figure 13 shows the parametric view of the passive scalar on a range from 0.0 to 0.001 and the quantitative aerosol distribution within the student occupied (constrained plane) zone as a function of the square footage of space that resides in each tier of aerosol concentration for both cooling and heating temperature models.

	Cooling Temperature Mode
Control Simulation	
Change in Room Layout With an Acrylic Barrier	

	Heating Temperature Mode
Control Simulation	
Change in Room Layout With an Acrylic Barrier	

	Cooling Temperature Mode
Change in Room Layout Without an Acrylic Barrier	

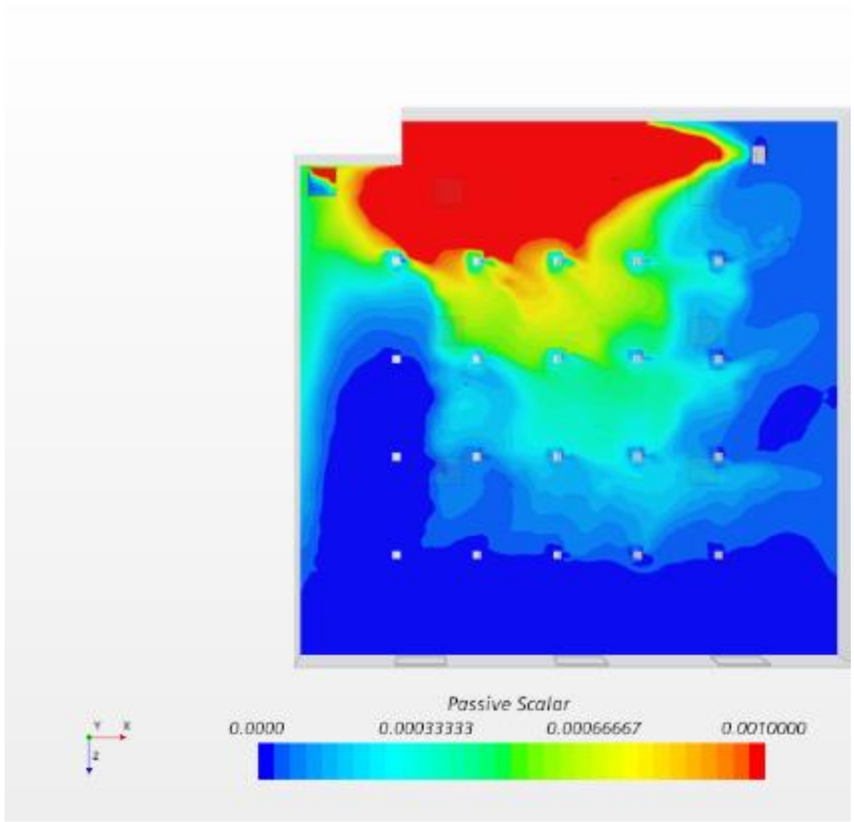
	Heating Temperature Mode
Change in Room Layout Without an Acrylic Barrier	

Figure 12: Horizontal Section Plane of the Aerosol Concentration at the Seated Breathing Zone of the Students for the Heating and Cooling Operations with the Implementation of a Change in the Room Layout.

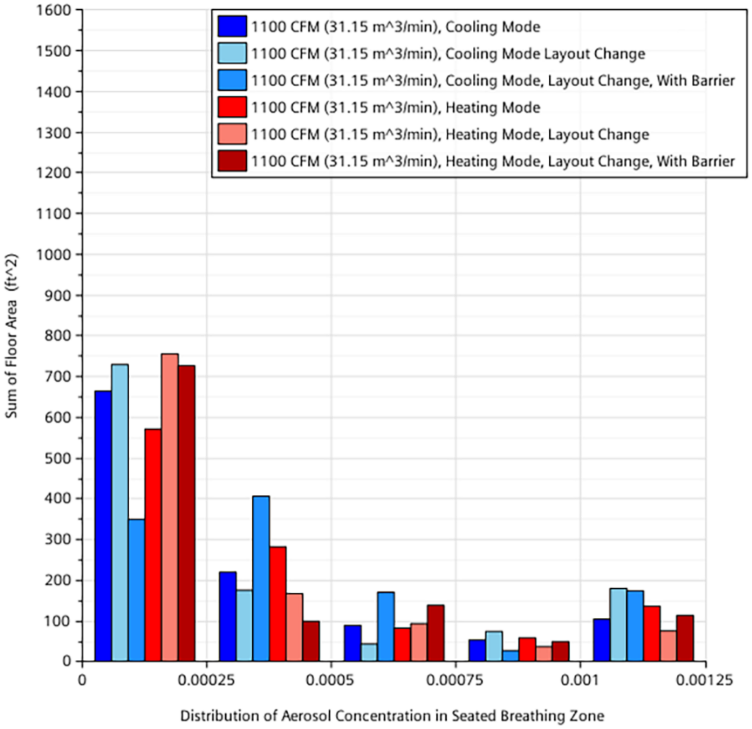
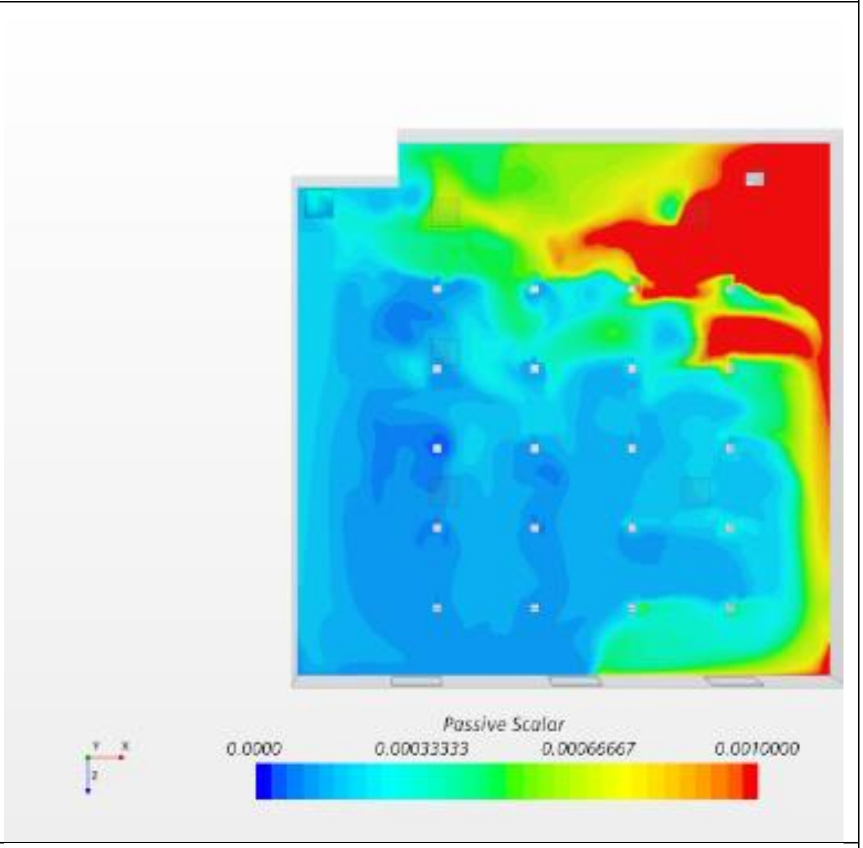
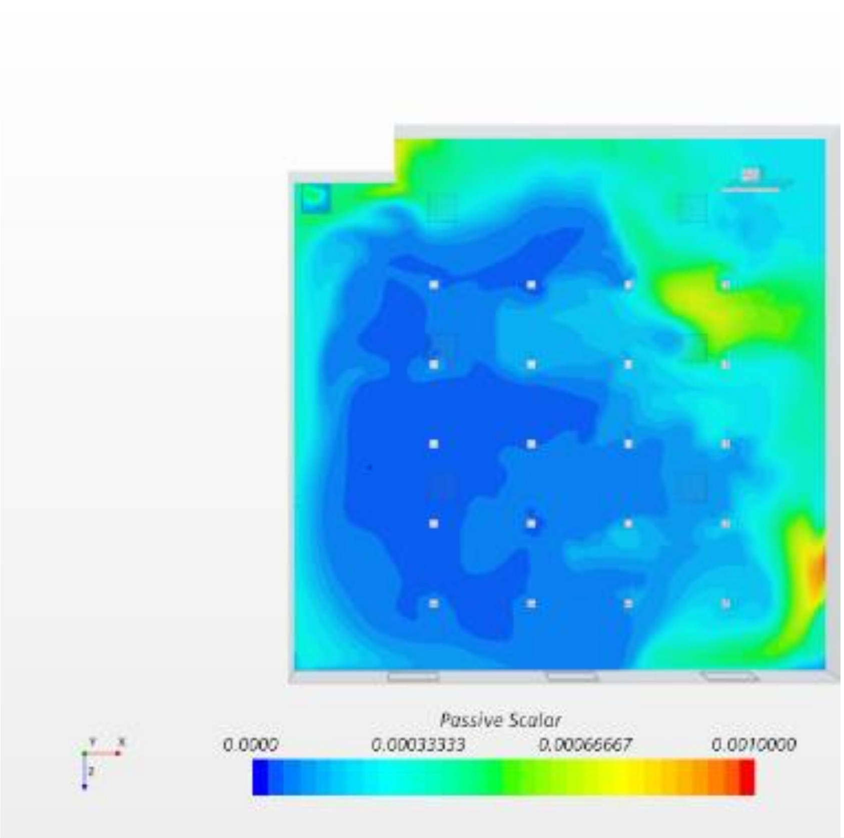
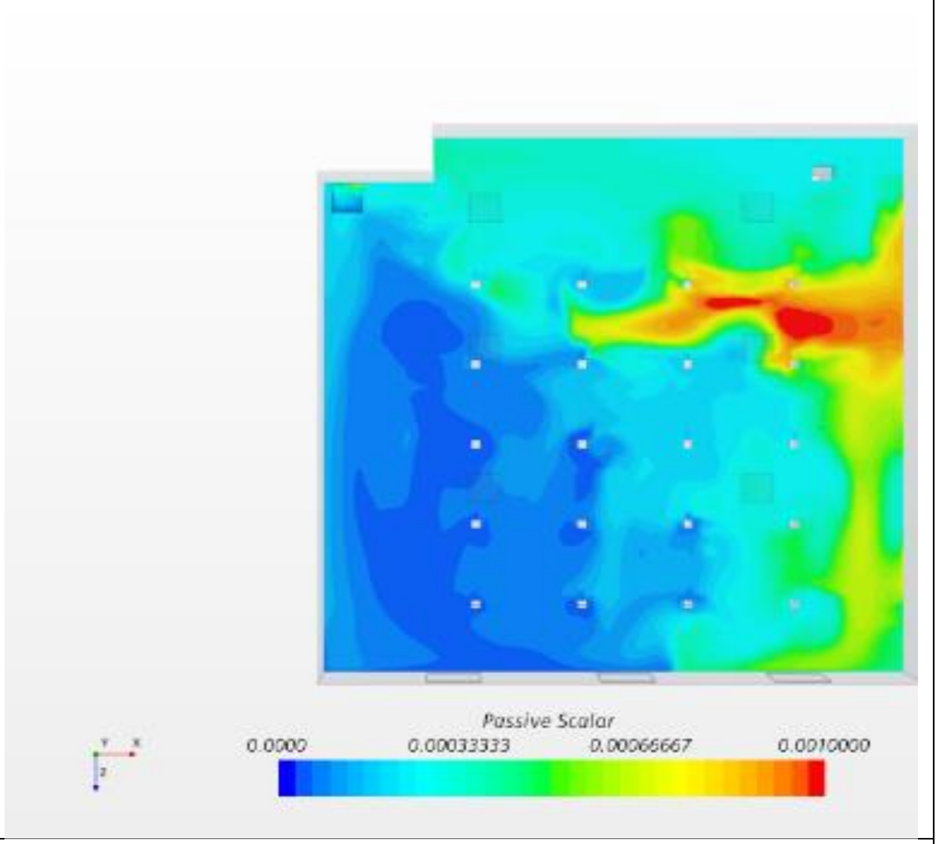
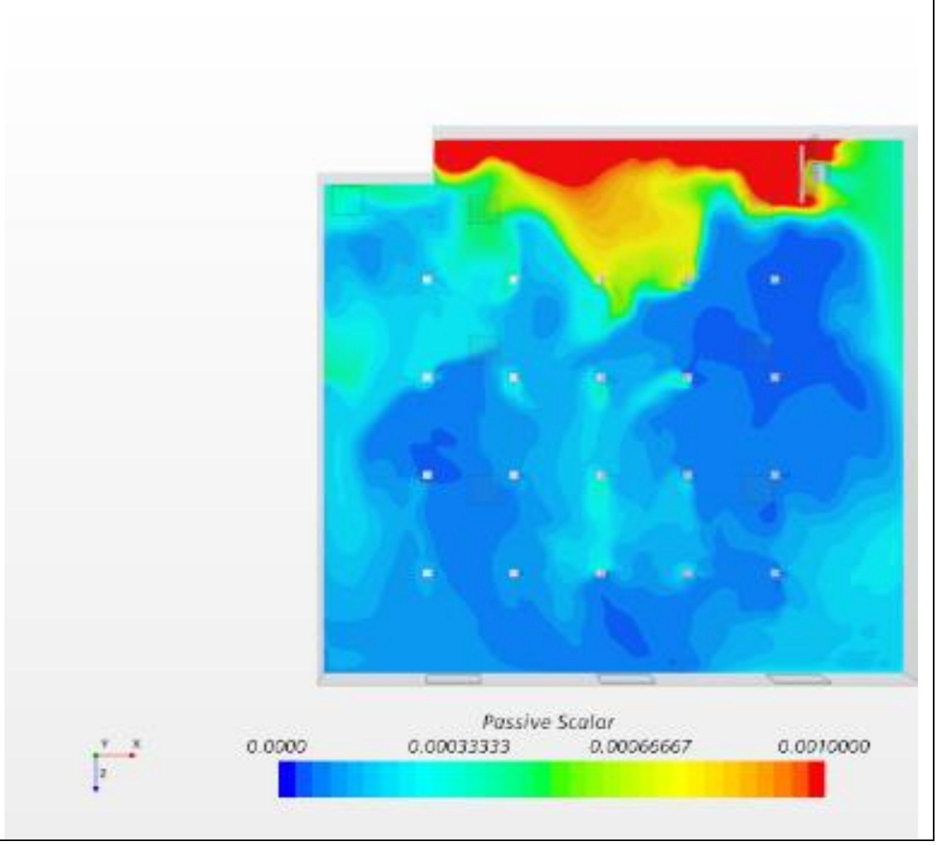


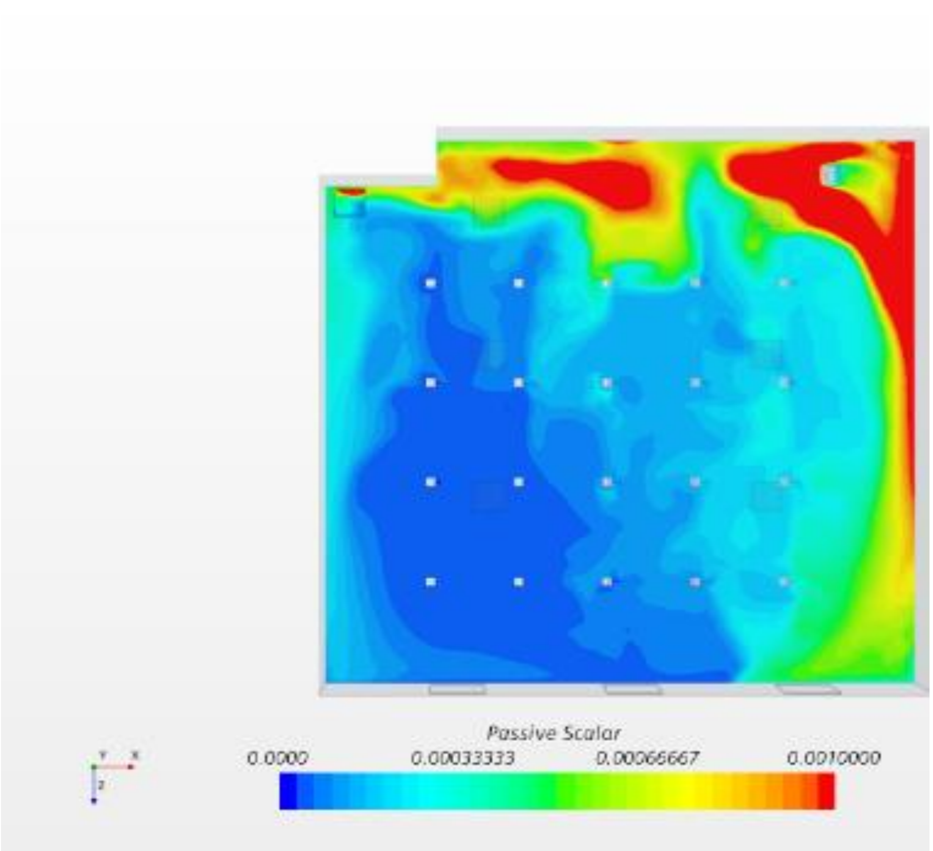
Figure 13: Square Footage Histogram at Various Concentrations of Aerosols in the Seated Breathing Zone of the Student-Occupied Space in Heating and Cooling Operation with the Implementation of a Change in the Room Layout.

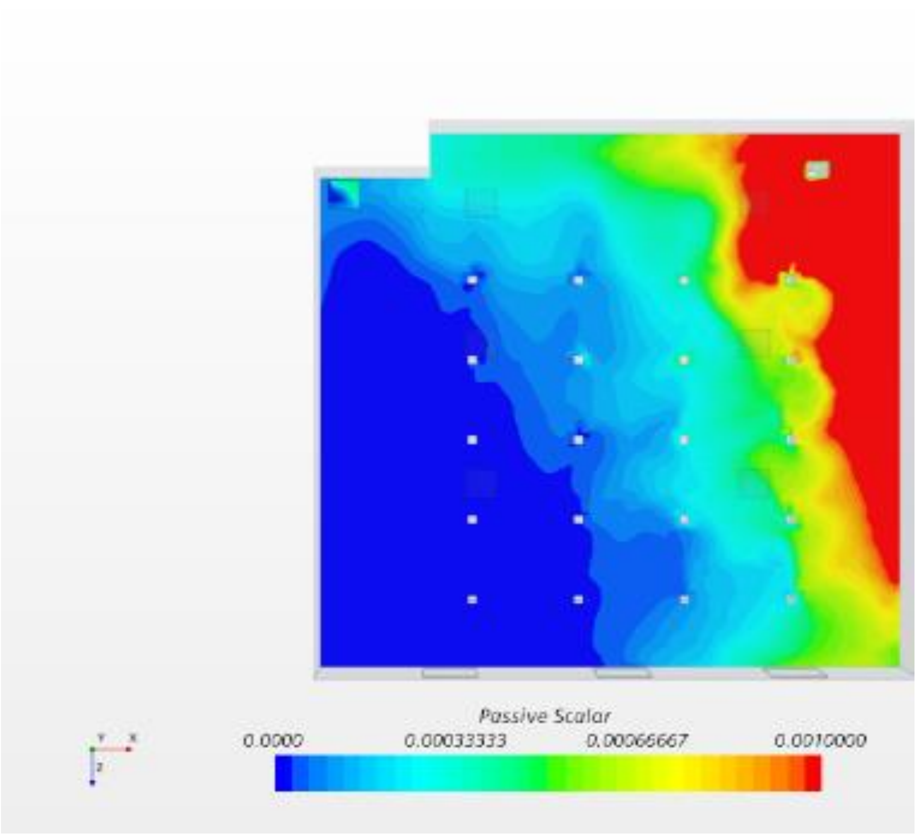
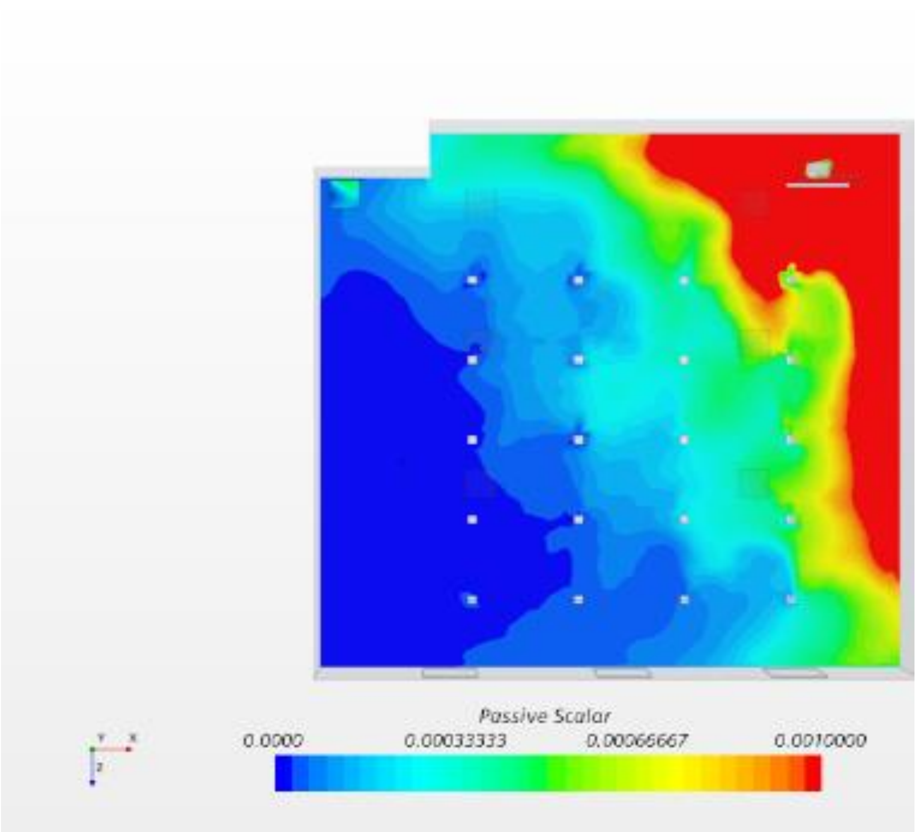
4.6. Air Redistribution

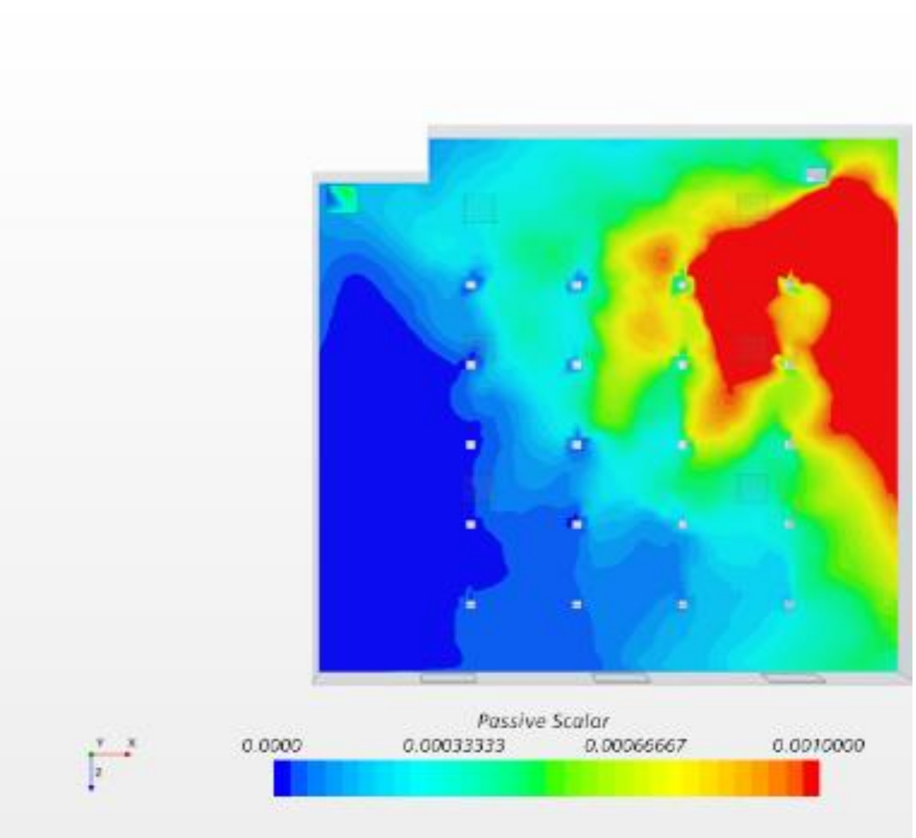
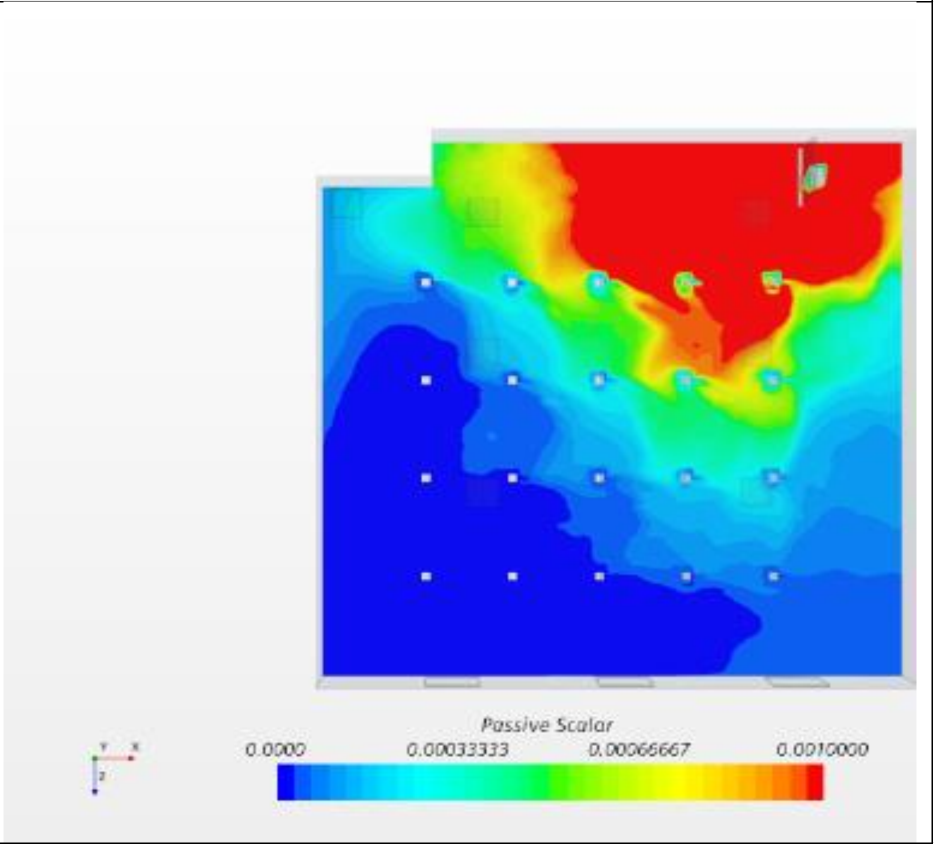
Lastly, considerations were made for how modifying the airflow distribution and balancing in the room might affect the aerosol distribution. Figure 14 and Figure 15 shows the parametric view of the passive scalar on a range from 0.0 to 0.001 and the quantitative aerosol distribution within the student occupied (constrained plane) zone as a function of the square footage of space that resides in each tier of aerosol concentration for both cooling and heating temperature models. The diffuser directly above the teacher was turned off, and the velocity for the five remaining diffusers was increased to allow the overall supply airflow rate to remain a constant value of 1100 CFM (31.15 m^3/min). all previous iterations of airflow modifications, introduction of an acrylic barrier and room layout adjustments were also considered for the fifth and final case to determine the best practice of mitigation strategies for the university classroom residing in CEH. Figure 16 shows the parametric view of all these combinations.

	Cooling Temperature Mode
Control Simulation	
Diffuser Closest to Teacher Off With an Acrylic Barrier	

	Cooling Temperature Mode
Diffuser Closest to Teacher Off Without an Acrylic Barrier	
Diffuser Closest to Teacher Off With an Acrylic Barrier Change in Room Layout	

	Cooling Temperature Mode
Diffuser Closest to Teacher Off Without an Acrylic Barrier Change in Room Layout	

	Heating Temperature Mode
Control Simulation	
Diffuser Closest to Teacher Off With an Acrylic Barrier	

	Heating Temperature Mode
Diffuser Closest to Teacher Off Without an Acrylic Barrier	
Diffuser Closest to Teacher Off With an Acrylic Barrier Change in Room Layout	

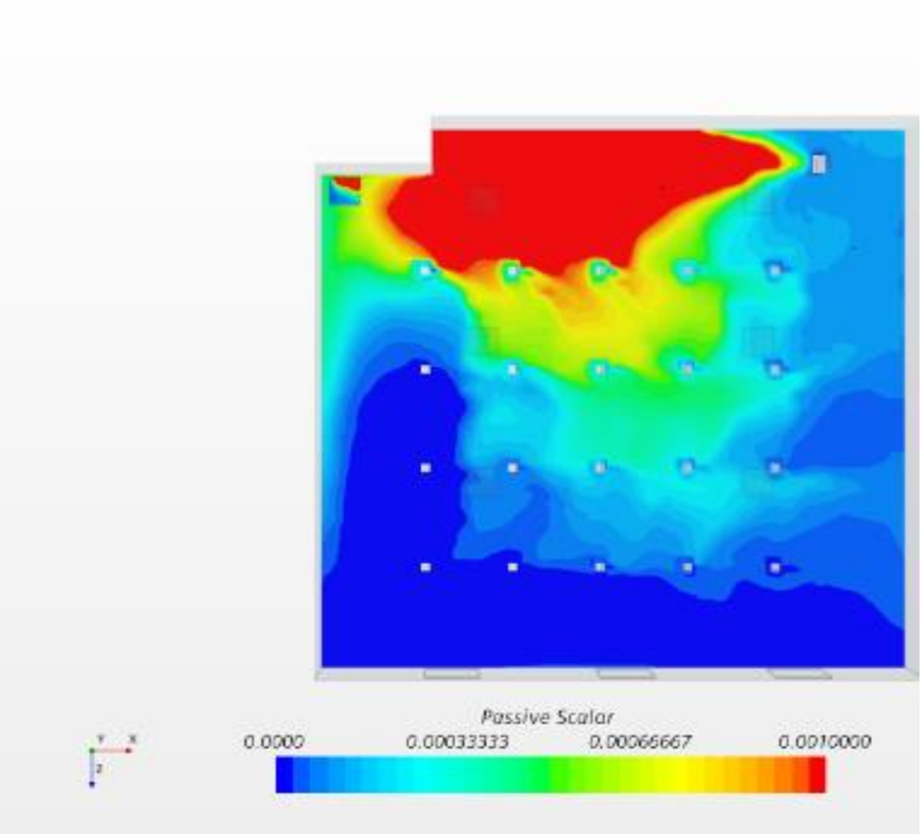
	Heating Temperature Mode
Diffuser Closest to Teacher Off Without an Acrylic Barrier Change in Room Layout	

Figure 14: Horizontal Section Plane of the Aerosol Concentration at the Seated Breathing Zone of the Students for the Heating and Cooling Operations in a Variety of Scenarios, with the Inclusion of the Closure of the Diffuser Closest to the Instructor.

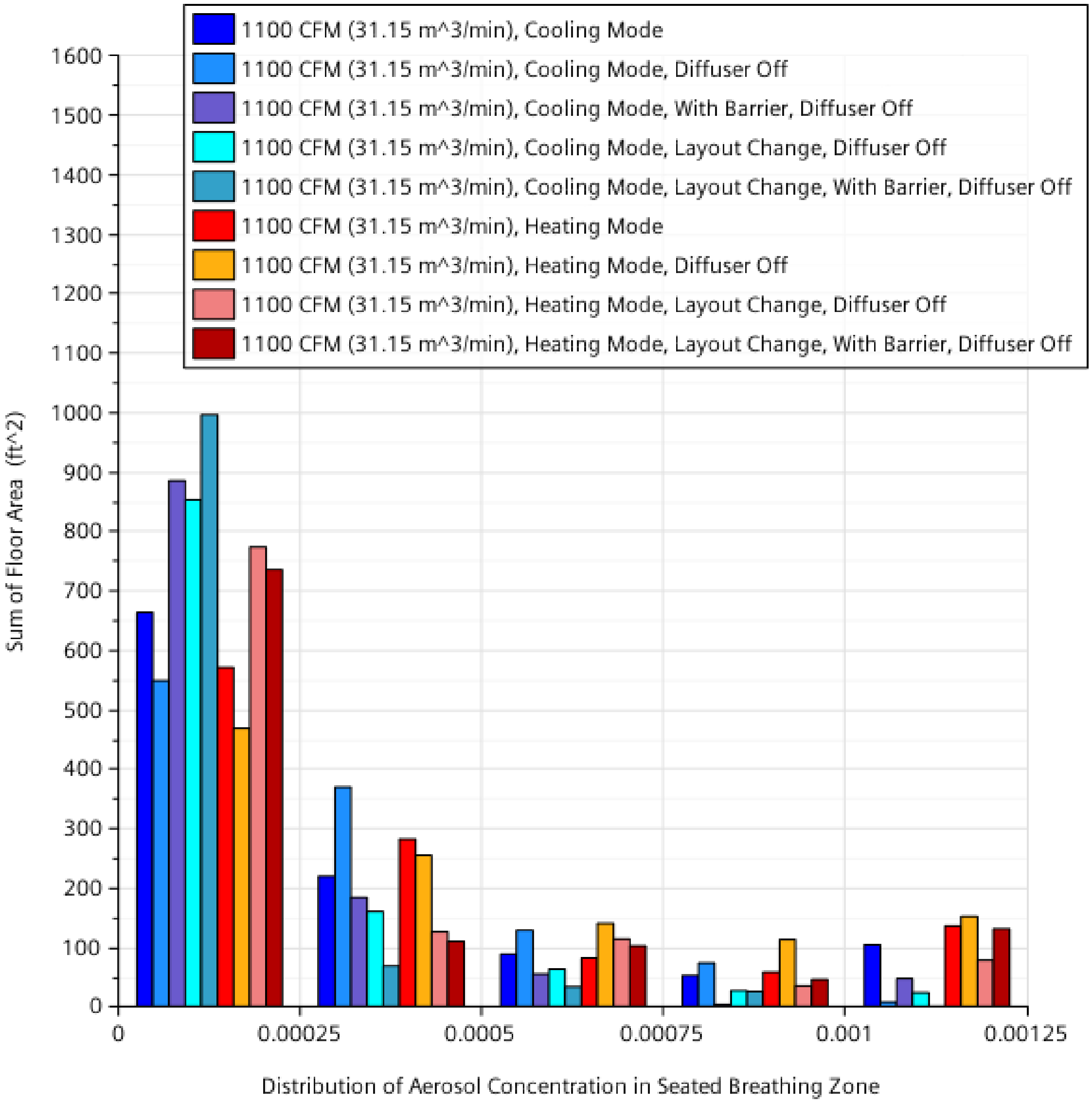
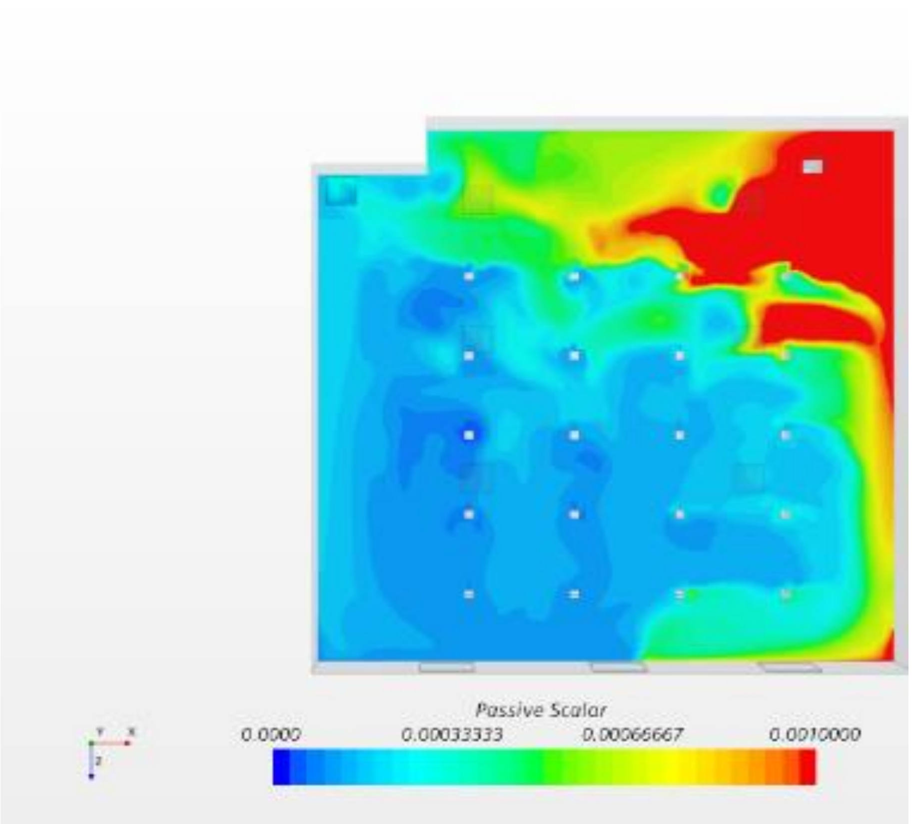
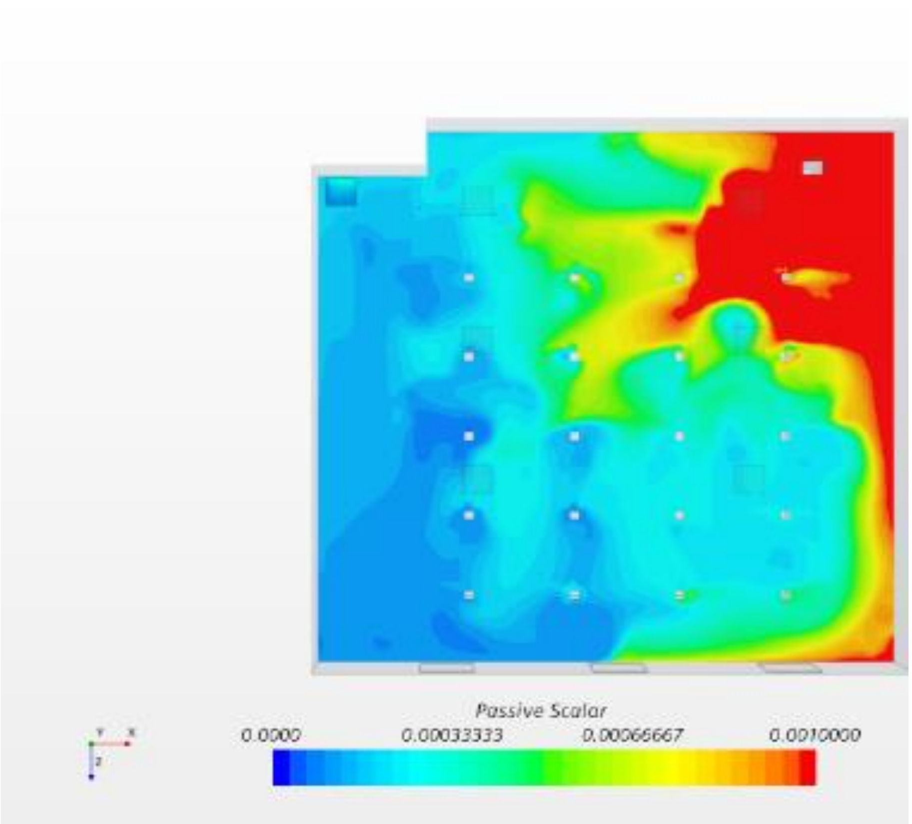
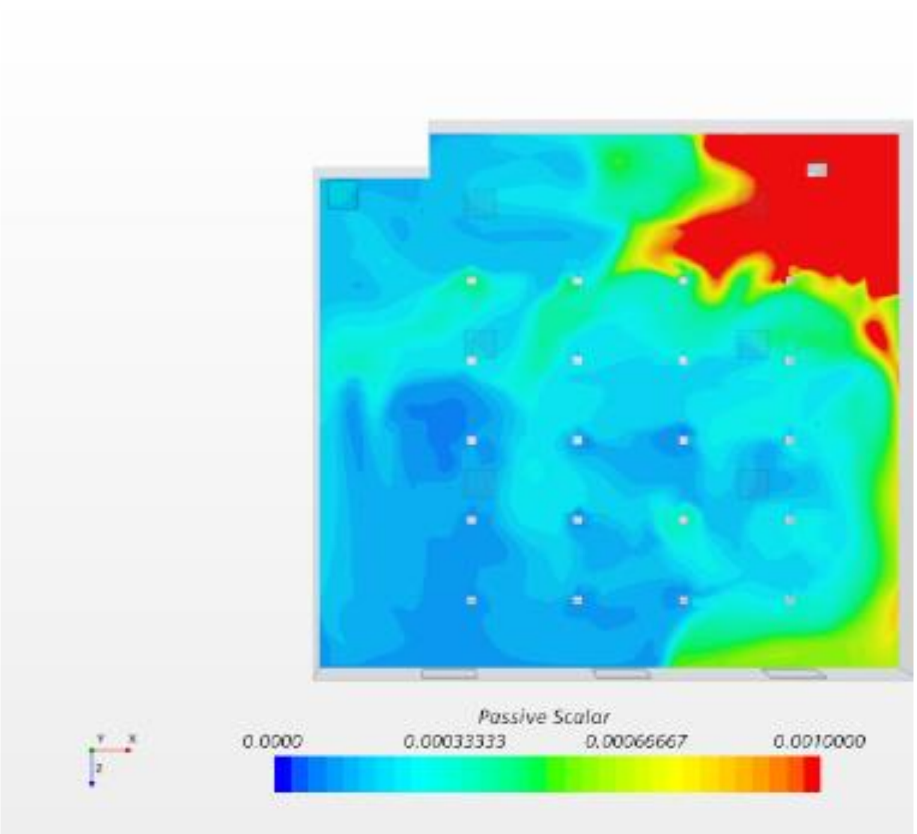
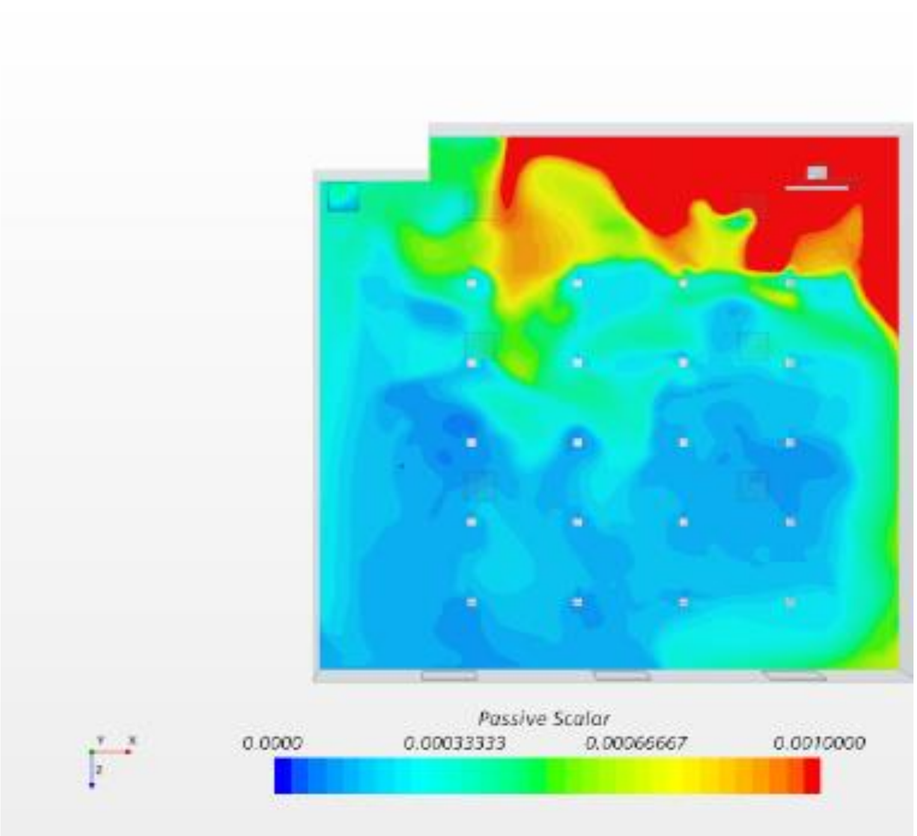
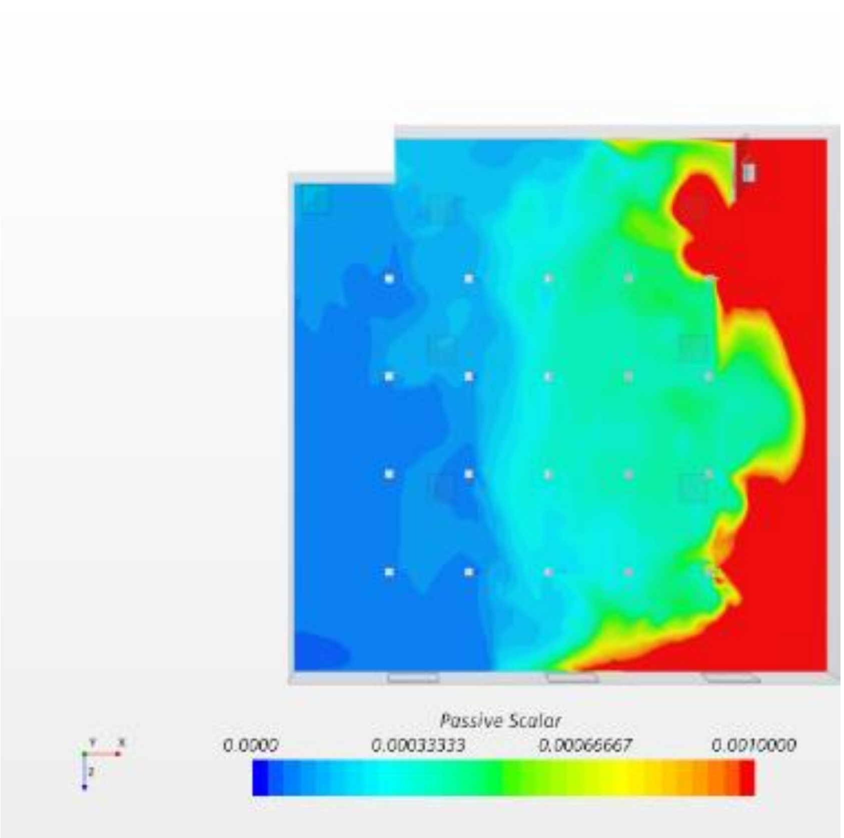
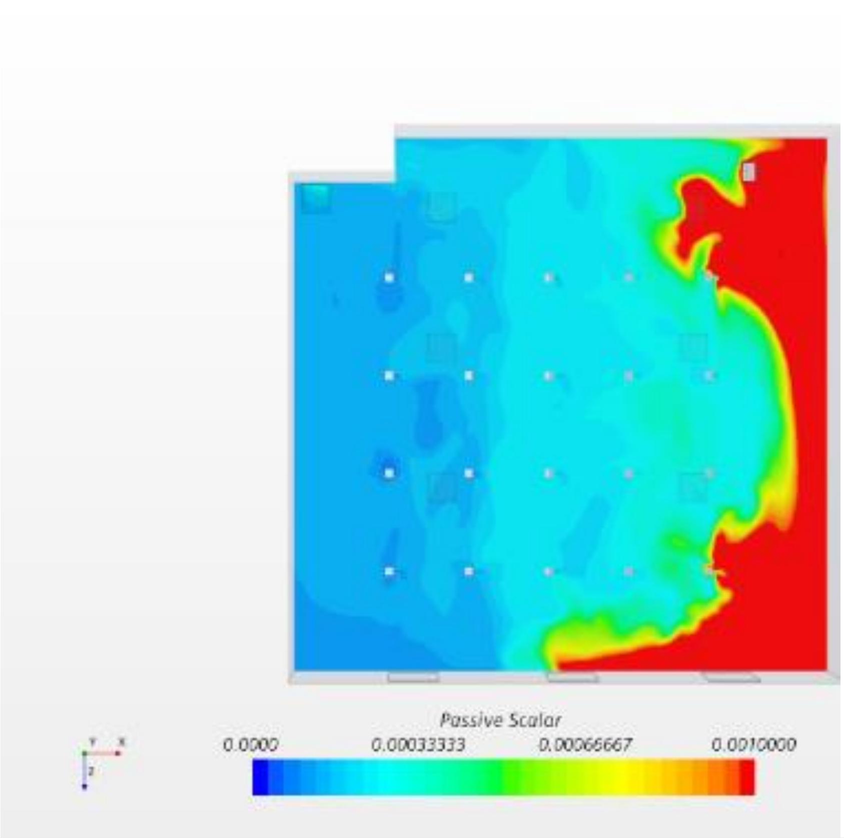


Figure 15: Square Footage Histogram at Various Concentrations of Aerosols in the Seated Breathing Zone of the Student-Occupied Space in Heating and Cooling Operation in a Variety of Scenarios, with the Inclusion of the Closure of the Diffuser Closest to the Instructor.

	Cooling Temperature Mode
Control Simulation	
800 CFM	

	Cooling Temperature Mode
1600 CFM	
With an Acrylic Barrier	

<table>
<tr><th></th><th>Cooling Temperature Mode</th></tr>
<tr><td>Change in Room Layout With an Acrylic Barrier</td><td>
</td></tr>
<tr><td>Change in Room Layout Without an Acrylic Barrier</td><td>
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<table>
<tr><th></th><th>Cooling Temperature Mode</th></tr>
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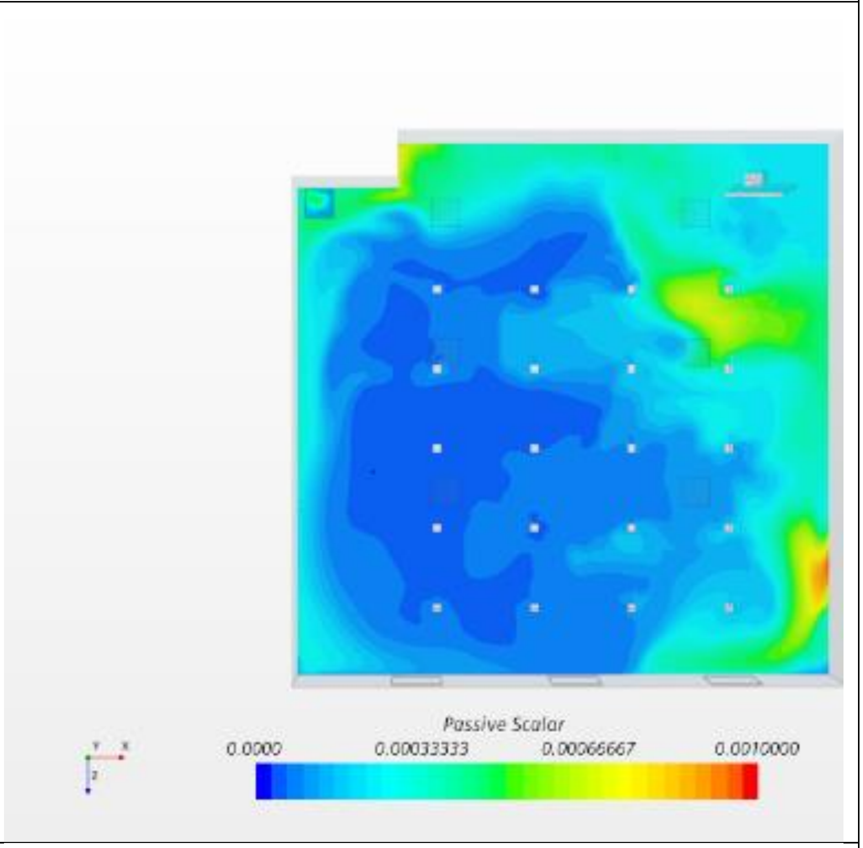
With an Acrylic Barrier</td><td>


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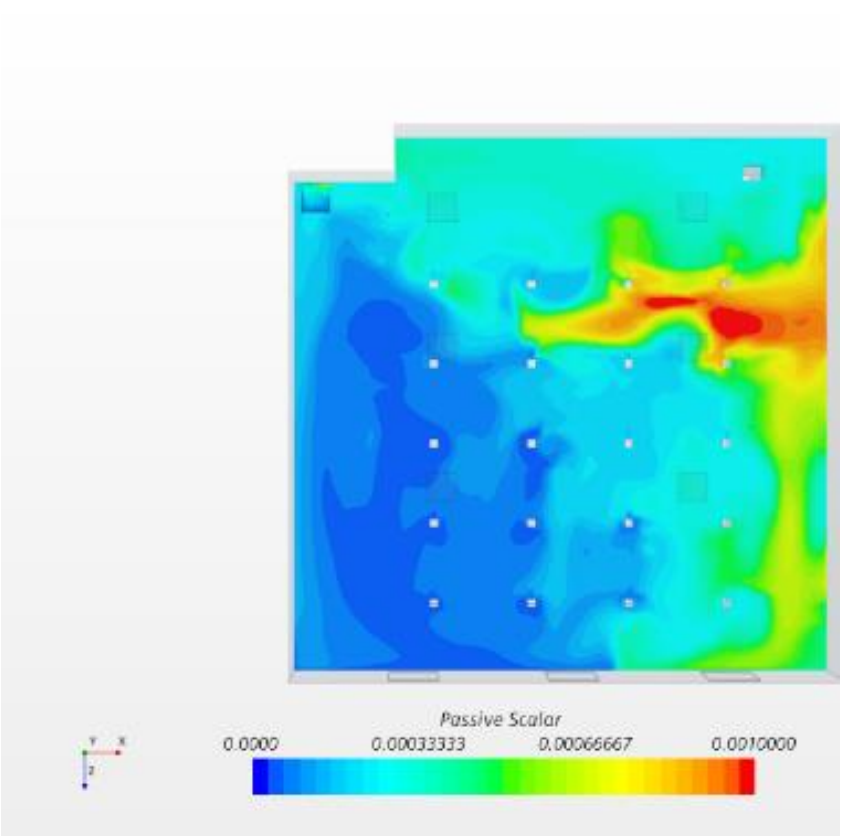
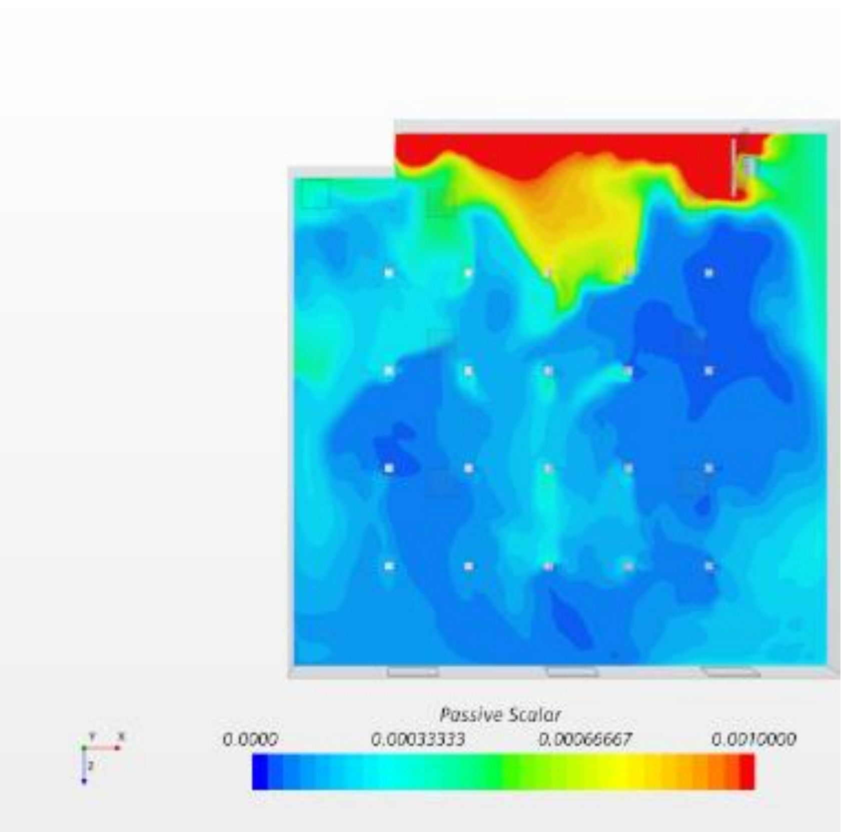
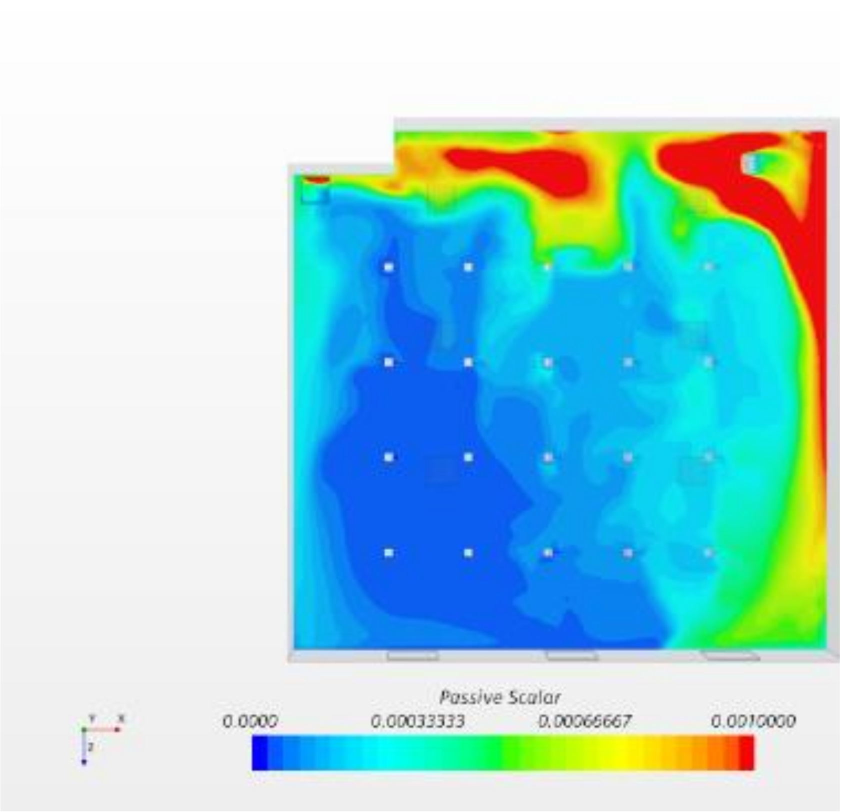
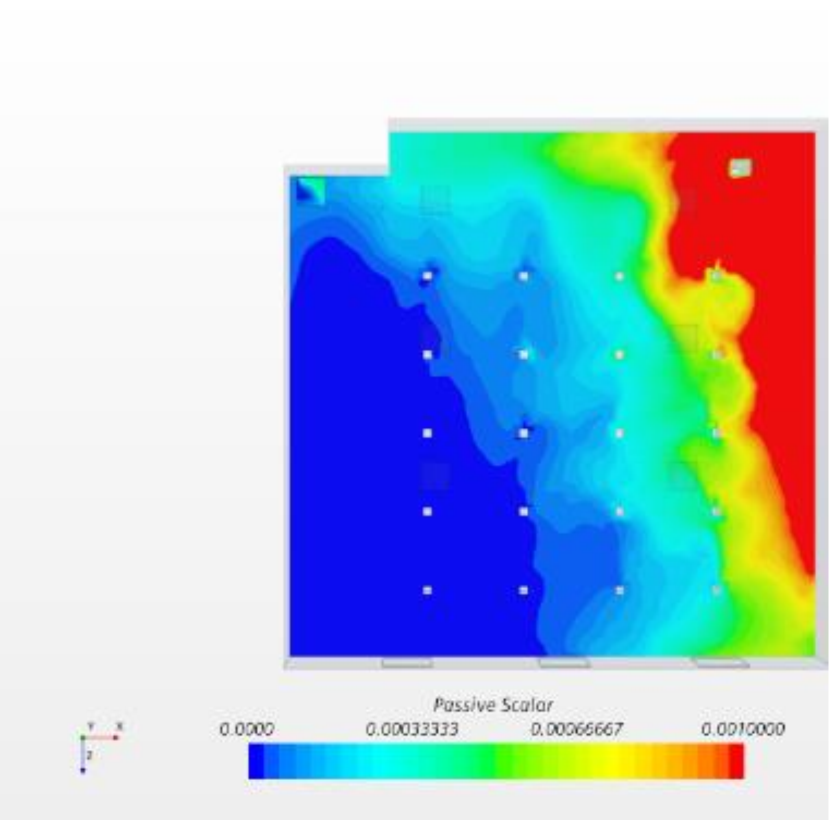
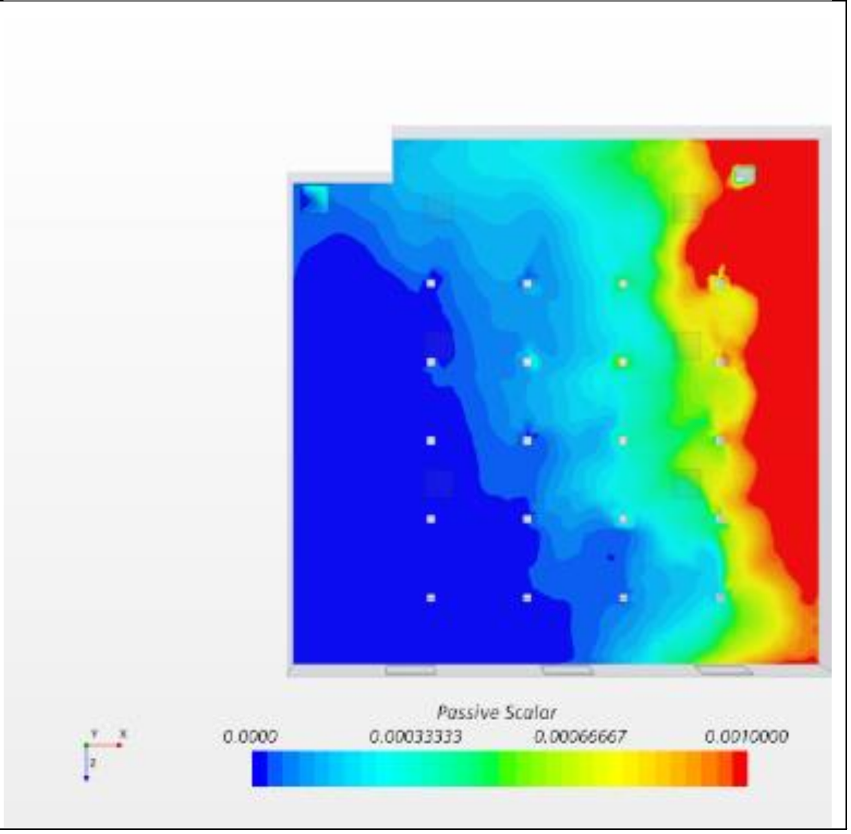
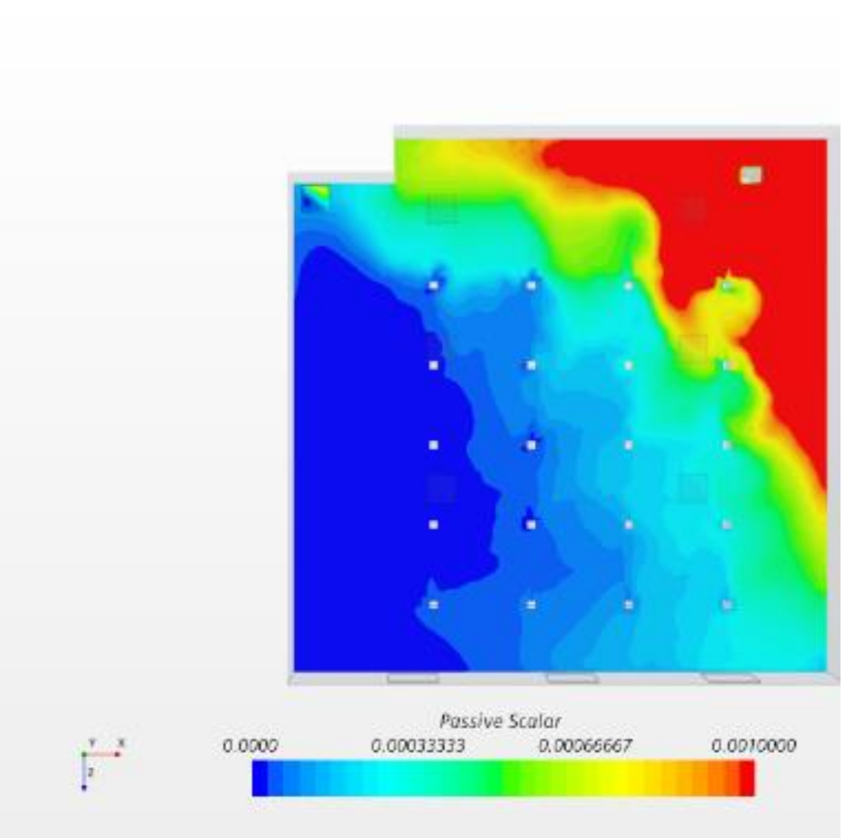
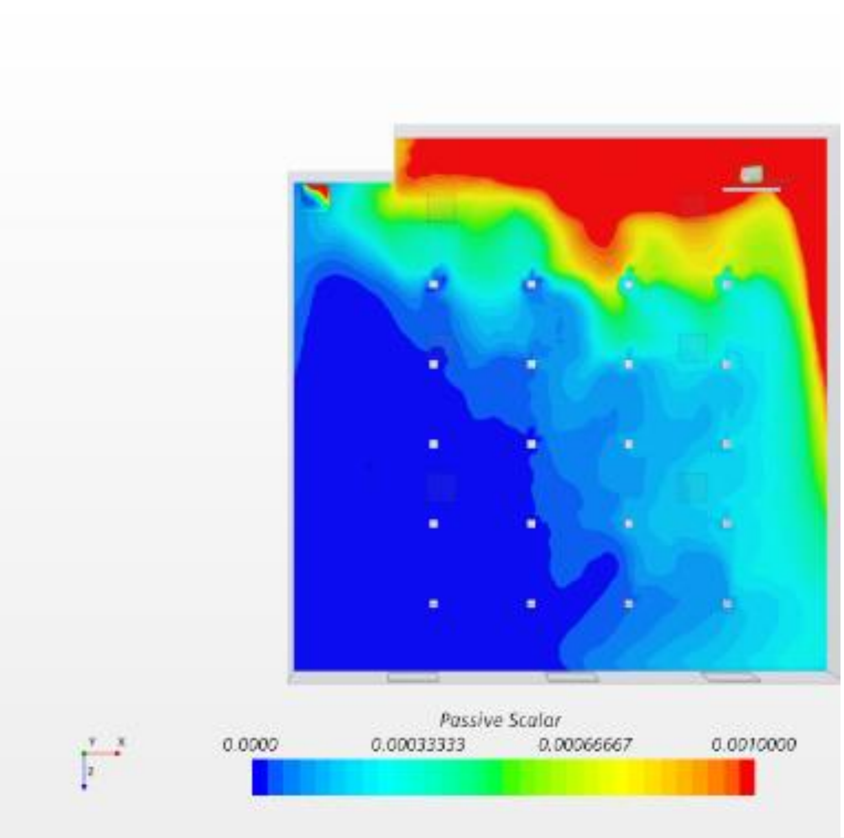
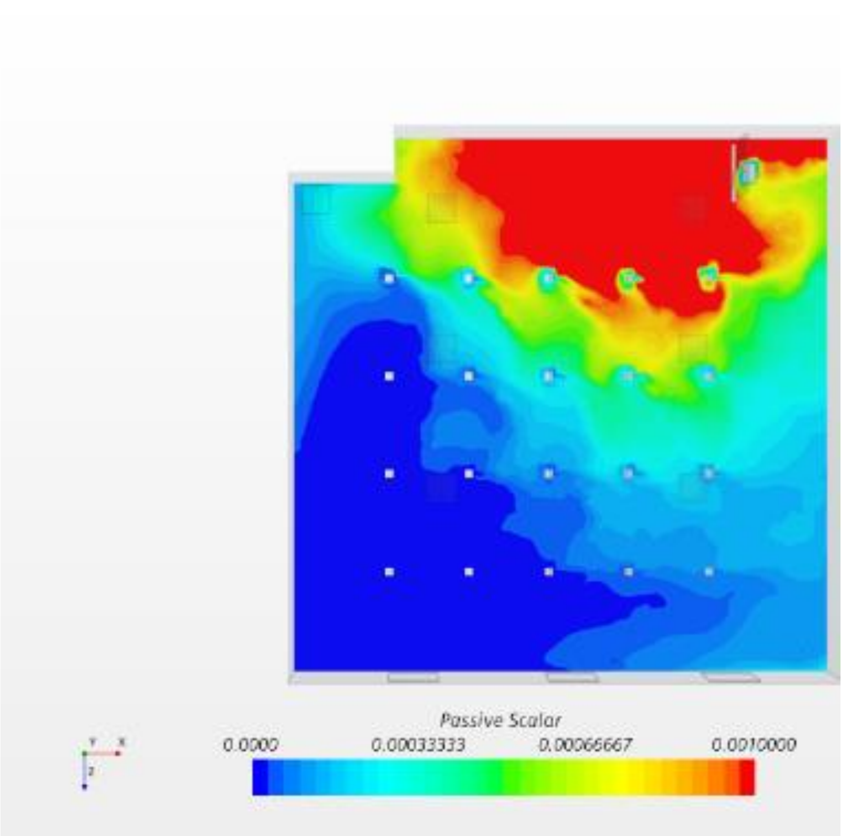
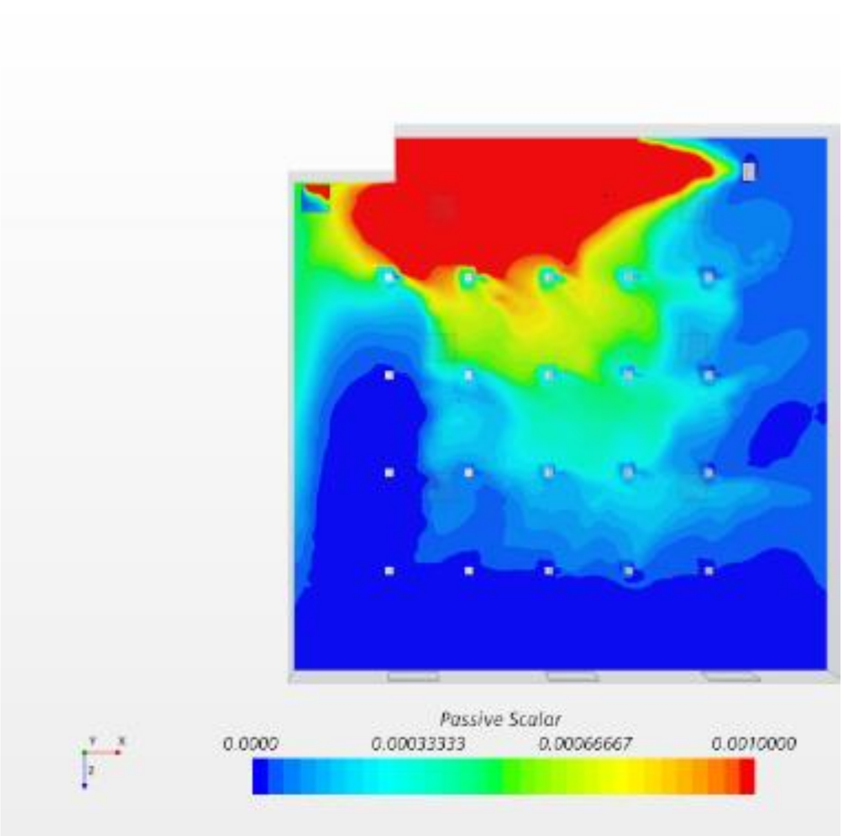
<tr><td>Diffuser Closest to Teacher Off
Without an Acrylic Barrier</td><td>


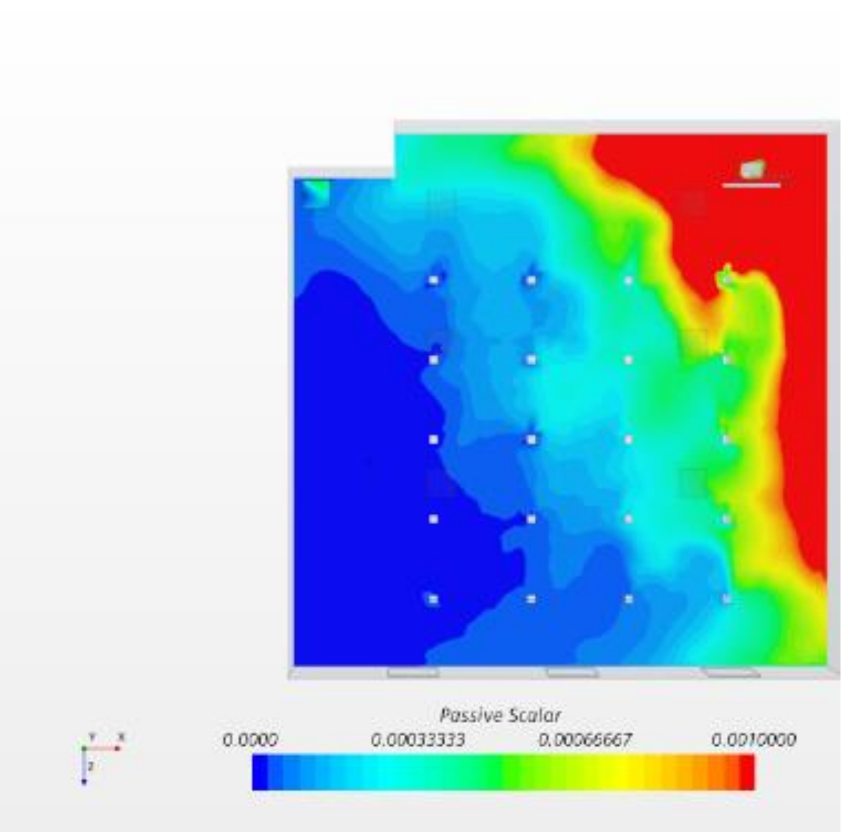
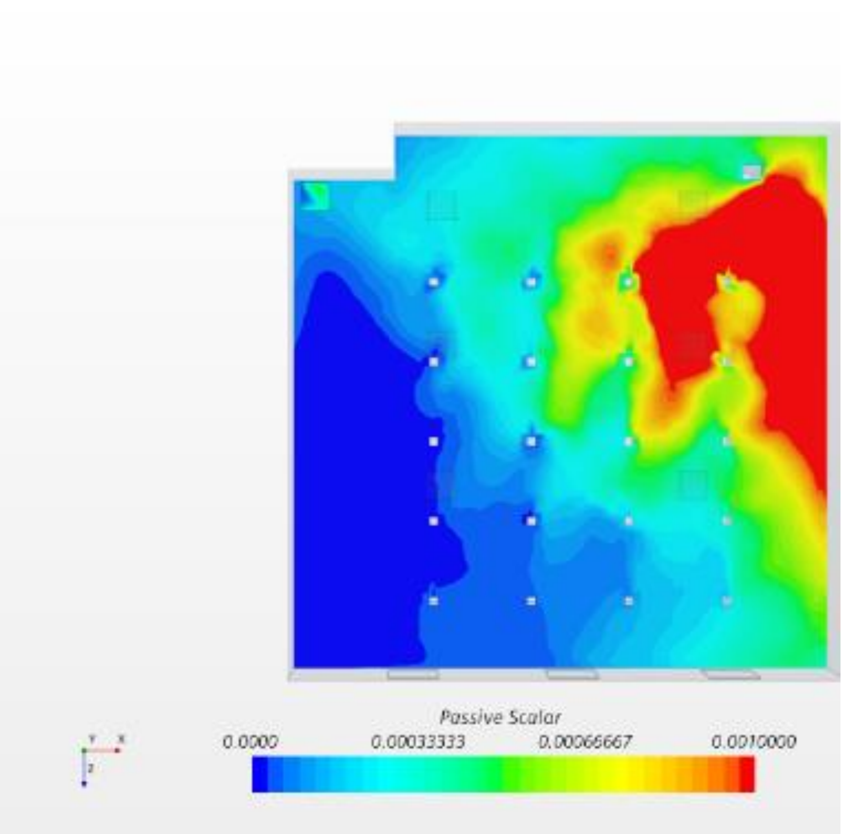
</td></tr>
</table>

	Cooling Temperature Mode
Diffuser Closest to Teacher Off With an Acrylic Barrier Change in Room Layout	
Diffuser Closest to Teacher Off Without an Acrylic Barrier Change in Room Layout	

	Heating Temperature Mode
Control Simulation	
800 CFM	

	Heating Temperature Mode
1600 CFM	
With an Acrylic Barrier	

	Heating Temperature Mode
Change in Room Layout With an Acrylic Barrier	
Change in Room Layout Without an Acrylic Barrier	

	Heating Temperature Mode
Diffuser Closest to Teacher Off With an Acrylic Barrier	
Diffuser Closest to Teacher Off Without an Acrylic Barrier	

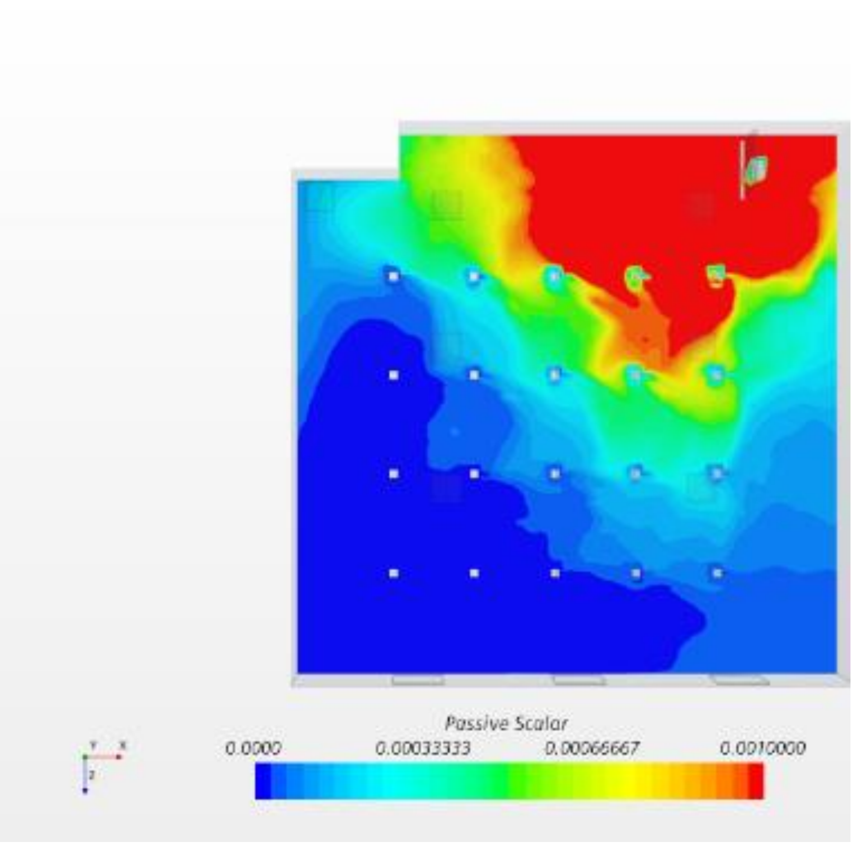
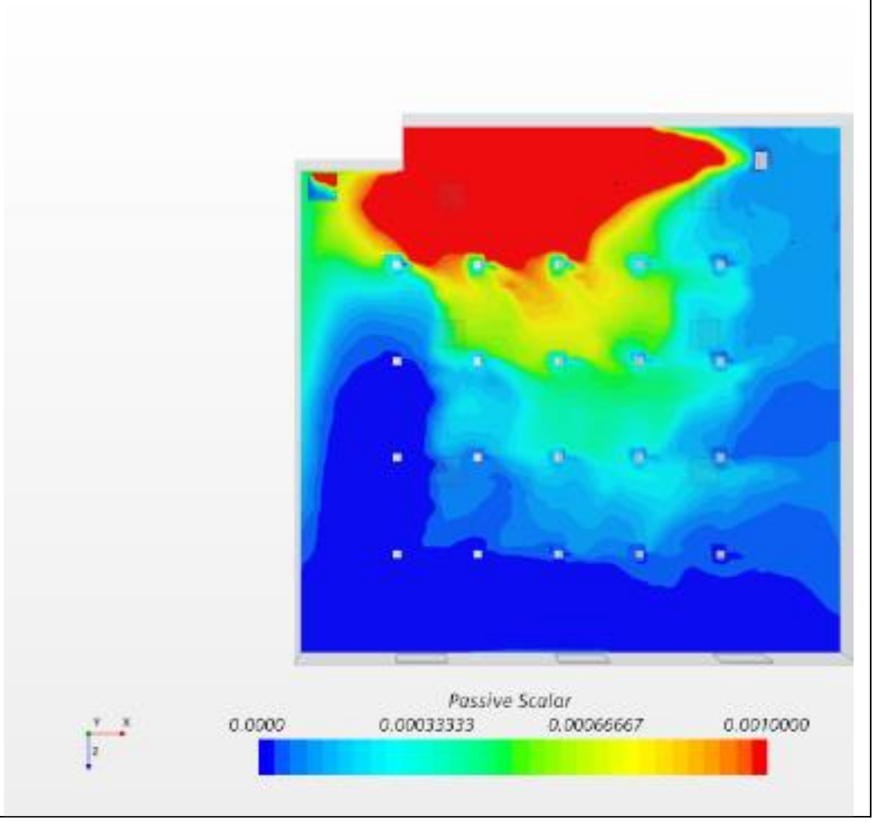
	Heating Temperature Mode
Diffuser Closest to Teacher Off With an Acrylic Barrier Change in Room Layout	
Diffuser Closest to Teacher Off Without an Acrylic Barrier Change in Room Layout	

Figure 16: Horizontal Section Plane of the Aerosol Concentration at the Seated Breathing Zone of the Students for all 20 Proposed Variations.

4.7. Validation

When considering the validity of these simulations the airflow patterns must be verified to experimental results of other university classroom case studies. As is shown in Figure 4 and Figure 5 the temperature distribution as well as the airflow are both closely exhibit what was is seen in the TRANSCOM study outlined in Chapter 3 Section 14. The airflow is clearly shown to exhibit a more homogenous distribution in the cooling application whereas the heating application is a layered temperature distribution both in the experimental and simulated data. This characteristic allows HVAC engineers to modify the design parameters of an HVAC system depending on the time of the year due to the change in the airflow physics.

4.8. Summary

Every combination of the five proposed mitigation strategies was evaluated in both heating and cooling temperature modes to account for the change in airflow and subsequently aerosol mitigation strategies throughout the calendar year within an indoor environment such as a traditional university classroom. Additionally, all CFD simulations were compared to corroborating studies that used similar baseline assumptions as this one and were verified to experimental data obtained from TRANSCOM in relation to the airplane cabin and other ICS configurations such as a commercial office building study as was outlined in Chapter 3 Section 14. Lastly the airflow characteristics that are to be expected from traditional HVAC practice in heating and cooling temperature modes was verified by observing the vertical temperature and airflow distribution from a pair of supply diffusers. This observation clearly shows that the heating temperature mode shows a layered air distribution whereas cooling provides a more homogenous distribution as was outlined in Chapter 4 Section 7.

CHAPTER 5 DISCUSSION

5.1. Airflow characteristics

Evaluating the quantitative data provided in Figure 7, it was interesting to note that the square footage of the student space in the various tiers of aerosol concentration are not vastly different when comparing heating to cooling modes. The cooling simulations provide a slightly greater area with a homogenous mixture of minimal aerosol concentration, but the heating simulations conversely provide slightly more square footage at the next highest tier of aerosol concentrations leading to localized hot zones within the space. Neither of these differences is likely significant, particularly at that low of concentration. However, just as importantly, each of the simulations were very similar in terms of areas with the highest levels of aerosol distribution. Thus, the data suggests, even though the different HVAC modes of operation create different airflow patterns and pockets of elevated aerosol concentrations, as shown in Figure 6, the overall degree of limitation and reduction of aerosol spread near the students is similar between heating and cooling operations.

Figure 6 shows the visualization of the aerosol flow characteristics under normal HVAC operations and room occupancy level. What is observed is that the homogeneous mixing of indoor air that is characteristic in cooling temperature modes shows an overall even, but higher level of concentration than what is seen in localized areas of the heating temperature mode application. In the heating aspect the thermal stratification of the air stream shows the relationship that, as the distance from the infected teacher increases, levels of concentration decrease beyond even the lowest level of concentration present in the cooling temperature mode. However, this overall minimum level of concentration at the greatest distance from the infected teacher is a localized benefit within the room. The drawback being that as an occupant approaches the source of the infected teacher the concentration levels appear to be higher than that of the cooling temperature mode, leading to the conclusion that there are localized hot spots and localized cold spots in the heating mode whereas the cooling mode naturally gives off a much more even distribution of aerosol concentration levels which can be thought of as both a benefit or detriment depending on the ratio of the volume supplied to the room of aerosol to clean air.

5.2. Temperature Profile

Several notable trends were noticed that can be tied directly to common HVAC phenomena. First, it was observed that spaces tended to promote a more even distribution of aerosols throughout the room during cooling, while spaces in heating mode tended to create larger zones of both high and low aerosol concentration. This can likely be attributed to the thermal aspects of the flow patterns, as the descending cold air during cooling tends to create a more thoroughly mixed volume of air in the room, while the warm air during heating remains high, thus creating a stratified airflow pattern and temperature distribution from the “lock-up effect”. In doing so, this barrier promotes a condition where aerosols may remain in the students’ breathing zone for longer periods of time. Thus, this provides evidence that, in order to run a thorough analysis of a space from the airflow pattern perspective, both modes of HVAC system operation (heating and cooling) need to be considered. Additionally, this may indicate that it could be beneficial to develop control systems that modify the airflow distribution based on the season and corresponding HVAC system setting.

Figure 5 visually illustrates the effect temperature has on a flow regime within an HVAC system. The cooling temperature tends to lead to a more homogeneous mixture of air due to the elevated supply diffusers and the ideal gas law. The cold air being supplied to the room wants to reach the lowest elevation possible thus forcing the much hotter room temperature air to rise as much as possible. This relationship causes fresh incoming air to mix with aerosols already present in the room temperature air of 72 F (22 C). The result is then a volume of well mixed air with an even level of concentration throughout the space as long as an occupant is a set amount of distance away from the infected source, in this case the teacher. Conversely the heating application in tandem with the ideal gas law would force the hot incoming supply air to stay at the already high elevation and the much colder room temperature air of 72 F (22 C) to remain at the already low elevation. The result in this case being that the aerosols are not mixing with the fresh supply air allowing much higher levels of concentration at the identical distance from the source as what would be present in the cooling application. The benefit however is that because the air is not well mixed the furthest points from the source in the heating application contain naturally significantly lower levels of concentration than in the cooling application. This then poses a question on which situations would provide a safer environment to lower the levels of concentration across the entire occupied breathing zone.

5.3. Variations in Supply Air

Regarding variations in the supply air volumes to the space, a few particular trends were noted from the data provided in Figure 9. First, in cooling mode, it appears that moderate airflows perform significantly better in creating the largest area of minimal aerosol distribution, compared to either lower or higher airflow rates. This could be attributed to the fact that low airflow rates are less efficient at evacuating the aerosols out of the space, but high airflow rates may increase the amount of mixing experienced near the students, spreading the aerosol further throughout the occupied region. By contrast, in heating mode, there appears to be lesser variation with the aerosol distribution profiles created by varying airflow rates. This may be due to that "lock-up effect" referenced previously, where the airflow patterns are less dependent on the actual volume of airflow being provided to the room and more to do with the motion of the airstream itself. During heating, increased airflow amounts may simply continue to push the "barrier" level down closer to the students, while continuing to keep the aerosols in the breathing zone for similar periods of time resulting in a greater risk to transmit infectious diseases. Lastly, at the highest aerosol concentrations, the amount of airflow supplied to the room had relatively little effect on the data.

Figure 8 is the observed characteristics to the differences in variations of fresh air volume being supplied to the room. When considering the cooling temperature mode, under ventilated HVAC systems tend to allow the aerosols to propagate within the occupied zone whereas over ventilation traps the aerosol concentration to the front of the room and near the source allowing for the rapid removal of the aerosols from the space. Conversely, the heating temperature mode shows characteristics of rapid propagation for under and over ventilation of aerosols when compared to the control simulations. This is likely due to the thermal stratification of clean incoming supply air being unable to reach the occupied zone as quickly as the aerosols are able to thus allow the higher levels of concentration to be present in the occupied zone.

5.4. Acrylic Barrier Effects

A few inexpensive modifications to the obstacles and workflows in the space were evaluated in Figure 11 and Figure 10. First, in Figure 11, shows that, while the inclusion of an acrylic barrier in front of the instructor did not make a noticeable difference in the aerosol concentrations in cooling mode, it did create a rather significant increase in the amount of student-occupied area with minimal aerosol concentration in the heating mode. This could be due to the fact that the heating operation of the HVAC system is already creating a less-mixed condition in the space, so further limiting the initial projection of the aerosols toward the students allows the aerosols to be evacuated more efficiently toward the return grille at the front of the classroom. Conversely, in cooling operation, even though the aerosols are initially blocked just after projection from the instructor, the HVAC system induces mixing throughout the entire space, still entraining the aerosols in one of the supply air streams from the diffusers, and thus limiting the effectiveness of the barrier by providing a similar degree of mixing of those entrained aerosols throughout the space.

Figure 10 visually shows the effects of an acrylic barrier in the classroom. When considering the cooling temperature mode, the introduction of an acrylic barrier directly placed in front of the instructor at a baseline ventilation rate shows significant improvement at containing the aerosols to the front of the room and the immediate removal to an even greater efficiency to that of over ventilated HVAC systems for the exact same temperature mode and baseline conditions. Conversely the heating temperature mode shows similar results, however higher levels of aerosol concentrations are more prevalent in the occupied zones by simply changing the setting of the HVAC system from cooling to heating.

5.5. Room Layout Adjustments

Figure 13 shows how re-orienting the room may affect the aerosol distribution. The hypothesis was that rotating the teacher to speak toward the return grille would help to create a more efficient evacuation of those aerosols out of the space and avoid aerosol entrainment in the supply air. Interestingly, this new room layout did seem to promote an increase in occupant area with minimal aerosol exposure, particularly in the heating operation, as well as in scenarios without a barrier near the instructor. However, the room in the cooling operation with a barrier present appeared to perform significantly worse compared to the control simulations. This may be attributed to the acrylic barrier to limit the aerosol projection toward the return grille, allowing the aerosol to rise with the thermal plume of the teacher and become entrained in the supply air streams. Without the acrylic barrier, a large portion of the aerosols emitted by the instructor may be able to avoid the air streams while hugging the outside wall until reaching the return grille. Additionally, in heating operation, a less-mixed environment is naturally created, so there is less of an opportunity for the aerosols to become entrained in the first place. Thus, by projecting the aerosols toward the return grille, those aerosols naturally flow toward the return path and promote quicker removal of aerosols from the space.

Figure 12 illustrates the propagation of aerosols within the new room orientation. When altering the orientation of the desks, the students, and the instructor by 90 degrees the cooling application shows a characteristic such as a wall of clean air preventing the removal of aerosols, allowing it to spread into the occupied zone and raise the concentration level slightly but also remain contained to one side of room. Conversely, the heating zone does allow for the removal of aerosols with the draw back that the removal is not occurring at a rapid enough rate which will allow the aerosols to propagate at a rate in which it would be more detrimental than the heating case for the baseline simulation.

5.6. Redistribution of Aerosols

Lastly, Figure 15 compares a scenario where the diffuser closest to the instructor was closed, and the airflow velocity was re-distributed to the other diffusers in the space to maintain a constant supply air volume. The hypothesis was that, by creating a less mixed local environment near the instructor, some of the aerosols may avoid entrainment and recirculation throughout the room. The closure of this diffuser was then included in each of the previous scenarios and compared to the control simulations. In doing so, several of the simulations showed greatly increased areas of minimal aerosol concentration near the occupants. The biggest improvement was noted in the cooling scenario with an acrylic barrier in place. This may be attributed to the closure of the diffuser limiting the mixed condition near the instructor, while the rest of the room remains well-mixed with minimal aerosols that originated from the instructor. The slower flow patterns near the instructor may be allowing the aerosols, blocked by the acrylic barrier, to migrate toward the return grille, avoiding the air entrainment near the occupants. However, without the barrier in place, the projected aerosols may still be reaching the mixed environment near the occupants, thus minimizing the effectiveness of this approach. Additionally, the heating simulations showed lesser improvements as well, once again likely caused by reduced mixing already occurring due to the "lock-up effect".

Figure 14 is the visual representation on how the redistribution of supply air velocities throughout the 2x3 diffuser grid while maintaining air volumes supplied to the space can mitigate the propagation of aerosols. The cooling temperature mode clearly shows the most significant impact to the propagation of aerosols in that it has the fewest area of hot spot zones at the occupied breathing zone allowing for the rapid removal of aerosols. Furthermore, the occupied zone itself has a relatively low but homogeneous mixture of concentration levels. Conversely in the heating application there is a significant increase in aerosol concentration in the occupied zone both of these characteristics present in the cooling and heating temperature mode are a direct result of the temperature profile and how that effects the flow of the airstream.

CHAPTER 6 CONCLUSION

6.1. Conclusion

Looking back at the five research questions asked prior to running these simulations, both qualitative and quantitative data was gathered and each of the five following questions are answered below based off of the simulated evidence.

(1) At what point does too much ventilation become detrimental to the mitigation of aerosols, and what is the ideal ventilation rate for minimal propagation of these aerosols? It is observed that the decrease in the flow rate from 1100 CFM to 800 CFM showed to be an improvement on aerosol mitigation strategies but when cooling the space maintaining 1100 CFM showed to be the most effective option.

(2) How does the temperature of incoming indoor air affect the spread of aerosols, specifically with regards to how a flu season is seen in the winter months as opposed to the summer months? Interestingly enough the mitigation of aerosols within a space showed that in cooling applications where the room is expected to have a more mixed temperature profile also shows a higher level of aerosol concentration throughout more of the breathing zone then what is seen in heating applications which is a contradiction to when the flu season typically takes place which is towards the beginning of winter.

(3) How effective is the introduction of an acrylic barrier in front of a speaker at impeding the flow of aerosols? When considering the introduction of an acrylic barrier the modification is observed to be significantly effective as opposed to the control simulation when considering the heating application of the space, but the effects of the barrier were negligible when considering the cooling application.

(4) Does physically changing the orientation of the room with relation to the direction the speaker is facing significantly affect the propagation of aerosols? Physically changing the orientation of the room showed to be a significant improvement to aerosol mitigation for all variations and that when considering the introduction of an acrylic barrier or not appears to show a negligible effect on how the aerosol is propagating throughout the space.

(5) Is it possible to create artificial quarantine zones by modifying the downward flow velocity of incoming air in five of the six diffusers while maintaining the same level of total ventilation rate being supplied by the HVAC system? Yes, it creating artificial quarantine zones by modifying the downward flow velocity of incoming air is possible if the individual is infected is known, while this can't be used as a preventive action to mitigate the spread of aerosols it can be used as a way to quarantine groups of individuals within a space.

Overall, this set of simulations shows that strategic minor adjustments to the room function and HVAC operation within a space have an effect on the air quality and the amount of aerosol exposure by the occupants present. For this particular set of simulations, a university classroom was investigated. In doing so, it was discovered that reducing local airflow mixture near the instructor may promote less likelihood of exposing the students in the space to the aerosols emitted, encouraging efficient evacuation of the aerosols. This is particularly prevalent when the HVAC system is operating in cooling mode, where airflow mixing is more significant throughout the space. On the other hand, localized airflow modifications were somewhat less effective in heating mode when compared to the control experiments, as the “lock-up effect” reduces the extent of thorough mixing of the airflow patterns near the occupants in general. However, implementing manners of inhibiting the initial projection of the aerosols toward the student-occupied zones appeared to be effective in reducing aerosol spread in the heating mode, taking advantage of that reduced degree of airflow mixing by keeping the aerosols more concentrated around the instructor.

Thus, the airflow created in a space by the HVAC system plays a significant role in how the aerosols are distributed near the occupants. By making particular adjustments, building operators can help to decrease the likelihood of viral exposure to the occupants in a particular space at relatively low-cost investment, particularly compared to other methods of air treatment and filtration. However, this research also demonstrates that there is no set of "one-size-fits-all" recommendations that can be made for all zones, as the airflow patterns and functionality of a room would be highly case-dependent. Specific analysis would be required on any particular space to determine which of these options may be the most beneficial for that particular building's operation, exterior climate, and time of year.

6.2. Future Work

The fact is human beings will need to find a way to live with all past, current, and future diseases without the need to rely on medicine as the only line of defense against aerosols. As a result, Future work should then focus on establishing a set of new HVAC standards that can make a significant impact on improving IAQ for state of the art HVAC systems. One example would be to analyze creative positioning of supply diffusers to monitor the effects on the mixture of air in cooling and heating temperature applications. This would include reallocating the entry point of airflow to all supply diffusers to the floor during the winter and maintaining the traditional supply diffusers in the ceiling during the summer to achieve a consistent level of IAQ mixing throughout the calendar year as IAQ mixture is proven to have a significant effect on aerosol mitigation.

Taking it one step further perhaps if state of the art HVAC systems could transfer to more efficient energy systems of heating air, as that tends to cost a significant amount of more energy than cooling applications, then the same level of air conditioning could be obtained year round thus leveling out the risk assessment of contracting an airborne disease depending on the time of year or even the location on earth. This would include achieving the same effects during the summer and winter as opposed to the traditional air conditioning systems where IAQ in the summer is being regulated heavily and the winter is simply heating the air with no parameters of IAQ being controlled such as humidity levels.

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