Designing and Simulating a Smart SARS-CoV-2 Air Purifier

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Abstract—The airborne nature of COVID-19 transmission has rendered indoor gatherings particularly risky due to the concentrated airflow in areas both with and without heating, ventilation, and air conditioning (HVAC) systems. This paper proposes a compact, smart air purification module meant to create isolated pockets of air for separate groups around tables. Multiple techniques for killing the SARS-CoV-2 virus were considered for the module, and it was decided that a High Efficiency Particulate Air (HEPA) filter would be used to capture the aerosolized virus and a ultraviolet C light-emitting diode (UVC LED) would be used to routinely clean said filter. This module’s structure was outlined using Computer Aided Design (CAD), its Internet of Things (IoT) networking capabilities were designed using microcontrollers and a mobile application, and its potential impact was modeled using computational fluid dynamics (CFD). The module was found to prevent contaminated air from spreading between tables in spaces both with and without HVAC systems.

I. INTRODUCTION

In July 2020, the Center for Disease Control (CDC) published an investigation which traced an early outbreak of COVID-19 back to a restaurant in Guangzhou, China, and concluded that the air conditioning system of the building enabled the micro-droplet, or aerosol, transmission of the virus between table groups (Fig. 1) [1]. In response to this and similar events, the World Health Organization has acknowledged the potentially airborne transmission of SARS-CoV-2 [2]. These developments have helped solidify a general consensus among experts that HVAC systems, although safer than a lack thereof, can still contribute to airborne transmission of SARS-CoV-2 due to their large-scale manipulation of airflow [3].

This project sets out to design an air purification module which, if used in a distributed manner, can address the transmission risk posed by HVAC systems in public indoor areas.

Fig. 1. CDC sketch of the Guangzhou restaurant where a COVID-19 outbreak is believed to have originated in early 2020 [1].

The costs, energy consumption, size constraints, and structures of potential air purifier designs are considered in selecting one of the potential disinfection methods. Upon selection of a method, the electronics and networking capabilities of the module are framed out, and the airflow of the model is experimentally examined using CFD simulation to determine the impact of the module in the presence of people as well as HVAC systems.
II. BACKGROUND

A. Copper

The reason for copper’s historically well-known antimicrobial properties is because of its electron configuration. Copper contains a lone valence electron which enables it to easily participate in several oxidation-reduction reactions that are harmful to cellular molecules [4]. When coming into contact with a microbe, copper releases highly reactive ions that seek and puncture cell membranes and viral coatings, targeting DNA and RNA to prevent mutations and render microbes inactive [5]. Modern applications of antimicrobial copper include high-traffic touch surfaces such as doorknobs, often used in high-risk settings such as hospitals [4]. More recently, copper has been tested as a possible face mask component against SARS-CoV-2 [6]. However, it was concluded that copper was not a viable solution because copper requires four hours of continuous contact to inactivate SARS-CoV-2, and is therefore less effective for aerosol uses. Existing face masks that incorporate copper-infused woven fabric lack antiviral effectiveness because copper air filters are incapable of capturing all viral particles. The finest copper filters available have a pore size of 100nm [7], and SARS-CoV-2 ranges from 60-140nm in size [8] [9] [10].

B. Nickel Foam

SARS-CoV-2, as a microbe, is susceptible to temperature variation [11]. At temperatures significantly above 70°C, SARS-CoV-2 inactivates almost instantly. Specifically, the virus’ membrane protein is particularly susceptible to thermal aggregation [12], and its nucleocapsid protein has low stability and fully denatures at 55°C [13]. These proteins are essential for viral function, rendering SARS-CoV-2 more vulnerable to high temperatures than other coronaviruses.

Recently, a heated air disinfection system based upon nickel foam filters electrically heated to 200°C was developed by Houston researchers [14]. This catch-and-kill system eliminates 99.8% of aerosolized SARS-CoV-2 viral load in a single pass through the filter. Surprisingly, the heated nickel filters do not significantly affect ambient temperature. However, a 20mm x 250mm x 1.6mm strip of nickel foam requires 480W to reach 200°C [11]. Batteries able to provide that wattage for extended periods of time are too large for use in a portable air purifier. Therefore, while mobile air purification devices were mentioned as a possible future application [11], it was concluded that heated nickel filters would likely be more effective when integrated into centralized air purification systems.

C. UV Light

Ultraviolet radiation damages the genome of viruses such as SARS-CoV-2 by breaking bonds and forming photodimeric lesions in ribonucleic acids, preventing transcription and replication [15]. Other viral components, including proteins, are also impaired by ultraviolet radiation, rendering the virus inactive due to its inability to complete essential biological functions such as attachment and penetration [16]. Four proteins constitute the structure of SARS-CoV-2, without which viral structure is lost [16]. The germicidal range for ultraviolet radiation ranges from 200-300nm, with peak effectiveness around 265nm [17]. This wavelength falls within the range for UVC, a form of ultraviolet radiation that does not produce harmful ozone [18].

Ultraviolet C is incredibly dangerous to humans because of its short wavelength compared to other forms of ultraviolet radiation, possibly causing acute photokeratitis, premature skin aging, and cancer. However, UVC is easily absorbed by plastics and other materials. With proper measures, UVC can be used safely within close proximity to humans while preventing harmful exposure [19]. A UVC dose of 1.5J/cm² was determined to be an effective method of sterilizing N95 respirators that were inoculated with SARS-CoV-2 [20]. UVC radiation can be artificially produced with light emitting diodes (LEDs). Therefore, it was concluded that because UVC LEDs are smaller and more energy efficient, they are ideal for portable use in the module [17].

D. Computational Fluid Dynamics

Due to limitations on computational power and access to software, the simulation of the air purification module’s external airflow was confined to static, 2D graphs in Python, enabled with the NumPy and Matplotlib libraries. The simulations are based on a 2D version of the Navier-Stokes fluid equations for an incompressible fluid. In every time step, three second-order differential equations were considered: two governing the velocity components and one governing pressure. The equations read as such:

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \\
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) \\
\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} = -\rho \left( \frac{\partial u}{\partial x} \frac{\partial u}{\partial x} + 2 \frac{\partial u}{\partial y} \frac{\partial v}{\partial y} + \frac{\partial v}{\partial y} \frac{\partial v}{\partial y} \right)
\]

where \(x\) is horizontal position, \(y\) is vertical position, \(u\) is \(x\)-velocity, \(v\) is \(y\)-velocity, and \(\rho\) is density [21].

These equations arise from the application of Newton’s Second and Third Laws to arbitrarily small cells of fluid. The model accounts for force due to pressure gradient and viscosity [21]. Gravity was deemed negligible.

These equations were discretized in Python, using 0.001s time steps and a 10,000 cell grid, and the final result of the simulation is a list showing the corresponding \(u\), \(v\), and \(p\) for each cell of fluid at a specific point in time. The plots of this data were visualized in two different formats (Fig. 2). In order to define boundaries in this space, a set of points were picked out and set at zero velocity at all time steps.
The airflow from the module’s fan was modeled using a permanent upward velocity at a given point, which would proceed to create a pressure gradient and mimic the upward fan flow characteristic of the proposed module. The speed (v) of the air coming out the fan was set to 1.59 m/s. This speed was found using the following equation:

\[ v = \frac{CFM}{\pi r^2} \]

where CFM is cubic feet of air per minute moved by the fan 0.01m³/s and \( r \) is the radius of the fan 0.046m. This information was known from the design specifications of the purchased fan [27].

![Fig. 2. Vector field visualization (left) shows the magnitude and direction of velocity at each point. The streamplot (right) connects the vectors to show larger scale airflow (at the expense of showing relative magnitudes). Both plots use color to denote pressure differences (pressure bar not shown).](image)

III. METHODOLOGY

A. Implementing the COVID-treatment Method

While ultraviolet C radiation can kill aerosolized SARS-CoV-2 particles, it requires a duration of exposure that is difficult to provide when air is quickly flowing past the irradiated area. With a fan flow rate of 0.63m³/min and an internal volume of 0.00182m³, air would remain within the module for only 0.173s. Furthermore, microorganisms, when exposed to UVC irradiation, will be killed or decreased in population at a rate according to a first order equation [23]:

\[ S(t) = e^{-kt} \]

where \( k \) is the standard rate constant (cm²/µJ), \( I \) is the UV intensity (µW/cm²), and \( t \) is the time of exposure (s).

The rate constant \( k \) is unique to each microorganism and defines its sensitivity to UVC radiation. The rate constant for SARS-CoV-2 is highly inconsistent in recently published literature as it is highly dependent on various factors such as inoculum size and culture medium [24]. From the equation, it is known that \( t \) has an inverse exponential relationship with \( S \). Increasing the time of exposure to UVC radiation decreases the microbial population. \( I \) also has an inverse exponential relationship with \( S \). Increasing the UVC intensity by raising the LED wattage decreases the microbial population. Because of battery limitations, increasing the LED wattage is unviable.

Therefore, increasing exposure time is necessary to significantly decrease the SARS-CoV-2 population passing through the module. Increasing exposure time can be accomplished by trapping aerosolized viral particles in the module while the remaining air passes through. As aforementioned, HEPA filters can capture over 99.99% of particles the size of SARS-CoV-2 [26]. By shining the UVC LED on a HEPA filter, viral particles can remain irradiated indefinitely. SARS-CoV-2 has a D90 dose of 0.00123J/cm² [26], meaning that 90% of SARS-CoV-2 is inactivated in 0.0889s of 1W UVC exposure. However, significantly higher doses of UVC radiation are required to guarantee air safety. While the minimum infectious dose of SARS-CoV-2 is still unknown, it is predicted to be very low due to the virus’ high infectiousness, with some experts estimating that as few as 1000 viral particles are enough to cause infection. Because a single cough or sneeze can release up to 200,000,000 SARS-CoV-2 viral particles into the environment [28], far higher levels of viral population reduction are required to guarantee that the filter does not output infectious doses of viral particles. UVC radiation at the dose of 1.5J/cm² has been proven to fully decontaminate N95 respirators [29]. These respirators have similar material, structure, and function to HEPA filters. Therefore it was concluded that for full decontamination of an 8.5cm x 8.5cm HEPA filter with a 1.5J/cm² dose, a 1W UVC LED must radiate for 108.375s.

B. Module Designs and Evaluation

1) CAD Design: The technical specifications of each custom component can be found in the Appendix.

Computer Aided Design (CAD) is a process involving computerized software to design, develop, and document a product. SolidWorks is a CAD software primarily used in the engineering industry and was utilized for this project to design and model the product’s structure. This software was used for the creation of an external shell and internal components that were critical to the structure of the product, and made it possible to create a final image of the product’s design with all components assembled. The use of CAD also allowed for animations and seeing moving parts prior to construction, making it easy to identify design flaws. The outer shell, fan, filter, and UVC light were designed in separate SolidWorks files, then combined into one assembly. Using technical drawings from NBM Technologies [27], the design for the fan was replicated in SolidWorks to create a realistic and to-scale model of the product.

The fan’s blades are 31.66mm long and the inner hub has a radius of 38.35mm (Figure 20). The fan casing has an outer dimension of 100mm and an inner blade insert with a radius 95.23mm (Figure 21). Both components were created in separate parts and then combined into an assembly, using the inner hub as the main point for the rotational mate. The fan and casing are plastic parts, making them lightweight, but still able to create a strong air current.

The UVC LED light was also replicated using dimensions from an online retailer [31]. It has a light of radius 2.1mm
and an inner shape of 14.37mm (Figure 22). An polygon shape was extruded and half circles were cut out to create the overall LED shape.

The filter was modeled off a HEPA filter design [22]. The shell of the filter is 100mm wide and 16mm thick. Each vent is 16.32mm wide and was cut through the entire surface of the filter (Figure 23).

To ensure accurate dimensions for the electronics, part files for the ESP32, L298N, and Single Channel Relay Board were downloaded from GrabCad [32][33][34]. As purchased parts, the dimensions needed to be exact to be compatible with the other components. The battery holders were each created using an extrusion of 11.43mm x 27.94mm x 25.40mm and contain the 12V Duracell Battery.

The outer shell was modeled last, as it contained the components of the entire product. The shell has external dimensions of 110mm x 110mm and internal dimensions of 100mm x 100mm. An extrusion of 200mm was made for the overall height of the module, with an inner cut 185mm tall to create hollow space for the other components. The bottom of the module has circular patterns of cut holes with radii of 2mm (Figure 24). These holes allow for air to be taken into the module and directed towards the filter. Consequently, there are cut extrusion vents at the very top and sides of the module for purified particles to be redistributed into the environment. The shell was made out of plastic, making it lightweight and also protecting it from the UVC light exposure.

After the individual parts were created, they were constructed into a SolidWorks assembly. Each part was precisely dimensioned in order for the entire structure to be visualized as realistically as possible. The positioning of the parts was also critical to the realistic appearance of the model. The ideal positioning of the UVC was at the base of the module to allow for the cone of light to get full reach on the filter. Figure 7 shows the cone of light produced by the LED. In order for the light to reach all parts of the filter, there is 35mm of space between the top of the LED and the bottom of the filter. Using reference geometry and concentric mates, the LED was placed on the base of the shell and the filter was placed exactly 35mm above.

The UVC required its own ESP32, Single Channel Relay Board, and battery. The Single Channel Relay Board was chosen because of its compatibility with the UVC. For this reason, these components were attached to the base on the same plane as the UVC itself. The close proximity allows for easy wire management, and the electronics will get cooled from the proximity to the fan.

The fan assembly was placed 31mm away from the top of the filter using reference geometry and concentric mates. The positioning was close to the filter and would be able to carry the purified air particles through the vents. Similar to the UVC, the fan required its own set of electronics: in this
case an ESP32, L298N, and battery. The L298N was chosen because of its compatibility with the fan. These components were attached above the fan to allow for easy wiring access and would also be cooled from the proximity to the fan.

Figure 9 shows an exploded view of the complete assembly, with the components aligned at their respective height locations in the module.

2) Integrating Parts and Electronics: The entire module design consists of one fan, one fan motor, one HEPA filter, one UVC LED, two batteries, two microcontrollers, one motor driver, one electromagnetic relay, and one outer shell.

As airflow is essential to the effectiveness of a filter, a commercial axial fan was selected in order to provide airflow. The fan selected included both fan blades and a motor [27] and is about 80mm x 80mm x 15mm. Although many household fans are powered using an AC current, a fan that could be powered with a DC current was chosen in order to maintain the viability of the module as a portable item.

For the axial fan’s power, which was 12V, a 12V commercial battery was selected [35].

The same 12V commercial battery [35] was chosen to power the two microcontrollers [48, 39, 40] and the UVC light [31] within the module design.

C. Smart Functionality

The core of the smart system lies in a Wi-Fi controlled IoT network amongst every device that can be controlled remotely with a mobile application. An application was designed for Android devices using MIT App Inventor and would allow business staff to control two features of each device across the location within 1km range: (1) the power state of the fan movement and (2) the power state of the UVC Light. This feature is shown in Figure 11, where each table has an on and off switch for the fan and the UVC light. The application utilizes the MIT Connectivity Feature to communicate with the ESP32.

1) IoT Scheme for Fan: The ESP32 (a microcontroller with integrated Wi-Fi and Bluetooth capabilities) is the core of the IoT Connection and contains the downloaded Arduino code, which the application controls through web connectivity to the ESP32’s IP Address. As shown in Fig. 12, When the ESP32 receives the signal from the app, it would output a PWM pulse to L298N to drive the DC fan, activating the full filtration function. The ESP32 and the L298N motor driver are connected to a stabilized battery source.

2) IoT Scheme for UVC LED: Here, a separate ESP32, with the downloaded Arduino data and code, is the core of this UVC LED IoT system. The application activates the ESP32 through web connectivity to its IP address, allowing the business owner to turn on the UVC light to clean the filter at any time. The ESP32 is then able to connect and turn off the UVC bulb through the Electromagnetic 5V Relay (shown in Fig. 13). The ESP32 and the UVC bulb are connected to a stabilized battery power source.
D. Airflow Modeling

These simulations were concerned with demonstrating the capabilities and limitations of the module in regards to filtering particulate air and creating safe airflow, both on a table level and a broader room level. For the purposes of evaluation, this section considers a simple, virtual indoor restaurant, consisting of four tables. Each table surface is a circle with a one-meter diameter, and the tables are in a square formation, where the tables, end-to-end, are 2m apart, in keeping with lower-risk indoor dining suggestions by the CDC (see Fig. 14 for more details) [30].

1) General Particulate Air Filtration: The main purpose of the module is not its particulate air filtration of large spaces. This expectation was explored by calculating the air changes per hour, or ACH, of the module in the theoretical room. ACH is calculated as follows:

\[
ACH = \frac{CFM \times 60}{V}
\]

where \( CFM \) is cubic feet per minute moved by the fan, and \( V \) is the volume of the room [30]. \( CFM \) was obtained from the fan information sheet to be 22.25\( \text{ft}^3/\text{min} \), and volume was 90\( \text{m}^3 \) [27].

It was found that four of the modules in the room with no other air conditioning system would have an ACH of about 1.7, less than the general benchmark of 4 for ACH in commercial buildings and well below the 10 to 15 range for cafeteria areas [43, 44]. As such, the module should be used in tandem with an HVAC system to ensure maximum air quality. The module is not a substitute but rather a supplement for a full ventilation system, and the supplemental value is due to the localized way it moves air around a table environment.

2) Airflow Around a Table: With an airborne disease like COVID-19, human breath, in the form of coughing, sneezing, or exhalation, is the vector that must be quickly and effectively treated in order to fight transmission. No matter how high its CFM or ACH, a large HVAC system will spread this vector around a room, as seen in Guangzhou, and possibly recirculate it to other parts of the building. The proposed module on a table, however, can simplify this issue by creating a localized, cyclical airflow around a table.

A simulation was made which monitored the airflow between the module and a breathing person sitting at the table (Fig. 15).

\[
u = 2.2\sin\left(\frac{2\pi t}{3000}\right)
\]

where \( u \) is the speed of the person’s breath (all horizontal), and \( t \) is the time in milliseconds. Note how the function models the maximum speed of breath as 2.2m/s and the period of breathing as 3s. These numbers fall well into the observed ranges of human breath behavior [36].
Both the inhale and the exhale led to slight disruptions in the module’s airflow, but ultimately they fit into the cyclical model of the purifier. Freshly cleaned air was taken in on the inhale, and possibly contaminated air was immediately directed to the module to be disinfected (Fig. 16).

The sneeze experiment was run under two conditions: one with the module, and one without. The sneeze was modeled to have a speed of 6m/s for 0.4s, which was an intended overestimation of both the speed and duration of a real sneeze [37]. Without the module, the sneeze propagated quickly and blew contaminated air to the other end of the table and beyond (Fig. 17 top). After the sneeze ended at \( t = 0.4s \), the contaminated air entered a stable cyclical flow due to the unrealistically isolated nature of the experiment (Fig. 17 bottom). In real life, the sneeze would diffuse faster and farther, especially with the help of background HVAC currents, and thus possibly spread germs to other tables.

With the module in place, the airflow was disrupted by the sneeze but quickly stabilized by the steady airflow pattern of the purifier. After the sneeze ended, the overall airflow appeared rotated counterclockwise (Fig. 18 top), but quickly stabilized such that \( t = 1.0s \) (Fig. 18 bottom) looked like the control situation. This simulation cannot rule as to whether all sneeze particles were caught by the purifier, but compared to the no-module scenario, there is quick localization of airflow, which would ostensibly reduce risk.

These two simulations together provide a proof-of-concept for how this module can isolate airflow around a table and quickly treat human breath in response to both a normal breathing pattern and a sneeze situation.
3) Airflow with Background AC: The second simulation considered the airflow of a vertical cross section of the room along two tables and too opposite AC vents. The goal was to visualize the airflow between the two tables and how it changes in the presence of the AC. The AC is modeled as a velocity inlet on one end and a velocity outlet on the other, and the speed of it is set at 3m/s, which is characteristic of maximum airflow in low to medium loss ducts \[35\].

It was found that the airflow of the modules was heavily distorted with the AC at 3m/s, although the airflow differs heavily between the placement of the vents (Fig. 19). The distortion was reduced but not fully eliminated with slower AC speeds, which were tested down to a fairly unrealistic 1:1 ratio between module speed and vent speed.

Fig. 19. Airflow with module on and AC flow entering and exiting. Top shows both vents near the floor, bottom shows outlet vent near the ceiling.

Human models were then placed at each table in different configurations, with different ventilation structures and inhalation and exhalation speeds, and the air currents were tracked. In all situations where the filter was implemented, the air from a person’s breath was quickly brought to their corresponding filter, and no clear line of transmission along the streamplot was identified (Fig. 20). Tracing the streamplot was deemed an effective way of determining a viable line of transmission since, over time, the streamplot lines tended to stay fairly consistent over time. While not entirely true to the dynamic nature of airflow, this method presumably offered a decent idea of where air, and thus potential SARS-CoV-2 aerosols, could go in future moments.

Ultimately, despite the distortion caused by the HVAC system, it was found that the airflow between tables was still largely isolated and thus the transmission risk was ostensibly reduced. The ultimate success of the module demonstrates how the air purifier and an AC system can coexist and manage to maintain a balance between high ACH and localized air purification.

4) Limitations: By looking at simple geometries in 2D, these simulations make numerous simplifications about real-life airflow. However, due to the symmetry of tables and the airflow current that the purifier creates, the patterns observed in the 2D cross sections can provide a general overview of what happens in 3D. As such, these simulations, while imperfect, still provide a valid proof-of-concept for the module’s abilities to create isolated airflow around tables.

E. Conclusions and Future Directions

By isolating and decontaminating the air both around and between tables, the proposed module has the potential to make a safer environment for indoor areas with groups of people around tables, such as dining areas, schools, and offices. If used on a large enough scale, this module could significantly aid public health initiatives around the world as quarantine restrictions are relaxed and public life is resumed.

Further development of this module would include creating and testing a physical prototype of the air purifier, first as an individual module and then as part of a larger network of modules in an entire building. Once the module is ready for large-scale production, the manufacturing process would be assessed and optimized to ensure cost-efficiency and quality.

In order to more accurately quantify and visualize the module’s impact, 3D CFD with more true-to-life geometries would be simulated in varying situations. Such experiments could track a cloud of SARS-CoV-2 aerosol particles from an infected person and more precisely quantify where they go in situations with and without the module. Using some approximations, these results could feed into a larger disease model to show how many cases this technology could reduce over an extended period of time. Other analyses could exist on a smaller scale and examine the internal airflow of the module and how that affects its external presence.
Furthermore, the application UI would be improved beyond the prototyping software of MIT App Inventor to contain interactive visuals, like dining tables. Additionally, the application could be expanded into other platforms beyond Android, such as Apple iOS application or web domain. The application could also include in-application data reports and tracking of device, energy usage, and possibly air flow analysis. Ultimately, the further vision for this project revolves around developing a professional, industry standard application to control these devices and offer maximal accessibility and smart functionality for the user.

APPENDIX

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