Redesign of an Airflow Test Bench: An Independent Student Project

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Abstract – An opportunity at Western Kentucky University for the redesign of an airflow test bench was provided to a mechanical engineering student, the first author, as an independent project. The redesign of the existing airflow test bench was required to minimize overall leakage rate and improve the aerodynamic performance of the system. The redesigned airflow test bench will be designed, built, and tested (DBT) for use as an instructional tool in an undergraduate mechanical engineering thermal fluids laboratory and for possible industrial outreach opportunities. An airflow test bench is a system used to measure the aerodynamic performance of complicated passive devices, such as HVAC duct networks or filters and of active or air moving devices (AMD's), such as fans and blowers. The test bench will be primarily beneficial for future junior and senior mechanical engineering students studying fluid mechanics phenomena in viscous internal flow regimes. They will have the ability to demonstrate the aerodynamic characteristics of various geometries and AMD's or turbomachines, and compare them with their theoretical predictions. Students can use the bench to gather pressure drop and volumetric flow rate data then prepare plots of system performance for the device under test (DUT).

Keywords: Student Engagement Project, Airflow Test Bench, Aerodynamic Performance, AMCA.

INTRODUCTION

The Mechanical Engineering program at Western Kentucky University provides numerous project-based learning experiences as well as traditional engineering science coursework for its baccalaureate students [1]. These project learning experiences are both internally and externally supported with past external funding derived from agencies, such as ASHRAE and ASME. In senior design, students have an opportunity to choose from a variety of projects in order to allow them to learn more about topics that align with their interests. To execute these projects professionally, students work with their faculty advisors to guide them, and an industrial sponsor to check periodically the outcomes of the project to ensure that the design criteria are being met. This project, which is a redesign of the WKU airflow test bench, was provided to the first author as an independent project that will serve future undergraduate mechanical engineering students in a thermal fluids laboratory.

An airflow test bench is a device to measure the airflow impedance of a test specimen or the performance of an air moving device (AMD). The results for the passive test specimen can be expressed as a pressure drop or loss across the specimen versus volumetric flow rate through the specimen, and for the AMD, results are typically represented

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by a characteristic performance curve of pressure head versus volumetric flow rate. The purpose of this project is to redesign the existing airflow test bench in order to minimize overall leakage and improve its aerodynamic performance.

Therefore, a proposed method to minimize leakage is to reduce the number of apertures through a redesign of the existing airflow bench. Figure 1 shows the two plenums of the existing airflow bench. Both were constructed of melamine coated panels joined at their edges to form a square plenum with a 36 inch x 36 inch cross-section,. The two plenums were secured together with DE-STA-CO clamps with a rubber seal at their interface, where the volumetric flow elements, seven ASME nozzles, were housed on a single bulkhead. Two windows were also designed into the largest wall of the 36 inch x 60 inch plenum as well as a window in the slightly smaller section after the flow elements.

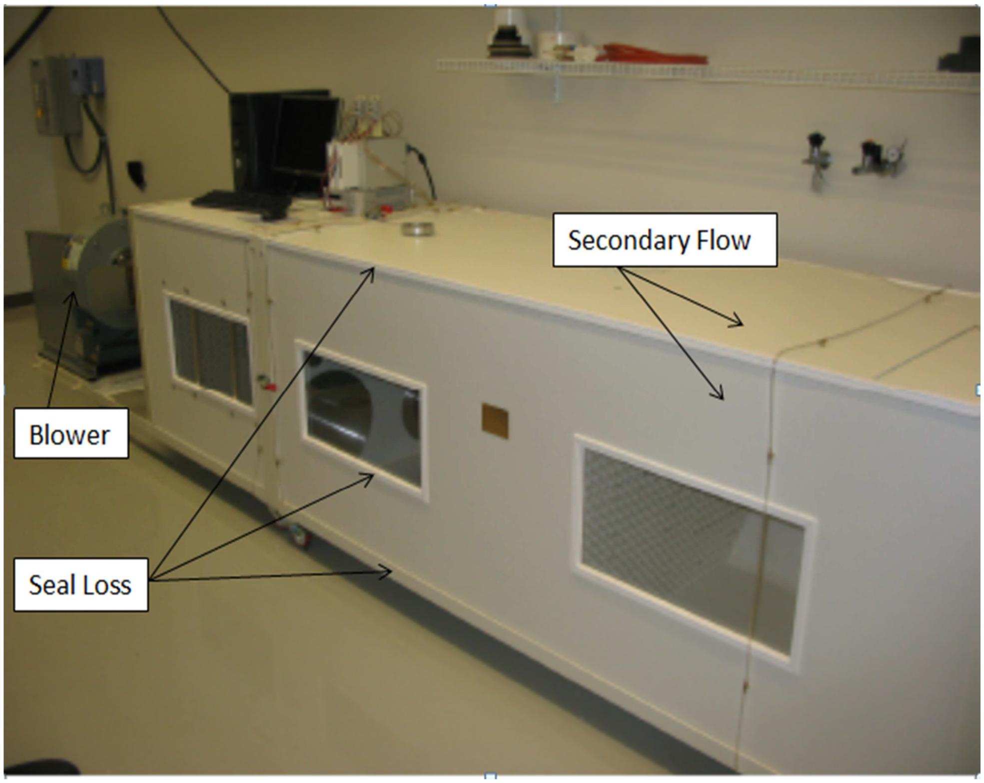


Figure 1: Existing Airflow Bench

In the existing airflow bench, it had been observed that significant air flow infiltration occurs during the evaluation of passive devices under test (DUT's) when both plenum sections experience a negative pressure relative to room atmospheric conditions. Expected locations of seal loss are shown in figure 1. Multiple attempts have been made to mitigate this leakage through the sealing of all corners and window joins of the plenums. These attempts have had limited success. The severity of the degradation in the airflow bench integrity had become so significant that attempts to even quantify leakage rate were unsuccessful.

Through a partnership with a regional design and manufacturing company, Des Case Corporation, the existing airflow bench had been used to characterize the impedance of one of their products - a filter/desiccant canister. The company generously provided data with the understanding that specific details be removed to protect their interests. The data was taken on two different occasions on the same canister. The impedance characteristics of a filter canister measured prior to and after the performance degradation of the airflow test bench is shown in figure 2. This data suggests that this infiltration or plenum leakage when downstream of the filter and upstream of the flow element represents a parallel impedance with the filter. This results in an unacceptable decrease in the pressure drop across the filter and an increase in measured volume flow rate through the filter. This data provides quantification of severity of the leakage rate for this application, and subsequently, a justification for the redesign effort.

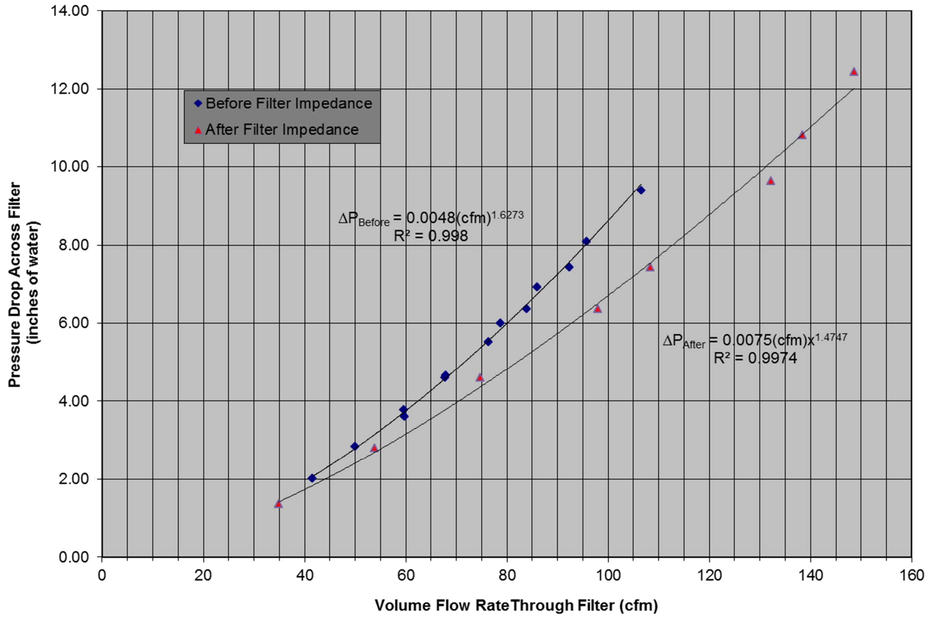


Figure 2: Impedance Test of Filter Assembly

When an AMD is tested; the section downstream of the AMD and upstream of the volumetric flow meter is under positive pressure with the respect to the room thereby expanding or "ballooning" the plenum further acerbating the seal failure and also creating unacceptable exfiltration or leakage. A heavy duty smoke pencil was used to visualize the behavior of air leaks from these apertures and cracks. The method proved useful and very successful in identifying leak locations in the bench when operated under the positive pressure conditions similar to an AMD evaluation. Figure 3 shows smoke is rising vertically from the smoke pencil's vapor chimney until it reaches a corner join of the existing bench and then the smoke starts changing direction away as it is entrained in the air escaping from the bench.

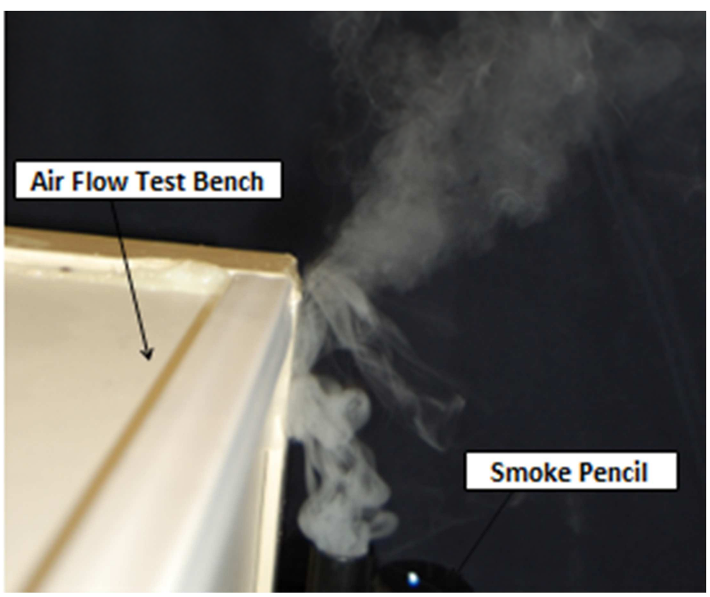


Figure 3: Flow Visualization of Air Leakage

A concept of the redesigned airflow bench is shown in Figure 4. The redesign replaces the melamine constructed plenums with circular cross-section plenums. The use of a circular versus square cross sections was the first major design consideration, since air leakage at the corners and around the windows would be a non-issue.

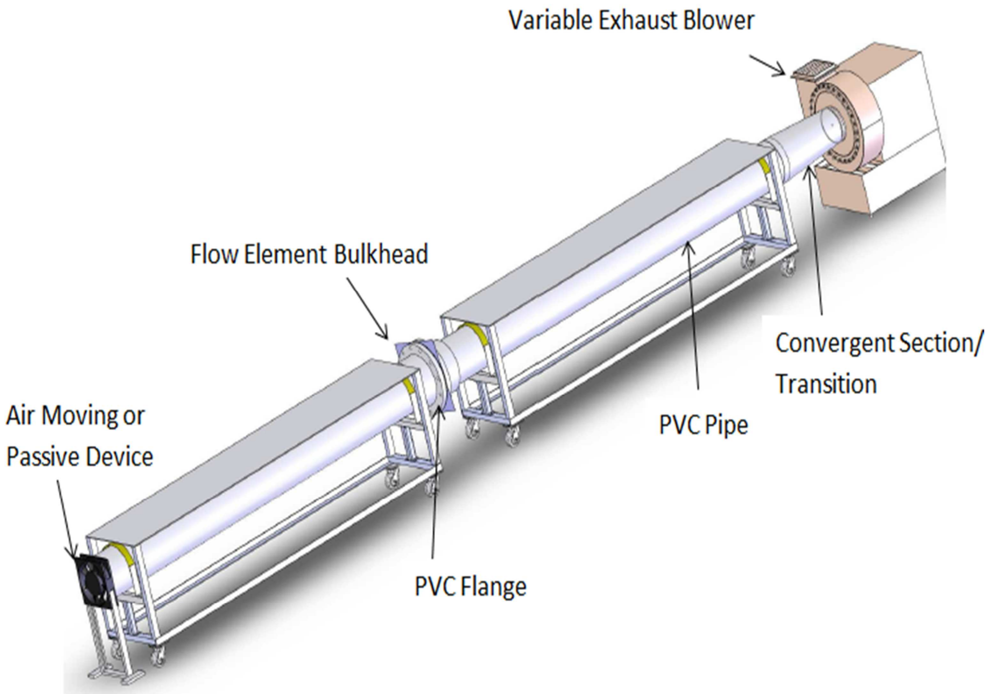


Figure 4: Redesigned Airflow Bench

This change will likely improve the overall results for DUT's –both passive and active. In this design, minimal leakage can possibly occur between the flange and the pipe because it is intended that the pipe and flange are not permanently joined. When finally assembled, a pressure test will be performed to determine the leak rate of the airflow bench. However, it is expected that the flexibility, afforded by this nonpermanent joining at the flange for maintenance and flow meter calibration, outweighs this possible minor leakage opportunity.

Another reason to support the decision of redesign with circular cross-section plenums is to improve the aerodynamic performance of the bench by elimination of secondary flows [2] created at the corners of the square plenums in location shown in figure 1 and an attempt to minimize entrance region effects. The modeling and measure of these effects are difficult; however, flow visualization of a properly dimensionally scaled "test bench:" is planned in early spring to qualitatively capture these phenomena. Additionally, flow straighteners or dampening panels will be incorporated perpendicular to the primary flow direction. These will serve to further eliminate any secondary flows and damp rotational behavior introduced by the DUT or the Variable Speed Exhaust Blower in the test bench.

DESIGN CRITERIA

In order to measure the success of the project, the following system level design criteria were established:

- The redesign airflow test bench must be able to generate volumetric airflow rates over the range of 10 to 2000 cfm at a maximum of 10 inches of water pressure drop and measure associated pressures and volume flow rates for the characterization of a passive DUT and of an AMD.
- The redesign airflow bench must meet the ANSI/AMCA/ASHRAE 41.2 – 1987 [3] for plenum dimensions, location of the flow elements, location of the flow straighteners, and the locations of the pressure static taps.

- The overall leakage rate must be minimized in the redesign airflow bench. A method outline [4] to characterize airflow leakage is given in equation (1):

$$Leakage\ Rate = 1800/(p_{atm} + 9.5)dt \quad \text{(cfm)} \tag{1}$$

- The aerodynamic performance of the system must be improved by reducing secondary flow effects and dampening air flow to ensure pressure measure repeatability in the airflow test bench at the pressure static taps. The location of static pressure taps will meet the standard based on a particular flow nozzle.
- The entire device must be durable and rigidly built to endure 10 years of service.

DESIGN OF THE TEST BENCH

In order to meet the acceptance criteria of the project, the student made use of the current bench components and integrated many of them into the redesigned airflow bench. The final redesign will consist of the following major components:

- Flow Bench Structure or Plenum (PVC Pipes and Flanges)
- Variable Speed Exhaust Blower (Not being considered in this redesign)
- Flow Elements (ASME Nozzles) (Not being considered in this redesign)
- Flow Element Bulkheads

Two of the above components, the variable speed exhaust blower and the flow elements (ASME nozzles) are not being considered in this redesign. However, some modifications will be necessary to properly incorporate these components into the bench. One of these is the flow element bulkheads. The following sections will outline relevant design criteria for the each of these major components.

Flow Bench Structure or Plenum (PVC Pipes and Flanges)

The design criteria for the flow bench structure or plenum (PVC Pipes and Flanges) include:

- The inside surface of the pipe must be smooth and obstruction free such that these surfaces will not create unnecessary air flow impedance or pressure drop beyond expected major loss at the prescribed flow rate.
- The length and diameter of the pipe must be chosen appropriately to minimize entrance region effects.
- The pipes and flanges when assembled must meet acceptable air leakage rates as defined by the system criteria.

In the redesign airflow test bench, two 10-foot long, 12-inch diameter PVC pipe sections with connecting flanges are to be used to satisfy these criteria. These materials were donated by Des Case Corporation to the engineering department. Des Case has a particular interest in the aerodynamic performance characteristics of filters, which may provide students with future opportunities for industrial outreach projects. The two sections of pipe will be installed on two Workplace® Systems laboratory benches, one for each section, and the two benches and their pipe sections will be connected together with a PVC flange. Between the two rings of the flange, a flow element bulkhead will be inserted with two rubber gaskets to seal and minimize air leakage. It is crucial to have the benches and their pipe sections on the same level horizontally in order to line up the pipe sections and the 12 bolt holes of each flange. To secure the pipes, four 2-inch wide steel straps have been designed and built to hold the pipes stationary. Two holes will be drilled into the strap tabs to bolt the straps to the box tubing of the laboratory bench structure where the pipes are to be secured. To enhance the structure of the Workplace® Systems laboratory benches, which were not intended for this type of application, four vertical post supports were also designed and built. These posts are to be positioned underneath the box tubing of the laboratory bench to support the additional load due to the 10-foot sections of PVC pipe.

Variable Speed Exhaust Blower

The design criteria for the variable speed exhaust blower system were demonstrated in the current airflow test bench to meet the following criteria. Preliminary calculations indicated that the redesign will not impact them.

- The blower must be able to overcome a minimum pressure of 10 inches of water created by the airflow bench and the DUT.
- The blower must create at least 2000 cfm @ 10 inches of water pressure drop.
- The laboratory facilities infrastructure provides 480V, 32.4 Amps, 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.
- In order to ensure safe operation, the blower must have guards for all moving parts.

The blower is very important component and must be able to overcome the pressure created by all components of the flow bench. From the previous design calculations with the largest nozzle, it was found that the pressure across the nozzle at 2000 cfm will create at most 8 inches of water head. Therefore, a centrifugal type is found to be the best choice for the air flow bench. A 9-IPA Greenheck blower was selected to be used in order to meet the requirements. This centrifugal blower is capable of creating more than 10 inches of water at the maximum designed flow rate, and it is available with a variable frequency drive motor and powered by 480V, 32.4 Amps, 60Hz, 3 phase.

Flow Elements (ASME Nozzles)

The design criteria for the flow elements (ASME nozzles) were demonstrated in the current airflow test bench to meet the following criteria. Preliminary assessment indicates that the redesign will not impact them.

- The flow elements must be capable of measuring an airflow rate from 10 to 2000 cfm with minimal non-recoverable head loss.
- The flow elements must be selected and designed in accordance with ASME MFC-3M-1989 [5] and ANSI/AMCA/ASHRAE 41.2-1987 [3].
- Traceable calibration of the flow element must be strongly considered.
- The flow element must be designed such that it may be removed for future maintenance, inspection, alteration, and calibration.

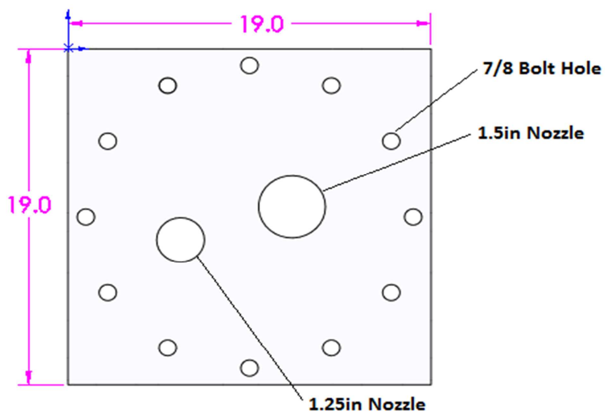
The flow elements are critical components of this bench to accurately determine volumetric air flow rate through them and therefore through the DUT. To achieve above criteria, ASME nozzles were selected to be used in the initial and retained for the redesign air flow bench. The nozzles in the original flow bench were arranged on a single bulkhead in an array. Each nozzle creates a known differential pressure at a prescribed volumetric flow rate. To measure air flow volume rates from 10 to 2000 cfm, a single nozzle was not sufficient because of the large range of the flow.

Therefore, seven nozzles were sized and designed based on ASME standards for the current airflow bench. Each nozzle measures a certain range of flow rate at maximum differential pressure of 8 inches and minimum of 1 inch of water. Static pressure taps will be installed along the pipe sections at specific locations upstream and downstream of the flow elements [3, 5]. Setra Systems, Model 264, differential pressure transducers will be used to measure the differential pressure across the DUT and the nozzle. In the redesigned flow bench, a nozzle array is not feasible given the limited cross-sectional area available in the 12-inch diameter PVC pipe. Therefore, either single or two nozzle configurations will be used to cover the desired operating range of the flow bench. The mounting bulkheads for the nozzles will be more fully described in the next section.

Flow Element Bulkheads

In the existing airflow bench, a square plenum cross-sectional area of 36 inch x 36 inch was designed to allow for the installation of a nozzle array housing all seven ASME nozzles. However, the redesign air flow bench cross-sectional area is 12-inch diameter PVC pipe, which does not provide sufficient surface area to mount all nozzles on one bulkhead; therefore, five bulkheads were designed. As shown in Figure 3, two smaller nozzles can be mounted on a 19 inch x 19 inch aluminum panel bulkhead and spaced such that no or limited effects between nozzles occur.

The other nozzles are either mounted in group of two or individually, as shown in Figure 4, per bulkhead, depending on the size of the mounting flange of the particular nozzle.



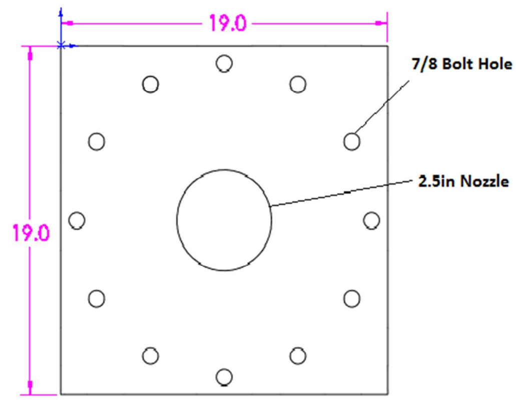


Figure 3: Drawing of one nozzle bulkhead **Figure 4**: Drawing of two nozzles bulkhead

Holes were drilled in the nozzles flanges to mount the nozzles on the bulkhead by using a rivet tool. These rivets will not mount the nozzles permanently; therefore, they can be removed for calibration, inspection, and maintenance as required. The flow element bulkheads are also mounted at the middle section of the bench where the two pipe sections are connected together by the flange as illustrated in Figure 5.

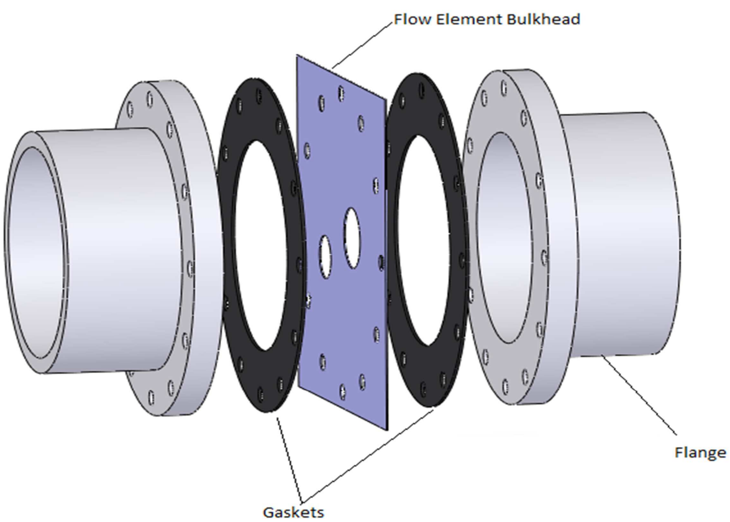


Figure 5: Schematic of the middle section of the bench.

Two Buna-N rubber gaskets were designed and fabricated to seal between the bulkhead and the rings of PVC flange. The gasket and flange material are compliant and will produce suitable seal under flange manufacture assembly instructions. During the test, one bulkhead or the selected nozzle at a time can be inserted into the bench, and if the bulkhead contains two nozzles, a nozzle cap will be used to stop flow through the nozzle not being used for the desired range of flow for the DUT.

SUMMARY

The paper provides overall description of the redesign of an airflow test bench. It has outlined the benefits to the infrastructure of a mechanical engineering thermal fluids laboratory and the design challenges in the redesign of the test bench. The redesign of the existing airflow test bench was required to minimize overall leakage rate and improve the aerodynamic performance of the system. This device will enhance future junior and senior students learning experiences in the demonstration of viscous internal fluids phenomena. The experimental results of a test specimen can be expressed as pressure loss versus flow rate, and for an AMD, the results are a characteristic performance curve. These results will help students to select AMD's or turbomachines based on the impedance characteristics of their particular system. Due to the project schedule, this paper does not include commissioning of the new airflow bench with results validating the minimization of overall airflow leakage and improvement of aerodynamic performance of the system. Also, an assessment of the learning outcomes for the student author has not been completed. These results will be included in the conference presentation.

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