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Work in Progress: Supplementing theoretical modeling with empirical data for improved design

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Introduction

Our first semester course in biomedical engineering includes a semester-long project that introduces students to the design process and allows them to practice working in teams. The students work for a fictional company with a hypothetical hospital as a customer to design, build, and test a portable air filtration system. While the experience for the students has overall been positive, they struggle in a specific section of the course and fail to make a connection between course content and application to the project. We are looking to address this short-coming with an experiential component by adding empirical data collection.

Part of the design process is to use theoretical modeling to inform the details within their design, specifically choosing a fan and filters. This step in the project utilizes manufacturer's data to produce graphs and compare velocity and volumetric flowrate to pressure to aid in the design of the portable air filtration prototype. They are then expected to apply this practice towards their design in order to choose an appropriate fan and filter for their prototype. However, the students as novices focus on completion of the activity instead of understanding [1]. Based on conversations with teams, the theoretical activity is very challenging and possibly too abstract for them to understand and apply the concepts to their design [2] [3]. Theoretical modeling is new to many first semester students including the skills of 1) extrapolating information from manufacturer's websites to produce a graph or representation of the data to show relationships between variables, 2) producing the graph using tools such as Excel, 3) using the graph to determine the dependent variable from an independent variable, and 4) translating this information into an application used to make decisions in the design process [4]. This results in an underperforming prototype.

The goal of this work in progress is to fill the gap and provide experiences to help students understand and practice reconciling theoretical models with empirical data in order to improve their use of theoretical modeling in the design process. Being able to collect empirical data that demonstrates relationships between variables such as filter ratings and air velocity will support the learning process, specifically points 3 and 4. This experiential addition will also give physical meaning to the theoretical values in the graph [2]. In order to create this experiential module, a demonstration chamber by which students can measure air flow and resistance as a function of fan speed and filter parameters has been created and is the focus of this work in progress paper. The ultimate expectation is for the prototypes designed and built by the students at the end of the course to show improved effectiveness as compared to prior semesters before a demonstration chamber was used in the course.

Course Structure and Expected Impact

The modeling activity is a few week section within this single credit, first semester biomedical engineering course. The steps in the design process are taught and applied over the course of the semester. A diagram of the steps covered in the class, the activities performed in the class associated with each step, and the learning outcomes specifically addressed by this project are shown in Figure 1. The problem definition step begins in the second week of class and the final testing is performed during the last week of class.

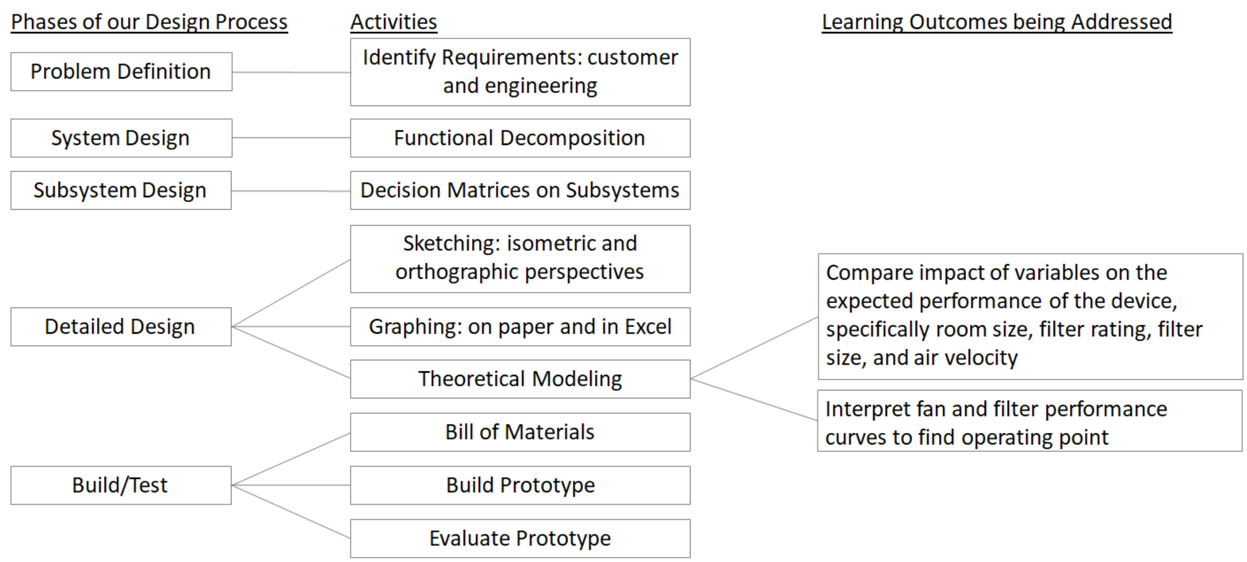

Figure 1. The course focuses on the included phases of the design process by practicing and applying these activities. The listed learning outcomes are the focus of this project.

During the detailed design phase, additional skills are introduced which are review for some students and new for others depending on their individual exposure in high school. Visual communication skills including sketching and graphing are imbedded into the course. Excel is used for graphing and then is also used to perform calculations and theoretical modeling. The theoretical modeling activity is a set of worksheets which begin with questions to teach students how to perform necessary unit conversions. The worksheets help students apply equations in Excel as they learn about MERV ratings and the relationships between velocity, surface area, and volumetric flow rate. As the section continues, worksheet questions have students create their own plots from manufacturer's data and manipulate that data by changing variables such as filter surface area or air velocity. By the end of a few weeks of the theoretical modeling section, the expectation is that students use the skill to properly size fans and filters for their design.

At the end of the semester, the prototypes are evaluated on four criteria: portability measured by weight and size, noise level, cost, and effectiveness of removing particulates. Effectiveness is measured using time lapse of the prototype as it clears fog created by a theatrical smoke machine. Many prototypes perform poorly at this criteria and some do not clear fog at all. For the total of 40 student teams over the last two course offerings, prototypes from 28 teams removed less than a quarter of the fog while prototypes from only 4 teams were able to remove at least three quarters of the fog in the allotted time. The expected outcome of implementing an empirical data collection activity to supplement the theoretical modeling via the hands-on use of the designed demonstration chamber is that students will create more prototypes which will be more effective at clearing the fog.

Experimental Methods and Materials

Demonstration Chamber Design and Assembly

The variables to be controlled in the experiential learning demonstration were chosen based on the current theoretical modeling activity: filter type, pleating depth, and air flow rate. Then a basic chamber was sketched where a variable speed fan and removable filter were on opposite ends of a clear tunnel. Desired measurement were identified and a pressure port and inlet for an anemometer were planned. Before sizing the tunnel, an appropriate fan was selected as this was identified as the limiting factor. The Vornado 573 Compact Flat Panel Air Circulator [5] had an acceptable compromise of a flat front and a 3 speed adjustment on the backside where it would be accessible.

Filters were sized to a similar area as the surface of the fan resulting in a 10in x 10in area. Multiple of each of the following filters were purchased (Filterbuy).

- 1in pleated MERV 8
- 1in pleated MERV 11
- 1in pleated MERV 13
- 2in pleated MERV 13
- 4in pleated MERV 13

Clear polycarbonate sheets 12in x 12in x 1/4in were trimmed to size for the clear tunnel. The sheets were glued with an acrylic cement. Rubber foam was used at each end of the chamber to form tight seals between the polycarbonate sheets and the filters and fan. Holes were drilled in the top for the anemometer (Extech 407123) and pressure sensor (PASCO Scientific PS-3600B with PS-2181).

Lastly a few parts were designed and 3D printed to complete the assembly. Feet under the fan and at the end of the tunnel were needed to stabilize and level the demonstration chamber. A holder was needed to secure the anemometer probe. Clasps were needed to hold a variety of filter depths onto the end of the tunnel. The clasps were designed to hold 1in, 2in, or 4in thick filters. Gorilla glue was used for adhering all 3D printed pieces.

Demonstration Chamber Validation

Once the chamber was assembled, pressure and air velocity were measured at all three fan settings with each of the filters attached as well as a series of two 1” pleated MERV 13 filters. The anemometer was positioned in the middle of the chamber for measurements. This data was compared to the data obtained from manufacturers that was used in the theoretical modeling activity in class.

Results and Discussion

Completed Demonstration Chamber

The final demonstration chamber design resulted in the device shown in Figure 2 with a tunnel that is 8.5in wide, 9in tall, and between 11 and 11.5in long due to the arch of the fan.

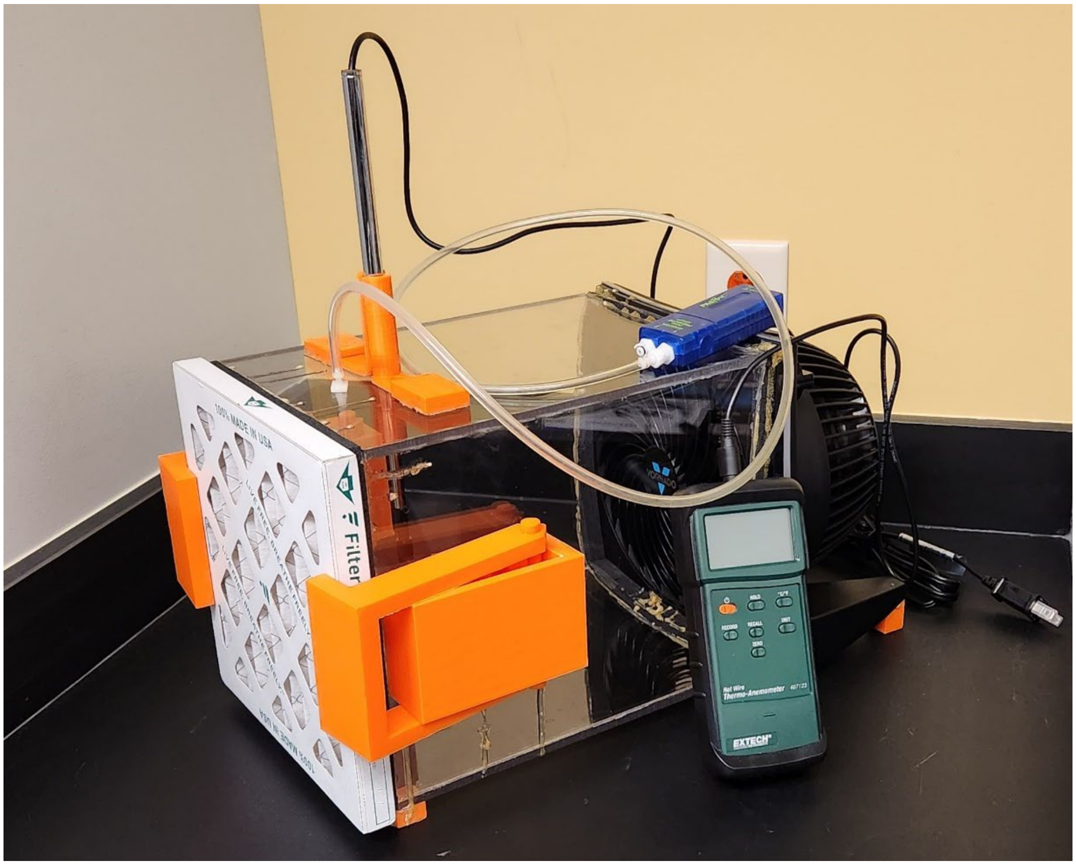

Figure 2. Built demonstration chamber shown with anemometer probe protruding from the top of the chamber, pressure sensor with tubing attached to the top of the chamber, and 1in pleated filter being held on the front of the chamber by two large 3D printed clasps.

Validation Testing

The fan was tested at three speed settings with no filter attached. These measurements were compared to the specifications of the manufacturer [5] as shown in Table 1. The differential pressure was not sensitive enough to detect a difference compared to outside the tunnel.

Table 1. Fan characteristics without a filter attached. The expected flowrate is obtained from the fan manufacturer [5].

Fan Setting	Velocity (ft/min)	Volumetric Flowrate (ft^3/min)	Expected Flowrate (ft^3/min)
1	275	146	147
2	452	240	-
3	590	313	236

Varied filter types and pleating depths were applied to the end of the chamber in order to study how the MERV value and the pleat thickness impacted pressure and volumetric flowrate; however, the anemometer did not have resolution to report flowrate. All measurements were either 59 or 78 ft/min for all filter combinations and all three fan settings. All data is reported as a function of fan setting.

To demonstrate how MERV value impacts performance, the empirical data was compared to theoretical data used in class [6]. Figure 3 shows a graph the students are expected to create from the theoretical information provided. Figure 4 shows the measured pressure for different MERV filters applied to the chamber at different fan settings. Figures 3 and 4 demonstrate an increasing pressure with increasing air flow and MERV value. An important concept students are expected to learn is that a higher quality filter as indicated by a higher MERV value increases the pressure that the fan is moving the air against which can decrease performance.

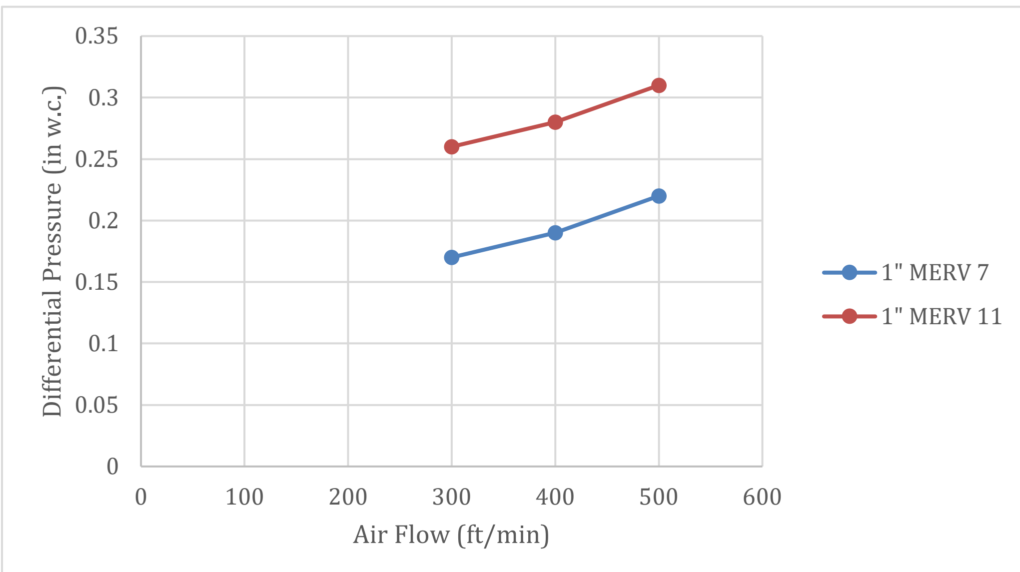

Figure 3. Theoretical model of two air filters and how pressure is dependent on air flow. Graph is produced from commercially available data [6].

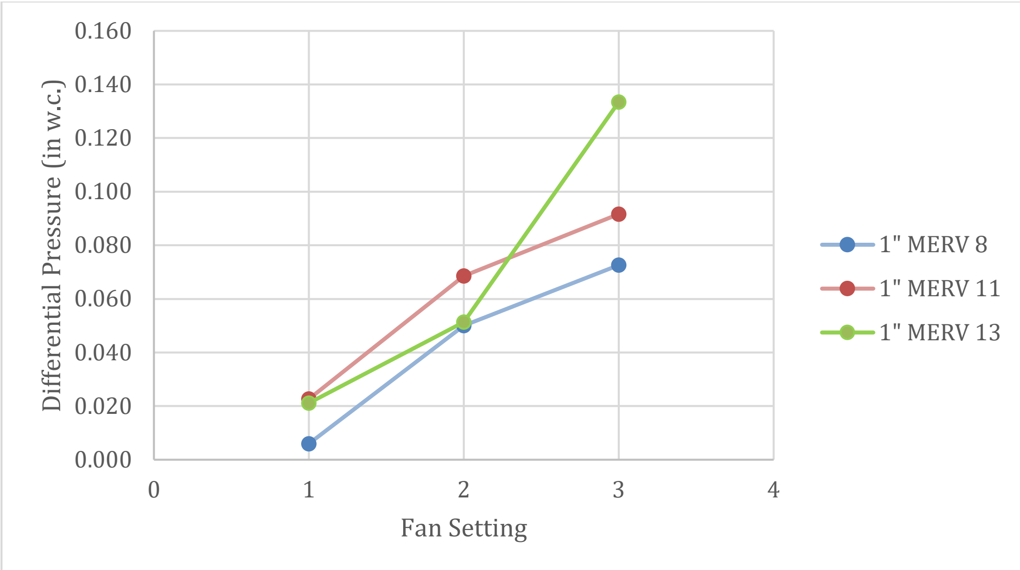

Figure 4. Measured pressure for air filters with different MERV values at varied fan settings.

To demonstrate how pleating depth and filters placed in series impact performance, the empirical data was compared to theoretical data used in class [7]. Figure 5 shows a graph the students are expected to use from the theoretical information provided. Figure 6 shows the measured pressure for filters with different pleating thicknesses applied to the chamber at different fan settings. Figures 5 and 6 demonstrate a decreasing pressure with increasing pleating depth. An important concept students are expected to learn is that increasing the surface area by increasing pleating depth decreases the pressure that the fan is moving the air against which can increase performance. The filters placed in series were expected to increase the pressure significantly more than the single filter. However, without the ability to accurate measure air flow, the exact relationship is inconclusive.

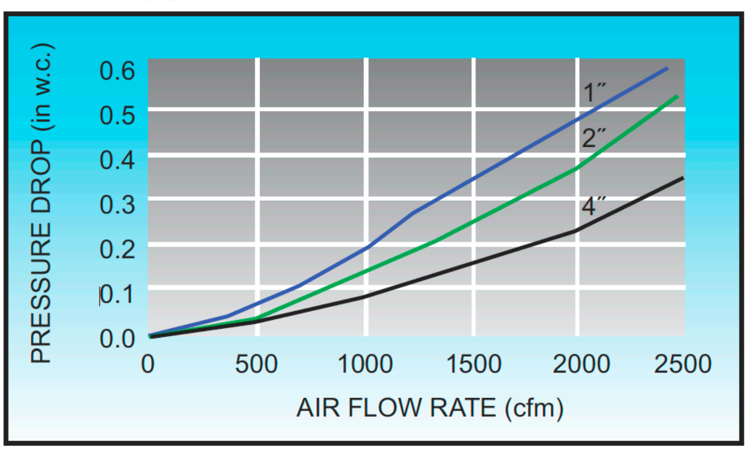

Figure 5. Data obtained from a commercial source and used in the theoretical modeling worksheet [7]. The data compares pressure for MERV 13 filters with different pleat thicknesses.

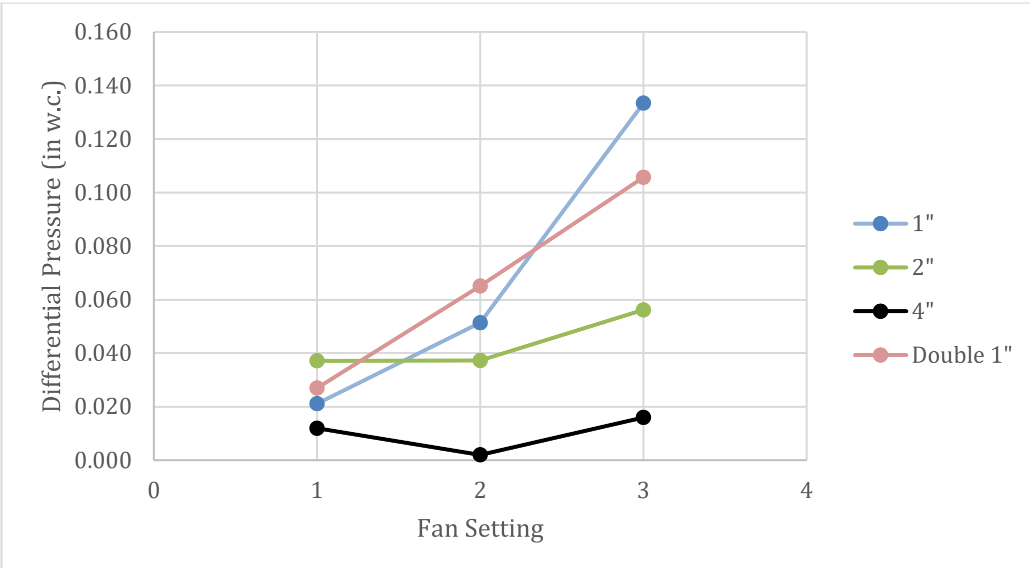

Figure 6. Measured pressure drop for varied pleat thicknesses for MERV 13 filters at varied fan settings. Two 1in pleated filters were tested in series (Double 1").

Limitations and Future Work

The current chamber physically demonstrates concepts that may not have been obvious to students when performing the theoretical modeling worksheets by themselves. One such realization that was observed with an incomplete chamber was simply how filter pleating works. Some students benefited from visualizing 1 inch and 2 inch pleated filters. Another concept is that adding a filter will impact air velocity and thus weak fans may not be able to move air. Currently some teams focus on portability with small, lightweight fans to the detriment of being able to remove air particles.

While the trends demonstrate the concepts, our current setup does not have the sensitivity to measure a variation in air flow when filters are attached. More sensitive anemometers will be explored as options for addressing this shortfall. Also more powerful fans will be explored which could address this shortfall as well as increase the range of data to be closer to the theoretical data.

In the fall of 2023, chambers will be used in class side-by-side with the theoretical modeling. The current worksheets will be updated so both techniques, empirical and theoretical, will be accomplished in parallel by the students. The expectation is that the final prototypes the students design and build will be more effective at removing particulates from the air than previous semesters as a result of the implementation of the demonstration chamber.

References

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