Testing the Efficacy of the 'Corsi-Rosenthal' Box Fan Filter in an Active Classroom Environment

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Abstract

Poor ventilation in classrooms can increase the risk of infectious disease transmission, such as COVID-19, because it allows respiratory aerosol particles that may contain viruses to accumulate. Air purifiers can effectively reduce transmission rates in community spaces, including classrooms, because they increase the air change rate in the room and reduce particle concentrations. In this study, we investigate the effectiveness of Corsi-Rosenthal Boxes (C-R Box) in reducing particle concentrations in active, occupied classroom settings. A C-R Box is a do-it-yourself, cost-effective alternative to commercial air purifiers built from a box fan, four readily available filters, cardboard, and duct tape. We collected measurements of coarse (particles with diameters > 2.5µm) and fine (particles with diameters 0.5µm - 2.5 µm) particle number concentrations and $PM_{2.5}$ (particles with diameter < 2.5µm) mass concentrations. Specifically, we compared measurements in occupied classrooms before and after we turned the C-R Boxes on. In our testing, C-R Boxes reduced fine particle number concentrations by 56-91% and $PM_{2.5}$ mass concentrations by over 70% after we turn on the C-R Boxes. We also simulated velocity profiles in the classrooms with running C-R Boxes showing mixing throughout the classroom ensuring that all air can encounter the filter.

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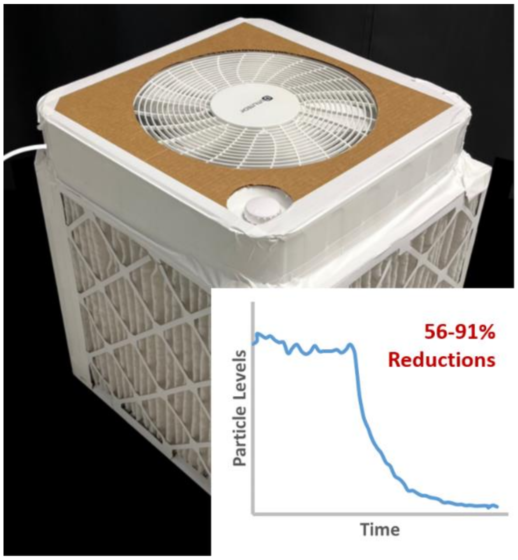

Keywords: COVID-19 transmission, indoor air quality, Corsi-Rosenthal Box, school exposures, air filtration

Synopsis:

We found that Corsi-Rosenthal Boxes lowered the $PM_{2.5}$ mass concentration by >70% and fine particle number concentration by 56-91% in an occupied classroom.

1. Introduction

The COVID-19 pandemic has proven to be a persistent problem that will require a multifaceted approach to solve[1], particularly in the wake of the appearance of newer, more easily transmitted variants of the virus[2–4]. Indoor air quality is highly linked to COVID-19 mitigation as it is primarily spread through respiratory aerosols (particles) dispersed by infected individuals[5–7]. Improved ventilation and air filtration in public, indoor spaces helps mitigate the spread of COVID-19[1,8]. Unfortunately, many schools are in need of updated ventilation which requires substantial budgets and time[9–11].

Indoor air purifiers are a reliable method to supplement insufficient ventilation[1,8]. Commercial high efficiency portable air (HEPA) filters have been shown to increase the air change rates and effectively remove potentially-infectious respiratory particles. When budgets allow, these types of air purifiers offer a possible solution to mitigate COVID-19 transmission in classrooms that cannot meet the recommended air changes per hour. Unfortunately, effective commercial air purifiers can be cost-prohibitive for large-scale deployment in many school districts.

The Corsi-Rosenthal Box (C-R Box) air purifier, pictured in supplemental information (Figure SI.1), is a cost effective, do-it-yourself (DIY) indoor air filter that can provide an increased amount of filtration at a fraction of the cost[12]. This air purifier consists of four 20”x20” MERV-13 (minimum efficiency reporting value - 13) filters, a 20” box fan, a cardboard bottom, a cardboard shroud for the top, and duct tape. The C-R Box can be built with either 1” or 2” thick filters. The thicker filters provide more structural stability for the final C-R Box and potentially longer times between necessary changes. MERV-13 filters are rated to remove at least 50% of particles 0.3-1μm in size, 85% of particles 1.0-3.0μm in size, and 90% of particles 3.0-10.0μm in size[13]. In contrast, HEPA filters are rated to remove at least 99.97% of particles that are 0.3μm in size[14].

The C-R Box has the potential to reduce overall particulate matter (PM) concentration in classrooms, which may lead to decreased infectious disease transmission and improved overall health of children in the classroom. The C-R Box has been shown to work well in laboratory settings and in an empty room[12,15]. Testing of the effectiveness of the C-R Box in an occupied classroom is necessary for full adoption of this potential solution. In this study, we present initial testing of the effectiveness in an occupied university classroom selected to mimic K-12 classroom designs in the Northeastern United States.

2. Materials and Methods

2.1 Standard Classroom Set-up

We tested C-R Boxes in two university classrooms while students were present to evaluate their efficacy under real-world conditions. The building housing the classrooms was built in 1906, was not built with central HVAC, and much of the building still lacks sufficient mechanical HVAC. We selected this building for testing as the classrooms most closely resembled the classrooms in the K-12 schools in the local districts based on size and ventilation. Classroom A had an approximate area and volume of $51m^2$ and $125m^3$, respectively. Classroom B had an approximate area and volume of $96m^2$ and $235m^3$, respectively. Classroom A best represents the size of a typical local K-12 classroom. Figure SI.2, in supplemental information, shows the approximate layout of the classrooms during testing.

2.2 Deviations from the Standard Classroom Set-up

Due to the nature of real world testing, not all tests had exactly the same set-up. Details on all five tests are included in the supplemental information (Table SI.1). Only the final three tests (Tests 1-3) are included in the results discussion below because the initial two tests (Initial Tests A and B) deviated substantially from the standard testing set-up. Specifically, Initial Test A only used one C-R Box on medium speed and the windows were open during the class. The noise from the fan on medium speed disrupted the class environment. Based on this test, we lowered the fan speed and placed two boxes in each classroom. The noise level from the C-R Boxes on low speed did not disrupt the class. Initial Test B used two C-R Boxes but the door to the classroom was left open during the class and both C-R Boxes were placed at the back of the classroom. The differences in the testing set-up in Initial Tests A and B from the other tests interfered with many of the results, as such, we took these as a learning experience and have not included them in our final results discussion below. Initial Test A and B results are available for completeness in the supplemental information. Tests 1-3 all used two C-R Boxes spaced at opposite corners of the classroom. In addition, we had the opportunity to upgrade our C-R Boxes to ones with 2" thick filters between Tests 1 and 2. These wider filters potentially allow for better flow and are more structurally sound than those built with 1" filters (which were used for Initial Tests A and B and Test 1).

2.3 Particle Measurement Approaches

We measured particle concentrations using three Dylos DC1100 Pro air quality monitors and one TSI DustTrak II Aerosol Monitor 8530EP. The Dylos DC1100 Pro measures the particle number concentration of two sizes of particulate matter (PM): fine particles larger than 0.5µm and coarse particles larger than 2.5µm. We used the TSI DustTrak II to measure particle mass concentrations of $PM_{2.5}$ (PM with diameters under 2.5µm) because this particle size range can remain suspended for a significant time and still harbor COVID-19 particles[5]. We zeroed the TSI DustTrak II before each test. We placed the measurement equipment around the perimeter of the classroom and the C-R Boxes in opposite corners (Figure SI.1).

For each test, we began monitoring as the students entered the classroom with the C-R Boxes turned off. About 30 minutes into the class, we turned on the C-R Boxes and ran them until just before the end of the class, typically 30-40 minutes after the C-R Boxes were turned on. We collected all data in one minute increments. We evaluated the data both as a time series and by comparing the average concentration before we turned on the C-R Boxes and the average for the last 5 minutes of class.

2.4 Calculating Air Filtration Rate

We used an anemometer (BTMETER BT-100 Handheld Anemometer) to find the velocity of the air flowing from the top of the C-R Boxes on each speed and averaged these values, excluding the direct center of the fan on the top of the C-R Boxes where there is no positive air flow. We multiplied this by the area, again excluding the center, to obtain a volumetric flow for each speed. From the volumetric flow, we calculated the air filtrations per hour using the volume of each room. This is similar to the air changes per hour except it is the number of times the air will encounter a filter each hour.

2.3 Modeling Air Mixing in the Classroom

We used COMSOL Multiphysics 5.6 to understand the impacts of the C-R Boxes on air flow and circulation in Classroom A. We simulated the classroom with two fans placed in opposite corners of the room similar to Figure SI.2 with the fans as the only obstacles in the room. We have included the specific dimensions used for the classroom and C-R boxes in supplemental information (Table SI.2). We set the volumetric flow rate of the fans to 0.3052 m^3/s. We considered only turbulent flow and used the "algebraic y plus" turbulence model. We assumed that the air in the room was weakly compressible and at standard temperature and pressure.

3. Results and Discussion

3.1 Time Series Concentrations in the Classrooms

Figure 1 shows the progression of $PM_{2.5}$ mass concentration and fine particle number concentration during the course of the class both before and after we turned the C-R Boxes on. Table 1 shows the size of the room and number of people present for each test. In all three tests, there is a noticeable decrease in both mass and number concentration at all the monitors after we turned the C-R Boxes on. Of the three tests, Test 1 (Figure 1a) shows the least clear trend for fine particle number concentration, but the fine particle number concentration still drops from 1.5-2.5 particles/cm^3 to 0.5-1.5

particles/cm^3 after we turned the C-R Boxes on. In Test 1, $PM_{2.5}$ mass concentration displays a more pronounced trend as it drops from 14-16µg/m^3 to 3µg/m^3. Test 1 took place in the larger of the two classrooms and was well below the maximum occupancy of the classroom with only nine people present during testing.

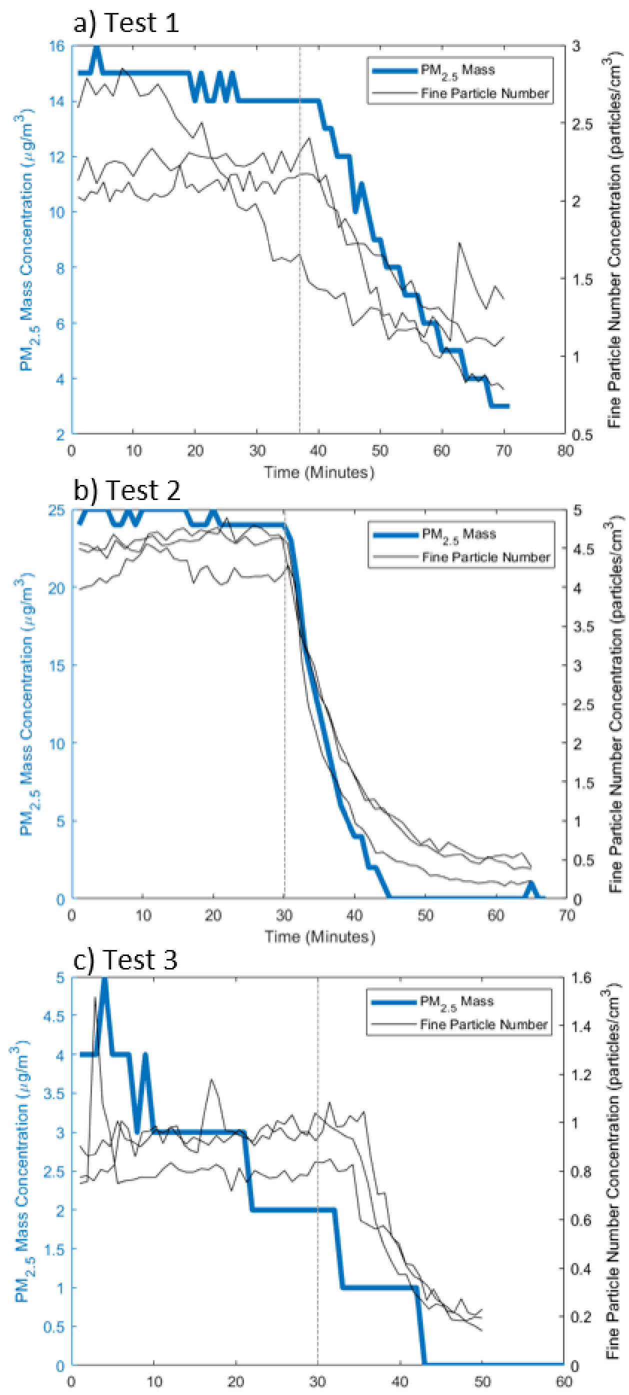

Figure 1: $PM_{2.5}$ mass concentrations (mass of particles with aerodynamic diameters < 2.5µm per m^3) [thicker blue line, left y-axis] and fine particle number concentration (number of particles with diameters 0.5-2.5µm per cm^3) [thin black lines, right y-axis] in each classroom measured with a TSI DustTrak II Aerosol Monitor 8530EP and three Dylos DC1100 Pro air quality monitors, respectively, from the start of class until the end of class for Tests 1-3. The vertical line shows the time the C-R Boxes were turned on.

Of the tests shown in Figure 1, Test 2 (Figure 1b) shows the clearest trend for all measurements. All measurements held fairly constant prior to the time the C-R Boxes were turned on and there were clear, rapid decreases in concentrations after the C-R Boxes are turned on. The fine particle number concentrations measured at all three monitors dropped from 4.0-5.0 particles/cm^3 to 0.25-0.75particles/cm^3 by the end of class. The $PM_{2.5}$ mass concentrations also dropped from a high of 24-25μg/m^3 to below the detection limit of 1μg/m^3. Test 2 was in the smaller classroom and had the highest occupancy (22 people) of the tests. This higher occupancy level led to higher starting levels of both measurements in Test 2 than the other two tests.

Test 3 (Figure 1c) shows a clearer trend for fine particle number concentration than $PM_{2.5}$ mass concentration but still shows decreases for all measurements. The fine particle number concentrations measured at all three monitors dropped from 0.8-1.2 particles/cm^3 to 0.2particles/cm^3 by the end of class. The $PM_{2.5}$ mass concentrations also dropped from a high of 4-5μg/m^3 to below the detection limit of 1μg/m^3. Test 3 was also in the smaller classroom and had moderate occupancy (16 people). The starting concentrations in Test 3 were under 50% of the starting concentrations for the other tests.

As mentioned above, the conditions for the first two tests (Initial A and B) deviated substantially from our ideal testing conditions due to the numbers of C-R Boxes in the room, placement of the C-R Boxes, and status of the windows and doors. As expected, this had substantial impacts on the measurements taken during these tests. We have included the results of these tests in the supplemental information (Figure SI.3).

We also measured coarse particle number concentrations at the same three locations as the fine particle number concentrations and found trends that followed those of fine particle number concentrations and $PM_{2.5}$ mass concentrations. We show these in the supplemental information (Figure SI.4).

*Table 1: Summary of the results from each test including the size of the room, the number of people present during the test, the total number of air filtrations per hour, the change in $PM_{2.5}$ mass concentration, and the change in fine particle number concentration. *In Tests 2 and 3, the $PM_{2.5}$ mass concentrations dropped below the TSI DustTrak II lower detection limit of 0.001 mg/m^3. The given value is based on this lower detection limit.*

Test	Room Area (Volume)	Number of people	Air filtrations per hr (AFH)	Change in $PM_{2.5}$ mass	Change in Fine PM Number Concentration
1	96m^2 (235m^3)	9	9.4	-79.7%	-55.9%
2	51m^2 (125m^3)	22	17.6	>-96.0%*	-90.6%
3	51m^2 (125m^3)	16	17.6	>-69.4%*	-77.7%

3.2 Average Changes in Concentrations

We averaged the concentrations for each test before and after the C-R Boxes were turned on. We took the average for the first 30 minutes of the class as the “before” value and the average during the last five minutes of the class as the “after” value to capture the minimum concentrations we observed. We show the percent changes in Table 1. For two of the tests (Test 2 and 3), the final $PM_{2.5}$ concentrations dropped below the detection limit of the DustTrak II. In these cases, we calculated the minimum decreases given in the table on the minimum detection limit of 1µg/m^3. The change in $PM_{2.5}$ mass concentration for Test 3 is smallest because the starting concentration was relatively low compared to the detection limit of the monitor. We observed decreases in $PM_{2.5}$ mass concentration over 69% in all three tests. We observed average decreases in fine particle number concentrations between 56% and 91% depending on the test.

3.3 Air Filtrations per Hour (ACH)

The C-R Boxes, after being adapted with the 2 inch MERV 13 filters, have an average volumetric flow of 0.305m^3/s, 0.394m^3/s, and 0.460m^3/s on low, medium, and high speed, respectively. This yields a range from 650 cubic feet per minute (CFM) on the lowest speed to 975 CFM on the highest speed as contrasted with the manufacturer (Utilitech) supplied maximum rating of 2300 CFM. This lower volumetric flow is because of the pressure drop created by the filters. We use the volumetric flow to calculate the air filtrations per hour (AFH) shown in Table 1. The AFH will impact the efficacy of the C-R Box intervention and must be considered when deciding how many fans to implement in each room.

3.4 Modeled Air Flow

We modeled the air flow in the room originating at the C-R Boxes using COMSOL Multiphysics 5.6. We applied fundamental assumptions, including isothermal flow, no obstructions in the room aside from the C-R Boxes, turbulent flow, and weakly compressible flow. Figure 2 shows the velocity profiles in the room 9.9s after the C-R Boxes are turned on. We have included profiles at additional time intervals in supplemental information (Figure SI.5). While much mixing occurs near the C-R Boxes, mixing does occur throughout the room with the placement of the C-R Boxes as shown in Figure SI.1. Figure SI.1 shows stream lines after only 9.9s, additional mixing would continue to occur after that point.

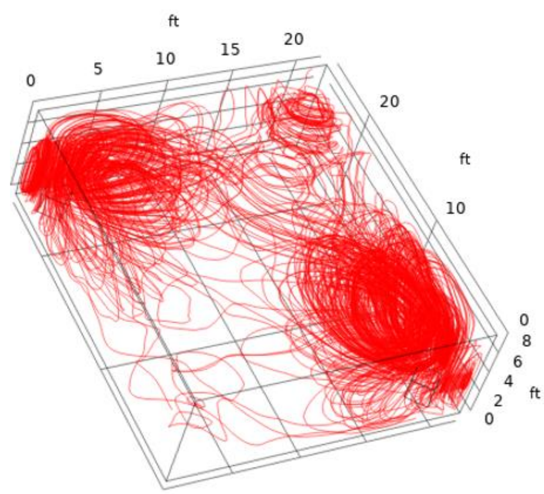

Figure 2: Modeled velocity profiles in the classroom 9.9s after the C-R Boxes are turned on.

3.5 Conclusions and Recommendations

With two C-R Boxes on low speed placed in opposite corners of the room, we saw substantial decreases in $PM_{2.5}$ mass concentration and fine and coarse particle number concentration after we turned the C-R Boxes on. It is clear the C-R Boxes are capable of significantly reducing particle levels throughout occupied classrooms. Due to noise considerations, the C-R Boxes are best used on low speed during most class activities, and kept on anytime people are present in the room. Measurements taken at different locations in the classroom and modeling results indicate the C-R Boxes provide sufficient air mixing to filter all the air in the room. These results support the use of C-R Boxes to supplement ventilation to mitigate COVID-19 transmission, particularly until schools can upgrade ventilation systems.

There are several limitations to this study. We only investigated the impact in two rooms and a small number of classes. We performed our tests in university classrooms rather than a K-12 classroom so do not account for behaviors and classroom use characteristics that might be specific to K-12 classrooms and not all tests had as many students as would be in a K-12 class. More tests are required to fully understand the efficacy in a broader range of classrooms.

Long-term C-R Boxes could help mitigate poor indoor air quality which has consequences beyond transmission of infectious diseases. Poor air quality can also severely impact individuals with asthma and allergies. Pediatric asthma is the leading cause of absentee days for school-age (K-12) students and improved indoor air quality has a significant positive impact on lung growth and development in children[16,17].

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