A Centrifugal Pump Project: An Extracurricular Student Project

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Abstract – A student worker at Western Kentucky University was recently given the opportunity to re-design a centrifugal pump test bed to make it into a valuable piece of lab equipment. The test bed was initially conceived for instructional purposes in a senior level Mechanical Engineering laboratory course; however, time and financial constraints prevented its completion and commissioning. The test bed incorporates two centrifugal pumps into a pipe network so that they can be linked in series or parallel. Changes were made in an attempt to simplify and improve certain aspects of the original design, some of which introduced new challenges. Students can observe and take data for relevant pump parameters in order to plot the pump performance curves. This paper presents the design decisions and challenges, as well as the benefit of allowing a student to collaborate with faculty to design, build, and test a system, rather than purchasing a solution.

Keywords: Student Engagement Project, Centrifugal Pump Performance, Computer Simulation

INTRODUCTION

Western Kentucky University employs a student centric, project-based curriculum to train engineering students. Students gain applicable skills and experience applying concepts learned in the classroom though a series of design courses. In several of these design courses, students design, build, test and troubleshoot devices. This begins in the freshman year when students build an oscillating steam engine with seven main parts which the student constructs from aluminum on a mill, lathe and basic workshop tools. ME 412 is the culmination of a senior student's career at Western Kentucky University, in which teams of 3-5 students collaborate with the assistance and guidance of faculty advisors and industry contacts to design an acceptable solution to a problem and to then build and test it.

The original centrifugal pump test bed, which this paper is written about, was built in the spring of 2006. A grant from the American Society of Heating, Refrigeration, and Air Conditioning (ASHRAE) provided the funds to purchase the necessary hardware. The students worked diligently and were able to deliver the majority of a test bed. Due to limitations in funding and time, the test bed was not extensively tested or commissioned in 2006.

In addition to course work, the Department of Engineering at Western Kentucky University works with a number of students outside of class work. Some of these students have an interest in working on extracurricular projects, and some are paid to assist with lab and outreach support. The author of this paper is a current student worker in the Thermal Fluids Laboratory. He chose to work on this project in the spring and fall of 2011.

Allowing students to work on projects like this has the potential to benefit Western Kentucky University in a number of ways. Because students design and build with the input of professors, in many cases the final result is a

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piece of equipment that is more easily serviceable than a purchased solution. In some cases, the final result may be lower in cost than a purchased solution, particularly if some components can be re-used from previous projects. The main benefit, however, is in the learning opportunity the student experiences. These projects provide an additional avenue for a student to gain experience in designing and building, as well as improve understanding of theory and the physics which govern the world in which we live.

DESIGN CHALLENGES

Somewhat significant problems were encountering in the testing and troubleshooting portion of this project. A test bed, which can be seen in Figure 1, had been constructed which consisted of a simple pipe network which connected two centrifugal pumps so that they could be run in a series or parallel configuration. Each pump is driven by a 240 volt, 3 phase motor which is controlled by a Variable Frequency Drive (VFD). Pressure taps at the inlet and outlet of each pump and a rotameter on the discharge side of the pump configuration allows differential pressure and flow rate to be simultaneously measured.

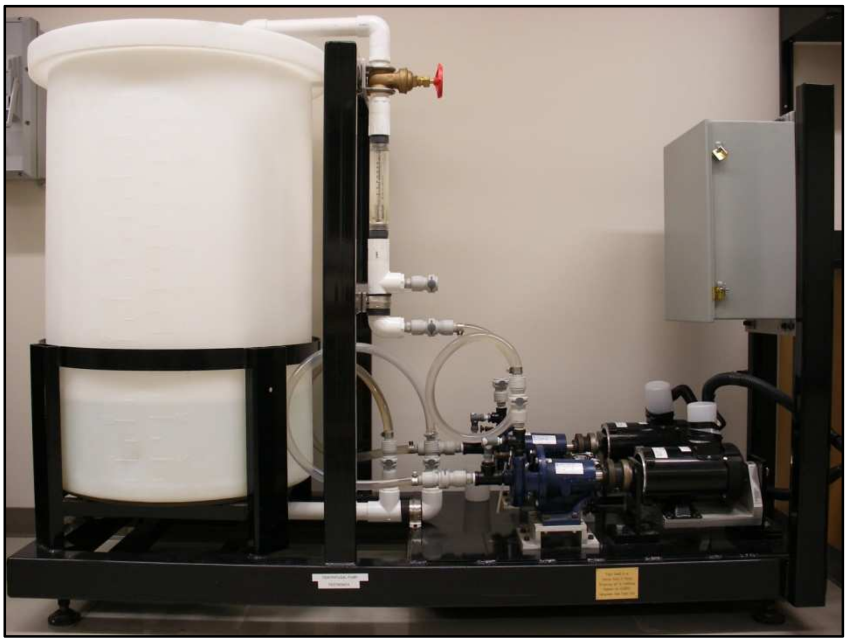

Figure 1: Centrifugal Pump Test Bed

A single pump performance curve was provided by the manufacturer to predict pump performance at varying operating points. This curve was given for a pump operating at 3500 RPM, with a 3.94” impeller installed. This curve is intended to be used to help a practitioner determine the correct pump for a given application, based on pressure and volume flow rate necessary. Figure 2 shows the manufacturer’s pump curve.

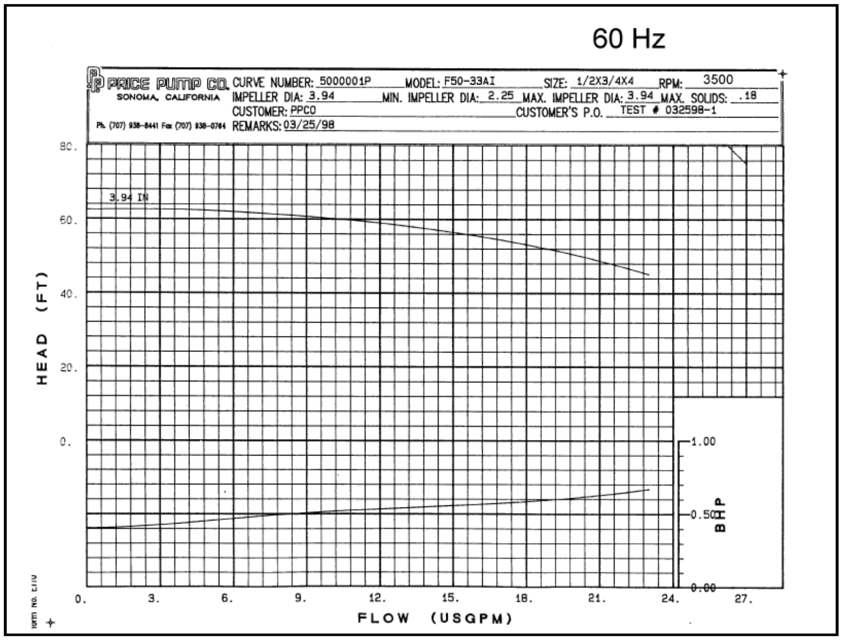

Figure 2: Manufacturer's Pump Curve [1]

There was significant challenge in understanding and reconciling the disagreement between empirical data and measured pump performance. A pump curve was given, and laws and relations known which govern pumps; however, there was still some disconnect between expected and actual performance. At the time of this draft's submission all of the causes for these disconnects are not fully known.

One of the most fundamental equations [2] which provides insight into the mechanics of fluid flow is the Generalized Mechanical Energy Equation (1). It is, in terms of pressure P, fluid density ρ, average velocity V, elevation z, gravitational constant g, and head h:

$$\frac{P_1}{\rho g}+\frac{V_1^2}{2g}+z_1+h_{pump}=\frac{P_2}{\rho g}+\frac{V_2^2}{2g}+z_2+h_{turbine}+h_{loss} \tag{1}$$

In this test bed, the $h_{turbine}$ term is zero, as there is no turbine extracting energy from the working fluid. Also, because the volume of water in the reservoir is large in comparison to the volume of water flowing through the pump and the pipe network, the average velocity in the reservoir can be assumed to be zero. Rearranging terms provides equation (2):

$$h_{pump,required}=\frac{P_2-P_1}{\rho g}+\frac{V_2^2}{2g}+z_2-z_1+h_{loss} \tag{2}$$

Equation (2) shows that the pump must provide a change in fluid pressure and fluid velocity while overcoming any differences in elevation between the inlet and outlet, as well head loss which is present in any pipe network.

Head (pressure) loss is due to friction as the fluid flows through pipes. The losses due to viscous effects between pipe walls and the fluid are called major losses, and are shown in equation (3). Losses that occur in pipe components such as fittings, tees, expansions and contractions, valves and other obstructions are termed minor losses, and are presented in equation (4)

$$h_{L,major}=f\frac{L}{D}\frac{V^2}{2g} \tag{3}$$

$$h_{L,minor}=K_L\frac{V^2}{2g} \tag{4}$$

where f represents the friction factor due to pipe roughness, L represents the length of the pipe, and D is pipe diameter. K_L is a simplified loss coefficient that can be determined from tables which were generated by experimentation for the specific component.

The two terms can be combined to yield equation (5).

$$h_{L,total} = \left(f\frac{L}{D} + \sum K_L\right)\frac{V^2}{2g} \tag{5}$$

These loss terms combine in the test bed pipe network and add to the necessary change in pressure, velocity, and elevation which the pump must overcome. This conclusion yields equation (6) which states that the head required must equal the head available from the pump.

$$h_{required} = h_{available} \tag{6}$$

The similarity laws are extremely useful methods to predict pump performance between geometrically similarly pumps. Pump curves are given, usually by the manufacturer, for a specific pump operating under specified conditions. Often the end user wants to use a slightly different pump, or use it under different operating conditions, such as at a different rotational speed. The similarity laws are useful to predict performance from one known operating point to another unknown operating point. These relations were used extensively to predict the performance of the pumps used from the pump characteristic curve given by the manufacturer. The similarity laws are:

$$\frac{Q_B}{Q_A} = \frac{\omega_B}{\omega_A}\left(\frac{D_B}{D_A}\right)^3 \tag{7}$$

$$\frac{H_B}{H_A} = \left(\frac{\omega_B}{\omega_A}\right)^2\left(\frac{D_B}{D_A}\right)^2 \tag{8}$$

$$\frac{bhp_B}{bhp_A} = \frac{\rho_B}{\rho_A}\left(\frac{\omega_B}{\omega_A}\right)^3\left(\frac{D_B}{D_A}\right)^5 \tag{9}$$

in terms of flow rate Q, rotational speed ω, impeller diameter D, head H, fluid density ρ, and brake horsepower bhp. Equation (7) is called the capacity coefficient, (8) is called the head coefficient, and (9) the power coefficient.

Figure 3 shows the manufacturer supplied pump curve, as well as two pump curves which were generated in Microsoft Excel using the above pump similarity laws. The manufacturer provided a performance curve for a 3.94" impeller, with a rotational speed of 3500 RPM. The test bed used for this project originally ran at 1780 RPM, and then was altered to run at 3400 RPM by changing the VFD settings. Additionally, the pumps incorporated in the test bed use a 3.69" diameter impeller rather than the 3.94" impeller which was used to generate the manufacturer's curve.

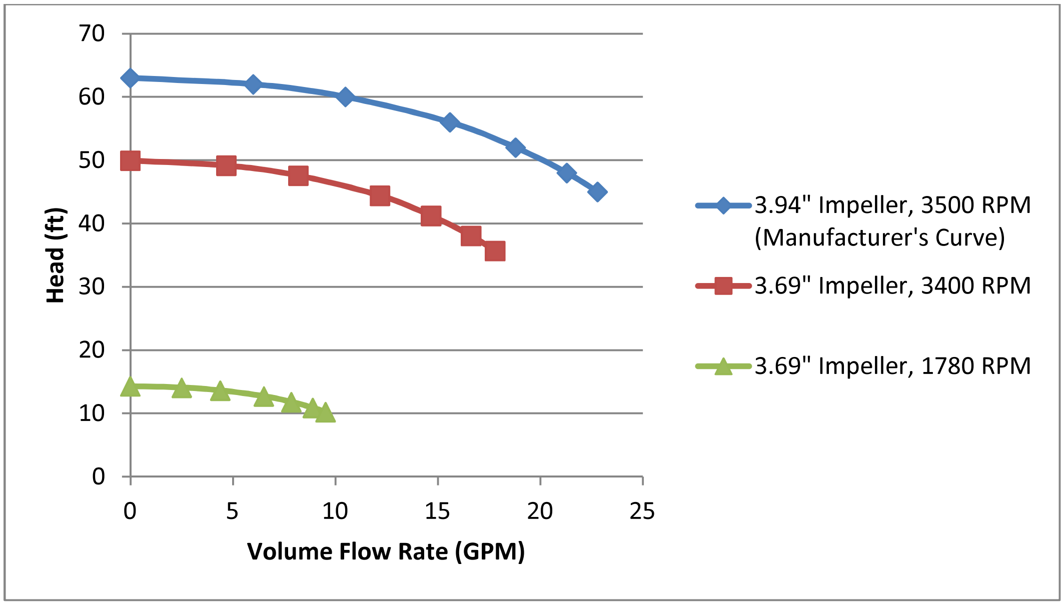

Figure 3: Manufacturer's Curve and Predicted Curves

The first time the test bed was run, no observable flow rate was measured by the rotameter. The flow meter does not begin to read flow until a flow rate of four gallons per minute of flow is observed. A pressure reading was taken and compared with the provided pump performance curve. Approximately 10 feet of water pressure difference was measured across the pump, which suggested a flow of around 40 gallons per minute according to the pump performance curve in Figure 3. A permanent method of measuring pump rotational speed had not been incorporated into the test bed at this point, so a hand held tachometer was used. At this point it was discovered that the VFD readout of RPM was incorrect, and the pump was rotating approximately 1780 RPM rather than the expected 3400 RPM. Settings were changed in the VFD to allow nearly 3500 RPM of rotational speed, and more data was taken of flow and pump head.

After making this change, there was still significant disagreement between predicted curves and the measured operating point of the pump. The operating point was measured to be at a flow of roughly 5 GPM, and 38 feet of water head across the pump. Figure 4 shows the pump performance curve as predicted from the manufacturer's curve, with parabolic curves representing the projected impedance curves of the system pipe network.

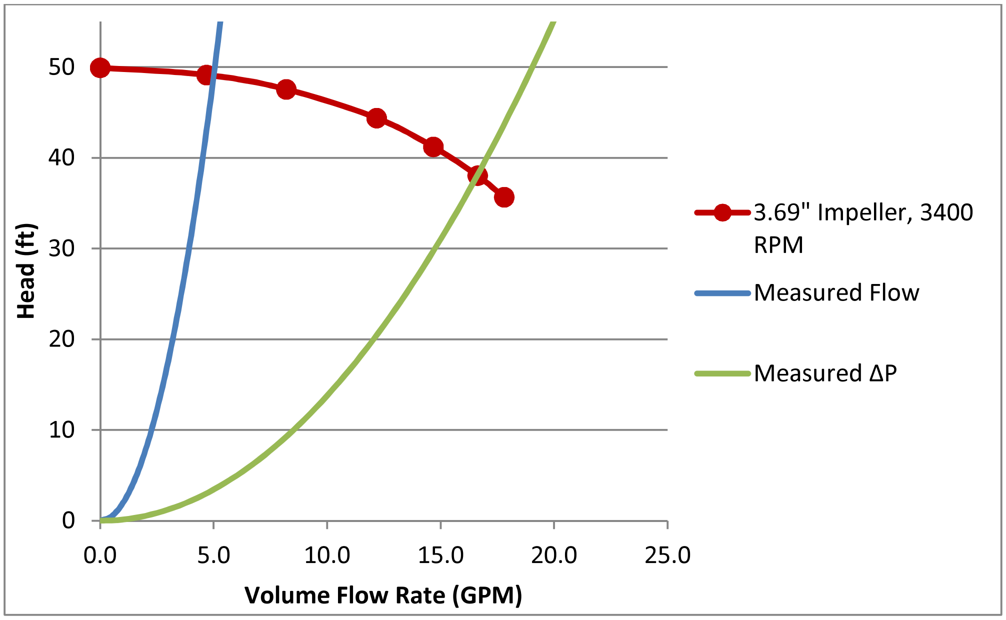

Figure 4: Pump Curve and Operating Point

The intersection of the lines for Measured Flow and Measured ΔP with the pump characteristic curve represent two possible operating points for the pump in the test bed. The actual operating point is likely somewhere in the region between these points. More analysis and data collection are necessary to discover the pumps operating point with the pressure loss caused by the pipe network.

A valuable tool for analyzing complex fluid flow problems is provided in a software package called Applied Flow Technology (AFT). AFT allows a user to build a simulated system model with all necessary pipes, junctions, pumps and other components, with all necessary geometry and characteristics input [3]. The software is able to make very complex systems easily and quickly solvable. In order to gain a better understanding of the expected operating conditions of the system, a model was created in AFT. Figure 5 shows the workspace model which was created in AFT.

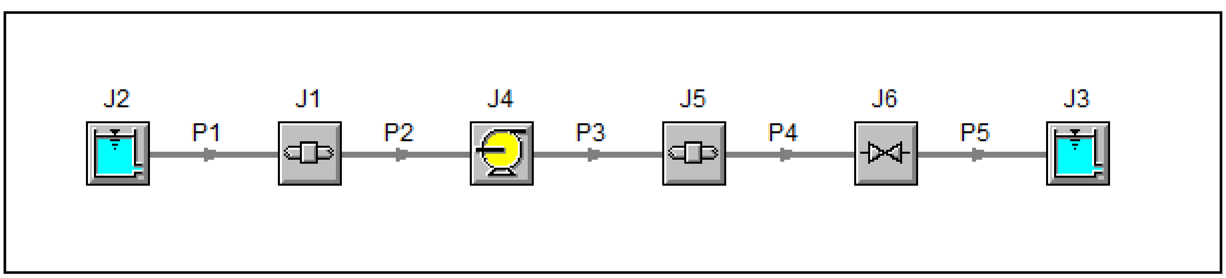

Figure 5: AFT Workspace

Output

General | Warnings | Pump Summary | Valve Summary | Reservoir Summary

Jct	Name	Vol. Flow (gal/min)	Mass Flow (lbm/sec)	dP (psid)	dH (feet)	Overall Efficiency (Percent)	Speed (Percent)	Overall Power (hp)	BEP (gal/min)	% of BEP (Percent)	NPSHA (feet)
4	Pump	9.968	1.384	20.02	46.27	100.0	100.0	0.1164	N/A	N/A	12.99

Figure 6: AFT Pump Output

Figure 6 shows the solved output of the AFT model. This model predicts a flow rate of roughly 10 GPM with a loss of 46 feet of water. When Figure 4 is consulted, this is clearly in line with predicted results. A data point at 46 feet of water and 10 GPM falls very near to the pump performance curve, and is between the two experimentally determined system impedance curves.

The main benefit that AFT provides is its ability to iterate and find a converged and appropriate solution. For all but the most simple fluid flow problems, a converged solution is difficult and time consuming to arrive at. Often multiple iterations are necessary, and multiple equations must be solved simultaneously. Additionally, many parameters which must be entered are dependent on flow rate, which is typically an unknown or a design criteria for the pipe network. An example of this is the quick disconnect fittings utilized in the test bed. Figure 7 shows pressure drop versus flow rate for the fittings used. Data points taken from this curve were input into AFT in order to determine the operating point of the pump in the test bed.

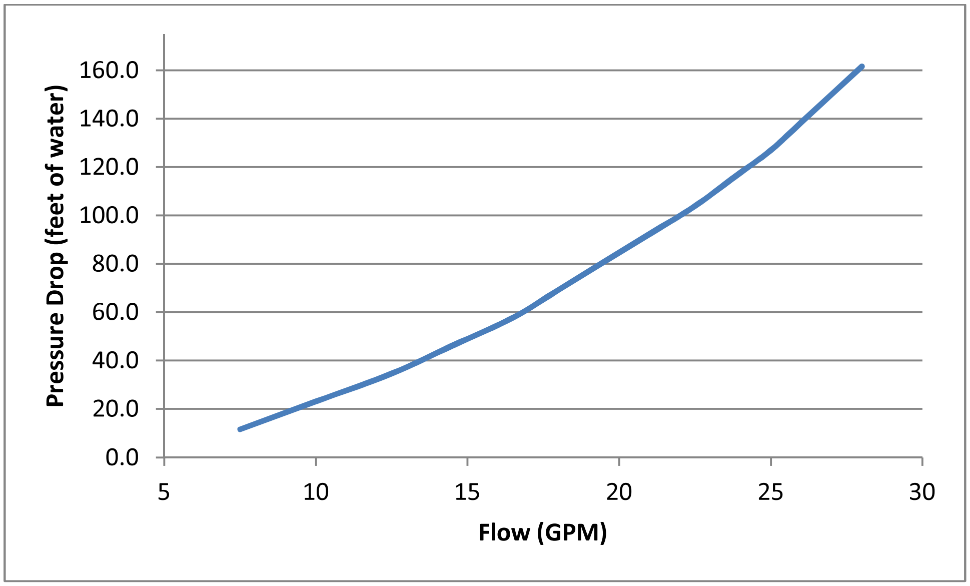

Figure 7: CPC Fitting Pressure Drop vs. Flow Rate [4]

DESIGN OF THE TEST BED

The majority of the test bed had already been constructed prior to the student undertaking this project. What remained were many of the smaller, yet important details, such as mounting and wiring of the electronics, selection and installation of control methods, and troubleshooting and commissioning. Additionally, some components which had been incorporated were clearly not the best solution, so a re-design of these components was desired. This included the pipe network and tank connection.

Pipe Network

A user friendly, easily understandable pipe network was desired for this project. Even with a simple two pump pipe network, the actual fluid flow can be somewhat complex to the typical student user who is not intimately familiar with it. This network is more complex when both series and parallel flow are desired to be included.

The pipe network was constructed from ¾” flexible hose was used in combination with leak proof quick disconnect fittings. Four lengths of hose were incorporated, so that the two pumps can be run in series or parallel, with the user making the required connection in a hands-on interface. Rather than opening and closing valves to re-direct the path of flow, the user makes the connection with clear hose. The leak proof fittings were key in this endeavor, as a quick disconnect that is not leak-free would provide a very messy and dangerous process to change the pipe network. The drawback to the use of these quick disconnects is their significant contribution to the minor losses of the pipe network. At the AFT predicted flow rate of 10 GPM, the quick disconnects could contribute approximately 40% of the overall head loss in the pipe network. Given this outcome, further research is needed to finalize this design decision.

The quick disconnect and flexible hose assemblies were only half of the pipe network. A good solution was needed to connect to the water reservoir, as well as incorporate a flow meter, throttling valve, and pressure measurement fittings.

The test bed originally incorporated copper pipes and necessary fittings to achieve these tasks. The copper was not the most aesthetically pleasing, and was somewhat cumbersome to work with. Cost of purchasing new copper for modifications was also significant. The decision was made to use standard PVC pipe. 1 ½" PVC was used, to provide minimal obstruction to flow. The PVC was easy to cut to length, clean and glue together. Unions were used in strategic locations to enable the assembly to be taken apart if necessary.

The quick disconnect fittings were purchased with ¾" MPT fittings, which were connected to ¾" FPT PVC fittings. The flow meter, which had already been purchased, was easily connected to the PVC pipe network using the appropriate threaded fittings. A gate valve was incorporated to enable flow to be restricted. A bronze gate valve was selected with 1 ½" FPT connections, which provided a large and robust valve which will provide a reliable means of throttling flow.

Pressure Measurement

A simple way to measure both inlet and outlet pressure for each pump was necessary. Handheld pressure gauges had already been purchased, and it was an obvious decision to incorporate more quick disconnect, leak free fittings to facilitate these measurements.

This solution allows the user to simply plug the appropriate pressure gauge into the static pressure tap at which a measurement is necessary. This method provides a more hands-on method rather than having a panel mounted set of gauges, which could be viewed as a disadvantage to student learning. This solution was chosen because it helps students to visualize and understand the readings being taken.

The quick disconnect fittings chosen were supplied with ¼" NPT fittings. The inlet and outlet of each pump is the logical place to measure flow, so cast iron "T" fittings were installed to allow flow in and out of the pump, as well as pressure measurement. These cast iron fittings proved difficult to make leak free. Brass, which would have been less leaky, was not used due to the desire to not mix dissimilar metals (the pump volutes were made of cast iron). The cast iron fittings were painted to prevent rust and keep the test bed looking as professional and orderly as possible.

SUMMARY

This DBT project was a valuable undertaking for both the WKU ME Program as well as the student who worked on it as an extracurricular activity. The Thermal Fluids Laboratory has gained a valuable piece of lab equipment which can be used by students in the future to better understand centrifugal pump performance. The test bed is simple in its design and fabrication, and consequently will be more easily serviceable and have good parts availability.

The main benefit of this project, however, is the learning outcomes for the student involved. The student worker has been given a learning opportunity which is not possible to make available in any one course. The result is a value added experience to his undergraduate education through application of the design, build, and testing process necessary to complete a project.

The test bed which is the subject of this paper has not been fully commissioned at the time of this draft. Future activities will provide proper data which can be used to better quantify the pump performance. It is intended to add to this paper, when the progression of the project allows, to include more details in the "Design Challenges" section, as well as include information regarding a student laboratory procedure.

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