DSC180 Capstone: Modeling and Simulation of Aerosol Flow in a Classroom Environment with Mobile Sensors

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Abstract

The COVID-19 pandemic has brought the issue of indoor air quality and safety to the forefront of public attention. With the realization that respiratory aerosols can linger in indoor spaces and potentially spread the virus, it has become imperative for individuals to have access to accurate and effective tools for assessing indoor safety. While existing apps are available for monitoring factors such as temperature and air quality, they do not consider the concentration of respiratory aerosols or other contaminants that may be present in the indoor environment.

To address this crucial gap, our team is dedicated to developing a mobile application that will leverage the built-in sensor data and machine learning models to simulate aerosol flow and forecast the aerosol concentration in the surrounding area and enable users to assess the risk of exposure to respiratory aerosols and other pollutants, providing them with valuable information to make informed decisions about their safety.

The app is not limited to COVID-19, as it can be used for various other purposes and illness. By processing the data we collected, our app can determine the safety of indoor environments and provide valuable insights to the quality of air.

Introduction

In order to inform, manage, and minimize risk factors related to airborne infections and other pollutants, we want to develop simulated digital twins of physical systems that model indoor air quality while monitoring risk related to human respiratory droplets and aerosols. That is, we are working on developing a compartment model of aerosol concentration and flow in the presence of dynamic human syndromic events. In addition to respiratory aerosols, other contaminants that may pose health hazards are to be taken into account (Rahman 1).

The installation of sensor-based systems that provide information on airborne virus and other pollution risk factors is difficult due to a number of issues, and one of them is the absence of sensor equipment for general use. Currently available devices are made for specific application situations, and their high cost makes their use prohibitively expensive in many general use scenarios. One way to approach the problem is that we can employ computational fluid dynamics (CFD) to provide information on the operation of indoor environments and the flow of air, but it's difficult to set up without the right domain knowledge for many situations and demand a lot of computing resources (Rahman 1). Therefore, our smartphone app could effectively resolve the cost problems and computing difficulties and provide the results accurately.

This project is divided into three stages: data collection, data visualization, and modeling and simulation. In the first stage, we created an iOS application that includes features such as thermal images, audio, and room layout capturing. To test the app and collect data, we set up a testbed in a small office room where we simulated human coughs mechanically and captured aerosol concentration using a particulate matter (PM) sensor. The cough simulation involved using a mannequin, mechanical ventilator, fog machine and air compressor, and we experimented under different room conditions like fan speed, door opening control, etc. In the second stages, we plotted the esplased time and aerosol concentration for several experiments under different room settings and discovered that the air exchange rate is a crucial factor in determining the resident time of aerosol. In the final stage, we used compartment models to forecast aerosol concentration, and Ansys Discovery software to simulate the aerosol flow. We used our experiment data to validate the performance of these performances. Overall, this project aims to provide a reliable and effective solution to the challenges of indoor air quality monitoring and risk mitigation, especially in the context of public health and safety.

Methods

Data Collection App and Tools

Our team developed an iOS application for data collection and proof-of-concept deployment of models. The app is equipped with various features, including capturing audio and classifying different sounds, with a focus on capturing human respiratory events such as cough sneezing while excluding speech to ensure privacy. It also captures thermal images using a FLIR one camera to detect human presence, movement, and surface temperature in the thermal images using YOLO model, and room layout and geometry using Lidar and camera, which are essential information for modeling and CFD simulation . We stored the collected data online using Firebase and fetched data for further analysis.

To support data collection, we used the SPS30 Particulate Matter Sensor to measure our ground truth aerosol concentration. We created a graph outlining our methods for a clearer understanding.

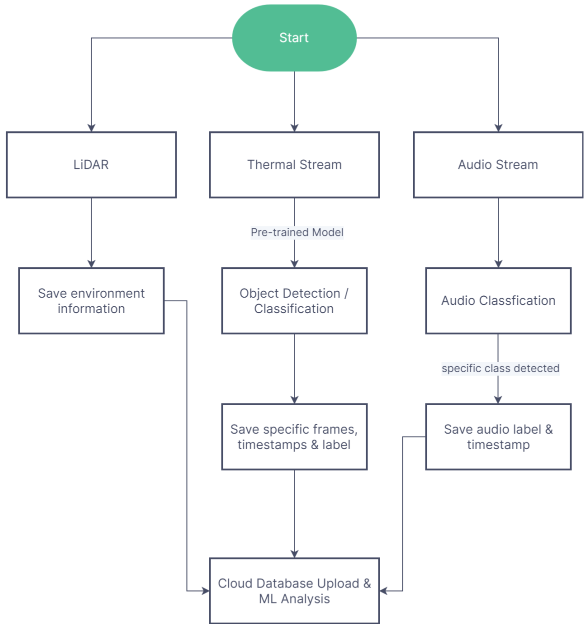


Figure 1: flowchart that describes the app that were created

Data Collection Process

1. Experiment Room

To ensure proper experimental conditions indoors, certain rules must be followed when selecting the indoor environment. The designated space for data must be followed when selecting an indoor environment. The room we chose is a compact office room with a dimension of approximately 3.2m x 2.6m x 3.2 m, and there was a desk and three chairs displayed in the room.

2. Set-up and Experiment

In order to collect data, the process involves simulating cough events and using mobile and particulate matter (PM) sensors to capture the data from these events. The fog machine and the mechanical ventilator were used as the cough simulator, and the mechanical ventilator emits a high-velocity air flow, which disperses the fog (aerosol) into the room. Both are placed on the desk in the room.

An example of the room display, sensor placements, and cough machines are shown below:

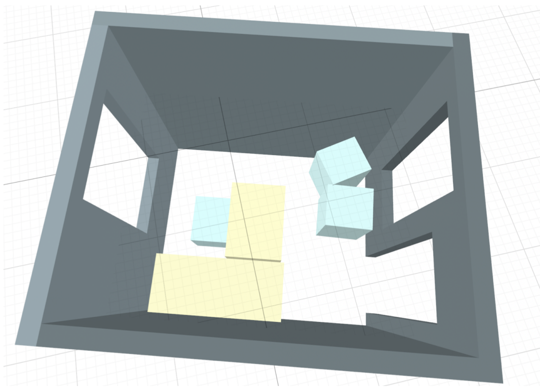


Figure 1: Room Layout

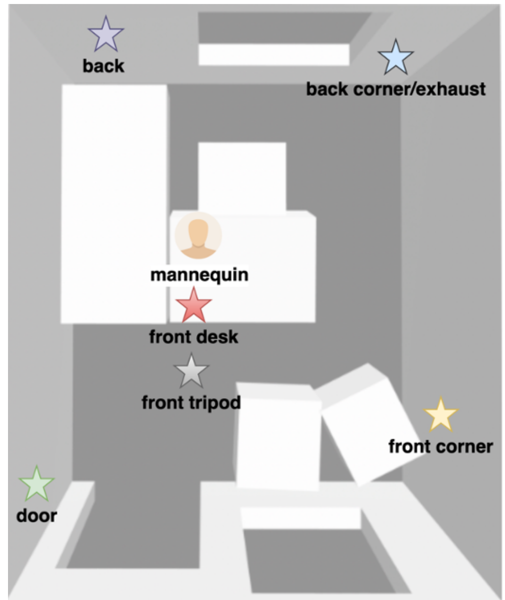


Figure 2: Sensors Placement

[a]

[b]

Figure [a] and [b]: picture of a part of the room (with cough simulators) and tripod is placed in front of mannequin

The aerosol release events are simulated five times for each room condition, taking into the factors such as furniture placement, door and window openings, and air conditioning status.

These simulations are conducted in a steady environment, with three to five minute intervals between each event to capture aerosol dispersion data. The ventilator button is manually pressed to trigger the events, and the fog machine is set to operate continuously with a five minute interval. To ensure accurate results, a human experimenter must be present in the room during the experiment for pressing the button.

To set up CFD Simulators, it's necessary to define the surface types and the temperatures. Our data collection app is designed to capture the rooms' thermal images using the smartphone-compatible thermal camera (FLIR One). Here's some examples:

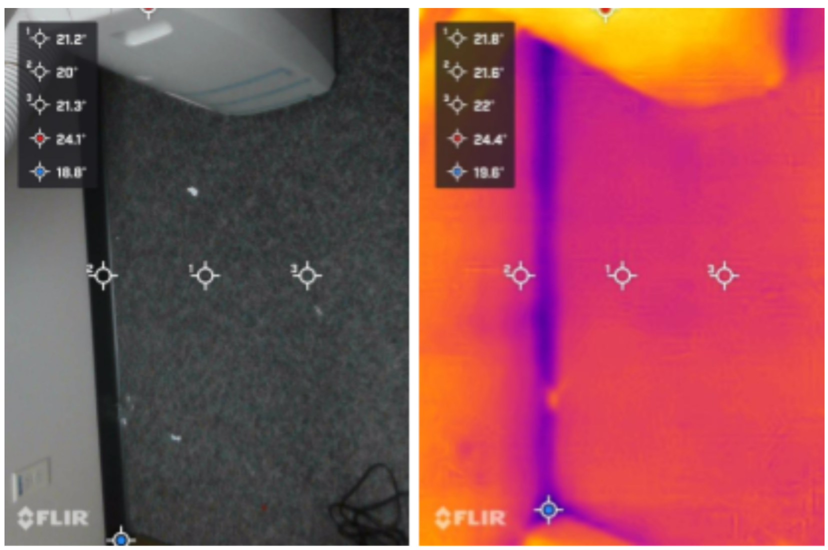


Figure 3: thermal images of floors

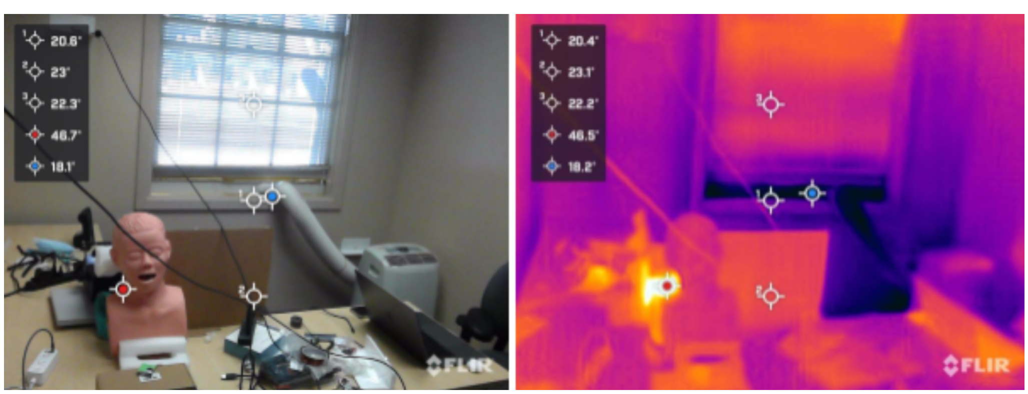


Figure 4: thermal images of mannequin (cough machine)

Data Preprocessing

1. Fetch Data from Firebase

After we collected data, the first step was to retrieve the required data from Firebase, where we had stored thermal images and audio. To automate the process, we developed a script that could download the data seamlessly.

2. Data Integration and Sensor Data Mapping

To merge the data from the six sensors, we developed a script that sorted the data based on their timestamp and matched the sensor location with their respective sensor ID. This ensured that the data was integrated accurately and could be used for further analysis.

Data visualizations

Graphs and description

We first conducted experiments at four different fan speed settings - low speed, medium speed, high speed, and no AC. We plotted the mass concentration levels from six different sensor positions over a 200-second period and observed that the dispersion and duration of aerosol concentrations varied across different fan speed settings and sensor locations during a cough event.

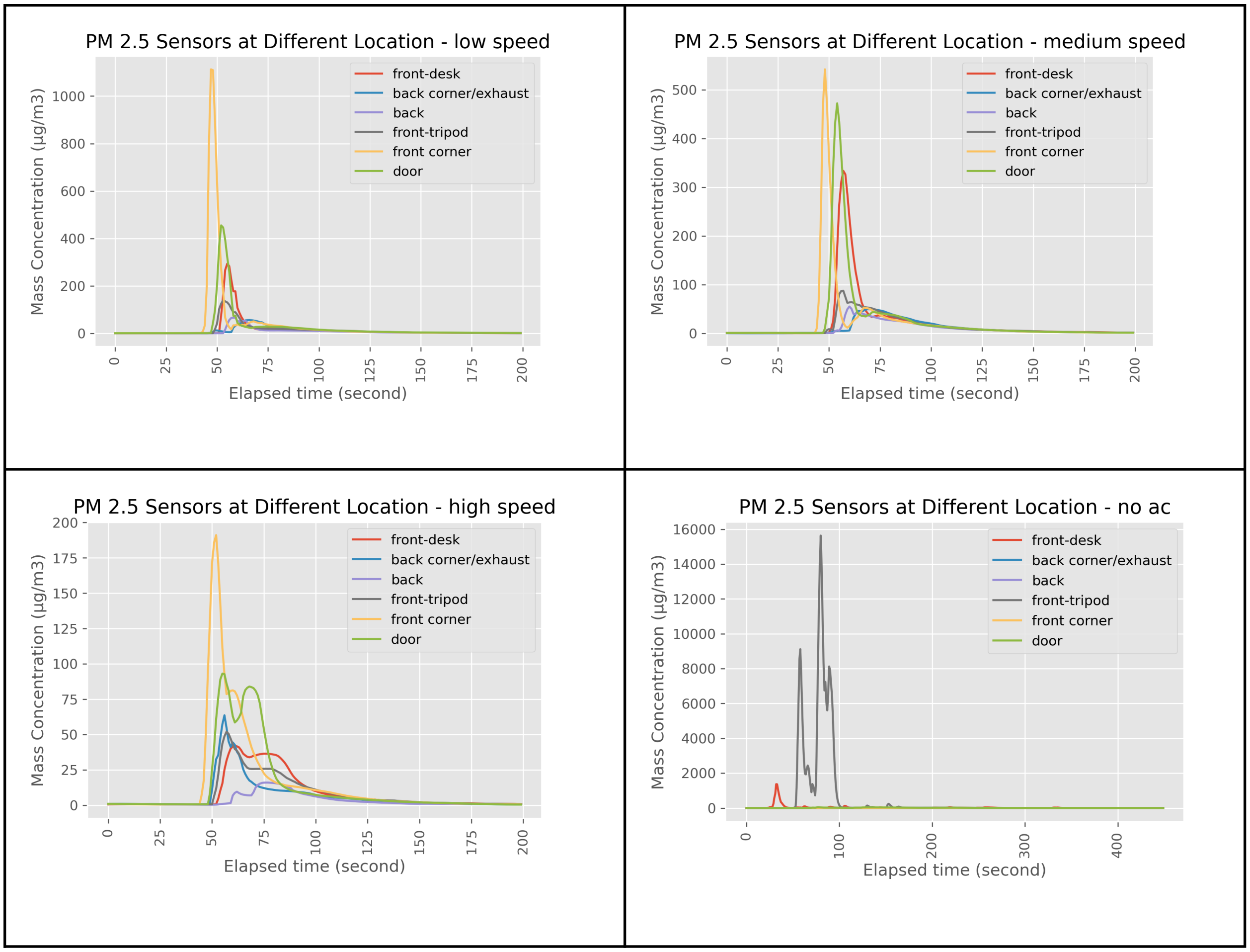


Figure 5: PM 2.5 Sensors at different locations and the corresponding elapsed time's mass concentrations

To better illustrate these differences, we used a log scale graph and an aerosol concentration at exhaust location graph for comparison. Our findings indicated that in the absence of air conditioning, aerosols tend to persist in a room for a longer time and disperse at a slower rate than when the fan is turned on. Additionally, under high-speed fan settings, the aerosol concentration was lower and dispersed faster than under low-speed settings. These observations suggest that the air exchange rate in the room plays a critical role in the changes in aerosol concentration.

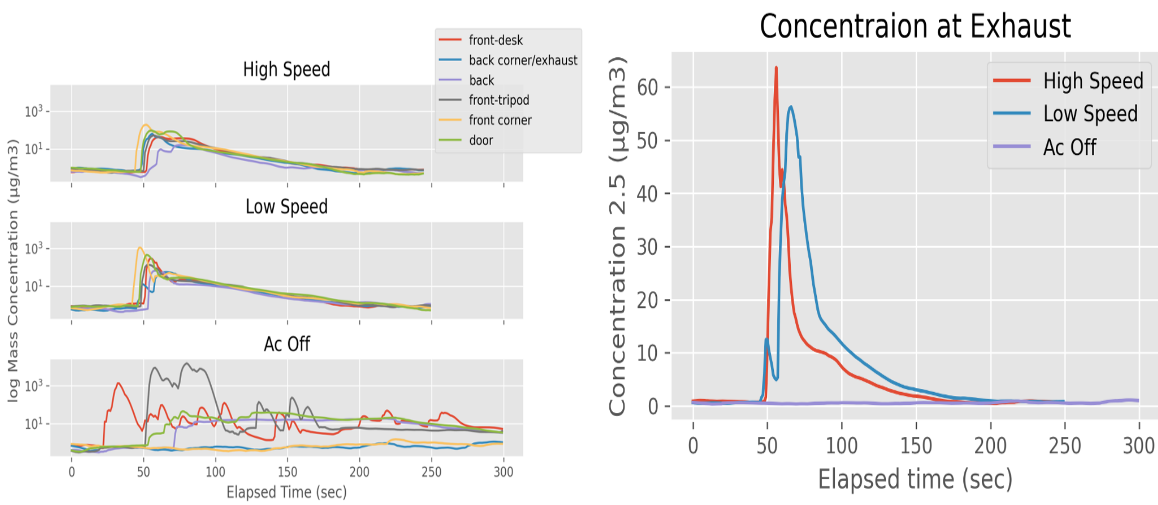


Figure 6: corresponding elapsed time's mass concentrations

Along with experiments conducted under different fan speed settings, we explored the impact of room conditions on aerosol dispersion during a cough event. Three different room conditions were tested: leaving the door open, keeping the door closed, and closing the door during the cough event and opening it afterward.

Our analysis revealed that air flow plays a critical role in the changes in aerosol concentration. When the door was open, the aerosol concentration was significantly lower than when the door was closed, indicating that the exchange of air with the surrounding environment can help reduce aerosol concentration in the room. Conversely, the resident time for aerosols was longer in enclosed environments.

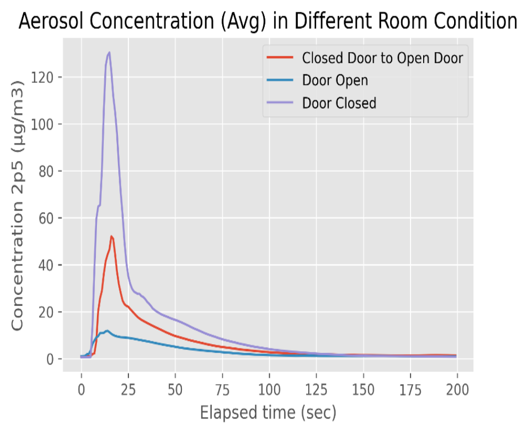


Figure 7: concentration measured for aerosol concentration in different room condition for time elapse

These observations highlight the importance of considering room conditions, such as ventilation and air flow, when developing models to forecast aerosol concentration in different settings. By taking into account the influence of room conditions, we can develop more accurate models and better understand the factors affecting aerosol dispersion.

Modeling and Simulation

1. Compartment model

To forecast aerosol concentration, we utilized two compartment models with one sub-compartment. We solved the equation of aerosol concentration in both the perfectly mixed parent compartment (C_p) and subcompartment C_s over time. However, for the sake of simplicity, we neglected the sinks (settling) factor and focused solely on the aerosol concentration in the parent compartment (Perez).

Variables	Description	
V_P	Volume of parent compartment	
V_s	Volume of sub-compartment	

Q	Room air exchange rate
m	Aerosol mass generation rate (source)
C_p	Aerosol concentration in the perfectly mixed parent compartment
C_s	Aerosol concentration in the perfectly mixed sub-compartment
t	Time
α	Compartment coupling coefficient

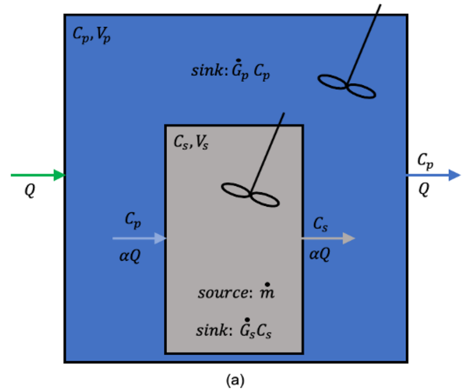


Figure 8: compartment model as graph

$$V_p \frac{dC_p}{dt} = -QC_p + \alpha Q(C_s - C_p)$$

$$V_s \frac{dC_s}{dt} = \alpha Q(C_p - C_s) + m$$

(Perez)

Software Simulation

Based on the mentor’s advice, we looked into various third-party software that is capable of performing computational fluid dynamics. The primary objective of using such software is to cross-validate the data collected from the particulate matter sensors (PM sensor) as well as potentially generating extra data for model training purposes. The software that we eventually decided to use is Ansys Discovery because it is relatively easy to configure, and the simulation result is quite straightforward. The diagram below shows a very basic simulated scene where one air vent is set up on one side of the wall (represented by the small square at the origin of the air flows) and the aerosol movement across the surfaces of the room. The scene gives our group some expectation of the software’s capabilities. Based on its ability to reflect fluid dynamics in an enclosed environment, the software could also provide guidance on where to place the PM sensors for more accurate readings during data collection.

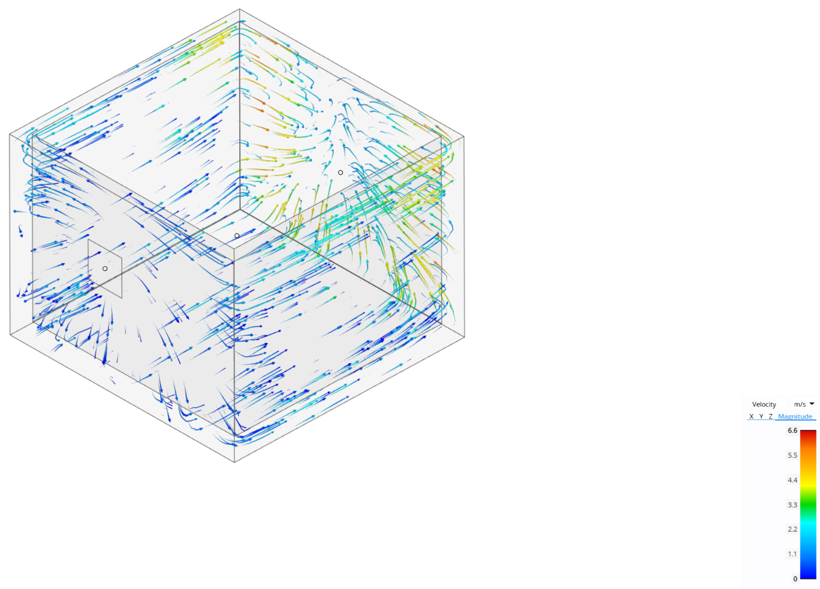


Figure 9: simulated scene

After getting used to the software, we tested the compatibility between the environment information collected from LiDAR and the modeling feature in the software. It turned out that by scanning around the room, the resulting model can be imported into Ansys Discovery directly, which saves the trouble of constructing the room from scratch. The scanned model is nearly perfect, despite the tessellation levels being slightly too high. To prepare the models, Ansys SpaceClaim is used to merge independent surfaces into solids and remove extra edges. The repaired geometry is shown in the figure below.

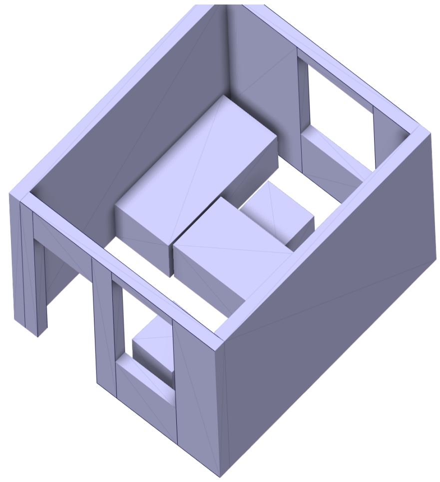


Figure 10: example of a prepared geometry (UC 302)

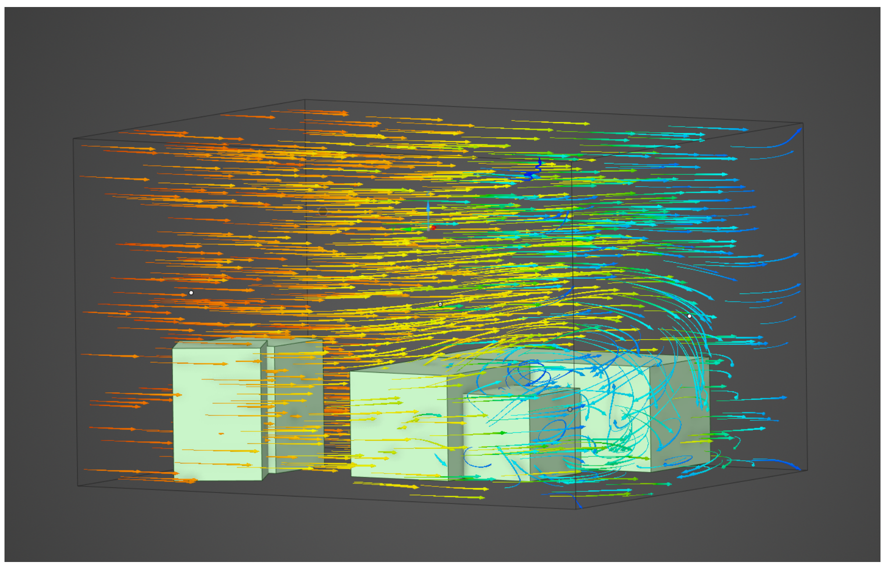


Figure 11: general airflow simulation

After some trial and error, we were able to replace the original walls with an abstract enclosure (filled with air) around the furniture in the room and assess the possible airflows in the room. From the figure above, it is obvious that when a series of normal airflow currents goes through the enclosed space from one side to the other, the air current is disrupted by the other side of the room as well as the furniture. As a result, the airflows form vortexes in which aerosols would be hanging around, increasing aerosol concentration temporarily in parts of the enclosed environment. The simulation serves as an extra data source for the group to verify that the sensor setups are correctly capturing the minute differences at various spots.

However, due to our limited knowledge of computational fluid dynamics, some parameters such as surface heat convection and boundary conditions still need further work and improvements before performing high-fidelity coughing simulations. The group has also been consulting Dr. Andres Tejada, a professional in CFD simulation from USF, to continue making progress over this topic. As of right now, the software simulation is a great baseline to visualize the possible airflow conditions in the room and validate our data collection process.

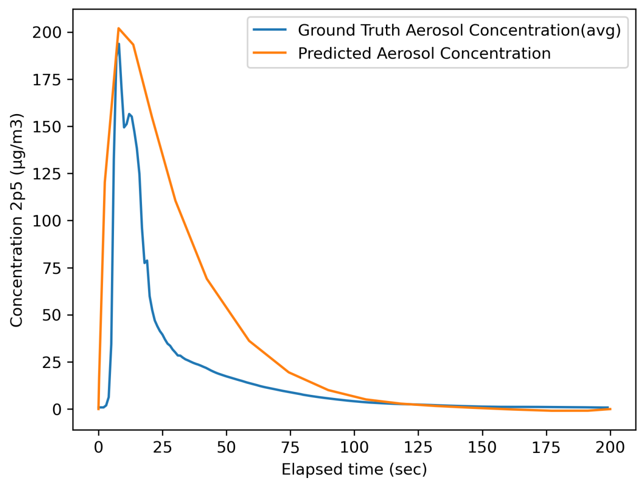
Results

1. **Model Prediction**

Our predictions of aerosol concentration are heavily influenced by the air exchange rate (Q) and compartment coupling coefficient (α). After researching common air exchange rates for different room settings (as listed on The Engineering Toolbox website) and conducting multiple trials and errors on the coefficient, we were able to determine the best-fit model with varying parameters under different fan speed settings.

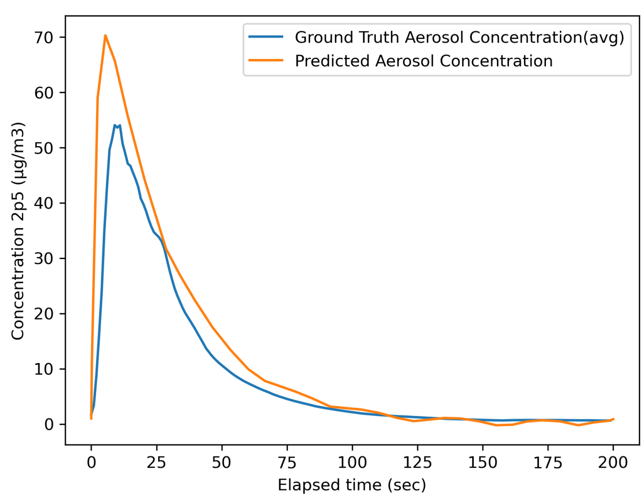
Subcompartment Number	**1**
V_P	**26.5**
V_s	**26**
Q	**4**
α	**0.4**
Initial C_p	**0**
Initial C_s	**0**
Aerosol mass generation rate	**500**

Prediction of aerosol concentration at low fan speed setting



Subcompartment Number	**1**
V_P	**26.5**
V_s	**26**
Q	**13**
α	**0.05**
Initial C_p	**0**
Initial C_s	**0**
Aerosol mass generation rate	**500**

Prediction of aerosol concentration at high fan speed setting



<table>
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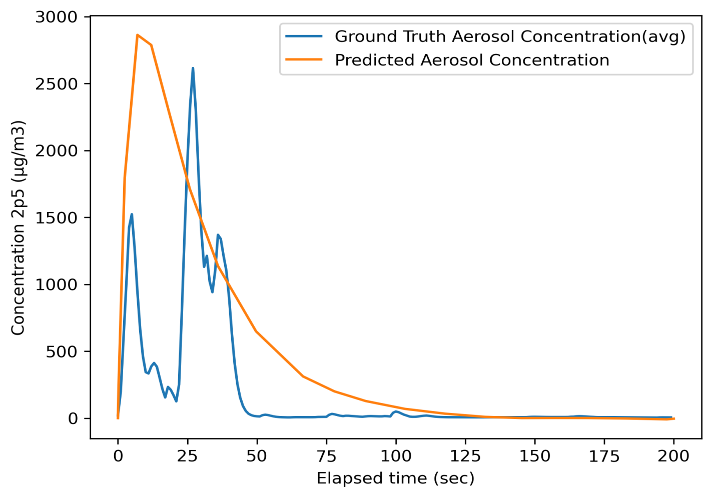
</td></tr>
<tr><td>V_P</td><td>26.5</td></tr>
<tr><td>V_s</td><td>26</td></tr>
<tr><td>Q</td><td>3</td></tr>
<tr><td>α</td><td>0.8</td></tr>
<tr><td>Initial C_p</td><td>0</td></tr>
<tr><td>Initial C_s</td><td>0</td></tr>
<tr><td>Aerosol mass generation rate</td><td>500</td></tr>
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Conclusion / Discussion

For this Capstone project, we developed models using measured sensor data and simulation data to develop robust models to predict aerosol resident time, and also performed experiments on human subjects to improve the model's accuracy in incorporating sound labels and subject movement. As for the graph part, we need a better way to determine the value of alpha and the air exchange rate instead of manually tuning parameters in the future.

References

[1] Rahman, Tauhidur. *Modeling indoor Air quality and Aerosol Transport with Simulation Digital Twins*, 2022. University of California, San Diego.

[2] The Engineering Toolbox. Air Change Rates in Typical Rooms and Buildings. https://www.engineeringtoolbox.com/air-change-rate-room-d_867.html

[3] A Perez, J Penaloza Gutierrez, A Tejada-Martinez. *APS Division of Fluid Dynamics Meeting Abstracts, 2021. Two-compartment modeling of a hospital isolation room informed by CFD*

[4] George Zhou, Garrett W. Burnett, Ronak S. Shah, Cheuk Yin Lai, Daniel Katz, and Eric A. Fried. *Development of an Easily Reproducible Cough Simulator With Droplets and Aerosols for Rapidly Testing Novel Personal Protective Equipment. Simulation in Healthcare: The Journal of the Society for Simulation in Healthcare*, Publish Ahead of Print, March 2022