A Potential Solution for Solid Particulate Matter Reduction in Large Indoor Spaces

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Abstract. Air filtration is an essential process in indoor air conditioning and its physical removal of particulate matter is critical for enhancing indoor air quality, especially in arid regions including United Arab Emirates. In such regions, meeting indoor air quality standard is challenging during sporadic sandstorms when common air conditioning systems are unable to maintain indoor air quality properly. Such inability occurs either due to air infiltration through building’s fenestrations exposing indoor air to excessive particulate matter or the failure of inlet air filters after rapid clogging and high pressure drops. Such failure may be observed frequently in buildings with frequent openings such as public buildings and warehouses. Aerosolized pathogenic microorganisms, e.g., SARS-CoV-2 virus, can be modelled through air particle matter and be removed to a certain degree. In addition, the recent global pandemic raised more awareness towards the necessity of particulate matter filtration in indoor environment. Employing independent air filtration units might be a great solution for intermittent or emergency situations, when primary or additional air filtration process is required to attain proper indoor air quality. The main objective of this paper is to attempt designing, manufacturing, and utilizing an easy to set portable filtration unit and to assist buildings’ existing air conditioning systems in airborne dust particle elimination. The unit is designed and manufactured with additional feature accommodating easy installation of commercially available filters for further performance studies. The unit was equipped with all necessary performance monitoring sensors to detect key parameters such as air velocity, pressure differential, temperature, humidity, and particulate matter before and after filtration. The results revealed interesting information associated with the performance of commercially available filters and the feasibility of such independent filtration units.

1. Introduction

Air quality is studied by examining the concentration of particulates within a specific volume of air. Air quality levels have been on the decline since the start of the industrial revolution, nonetheless, have always been low in arid and desert regions due to sandstorms, seasonal winds, and sand erosion [1]. Large desert areas such as the Sahara Desert and the Empty Quarter Desert in the Arabian Peninsula are the origin of extremely fine dust particles; the main contributor to low ambient air quality levels in the regions [2]. Areas surrounding major deserts suffer greatly from the seasonal winds that carry substantial amounts of dust particulates. The Middle Eastern countries surrounding...
the Empty Quarter Desert have ranked within the top 23 countries with the worst air quality levels globally.

The concentrations of particles smaller or equal 2.5 microns size or smaller or equal 10 microns size are called PM$_{2.5}$ and PM$_{10}$, respectively. PM$_{2.5}$ and PM$_{10}$ were considered the main pollutants in the region with an average air quality index (AQI) of 100; equivalent of 35.4 of PM in air, which is considered unhealthy for sensitive groups [3]. Air quality in industrial zones or in high population density areas such as central hubs only declines due to increased smoke and dust circulation, averaging at an AQI of 107 and peaking at 160 [3]. Exposure to increased levels of particulate matter can lead to serious health problems, affecting Human respiratory and cardiovascular systems. Increased PM count serves as a medium to accommodate the growth and spread of airborne pathogens and viruses that exist at nanoscales [4]. According to recent studies, increased exposure to high PM levels did not only accelerate the spread of SARS-CoV-2 virus, but also contributed in observed mortality rates. The long-term exposure to high PM levels can cause increased damage and inflammation to respiratory organs [5], hence increasing the virus’s spread and mortality rates. High population density districts such as schools, airports, and shopping centers, were the main scope of attention when it came to reducing the spread of the virus and similar airborne pathogens and seasonal flus. Hence, organizations have focused on methods of reducing the PM count within public indoor areas, in order to minimize the spread of pathogens such as the SARS-CoV-2 virus [6]. The Centers of Disease Control and Prevention (CDC) and the United States Environmental Protection Agency (EPA) have both advised using Minimum Efficiency Reporting Value (MERV) above 13 or High-Efficiency Particulate Absorbing (HEPA) filters in public spaces to reduce the spread of viruses and pathogens. Using lower grade filters can be a vital solution to prevent the spread of the virus between different rooms of a facility, through ventilation ducts. Using high grade filters, HEPA filters or MERV 13 and above, with perfect seal, can help prevent pathogen transmission and capture the existing nano-size viruses in the indoor environment, such as the SARS-CoV-2 virus [7].

The average PM$_{2.5}$ concentration in indoor public facilities, such as schools and airports, is about 35.4, between moderate and unhealthy to a certain group [3]. The World Health Organization’s (WHO) ideal PM$_{2.5}$ concentration target for indoor environments varies between 0 to 10, that can be accomplished using HEPA (or MERV grade 13 or above) filters such as in hospitals. Independent air filtration units make great application of HEPA filters for emergency uses. In the event of patient isolation or any other spread of airborne pathogen, independent filtration units are recommended to enhance the air filtration efficiency alongside the fixed Heating, Ventilation, and Air Conditioning (HVAC) system for indoor environment. This method has been proven to be effective for removing and capturing more than 99% of the H1N1 influenza fed into a 28.5-m$^3$ room within 20 minutes [8].

It is noteworthy that Leadership in Energy and Environmental Design (LEED), the dominant green building rating system, has devoted a category of its guideline to Indoor Environment Quality to address wellbeing of indoor environment. LEED version 4.1 requires minimizing the exposure of building occupants, and ventilation and air distribution systems to tobacco smoke having size of 0.1 to 1 micron [9,10]. An affordable and portable independent filtration system can be used in occasions that either indoor air cross contamination or exposure of external ventilation components to intensive particulate matter take place. The credit titled “Enhanced Indoor Air Quality Strategies” provides some strategies that somehow justifies the application of such portable independent filtration. For instance, the recommended permanent entryway systems may require occasional backup of independent portable filtration during sandstorms in desertic regions.

2. Objectives of the current study
The main objective of this paper is to assess the feasibility of airborne dust particle reduction in large indoor areas with a portable filtration unit which can be operated at a low cost and has a low energy consumption rate, without disrupting the indoor activities and mobility. Such a portable unit can be placed inside industrial factories or emergency lodgings with minimal effort and cost to improve the air quality at a relatively large capacity and to diminish the risk of infection via aerosol transmission.
3. Literature review

A standard that provides the tools to examine and compare the air quality is essential in the current work. The Air Quality Index (AQI) is a common indicator used to quantify the level of air pollution. The AQI ranges from 0 to 500 and is divided into 6 sections. Each section encompasses a range of AQI numbers and contains the information on the health risks associated with the corresponding range of air pollution. The AQI number is based on the concentration measurements of five pollutants over a set period of time. These pollutants are nitrogen dioxide, carbon monoxide, ground ozone, sulfur dioxide and particulate matter (especially PM10 and smaller particulates). In the UAE, the AQI readings in indoor areas for PM2.5 and PM10 vary considerably throughout the year [11]. On average, the highest PM readings were recorded during the summer months. During these periods, the PM in indoor spaces may sometimes exceed the maximum allowable concentration, hence, making the indoor environment unhealthy. A long-term study in the UAE suggests that the majority of the particulate matter pollution is produced via natural processes [11]. These include dust emissions and dust storms. The SARS-CoV-2 virus can also be modelled through particle modelling. Recently, many studies have been conducted to predict the movement and distribution of aerosolized SARS-CoV-2 droplets in indoor environments. To achieve this, aerosolized SARS-CoV-2 virus droplets are modelled as particulate matter via various numerical tools [12]. This work is important as it may promote the development of more effective solutions to combat the spread of SARS-CoV-2. The CDC has concluded that increased ventilation and HEPA filtration is effective in combatting the spread of SARS-CoV-2 in enclosed areas [13].

Filters have long been used in HVAC systems to improve air quality. In fixed air-conditioning system applications, such as residential buildings, mechanical filters are commonly used to target and remove particulate matter pollution. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is the global standard used to examine and compare the performance of mechanical air filters. The ASHRAE standard evaluates the performance of filters according to three criteria. These are the arrestance, the atmospheric dust spot efficiency and the dust holding capacity [14]. The MERV number is another important feature of the ASHRAE standard. The MERV provides information on the filter’s efficiency at filtering smaller sized particulates. A low MERV number means that the filter is not very efficient at removing smaller particulates, and a high MERV number means that the filter is very efficient at filtering smaller particulates. For medical applications and aerosolized SARS-CoV-2 droplets, HEPA filters are generally employed [13]. HEPA filters are mechanical filters that are extremely efficient at filtering smaller particulates, to the extent that they cannot be rated according to the ASHRAE MERV scale. One drawback of mechanical air filters is clogging, since the deposited particles in the filter’s fibers increase the flow resistance. Consequently, the pressure drop across the filter increases. Filter clogging can lead to increased energy waste, poorer filtration performance and in extreme cases, filter section failure [15].

Ventilation is another process used (in tandem with filtration) to reduce indoor air pollution. In response to the SARS-CoV-2 pandemic, many countries have proposed new guidelines calling for increased ventilation in buildings and other indoor environments. Consequently, these countries have experienced a significant increase in energy consumption, specifically in the HVAC sector. In China, recent studies have shown that increased ventilation rates have increased energy consumption of HVAC systems by 128% [16]. Through the process of ventilation, indoor air is replaced with outdoor fresh air. Before the outdoor air is introduced to the indoor environment, it must first be filtered, heated or cooled and humidified or dehumidified. Therefore, the thermal load of the HVAC system is increased when the rate of ventilation increases, as a greater volume of air is either heated or cooled. In emergency situations, such as the SARS-CoV-2 pandemic, where the ventilation and energy demands have increased significantly, the corresponding increase in energy consumption may place global energy security at risk [17]. This opens an opportunity for an independent air filtration unit that does not require a substantial thermal load. Such an air filtration unit would be employed in emergency situations while minimizing the ventilation demand.
4. System design and components

The design of this test bench focuses on functionality, efficiency, and practicality. First, a round shape duct is considered since it has the highest efficiency (least resistance) in conveying moving air due to the greatest surface area with a minimum contact surface compared to other duct shapes [18]. Spiralite® is the world’s first energy-efficient ductwork developed in the UAE and the chosen material for this project. It features a pre-insulated sandwich design with a 30-mm thick phenolic board in the middle layer surrounded by reinforced silver foil and continuous airtight aluminum foil-based laminates on the inner and outer layers of the duct, respectively. The circular shape guarantees an ultra-smooth airflow performance, lower static friction and pressure drop, and optimal thermal insulation efficiency compared to Galvanized Iron (GI) ducts available in the market. Other benefits include a class C air leakage at 2500 Pa and over 80% weight reduction over insulated steel ductwork which makes it highly cost-competitive and easy to fabricate and install [19].

The test bench, with the schematic demonstrated in figure 1, is made up of two 1000-mm long duct sections with an inner diameter of 592 mm. A 150-mm filter drawer frame with a thickness of 25 mm, made out of GI for better corrosion resistance, is placed between the two sections. The filters were F5, F6, and F7 grades with a square cross-section of 592 mm by 592 mm and a thickness of 48 and 98 millimeters. At the tail of the duct, a 900-mm long reducing transition section duct is connected to a 10-inch axial exhaust fan. The 2800-RPM fan has a power requirement of 300 W, and delivers a maximum flow rate of 2700 m³/hr with a pressure differential of 295 Pa. The test bench was manufactured at a total cost of 950 USD and the components were selected based on ease of use and installment.

A single-phase electrical supply of 220-240V at 50 Hz frequency was selected to ensure that the test bench works in almost every environment and its speed can easily be controlled later on using a single-phase input-output Variable-Frequency Drive (VFD). Different instruments were installed along the duct for analyzing the airflow. Starting from the inlet, a handheld analog anemometer is installed on the mesh with a resolution of 0.1 m/s and an accuracy of ±5%. On the upstream and downstream sides of the filter, PM, temperature and humidity sensors are installed. Senserion SPS30 PM digital sensor was chosen due to its small size, optical laser measurement principle, and its ability to measure precisely the concentration of a wide range of particular matter sizes from PM 1.0 to PM 10.0. Temperature and humidity were measured by DHT-22 digital sensors. This sensor type can operate reliably in temperatures that range from -40 to 80°C with ±0.5 degrees accuracy, and a humidity range of 0-100% with ±2.5% accuracy. An analog to digital conversion chip in the DHT-22
also ensures that the IO communication protocol can then be used to send the digital signal from the sensor to the microcontroller. Finally, the pressure differential is measured via Senserion SDP810 dP gauge pressure sensor. It features a measurement range of -500 to 500 Pa with a span accuracy of 3% of the reading. One Arduino Mega and 2 Arduino UNO microcontrollers are used for connecting all the sensors to a real-time continuous data acquisition system. The testing process took place in the American University in Dubai’s Fluid Mechanics laboratory. This lab has a large opening gate that provides the opportunity for further experimentation of outdoor environment and an exhaust fume to discharge the injected dust in future.

5. Results and discussion

Figure 2 demonstrates the experimental results for the tested filters with grades F5, F6, and F7, which has two thicknesses of 2 and 4 inches, referred to as F7 (2”), and F7 (4”), respectively. The F5 and F6 filters were tested four times and F7 filters were tested three times, during different days, which explains why the PM2.5 count before the filtration is dissimilar. Each test lasted three hours and the measurements were recorded over 15-minute intervals. Then, the PM counts before and after filtration were obtained from calculating the mean value. The mean temperature and relative humidity in the lab during the tests were 22oC and 50%, respectively. It should be noted that all of the filters except F7 (2”) had a thickness of 4 inches and were able to filter at least 80% of the PM2.5 dust particles. The average reduction of PM2.5 count was 85%, 83%, 60%, and 80% for F5, F6, F7 (2”), and F7 (4”) filters, respectively. Using a 4-inch filter, the air velocity at the inlet was around 1.2 m/s with a pressure differential of 63 Pa, while the manufacturer data approximated it to be around 159 Pa. The difference is due to the fact that the electrical input to the fan was limited to 180 W and the addition of a variable duct diameter increased the minor losses.

6. Conclusions and ongoing work

The main focus of this research was to examine the performance of commercially available air filters using a bench scale air filtration apparatus equipped with required air quality inline sensors. The apparatus was designed, manufactured, and assembled according to the latest energy-efficient technologies and methods. Noise level, air velocity, pressure drop, particulate matter concentration, air temperature and humidity levels were taken into consideration prior to designing the system. The proposed design of the unit would allow an easy filter insertion and replacement with a slide in and out mechanism. Furthermore, most commercial air filters, with a square cross-section of 23.5 inches and a
maximum thickness of 4 inches, can be placed in the drawer and secured firmly to prevent vibration. The air flow rate is about 1555 m$^3$/hr (0.432 m$^3$/s). It is noteworthy that a continuous flow rate of about 0.432 cubic meters per second would mean that the entire air in an indoor space of 23 m by 23 m by 3 m is filtered about once per hour. In addition, it is recommended to supply air ventilation per person at an average rate of 30 m$^3$/hr [20], which means that one single unit of the proposed design can supply filtered air to approximately 50 people in an enclosed area.

Regarding the ongoing work, the aim of this project expands to testing the device for maximum dust accumulation. The further tests would be done by injecting a measured amount of dust particles into the test bench duct under controlled conditions. The tests will be carried out using real dust collected from the air in Dubai, UAE, at an almost constant room temperature and humidity, by conducting the test in the same lab. However, to test the variable PM count present in the atmosphere, the tests should also be conducted in an outdoor environment. A disadvantage of such tests would be the lack of control on the temperature and humidity in the air. Future works also include improving the physical prototype. A stronger fan is needed to be able to overcome the initial pressure drop of the filters and allow for a higher velocity of the air passing through to be attained. Another improvement would be adding a VFD to allow for the speed of the fan to be controlled and test the filters’ performances at different air velocities. A relay system would also be installed to turn off the fan when the filter is clogged to prevent any damages to the equipment. Different types of filters could also be tested such as the HEPA filters.

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