

## **AC 2007-142: AIR FLOW TEST BENCH: A SENIOR CAPSTONE PROJECT**

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# Airflow Test Bench: A Senior Capstone Project

## Abstract

An airflow test bench system was designed, built and tested for the undergraduate mechanical engineering thermal fluids laboratory at Western Kentucky University. A two-semester senior capstone design sequence, ME 400 – Mechanical Engineering Design and ME 412 – Mechanical Engineering Senior Project, provided a four-member mechanical engineering student team with sufficient time to plan and execute this engineering process.

The final airflow test system is primarily intended for instructional situations, but has the potential for external industrial interaction as well. The system delivered by the project team is usable over a range of flows and system impedances. Primary benefactors of this test bed will be future students in Mechanical Engineering Senior Labs. These hands-on laboratory courses now have an airflow test bench for use in the demonstration of the impedance characteristics of various system geometries, which can then be compared with their theoretical predictions, and the characterization of the performance characteristics of air moving devices through the generation of pressure head and rpm versus volumetric flow rate curves. The system can provide further extension for student engagement in industrial projects.

During the course sequence, the students had a variety of meaningful engineering experiences. The design and selection of the critical test bed components clarified uncertainty regarding measurement impact on the final system. Through the test bed construction, teamwork, project management and maintaining a schedule within time and budgetary constraints were reinforced. Finally, the system testing development and implementation of an experimental test plan yielded the delivery of a quality product. This paper will detail faculty observations and project outcomes.

This project was completed with the assistance of an Undergraduate Senior Project Grant from the American Society of Heating, Refrigeration, and Air Conditioning Engineers, Inc.

## Introduction

Every year the American Society of Heating, Refrigeration, and Air Conditioning (ASHRAE) funds the Undergraduate Senior Project Grant Program, which awards schools grants for the execution of senior projects. The grants are often used to design, construct and test projects. The distribution of these funds is based on the relevance of the proposal to educational endeavors in the Heating, Ventilation, Air Conditioning and Refrigeration (HVAC&R) disciplines.<sup>1,2</sup>

In 2004, ME seniors and their faculty advisor in the ME Senior Lab I course at Western Kentucky University submitted a proposal to the ASHRAE Undergraduate Senior Project Grant Program, requesting funds to design, build and test (DBT) an airflow test bench. The proposal was selected by ASHRAE as one of the projects to be funded for the 2005 – 2006 academic year.

The objective of this project was to design, assemble, calibrate and test the performance of an airflow test bench per the standards ANSI/ASHRAE 51-1999 and AMCA 210-99. This work was performed by a group of seniors in ME 400- ME 412 at Western Kentucky University. The airflow test bench will be used supplemental to the curriculum to provide students with hands on experience in the characterization of performance of air moving devices and of pressure drop across passive devices. The project was completed in May 2006 and was turned over to the Department of Engineering.

## Description of an Airflow Test Bench

An airflow test bench is a device used to measure the airflow resistance of a test specimen or the performance of an air moving device. The result for the tests specimen can be expressed as a pressure loss or K-factor versus flow rate or approach velocity and for the air moving device is typically a characteristic performance curve of static pressure head versus volumetric flow rate. The volumetric airflow rate through the system is usually determined by the pressure drop across a Bernoulli obstruction device or volumetric flow meter. The airflow test bench is typically designed using the standards, ANSI/ASHRAE 51-1999 and AMCA 210-99, as the basis for design within associated budgetary constraints. Figure 1 shows a schematic of a typical airflow test bench meeting these standards. As shown, an airflow test bench consists of the following primary components:

- Variable Exhaust System (Blower)
- Flow Element (Nozzles)
- Plenum (Structure or Housing)
- Airflow Straighteners
- Data Acquisition System (DAS)

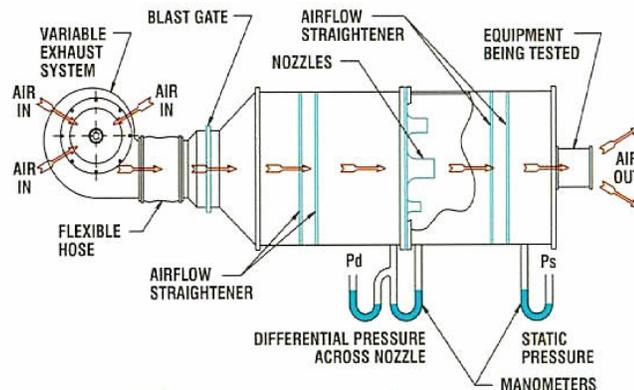


Figure 1 Schematic of an Airflow Test Bench (AMCA 210-99)

## General Airflow Test Bench Design Criteria

In order to determine the direction of this project, general design criteria were established to provide the student design team with the necessary guidelines in which to proceed. The criteria selected below were presented to their faculty advisor for approval and were considered Acceptance Criteria. These Acceptance Criteria are strict guidelines for student design team to adhere to throughout the project, which were validated through testing upon project completion:

- This airflow test bench must be able to generate volumetric airflow rates over the range of 10 – 2000 CFM at a maximum of 10 inches of water pressure drop and measure associated pressures and temperatures to allow for the characterization of a test specimen (passive device) and of an air moving device.
- The airflow bench must meet the ASHRAE 41.2 – 1987 for plenum dimensions, location of the flow element, location of the flow straighteners, and the locations of the sensors.
- The Data Acquisition System (DAS) for this device must be constructed to only collect and reduce the data.
- The entire device must be durably and rigidly built to endure 5 years of service.
- The airflow test bench must be built within the budget provided by ASHRAE and Western Kentucky University.

The airflow test bench, which was constructed to meet these criteria, is shown below in Figure 2 and its primary components as outlined above are discussed in the following section.



Figure 2 WKU Airflow Test Bench

## Major Components

The student team researched feasible options for the various components of the system in the fall semester, performed technical calculations and professionally justified all necessary aspects of the airflow test system. The major components that they designed and integrated into their final system were the blower with variable exhaust capabilities, the system flow measurement device, the plenum to house the test objects, flow straighteners for measurement accuracy, and a data acquisition system. Each of these aspects is described below.

### A. Blower or Variable Exhaust System

#### *Design Criteria:*

- The blower must be able to overcome a minimum pressure of 10 inches of water created by the plenum/nozzles/specimen of the airflow bench.

- The blower must create at least 2000 CFM @ 10 inches of water pressure drop.
- The laboratory facilities infrastructure provides 480V, 60 Hz, 3 phase power. Therefore, the blower motor is required to be compatible with the existing laboratory infrastructure.
- The blower must have a variable frequency drive compatibility to achieve variable speed to obtain flow rates from 10 to 2000 CFM.
- Safety of the blower must have guards for all moving parts.
- The blower cost must be within the project budget.

The blower must be able to overcome the pressure created by the flow bench itself. This includes all the components of the bench with the main two components that effect this most being the flow measuring device and the device being measured. From the performed calculations on a potential nozzle array to measure the flow rate, it was found that the pressure across a nozzle at its maximum designed flow rate will create at most 8 inches of water. With an assumption that the flow device will not create more than 2 inches of water pressure drop, the student design team specified an air moving device capable of a minimum of 10 inches of water capability at 2000 CFM. For the airflow test bench, the best available choice was the centrifugal type. This blower type provided the flow rate needed to meet the requirements of the proposal and created more than 10 inches of water at 2000 CFM. A 9-IPA Greenheck blower was selected for the airflow test bench. It was available with a variable frequency drive motor and powered by 480V, 60Hz, 3 phase.

## **B. Flow Element**

### *Design Criteria*

- The flow element must be capable of measuring an airflow rate from 10 to 2000 CFM with minimal non recoverable head loss.
- The flow element must be selected and designed in accordance with ASME MFC-3M-1989 and ASHREA 41.2-1987.
- Traceable calibration of the flow element must be strongly considered. If such calibration can not be afforded at this time, an alternate future means of calibration must be considered.
- The flow element must be designed such that it may be removed for future maintenance, inspection, alteration, and calibration.
- The flow meters cost must be within the project budget

A critical feature of this flow bench is ability to accurately measure airflow volume through it. To achieve this criterion, the student design team selected a nozzle array. The nozzles allow the measurement of the volumetric airflow rate by creating an accurately controlled differential pressure that can be converted to a volume flow rate of air moving through the specimen or the air moving device. Flow nozzles create this controlled pressure drop, used to measure flow rate, with a convergent inlet to a small throat section that channels the air and thereby increasing the pressure on the inlet side of the nozzle. This nozzle array will allow the bench operator to measure the flow rate of air through the air flow test bench, which can be compared to the differential pressure drop across the unit under test, allowing the operator to evaluate the performance of the unit under test.

Design guideline as outlined in ASME MFC-3M-1989 was used to govern nozzle selection and sizing. For example, after the differential pressure was determined, the flow rate is set to 2000 CFM and the nozzle throat diameter is adjusted until a differential pressure of no more than 8 inches of water is achieved. Next, the flow rate was adjusted for that same throat diameter until a minimum of 1 inch of water is achieved. This manipulation process identified a nozzle size that will measure a range of flow of 775 to 2000 CFM. This process was repeated 6 times until the entire range of 10 to 2000 CFM was accommodated. The flow range of each nozzle intentionally overlaps the nozzle that is one size smaller and/or larger in order to allow more flexibility during testing and for some measurement error.

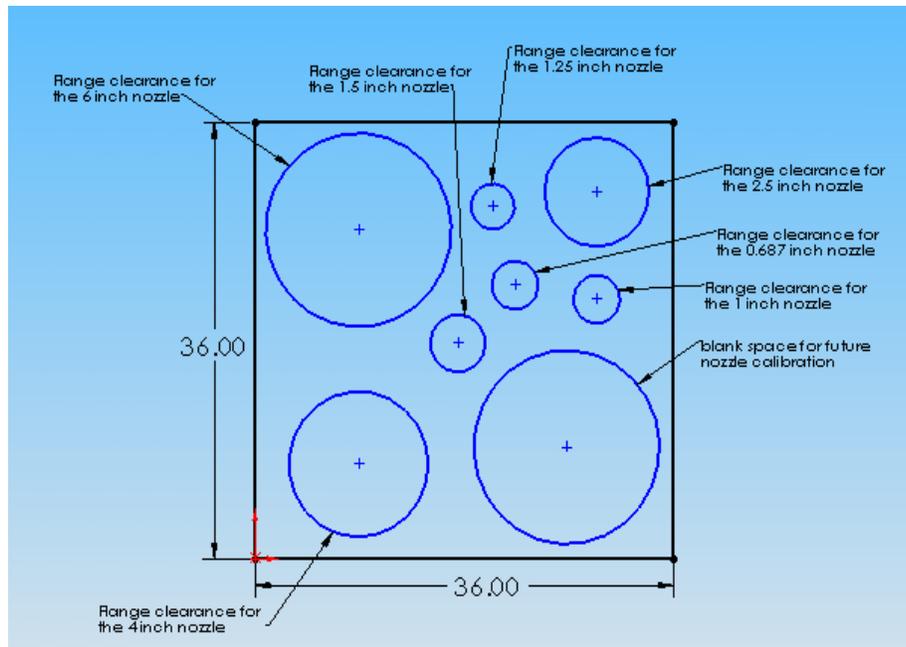


Figure 3 Airflow Nozzle Array

### C. Plenum

#### *Design Criteria*

- The plenum will be dimensioned according to ASHRAE 41.2.
- The inside walls of the plenum must be smooth and obstruction free such that these surfaces create little airflow drag or resistance.
- The plenum must be constructed out of affordable materials as the budget does not allow much flexibility after selecting more critical and expensive components.
- The plenum cost must be within the project budget.

A plenum provides both a sealed enclosure and a structure for several of the other primary components of the system. Based on the blower and nozzles selection, the plenum will be subjected to air at pressures as high as 8 inches of water and the size of this plenum is governed by the ASME-MFC-3M standard used for our nozzle selection process and the ASHRAE-41.2 standard which illustrates commonly used methods for laboratory air flow measurement. The dimensions of this plenum are also governed by the size of the nozzle array used for measuring

air flow within this plenum. This plenum is an integral part of this air flow test bench and provides structural support for the flow element, flow straightener, fan, and unit under test. The plenum was made of two separate pieces that join at a specified mid section based on location of the flow element and it must be structurally sound enough to endure repetitive separation for nozzle array adjusting and maintenance. To provide mobility in the laboratory space, the plenum was mounted on casters.

Another important factor in the plenum design is its strength. COSMOSWorks© Finite Element Analysis software was used to model the stress on the largest span in the wall section of the plenum to test for flexure. A 1/4" x 36" x 60" section was designed in SolidWorks© and modeled with zero degree of freedom boundary conditions constraints at the edge the panel where it will be braced with angle iron and a distributed load of 0.5 psig which is approximately equal to the blower's maximum head pressure of 14 inches of water at dead head. Figure 4 shows the FEA results illustrating the deflection of this wall when introduced to 14 inches of water. The maximum deflection is in the center with a magnitude of 0.086" which is insignificant considering the group does not anticipate operating this fan at dead head plus an increase in material width to 3/8" and ribbing the exterior would significantly reduced this flexure.

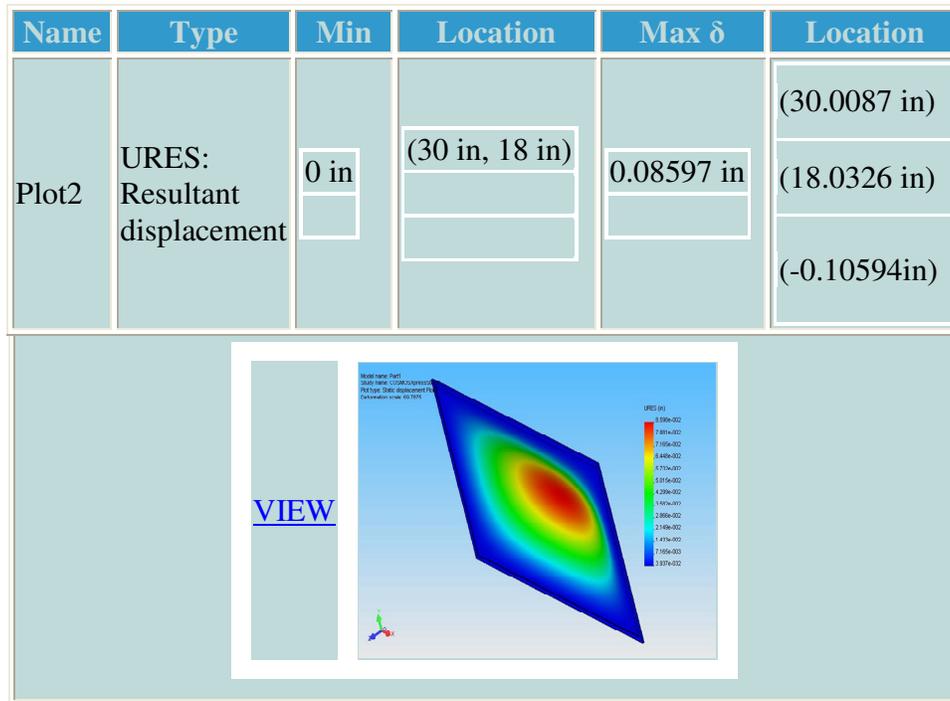


Figure 4 FEA Deflection Results for Largest Plenum Wall

To meet this design goal, the student design team constructed the plenum out of a composite wood, Melamine, which provided with good strength, durability, machinability, and a smooth finish. To provide view ports to instrumentations, Plexiglas windows were installed selected locations. These windows are flush with the wood surface because the inside of this plenum must be smooth and free of obstructions.

## **D. Flow Straighteners**

### ***Design Criteria***

- The flow straightener must be sized and modifiable to fit properly within the cross-section of the plenum.
- The individual cell sizes must be dimensioned in order to produce the minimal amount swirl within the flow.
- The flow straightener must be rigidly constructed in order to minimize any vibrations.
- The cost of the flow straightener must be minimized to fit within the required budget.

Two flow straightener configurations, a PVC pipe array (8" Length/1.25" Diameter) and an Indy Honeycomb panel, were identified, which clearly met three of the four above criteria. However, their claim of swirl free flow was considered application dependent and is best determined empirically; therefore, a scaled down model of the plenum and of the air mover with each of these flow straighteners was constructed in order to conduct the necessary tests. Upstream and downstream of the flow straighteners (i.e., approximately halfway between the air mover and the straightener and halfway between the straightener to the plenum exit) two perpendicular strings forming a cross hair through the vertical and horizontal centerlines of the plenum were attached through the plenum wall. Flow visualization tufts were secured to these cross hairs to show the amount of swirl within the flow field. With the air mover energized, the amount of swirl, upstream and downstream of the straighteners, could be easily visualized and effectively evaluated. The student design team observationally determined if the swirl had been eliminated or reduced to acceptable levels. After performing number of tests with the cross hairs at various distances from of the Indy Honeycomb Panel and the PVC piping array, the array yielded the desired swirl free results. Therefore, the PVC piping array met the ASHRAE standard, as well as criteria presented above at a significantly lower cost, and was incorporated into the airflow test bench.

## **E. Data Acquisition System**

### ***Design Criteria***

- The Data Acquisitions System (DAS) will not control bench operation but will be a "One-Way Talking" system.
- All inputs from sensors to the DAS will be analog with conversion to digital in LabVIEW.
- The DAS will perform data reduction and some initial analysis (functional relationships and measurement uncertainty).
- The DAS must be User Friendly

The Data Acquisition System (DAS) for the Flow Bench provides a method for systematic collection and monitoring of the data reported by the pressure and temperature sensors incorporated in the bench. The DAS was designed to be a "one-way talking" system, meaning the DAS does not control the airflow test bench, but only receives data from the sensors incorporated into the air flow test bench. The data collected is then reduced and analyzed by the computer software system. The DAS software system is designed to calculate the volumetric flow rate and differential pressures from the proper inputs from the system. The computer

program shows results including the pressure loss or K-factor versus flow rate or approach velocity for a passive device, a characteristic performance curve/table of static pressure head versus volumetric flow rate for an air moving device and environmental conditions when the test was conducted. The final requirement, which the DAS meet, was to be a “user friendly” system. By selecting LabVIEW as the data collecting and reduction system, a “user friendly” man machine interface was created, which is both easily read and is able to perform the needed options at the user’s convenience. Plus, it has allowed the student design team to approach the DAS requirement with a high level of versatility and functionality for future modifications as they might arise.

## **Project Assessment and Outcomes**

Over the past five years, the ME faculty at Western Kentucky University have developed and implemented a professional experience sequence for ME students pursuing a baccalaureate degree that is consistent with overall mission of the engineering department <sup>3</sup> (the complete Department of Engineering mission statement is found at <http://www.wku.edu/engineering/depmiss.php>):

*...to produce, as its graduates, competent engineering practitioners. An engineering practitioner is one who has a foundation of basic science, mathematics, and engineering knowledge, combined with practical knowledge and experience in applying existing technology to contemporary problems. ... Program curricula will be project-based. Students will have sufficient opportunity to engage in project activities to support development of a clear understanding of engineering practice. ... Projects that provide opportunity to accomplish design, development, and implementation should be available.*

A Professional Component Plan has evolved into a framework for defining, teaching, assessing and improving students’ competencies as they implement mathematics, basic science and engineering science in professional experiences. As required by EAC of ABET’s Criterion 4: “Students must be prepared for engineering practice through the curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier course work and incorporating engineering standards and realistic constraints”.<sup>4</sup> To accomplish this, the ME Program Professional Component Plan has four areas:

- Engineering Design Plan (teaching and practicing of design skills)
- Professional Communications Plan (conveying designs and interacting with peers)
- Computer Skills Plan (teaching and implementing of design tools)
- Engineering Ethics Plan (evaluating and practicing appropriate professional behavior)

Engineering Design Plan and its associated experiences combine a structured approach to solving problems with an appreciation for the art of engineering. Professional Communications and Computer Skills Tools are introduced and then required throughout the four-year sequence to support the execution of design projects. The Engineering Ethics component provides students with a framework for understanding professional expectations and techniques for clarifying the ambiguity that is common in ethical dilemmas.

The primary purpose of the Professional Component course sequence is to link all these skills to engineering design and to assess the progress of student capabilities through the curriculum. The integrated structure of the Professional Component courses provides a framework for building upon previous coursework, assessing student progress often, and more quickly adjusting course coverage based on prior assessments to effectively assure that graduates of the program are capable of practicing as engineers upon graduation.

The Professional Component as defined by EAC of ABET Criterion 4 has two major areas. The first area, Curricular Content, deals with whether the program provides the students with course-specific content in the areas of mathematics, basic science, engineering science, and General Education. The second area, Extra-Curricular, deals with the professional experiences of a student pursuing their degree: "Students must be prepared for engineering practice through the curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier course work and incorporating engineering standards and realistic constraints."

The mechanical engineering program at Western Kentucky University is becoming established, with the fourth cohort of seniors currently progressing towards a May 2007 graduation. As an undergraduate-only engineering program, the ME faculty members place a strong emphasis on graduates possessing this Extra-Curricular professional competence. To achieve this outcome, it is necessary to provide students with the opportunity to acquire design tools and skills, as well as competency in mathematical and technical analysis, and communication. Throughout the four-year plan of study, the ME students receive coordinated instruction from both thermal-fluids and mechanical systems faculty, and are required to demonstrate varied levels of professional competence in both tracks.

The ASHRAE funded project provided an excellent vehicle for this integration and major design experience to occur. The four students on this project team demonstrated the technical competencies from a number of engineering science courses to successfully design, build and test the WKU Air Flow Test Bench. The fall and spring two-course sequence coupled with ASHRAE's Undergraduate Senior Project Grant Program Student were partnered very effectively to achieve our program outcomes. An external sponsor, who required periodic status reports, also added a level of creditability to the project.

### **Course Assessment and Outcomes**

The course, which housed this DBT project is a continuation of ME400 and provides students with a capstone engineering design experience. The final product of ME400 was a design proposal document that is executed in ME412. The grading in ME412 continues to be 2/3 team based and 1/3 individual. This year's teams continued to perform well, improving on both the 2004 and 2005 classes. All projects were finished on time and to expected quality. Again, there remains room for improvement.

The eleven students in the class were divided into three teams (one 3-member, two 4-member) and completed projects for Span Tech, WKU ME/ASHRAE and WKU CE/ME Program. The

projects involved the design, construction and testing of either final systems or prototypes; typical project budgets were approximately \$10,000.

The student performance was assessed via their scores on several intermediate activities related to their final projects (design reviews, update presentations) and the final results of their projects (reports, presentations, demonstration). These assignments have been matched with the course outcomes. A target score of 8.0 for all outcomes is based on the need for students to demonstrate competence in these professional components. Students' self-evaluation was consistently either comparable or slightly higher than faculty evaluation; however, student performance indicates that students have achieved the course outcomes. Outcome 5 (peer evaluation) remains the weakest area, and efforts to increase coverage of this topic in sophomore and junior design classes are ongoing.

In general, students are proving themselves to be effective team members; they are less capable of providing quality feedback regarding the performance of their peers. Currently, there are 22 students, eight projects, and four faculty members involved; lessons from the past years allow us to effectively manage these experiences. The program Professional Plan is well in place and appears to be working to evaluate activities and make decisions regarding these courses to properly address the Professional Component of the program.

## **Conclusions**

Overall this project provided the experiences necessary to achieve the desired outcomes of our ME Program Professional Component Plan. In particular, this project was very suitable to the two course sequence for our capstone senior project, ME400 – Mechanical Engineering Design (Fall semester - 2 credit hours) and ME 412 – Mechanical Engineering Senior Project (Spring semester - 3 credit hours).

The students on this project team effectively demonstrated engineering design principles in the selection of the flow meters (nozzles), sizing and selection of the air mover, design and selection of the flow straighteners, design of the plenum and design of the Data Acquisition Systems and selection of associated instrumentation. The design and selection of these project components were constrained by both financial and time lines typical of a “real world” engineering projects and were managed by two faculty acting as advisor and industrial contact, respectively, to further give the student a “real world” experience in highly dynamic environment with multiple “managers”.

Other components of the plan were exercised as well. Students drafted both the interim and final project status reports and the faculty edited to meet the specific guidelines of the sponsor. Additionally students presented this project at the 36<sup>th</sup> Annual Western Kentucky University Sigma Xi Student Research Conference where their work was favorably reviewed by peers and other faculty within the university community and will also present this project to the Department of Engineering and our Mechanical Engineering Advisory Committee.

In addition to the senior students on this project team, the other benefactors of this test bed will be future students in ME 420 - Mechanical Engineering Senior Lab I and ME 430 – Mechanical Engineering Senior Lab II. These hands-on laboratory courses will have an air flow test bench for use in the demonstration of the impedance characteristics of various system geometries, which can then be compared with their theoretical predictions, and the characterization of the performance characteristics of air moving devices through the generation of pressure head and rpm versus volumetric flow rate curves.

### **Acknowledgements**

This senior project was sponsored by the American Society of Heating, Refrigerating and Air-Conditioning Engineers under the Senior Undergraduate Project Grant Program. This program provided the faculty advisors and engineering students with a grant of \$5000 for this project. The intention of this grant program is to provide engineering schools with funds that help to increase student knowledge and awareness of the HVAC&R industry. In addition, the Western Kentucky University Department of Engineering and Office of Sponsored Programs provided matching funding to support the project of \$9890 and \$940, respectively.

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