Project-Based Learning: The Evolution of a Senior Project to a Laboratory Test Bed

Darren Tinker[1], Robert Choate[2], Joel Lenoir[3]

Abstract – The proper selection and integration of centrifugal pumps require that engineering students understand their performance characteristics and operational parameters in various configurations. To support student learning, a centrifugal pump test bed was designed, built and tested for the Thermal Fluids Laboratory at Western Kentucky University. Initially fabricated as a senior capstone project, the test bed has since been enhanced by student workers of the Thermal Fluids Laboratory. Modifications of the test bed include multiple design iterations of the pipe network, revision of measurement techniques, and incorporation of an electronic enclosure with an external control system. The purpose of this paper is to present justification and an analysis of the evolution of the senior capstone project as well as elaborate on the significance of the test bed's functions in a laboratory setting. In addition, the importance of the test bed as an augmentation of the curriculum for the student worker will be addressed.

Keywords: Fluids, Centrifugal Pumps, Test Bed

INTRODUCTION

A unique aspect of Western Kentucky University engineering programs is the project-based curriculum to educate and guide students in order to develop strong engineering practitioners. The program normally concludes with a senior project where students, under the guidance of a faculty advisors and criteria of industrial clients, develop solutions to real world problems faced by their clients. While theoretical solutions are presented by the senior project teams, the majority of students gain experience firsthand by developing experiments and personally fabricating the solutions. From the beginning to the end of the curriculum, students are immersed in projects where they become acquainted with the processes associated with professionalism, acquiring materials, fabricating, experimenting, testing, and applying their knowledge of the engineering sciences.

The faculty at Western Kentucky University recognized the need for a test bed to characterize the performance of centrifugal pumps and their operation in various configurations. Due to said need, a senior capstone project to design, build and test a centrifugal pump test bed for the Thermal Fluids Laboratory was proposed. The proposal was accepted and then funded by the American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc. (ASHRAE, Inc.) though their Senior Undergraduate Project (SUP) Grant program for the 2005 – 2006 school year.

The senior project team responsible for the test bed worked with great diligence to complete the test bed. Their deliverable was a test bed capable of operation in series and parallel configurations with the ability to measure pump inlet and outlet pressures, volumetric flow rate, pump shaft angular velocity, shaft torques and the water

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temperature. Due to time constraints, unfortunately, the test bed was not yet capable of safe and consistent operation by students as a laboratory test bed.

The nearly completed test bed was turned over to the mechanical engineering program in June 2007 and incorporated as part of the Thermal Fluids Laboratory. Over the following few years, modifications of and responsibility for the centrifugal pump test bed were handed down to student workers of the laboratory. The two previous workers, Nick Harlow and Taylor Weatherford, sequentially adopted and worked to enhance the test bed [1]. Specifically, significant improvements of the test bed have been multiple design iterations of the pipe network, more precise measurement techniques, production of the pump performance curves, and material purchases.

The most recent student worker, the first author of this paper, modified and completed the test bed with the most significant additions being an electronic enclosure to protect the control and power systems and replacement of the cast iron volutes with bronze volutes. The current test bed offers continuous operational control without the need to open the electronic enclosure, thereby protecting students from exposure to electrical hazards. Additionally, the volute replacement will improve longevity of the test bed by preventing corrosion.

METHODOLOGY

Evolution of Design

The layout of the test bed consists of two centrifugal pumps interconnected by a series of valves and pipes. The pumps are powered by two 240-volt 3-phase motors. The pumps are supplied by a 100-gallon reservoir to which the water is recycled upon exiting the pipe network. A globe valve at the end of the pipe network is used to alter the impedance of the system. Control of the pumps is attained through two variable frequency drives (VFD's), two externally operated potentiometers, and a master shut off switch. A schematic of the piping system is shown in Figure 1.

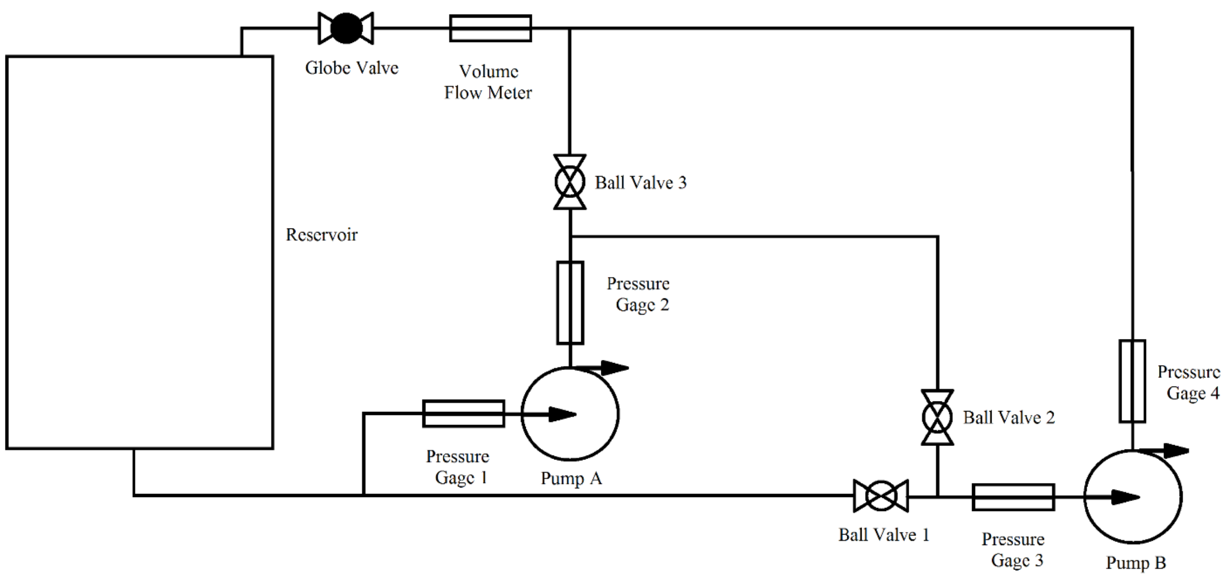

Figure 1: Centrifugal Pump Test Bed Schematic

As shown in Figure 1, pressure is measured prior to entering and after exiting each pump. The volume flow rate is measured before reaching the globe valve where water is then returned to the reservoir. The mechanical measurement methods are shown in Figure 2. Specifically, the torque is measured via force probe at the base of one of the motors. Additionally, rotational speed of each motor is measured by two optical sensors aimed at the coupling joint.

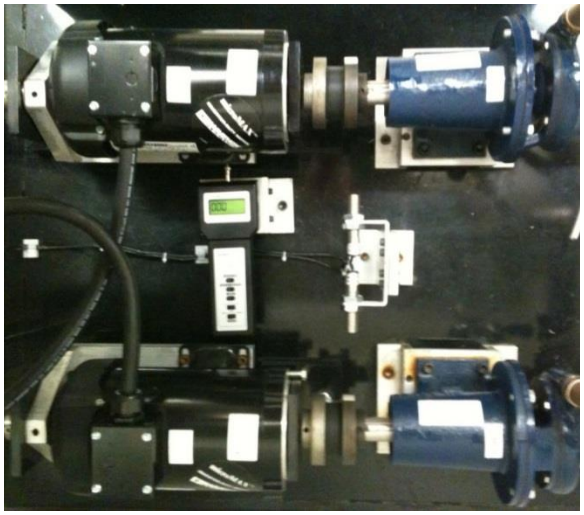

Figure 2: Top View of Motor-Pump Assembly, Force Probe, and Optical Sensors

As shown in Figure 3, the initial design by the senior project team consisted of copper pipes and fixed pressure gages before the inlets and after the outlets of the pumps. Given this construction method, repair and maintenance were difficult, but a more significant hindrance was that the pressure gages employed had low resolution and produced unreliable data. In addition to the goal of producing better data, a third necessity was placement and storage of electronics as the senior project team did not have time to prepare and mount the electronic enclosure.

After the test bed was adopted by the Thermal Fluids Laboratory, a student worker replaced the copper piping with a flex hose network to lessen the amount of work required for maintenance and repair. A second benefit of the new network was addition of valves for a digital manometer for measuring differential pressure, replacing the analog pressure gauges. The flex hose assembly was successful regarding simplification and ease of use, but led to higher-pressure losses from the no-leak connecters. A significant reduction in losses has been demonstrated when comparing the original data to the revised system. Furthermore, the characteristic curves developed align themselves significantly closer to those provided by Price Pump, the manufacturer.

Figure 3: Front view of the pipe network of the centrifugal pump test bed as of 2006

The same student worker shortly graduated, but had acquired the majority of materials to complete the test bed. In turn, the following student worker was informed of the goals and expected to complete, test, and commission the test bed. In an attempt to reduce the losses from the no-leak fittings, the flex hose assembly replaced was with a PVC pipe network similar to the initial copper network. The modification produced sufficient data proving that the losses from the no-leak fittings were significant, but was cumbersome with regards to maintenance. As shown in Figure 4, sections of the PVC pipe were removed and replaced with flex-hose and barbed adapters. With this replacement, the objectives of simplicity and ease of repair were obtained without interference to functionality.

Figure 4: Current design of flex-hose/PVC pipe network

The next major enhancement was the inclusion of the enclosure for electronics. Openings were cut for potentiometers and tachometers used to dictate the motor speed as well as for the electrical cables. NEMA 6 rated grommets were used to protect electrical cables of the motors, optical sensors, and the power cable entering the enclosure. The cables leaving the motor head were also guarded by the same style grommet.

As envisioned, the design of the test bed ensures that the safety of students is held paramount. Since completion, the enclosure has been subject to an unintentional blast from a jet of water. The internal components were found completely dry upon inspection. Due to the design and the performance of the enclosure during the blast of water, the test bed is considered safe for students to operate without risk of electrical shock. In addition, the enclosure is lockable, preventing damage to the test bed components as students are unable to alter the VFD programming.

Additional precautions were warranted should the piping system fail or the system begin to act hazardously. Given the possibility of either event, a latching emergency pump shut-off switch has been incorporated. The switch has been tested and hastily stops the pumps.

Key Concepts

Centrifugal pumps, specifically, are some of the most common machines used to provide flow work; hence, comprehension of the performance of the machine is critical. Poor selection of a centrifugal pump can result in failure or costly operation due to the pump's strength and efficiency. In fact, it is sometimes more cost efficient to use a pump with lower efficiency [4]. As engineers may be tasked with the design or selection of turbomachines, understanding the requirements of a fluid flow system and the performance of a turbomachine is a necessity for undergraduate mechanical engineers.

To start, students must consider the energy-equation during steady-state as shown below [2]:

$$\dot{Q}_{\text{net in}} + \dot{W}_{\text{net in}} = \dot{m}_{\text{outlet}}\theta_{\text{outlet}} - \dot{m}_{\text{inlet}}\theta_{\text{inlet}} \tag{1}$$

where theta, θ, from Equation (1) is defined as:

$$\theta = h + \frac{V^2}{2} + gz \tag{2}$$

and the definition of enthalpy, h, in Equation (2) is:

$$h = u + \frac{P}{\rho} \tag{3}$$

Given that the diameter of the inlet and outlet are essentially equal and the flow is incompressible, the mass flow rate and therefore the average velocities at each control surface are considered equivalent. In addition, the potential energy increase is considered negligible. The simplification of the energy equation becomes:

$$q_{\text{net in}} + w_{\text{net in}} = \left[u + \frac{P}{\rho}\right]_{\text{outlet}} - \left[u + \frac{P}{\rho}\right]_{\text{inlet}} \tag{4}$$

Dividing Equation (4) by gravity and rearranging gives:

$$\left[\frac{P}{\rho g}\right]_{\text{outlet}} - \left[\frac{P}{\rho g}\right]_{\text{inlet}} = \frac{w_{\text{net in}}}{g} - \frac{u_{\text{outlet}} - u_{\text{inlet}} - q_{\text{net in}}}{g} \tag{5}$$

The differential pressure, expressed as head, is replaced with H, the net head. The net-shaft work in from the pump expressed as head is replaced with the term h_s. In the same way, the last group of variables is replaced with h_f, representing the frictional and heat losses of the system:

$$H = h_s - h_f \tag{6}$$

Therefore, the net head of the fluid system becomes the difference between the energy added by the pump and the system's losses. The net head (or differential pressure) is then used to calculate the energy given to the fluid, more commonly called the water horsepower (whp):

$$whp = \rho * g * H * \dot{V} = \Delta P * \dot{V} \tag{7}$$

The total energy supplied to the pump, the brake horsepower (bhp), is found using the rotational velocity and torque of the motor:

$$bhp = T * \omega = F * d * \omega \tag{8}$$

The ratio of the water horsepower and brake horsepower gives the efficiency of the pump as shown:

$$\eta_{\text{pump}} = \frac{whp}{bhp} = \frac{\Delta P * \dot{V}}{F * d * \omega} \tag{9}$$

Given that students measure all variables in Equation (9) for a range of operating points (with the distance of the force supplied), students are able to calculate the efficiency at any given point of operation. With multiple measurements, students should be able to estimate the best efficiency point.

In addition, dimensional analysis with the affinity laws can be used by students to predict the performance curve of the pump given the manufacturer's curve and system parameters. For any two geometrically and dynamically similar systems, the affinity laws are [4]:

$$\frac{\dot{V}_1}{\dot{V}_2} = \frac{\omega_1}{\omega_2}\left(\frac{D_1}{D_2}\right)^3 \tag{10}$$

$$\frac{H_1}{H_2} = \left(\frac{\omega_1}{\omega_2}\right)^2\left(\frac{D_1}{D_2}\right)^2 \tag{11}$$

$$\frac{bhp_1}{bhp_2} = \frac{\rho_1}{\rho_2}\left(\frac{\omega_1}{\omega_2}\right)^3\left(\frac{D_1}{D_2}\right)^5 \tag{12}$$

Since the impeller diameters and fluid densities remain constant, students are easily able to estimate the performance curves of the pumps. Additionally, students could perform calculations for alternate operational configurations (i.e. coupling the pump to a different motor, changing impeller diameters, and varying fluid densities).

It is worth noting that the test bed used by Western Kentucky University and the manufacturer are likely not identical with regards to piping network geometry and operational conditions. For these reasons, the actual performance is not expected to be equivalent to that of the manufacturer, but relatively close.

For example, to properly develop the manufacturer's curve, the system must have a zero pressure differential excluding what the pump creates. The pump pressure differential can be expressed as the difference between the energy-grade-line (EGL) in and out. Measurement of the EGL's could be taken with a pitot tube at the center of the flow at the entrance and exit of the pump as illustrated in Figure 5.

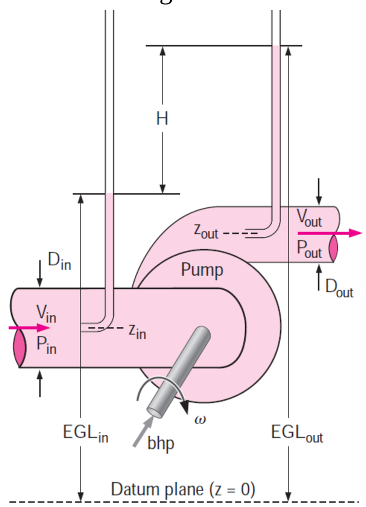

Figure 5: Pump parameters and EGL measurement locations [4]

Theoretically, the difference between each EGL is the same differential as the net shaft work out (h_s) and the net frictional losses (h_f), where the frictional losses are equal to zero. For clarity, this is shown in equation (13):

$$\mathrm{H} = \mathrm{EGL_{out}} - \mathrm{EGL_{in}} = \mathrm{h_s} - \mathrm{h_f} = \mathrm{h_s} \tag{13}$$

To overcome the aforementioned losses, it is likely that the manufacturer operates two pumps in series. The first pump is the pump under examination. The second pump is used to compensate for losses of the system.

As our lab has not investigated the development of a pump curve using two pumps in series, the hydraulic grade line (HGL, the sum of state pressures and elevation heads) was increased. Explicitly, the reservoir was filled to the maximum level. The increased HGL was used to compensate for dynamic losses of the system.

Developing the Curve
The performance of the test bed has been documented lightly for two previous iterations and examined thoroughly for the existing version. Before elaborating on the results, the procedures to gather the data will be explained comprehensively.

The reservoir is able to hold just over one-hundred gallons (roughly 400 liters). As the height of the water directly influences the head at the inlet of the pump, each test (on the existing version of the test bed) was performed with approximately one-hundred gallons of water, the uncertainty near one gallon. One-hundred gallons was chosen to ensure the water level inside the reservoir adequately envelops the end of the pipe returning water. Without the end of the pipe submerged, the water becomes aerated, clearly hindering the efficiency of the pumps and the reading of the volume flow rate. The large volume also prevents cavitation of the pump impeller at high rotational speeds.

Once the reservoir is filled, the globe valve is fully opened, all ball valves on the pipe network are opened, the pumps are primed, and water is allowed into the pipe network. Parallel or series configuration is used (temporarily) to prevent backflow, and the pumps are activated to evacuate the air from the remainder of the pipe network. If necessary, the water level is readjusted to the desired volume after air has been sufficiently removed from the system.

From here, the pipe network is adjusted for operation of the pumps in series or parallel configurations, or as singular units. The system is energized and data collection may begin.

The pumps are simultaneously increased to the desired rotational speed and then allowed to reach a steady state. At this point, the volume flow rate, differential pressure, rotational speed, and force from the motor are all measured. The ball valve at the end of the pipe network is slowly turned until the volume flow rate has decreased to the desired operating point. A steady state is acquired and the data is recorded again. The process is repeated until the shutoff head is reached.

The aforementioned steps are parallel to the laboratory procedure created for the experiment, the exception being that students are instructed in which configuration to operate the test bed. The post lab requirements for students are to plot the performance curves of each configuration, calculate the efficiency of the pumps, and compare the performance curve of a single pump to the curve given by the manufacturer.

RESULTS

Using the affinity laws and the pump performance curve provided by the manufacturer, the experimental curve of the system was compared with a scaled manufacturer's performance curve (adjusted from 3500 RPM to 3215 RPM), as shown in Figure 6. The scaling was necessitated by a maximum rotational speed of 3215 RPM of the test bed. As expected, the performance of the test bed was not equal, but close to the scaled manufacturer's curve. Visually, an estimated head difference between each of the curves is 6 to 7 feet of H_2O. The major differences between head levels are due to the viscous and mechanical losses of the system. Differences between the shapes of the curves are attributed to the fact that the test bed at Western Kentucky University is not geometrically or functionally identical to that used by the manufacturer to produce their curve (as mentioned in the Key Concepts).

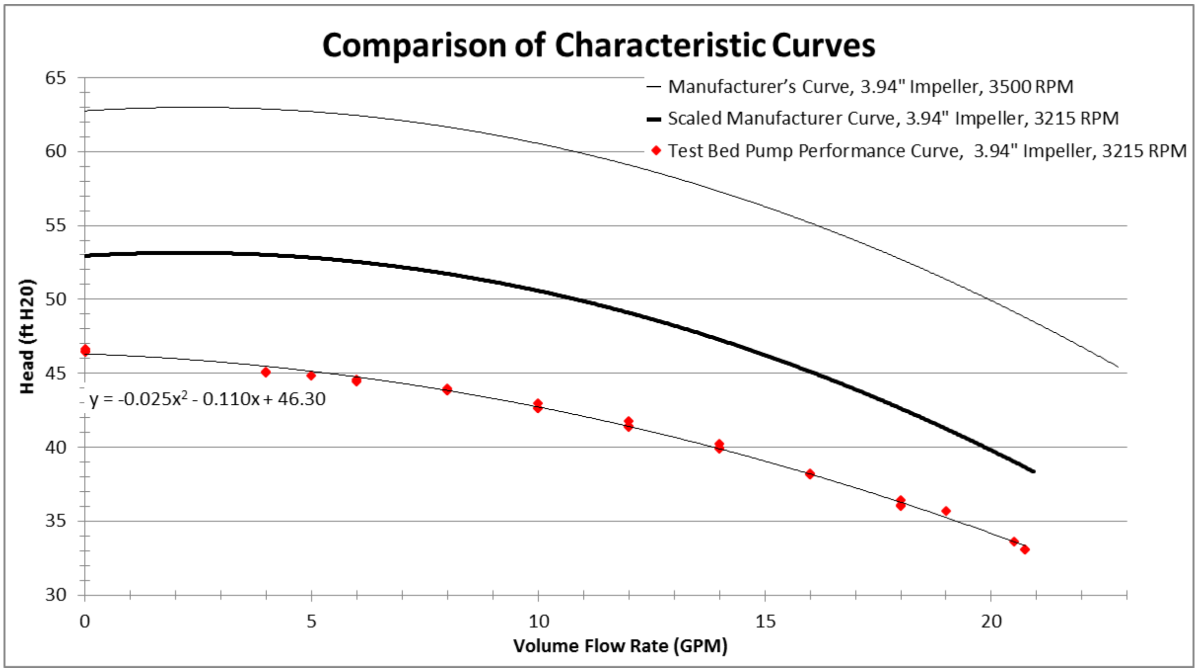

Figure 6: Comparison of Characteristic Curves for Pump A [3]

The pipe network was minimalized with regard to length, meaning that the bulk of the losses can be attributed to minor losses. The expressions for major losses (due to viscosity between pipe walls and the fluid) and minor losses (due to pipe components) respectively are:

$$h_{l_{major}} = f\frac{L}{D}\frac{V^2}{2g} \tag{13}$$

$$h_{l_{minor}} = K_L\frac{V^2}{2g} \tag{14}$$

Minor losses were calculated for each pipe component (four 90 degree bends, three inline T joint, and two inline valves) at the free flow velocity (approximately 10 ft./s with a flow of 15 gal/min) using the frictional and loss coefficients from Fluid Mechanics Fundamentals and Applications [4]. Major losses were estimated from the same loss coefficients for the system. The summation of losses, within reason, was found to be seven feet of head for operation of a single pump. The calculated losses closely resemble that visually estimated from Figure 5; however, further study will be performed using AFT Fathom, a fluid dynamic simulation software for calculating pressure differentials and flow distributions in liquid and low velocity gas piping and ducting systems.

Conclusions and Future Work

As stated, the proper selection and integration of centrifugal pumps require that engineering students understand their performance characteristics and operational parameters in various configurations. The final version of the centrifugal pump test bed, its laboratory procedures, and future uses act as a gateway for students to acquire the necessary knowledge to be successful.

The goals of minimalizing losses, continuous external data acquisition and pump control, the production of reliable and repeatable data, and safety for students were all met without compromise. The test bed is of great value to the Thermal Fluids Lab as it is a new means for students to connect their knowledge of fluid mechanics to experimental analysis. The final version of the test bed meets the standards of the laboratory, well exceeding that of previous design iterations, and is ready for experimental use by future students. Implementation will begin in the ME332 Fluid Mechanics laboratory to be taught in the spring semester of 2014. Due to length restrictions of this paper, the lab procedure has been withheld, but can be viewed upon request.

Further value of the test bed is shown through the significant amount of experience gained by the author of this paper, previous student workers, and by the senior project team. The author of this paper has had the opportunity to become engaged in a project outside the classroom, where aspects of fluid mechanics, instrumentation, experimental methods, and other engineering sciences converged. Due to said opportunity, the bridge between the analytical and experimental approaches of engineering was expanded and the student developed a stronger sense of the compromises one makes between each approach to find solutions.

At this moment, the status of centrifugal pump test bed is considered complete. As all of the initial goals were accomplished and the student workers involved with the development of the test bed gained valuable experience, the project is deemed successful.

However, the test bed will still function as a learning tool outside the classroom. Future aspirations of Thermal Fluids Laboratory student worker(s) will involve uncertainty analysis of the pump performance curves with regards to the data collected by students (i.e. pump inlet and outlet pressures, volumetric flow rate, pump shaft angular velocity, shaft torques and the water temperature). Given the uncertainties in each measurement, one will have the ability to perform a regression analysis of the characteristic curves. After completion of analysis, the student worker(s) will be expected to refine the experimental procedure for operation of the test bed in series and parallel configurations. Additionally, the student worker(s) will have the ability to produce the performance curve in a fashion similar to that of the manufacturer.

The development of the test bed is an excellent example of how students, on an undergraduate level, are able to invest not only in themselves, but also in their university through extracurricular projects.

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