

Lab Procedure

PumpLab™ Centrifugal Flow/ Process Control System

Introduction

Industry utilizes pumping systems as an integral part of their production process strategy. Understanding the proper operation of centrifugal pumps and their ability to function as part of an integrated processing environment is a key to obtaining effective production results.

PumpLab™ efficiently provides hands-on educational flow training in two parts:

1. the basics of centrifugal pumping
2. the application of that knowledge to programmable process flow control.

Lab Process

This sample lab procedure is divided into three major sections

1. Pump Lab Familiarization
2. Developing Centrifugal Pump Performance Curves
3. Centrifugal Pumping Process Control Applications

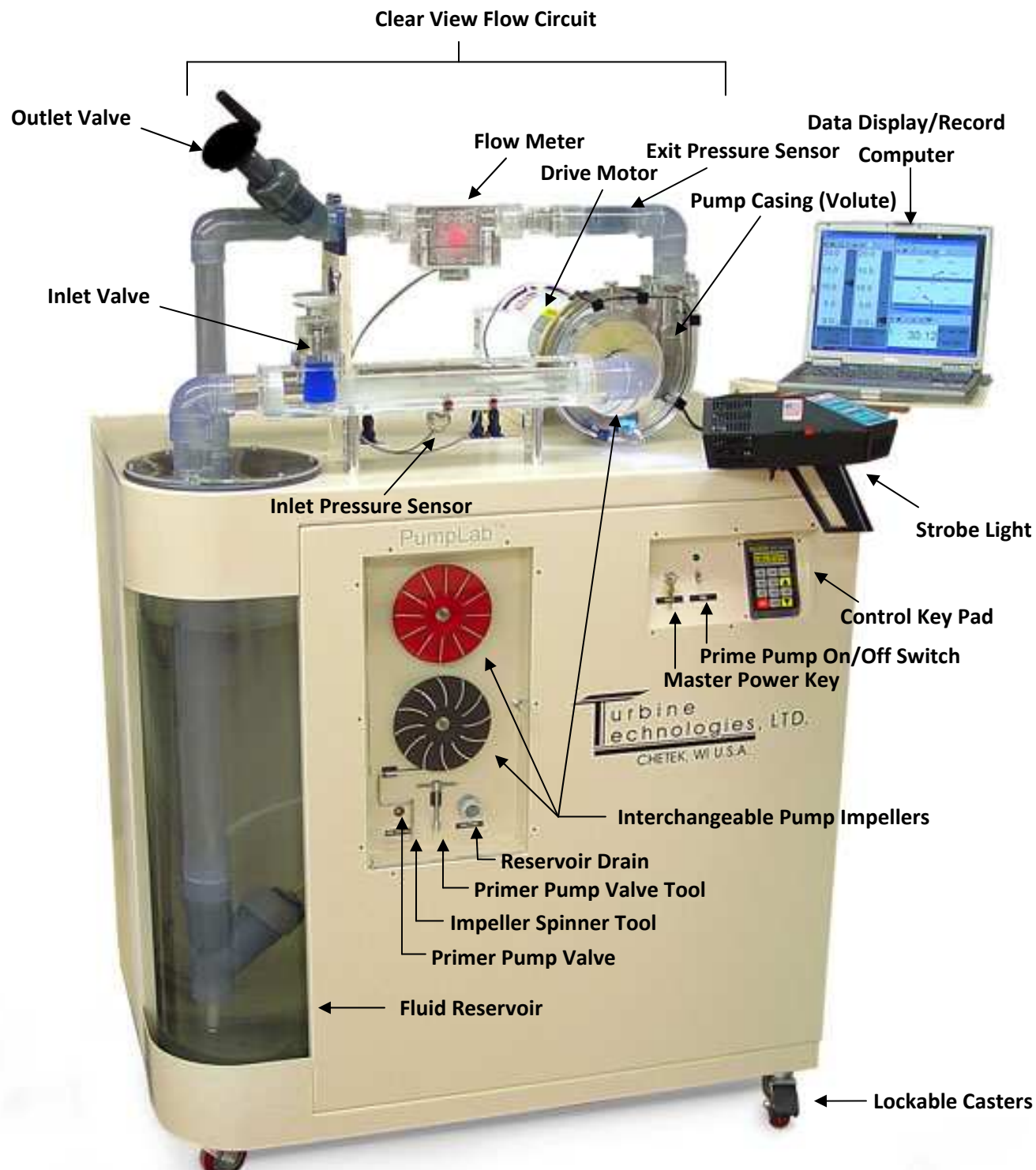


Pump Lab Familiarization

The Pump Lab™ Centrifugal Flow/Process Control System combines industrial pumping and programmable process control into one convenient and effective hands-on educational package.

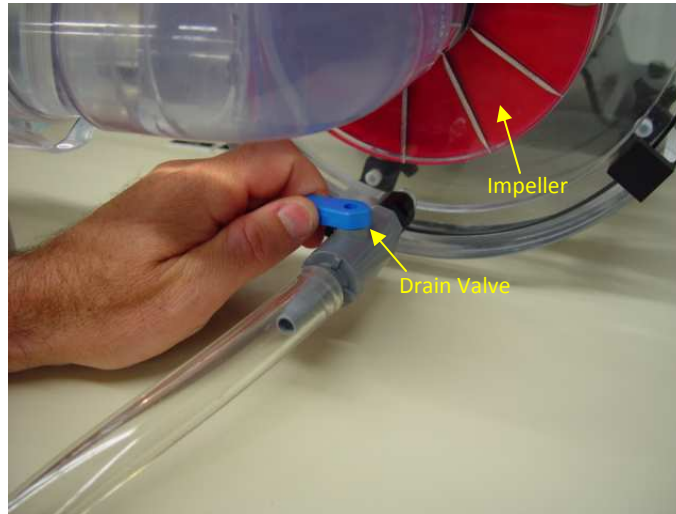
The diagram on the next page covers the basic elements of the PumpLab™. Take a few minutes to familiarize yourself with it and plan to refer to it during the lab exercises.

PumpLab™ Main Features

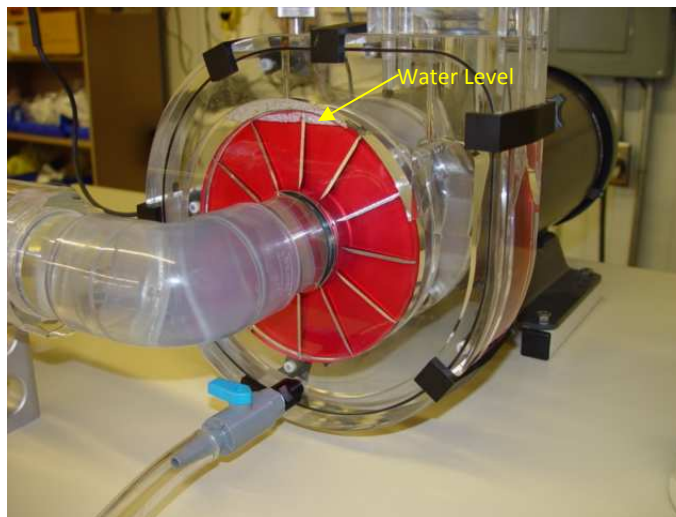


Pump Lab Setup

- Be sure impeller is installed and drain valve is closed.



- If you need impeller installation instructions, please see Appendix A.
- Check that inlet and outlet valves are both fully opened (See Main Features Page).
- Be sure system is primed (piping and impeller housing immersed in water) For Priming Instructions, see last page of Appendix A.



- Verify system is plugged into 220V.

PC Data Acquisition Program

Data acquisition for the PumpLab™ centrifugal pump system is achieved with the PumpLab™ PC application.

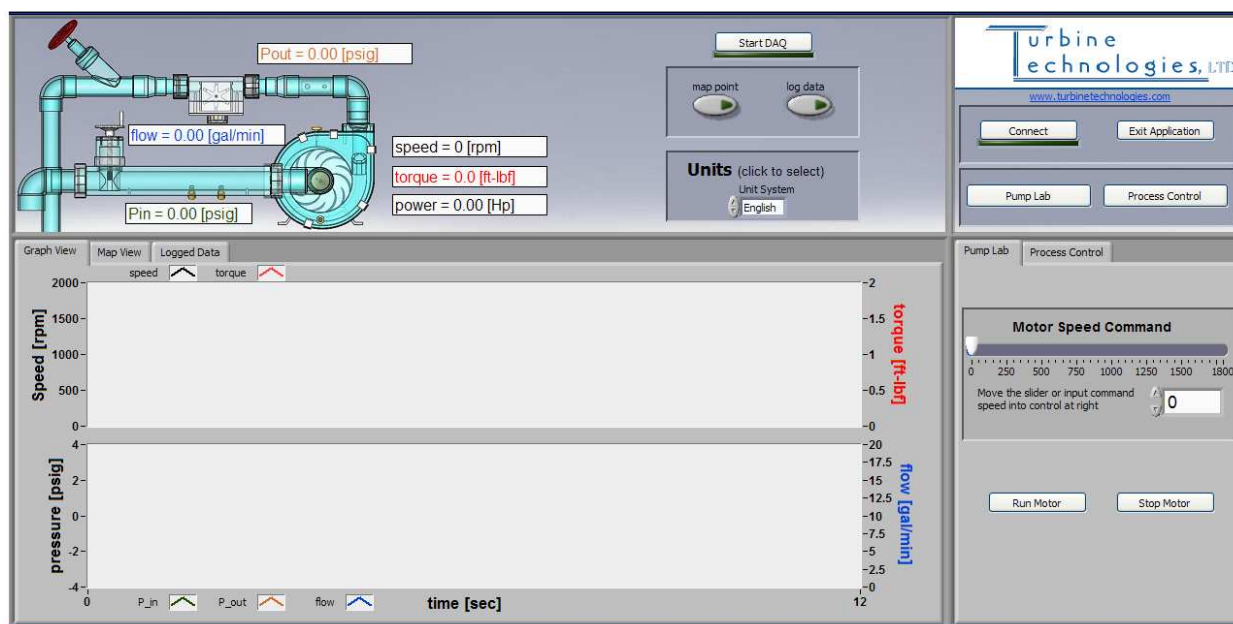
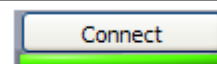


Figure 1: Screenshot of the PumpLab™ PC application used for data acquisition

Data Acquisition Setup

1. Turn Computer On
2. Connect USB Cable if not connected
3. Open Data Acquisition Program from Computer Desktop
4. Turn Pump Lab System Key On
5. Click Connect Button on Computer Desktop*



** If an error message pops up*

- Unplug USB Cable
- Power PumpLab™ Off
- Reconnect USB
- Power PumpLab™ Back On
- Click Connect on Desktop

Developing Centrifugal Pump Performance Curves

Every pump designed by a manufacturer has certain performance characteristics. These “Pump Curves” are used by engineers to determine the proper pump selection for a particular application. Typically, the pump manufacturer will supply these performance curves. As a student, you will develop the performance curves for each supplied pump impeller (Red, Black, and Gold). These curves will be used later in application scenarios.

Performance curves for a typical centrifugal pump look something like the following:

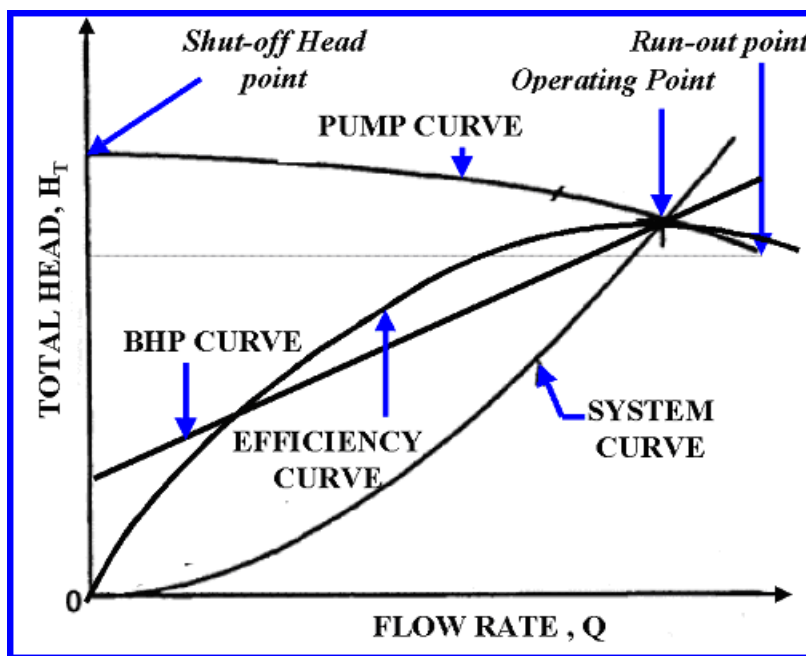


Figure 2: Typical performance curve for a centrifugal pump

Performance elements typically published are:

- Total Dynamic Head
- Flow rate (the element all others are measured against).
- Efficiency
- Brake Horsepower
- Net Positive Suction Head (NPSH); required and available

Three sets of data will be gathered for each impeller:

1. Total Dynamic Head (TDH)
2. System Curve
3. Net Positive Suction Head Required (NPSH_r)

Total Dynamic Head (TDH)

This is a term that's used in place of pressure in industry. A centrifugal pump will pump any liquid to a given height, or "head" depending on the diameter and speed of the impeller. The amount of head you get depends upon the weight of the liquid (specific gravity). Pump manufacturers do not know what liquid will be pumped, so they give you the "head" the pump will generate (in units of feet or meters).

System Curve

A centrifugal pump will operate at the intersection of its pump curve and the system curve. The pump curve is often the data supplied by the manufacturer and it describes the performance of the pump only. When tasked with installing or sizing a pump for a particular application, it is important to understand the system in which the pump is being placed. Changes to the system will cause the pump to operate at a different point and this operating point may or may not be acceptable. For instance, additional piping or excessive bends and elbows may be placed in the pump flow circuit resulting in higher losses that the pump must overcome. This typically results in a higher head required from the pump at the expense of reduced flow rate or capacity. This also may move the pump away from its design point or best efficiency point.

Since the PumpLab™ centrifugal pumping system utilizes a variable frequency drive (VFD), it is possible to run the pump at different operating speeds. Recording the total dynamic head at each speed allows us to map out the head required for this particular system and will also show how the system curve changes with different flow rates.

Net Positive Suction Head (NPSH)

When pumping a fluid using a centrifugal pumping system, it is important to design your system with a Net Positive Suction Head (NPSH) to prevent a problem called Cavitation. Cavitation is a phenomenon that occurs when vapor bubbles form ahead of the pump impeller due to pressure drop in the pumping system. As the bubbles enter the pump and are swept along the impeller vanes, they implode due to rising external pressure around the bubble. The implosion creates a shock wave, which impinges on the impeller vanes and face. When thousands of bubbles are imploding at once, damage to the impeller can occur (including pitting, erosion and ultimately failure). As Cavitation grows in severity, uneven loading on the impeller face can develop due to the large amount of vapor bubble impingement. This can cause excess vibration, leading to further mechanical damage to the pump (damaged seals, bearings, housing). This activity also creates noise, which can be problematic for people having to work in the same space. Furthermore, pumping efficiency declines due to the high amount of vapor in the system.

The pumping system must be designed to overcome all possible losses that can occur in the flow circuit to prevent the working fluid from reaching its vapor pressure (allowing vapor bubbles to form). This is **Net Positive Suction Head (NPSH)**.

As we have learned, the boiling point of a fluid is a function of pressure and temperature. At normal atmospheric pressure, water can boil and create vapor bubbles at 212°F. If we create a sufficiently large pressure drop in a system, the liquid will reach its vapor pressure (the pressure the liquid will turn to vapor) at a relatively low temperature (such as room temperature). In the earlier lab exercise, we used the Pump Lab™ to set up a pressure drop scenario that will generate vapor bubbles and allow the

recording of resultant system performance parameters. As a continuation of plotting performance curves, operational graph will be plotted and NPSH and cavitation will be investigated in the operational curves of the system.

In a typical pumping system, piping bends, valves, transitions, as well as the location of the supply reservoir ahead of the pump impeller can be responsible for creating enough of a cumulative pressure drop to form vapor bubbles in the system. Also, sharp bends right before the inlet of the pump can add significantly to this problem, as the bend acts as a significant constraint to the fluid right before it enters the impeller. It is here a pressure drop will occur that could possibly be enough to form vapor bubbles and also magnify any existing vapor bubbles already in the system. Piping and supply reservoirs positioned at an elevation below the pump also contribute to this problem due to the higher suction head required to draw the fluid to the pump.

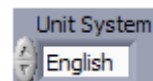
To simulate numerous pipe bends, valves, transitions, etc., ahead of the pump impeller, the inlet valve of the Pump Lab will be slowly closed, causing a constriction in the line. At a certain point, the pressure drop across this constriction will cause vapor bubbles to form. Since the liquid supply tank is positioned lower than the pump itself, it initiates a negative head pressure, which also needs to be overcome by the suction head of the pump. This adds further to the possibility of the liquid in the system reaching vapor pressure. To further compound vapor bubble generation, a sharp 90-degree bend was built into the flow system right before entering the pump impeller. This sharp bend, near the pump suction inlet, adds more pressure drop, which aids in the development of destructive bubbles contacting the impeller vanes and face. The following lab process is designed to make cavitation visible to allow a better understanding of its harmful characteristics.

Data Gathering Procedure

The following pages outline the procedure for gathering data used in constructing the PumpLab™ centrifugal pump performance curves. This procedure is meant as a starting point for developing a sample lab using the PumpLab™ system.

TDH at 1800 RPM

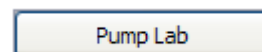
1. Select UNITS on Computer Screen; English or SI



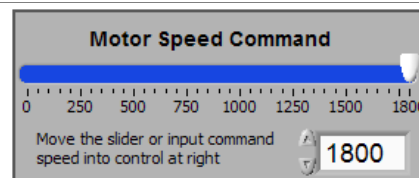
2. Click **START DAQ** Button (data should be flowing on graphs)



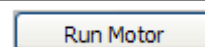
3. Click **PUMP LAB** Button



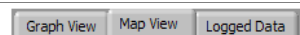
4. Set **SPEED** to 1800 RPM using on screen slide switch (or type in value).



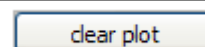
5. Click **RUN MOTOR**



6. Click on **MAP VIEW** Tab



7. Click **CLEAR PLOT**



8. Click **MAP POINT**



9. Close Discharge Valve 1 full turn

10. Click **MAP POINT**



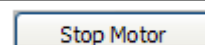
11. Close Discharge Valve another full turn

12. Click **MAP POINT**



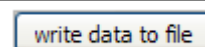
13. Repeat these steps until Discharge Valve is fully closed

14. Click **STOP MOTOR**



15. Open Discharge Valve all the way open

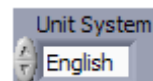
16. Click **WRITE DATA TO FILE**



17. Save File as: **RED_1800_TDH.txt**

TDH at 1700 RPM

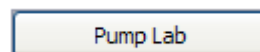
1. Select **UNITS** on Computer Screen; English or SI



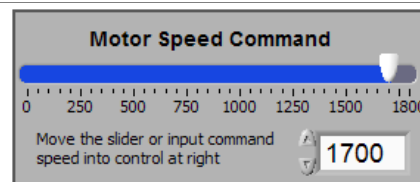
2. Click **START DAQ** Button (data should be flowing on graphs)



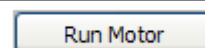
3. Click **PUMP LAB** Button



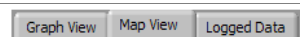
4. Set **SPEED** to 1700 RPM using on screen slide switch (or type in value).



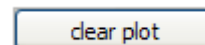
5. Click **RUN MOTOR**



6. Click on **MAP VIEW** Tab



7. Click **CLEAR PLOT**



8. Click **MAP POINT**



9. Close Discharge Valve 1 full turn

10. Click **MAP POINT**



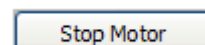
11. Close Discharge Valve another full turn

12. Click **MAP POINT**



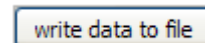
13. Repeat these steps until Discharge Valve is fully closed

14. Click **STOP MOTOR**



15. Open Discharge Valve all the way open

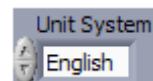
16. Click **WRITE DATA TO FILE**



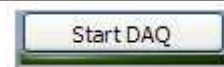
17. Save File as: **RED_1700_TDH.txt**

TDH at 1600 RPM

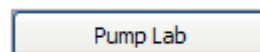
1. Select **UNITS** on Computer Screen; English or SI



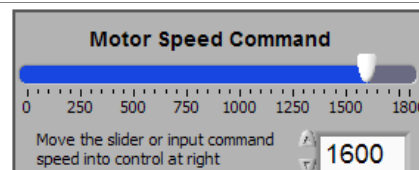
2. Click **START DAQ** Button (data should be flowing on graphs)



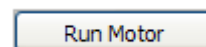
3. Click **PUMP LAB** Button



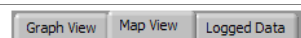
4. Set **SPEED** to 1600 RPM using on screen slide switch (or type in value).



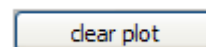
5. Click **RUN MOTOR**



6. Click on **MAP VIEW** Tab



7. Click **CLEAR PLOT**



8. Click **MAP POINT**



9. Close Discharge Valve 1 full turn

10. Click **MAP POINT**



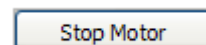
11. Close Discharge Valve another full turn

12. Click **MAP POINT**



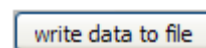
13. Repeat these steps until Discharge Valve is fully closed

14. Click **STOP MOTOR**



15. Open Discharge Valve all the way open

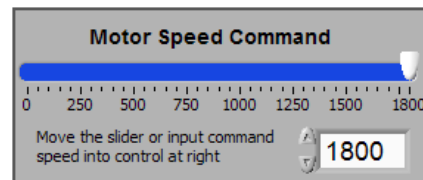
16. Click **WRITE DATA TO FILE**



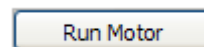
17. Save File as: **RED_1600_TDH.txt**

System Curve

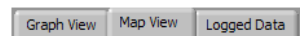
1. Set **SPEED** to 1800 RPM using on screen slide switch (or type in value).



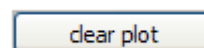
2. Click **RUN MOTOR**



3. Click on **MAP VIEW** Tab



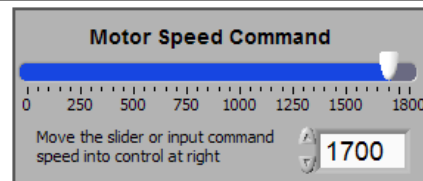
4. Click **CLEAR PLOT**



5. Click **MAP POINT**



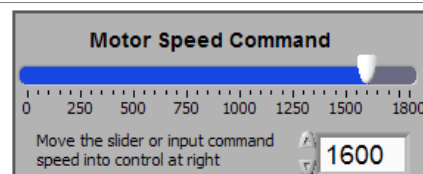
6. Reduce Speed to 1700 RPM



7. Click **MAP POINT**



8. Reduce Speed to 1600 RPM

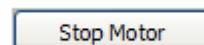


9. Click **MAP POINT**

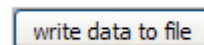


10. Repeat these steps until motor speed is 0.

11. Click **STOP MOTOR**



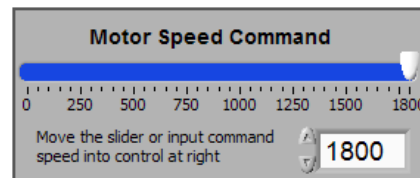
12. Click **WRITE DATA TO FILE**



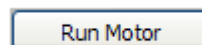
13. Save File as: **RED_system_curve.txt**

NPSHr at 1800 RPM

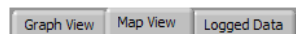
1. Set **SPEED** to 1800 RPM using on screen slide switch (or type in value).



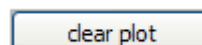
2. Click **RUN MOTOR**



3. Click on **MAP VIEW** Tab



4. Click **CLEAR PLOT**



5. Click **MAP POINT**



6. Close Suction Valve 1 full turn

7. Wait 3 seconds for system to settle

8. Click **MAP POINT**



9. Close Suction Valve another full turn

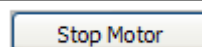
10. Wait 3 seconds for system to settle

11. Click **MAP POINT**



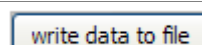
12. Repeat these steps until Suction Valve is fully closed

13. Click **STOP MOTOR**



14. Open Suction Valve all the way

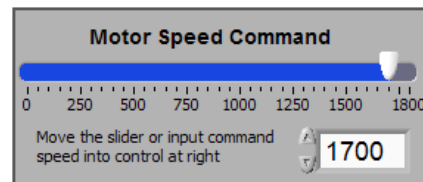
15. Click **WRITE DATA TO FILE**



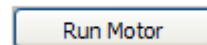
16. Save File as: **RED_1800_NPSHr.txt**

NPSHr at 1700 RPM

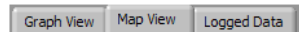
- Set **SPEED** to 1700 RPM using on screen slide switch (or type in value).



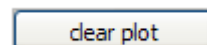
- Click **RUN MOTOR**



- Click on **MAP VIEW** Tab



- Click **CLEAR PLOT**



- Click **MAP POINT**



- Close Suction Valve 1 full turn

- Wait 3 seconds for system to settle

- Click **MAP POINT**



- Close Suction Valve another full turn

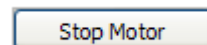
- Wait 3 seconds for system to settle

- Click **MAP POINT**



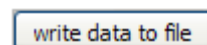
- Repeat these steps until Suction Valve is fully closed

- Click **STOP MOTOR**



- Open Suction Valve all the way

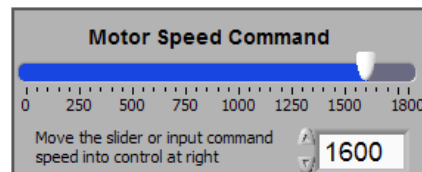
- Click **WRITE DATA TO FILE**



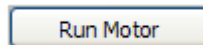
- Save File as: **RED_1700_NPSHr.txt**

NPSHr at 1600 RPM

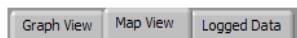
1. Set **SPEED** to 1600 RPM using on screen slide switch (or type in value).



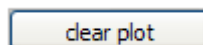
2. Click **RUN MOTOR**



3. Click on **MAP VIEW** Tab



4. Click **CLEAR PLOT**



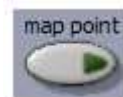
5. Click **MAP POINT**



6. Close Suction Valve 1 full turn

7. Wait 3 seconds for system to settle

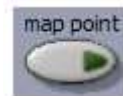
8. Click **MAP POINT**



9. Close Suction Valve another full turn

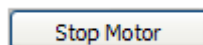
10. Wait 3 seconds for system to settle

11. Click **MAP POINT**



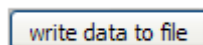
12. Repeat these steps until Suction Valve is fully closed

13. Click **STOP MOTOR**



14. Open Suction Valve all the way

15. Click **WRITE DATA TO FILE**



16. Save File as: **RED_1600_NPSHr.txt**

Data Analysis

Data recorded in all runs include; Inlet Pressure, Outlet Pressure, RPM, Flow rate and Torque.

To develop an understanding of centrifugal pumping, we will want to calculate and plot:

- Total Dynamic Head
- Flow rate
- Efficiency
- Brake Horsepower
- Net Positive Suction Head (NPSH); required and available

To aid in analyzing the data, the system description is shown in Figure 3.

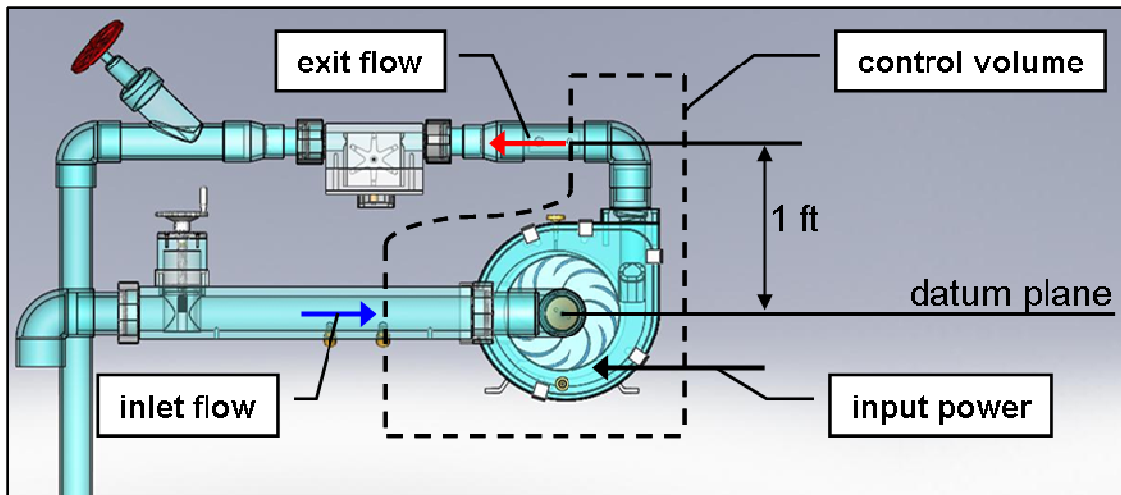


Figure 3: System definition showing the inlet flow, exit flow, input power and a generic control volume. Specifying the pump performance requires knowledge of the geometry of the system and relies on the measurement of the inlet and exit pressure and the volumetric flow rate.

Head – Capacity Curve

The first key concept for understanding the performance of a centrifugal pump is the head-capacity curve. This is a graphical depiction of the power delivered to the fluid versus the volumetric flow rate.

The steady flow energy equation for a pump in terms of “head” can be expressed as:

$$h_{pump} - h_{friction} = \left(\frac{P}{\gamma} + \frac{\bar{v}^2}{2g} + z \right)_{exit} - \left(\frac{P}{\gamma} + \frac{\bar{v}^2}{2g} + z \right)_{inlet} \quad (1)$$

Pump manufacturers will often specify their pump performance in units of head (units of length) versus pressure in order to eliminate specifying a particular fluid. For instance, a pump that supplies 10 ft of head will supply 10 ft of water or 10 ft of mercury. However, the pressure rise will be different for the two fluids at the same head conditions.

If we assume that the friction losses through the pump are negligible, then the total head added by the pump (**Total Dynamic Head, TDH**) is equal to the difference between the head at the exit (**Total Dynamic Discharge Head, TDDH**) and inlet (**Total Dynamic Suction Head, TDSH**) sections.

In order to plot the head-capacity curve, we will first use the acquired data and calculate the TDDH and the TDSH. These calculations can be done with any standard data analysis software package such as Microsoft Excel

TDH

The total dynamic head is the parameter used when creating a head – capacity curve. It is the difference between the total dynamic discharge head and the total dynamic suction head. For this exercise, you will be asked to compute both the total dynamic discharge head and the total dynamic suction head from which the total dynamic head can be computed. Note that the TDDH and TDSH are heads at a single point and the total dynamic head is the head difference across the pump. This is an important point that will be made more clearly when discussing net positive suction head.

Both the TDSH and TDDH are composed of a pressure head, velocity head, and a static “height” head at the location of the pressure measurement. When determining the pump performance, it is customary to use the eye of the impeller as the height reference as shown by the datum plane in Figure 3.

$$TDSH \text{ or } TDDH = \underbrace{\frac{P}{\gamma}}_{\text{pressure head}} + \underbrace{\frac{\bar{v}^2}{2g}}_{\text{velocity head}} + \underbrace{z}_{\text{static head}} \quad (2)$$

In order to compute the TDSH and TDDH, use the data acquired from the PumpLab™ to calculate these three heads and then add them together to form the total dynamic suction head.

Pressure Head

The pressure head term in equation 2 is the ratio of the absolute pressure to the specific weight of water. The specific weight is the product of the density of the water and the gravitational constant. Since the pressure transducer measures the gauge pressure we must add the barometric pressure to our readings to obtain the absolute pressure. Often times you will see the pressure head given in terms of the specific gravity instead of specific weight. The equation for the pressure head is the following:

$$h_p = \frac{P}{\gamma} = \frac{P_{\text{gauge}} + P_{\text{barometric}}}{\rho_{h_2o} \times g \times SG_{h_2o}} \quad (3)$$

$$\rho_{h_2o} = 62.43 \frac{\text{lbm}}{\text{ft}^3} \quad (T = 39.2^\circ F, P = 1 \text{ atm})$$

$$g = 32.2 \frac{\text{ft}}{\text{s}^2}$$

After including the proper unit conversions, the pressure head can be computed with the following relationship:

$$h_p = \frac{2.31 \cdot P}{SG} \quad (4)$$

$P \equiv$ absolute pressure in psi

$SG \equiv$ specific gravity

$SG_{h_2o} = 1$

Velocity Head

The velocity head component of the total head is:

$$h_v = \frac{\bar{v}^2}{2g} \quad (5)$$

The velocity, \bar{v} , can be calculated by knowing the volumetric flow rate (measured in the experiment) and the cross sectional area at the point of interest. Rewriting this equation in terms of the flow rate, the velocity head can be expressed as:

$$h_v = \frac{0.002593 \cdot GPM^2}{I.D.^4} \quad (6)$$

$GPM =$ volumetric flow rate in gal/ min

$I.D. =$ inside diameter in inches

$I.D._{suction} = 1.85$ in

$I.D._{discharge} = 1.6$ in

Static Head

The static head is simply the height of the point of interest from some datum or reference position. As mentioned earlier, the eye of the impeller is usually taken as the reference point. For the PumpLab™, this means the inlet head or TDSH has zero static head and the TDDH has 1 foot of static head since the pressure measurement at this point is 1 foot above the eye of the impeller.

Upon computing these components of the total head, it should now be possible to make a plot like the following:

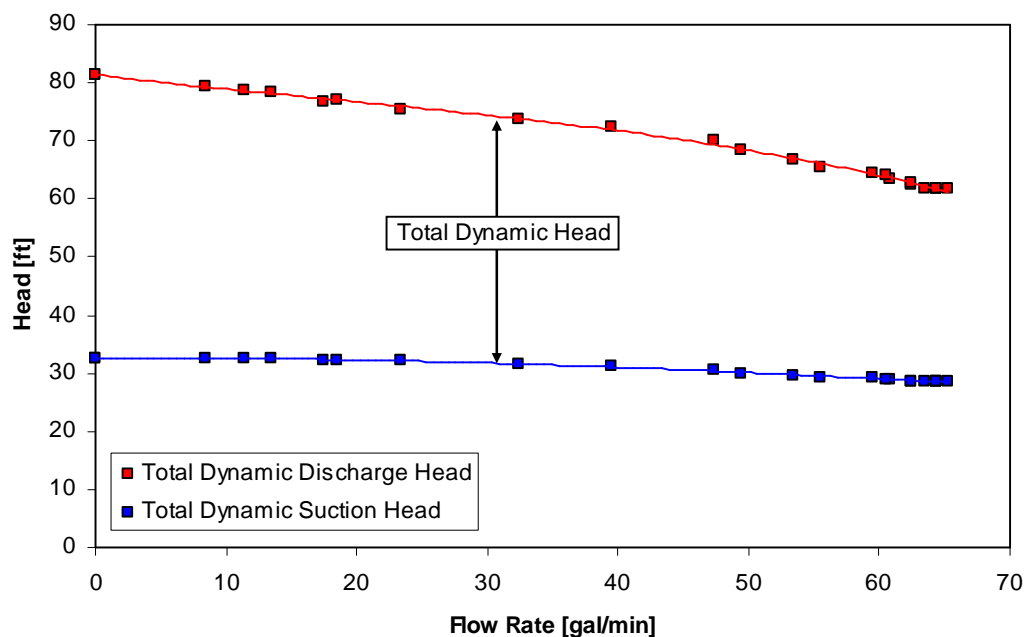


Figure 4: Curves showing the total dynamic discharge head and the total dynamic suction head versus flow rate for the red impeller at 1800 rpm. The difference between these two curves is the total dynamic head.

Since data has been obtained at 3 different impeller speeds, make a plot of the TDH for each impeller versus flow rate. This plot will give the head – capacity curve for the PumpLab™ centrifugal pump.

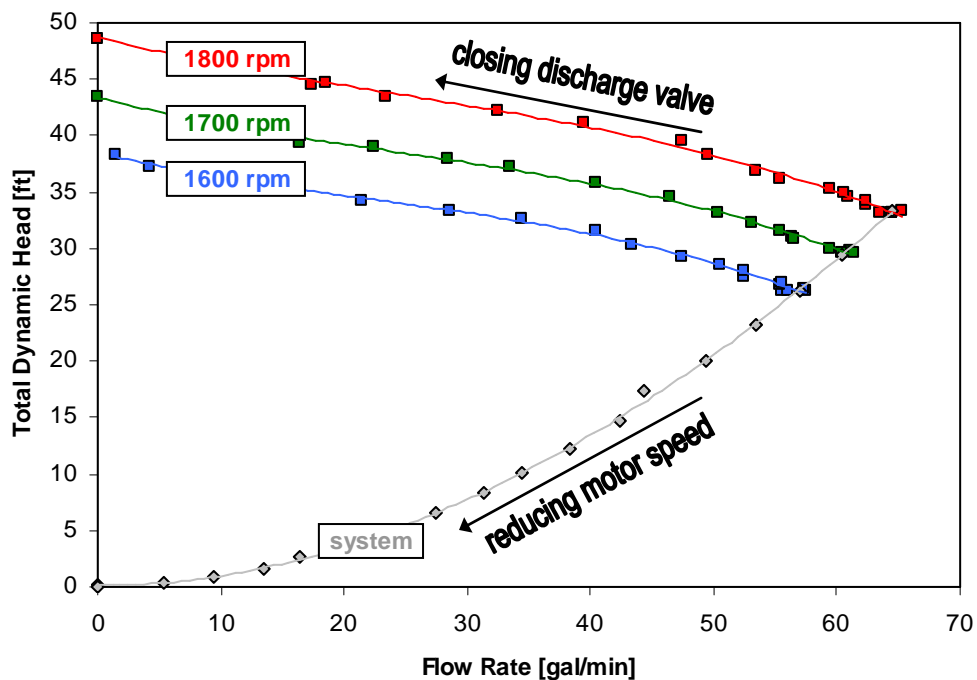


Figure 5: The head – capacity curve for the red impeller at 3 different operating speeds.

In Figure 5, the total dynamic head is plotted versus the volumetric flow rate for 3 different impeller speeds. In creating these curves, the flow rate was reduced by closing the discharge valve all the way to

the point where the valve was fully closed (the shut-off head point). Also shown is the system curve. All pumps will operate at the intersection of their pump-capacity curve and the system curve. The system is everything outside of the pump so any change in the flow circuit such as adding additional length of pipe or bends will change the system and move the pump to a different point on its pump curve.

Brake Horsepower (bHp)

This is the power being fed to the pump by the electric motor. The PumpLab™ system measures the torque and speed of the motor so the brake horsepower can be calculated using the following equation.

$$bHp = \frac{\text{Torque} \times \text{RPM}}{5252} \quad (7)$$

The data saved with the PumpLab™ data acquisition system already includes this parameter so it should be straightforward to create a plot of the bHp versus flow rate.

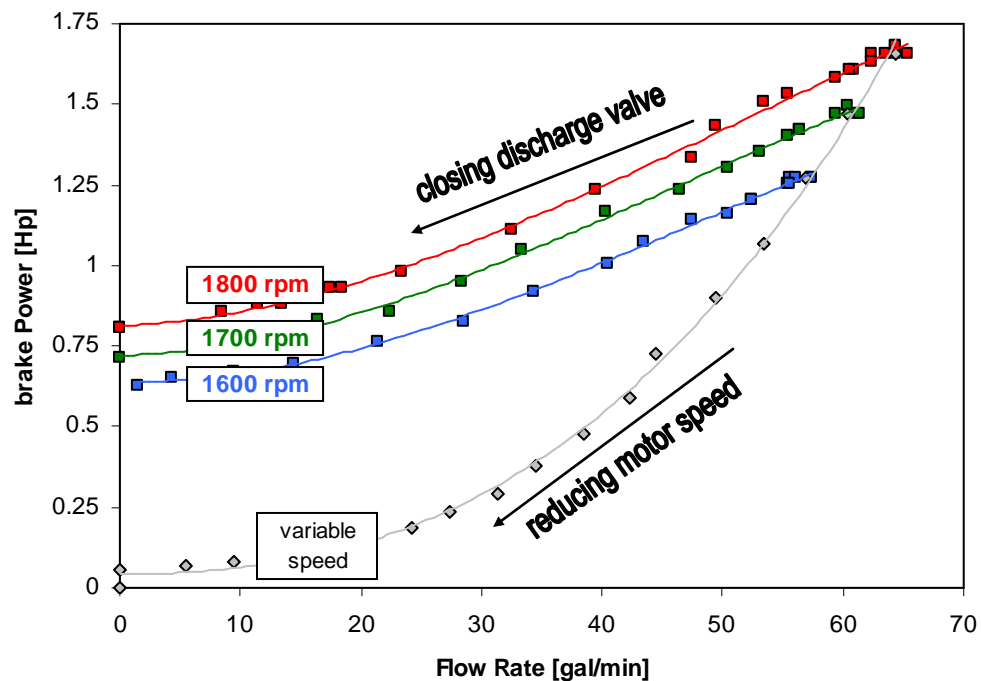


Figure 6: Curves of the power supplied to the pump (bHp) versus flow rate.

Efficiency

This compares the amount of work or power we get out of the pump to the amount of power being supplied to the pump. That is, it is a ratio of the power supplied to the working fluid by the pump impeller versus the mechanical shaft power supplied to the pump by the electric motor. In order to calculate the efficiency, we must first calculate the power supplied to the working fluid by the pump. This power is sometimes called the water power and is given by the following expressions.

$$wHp = \gamma \cdot \dot{V} \cdot TDH = \gamma_{h2o} \cdot SG \cdot \dot{V} \cdot TDH \quad (8)$$

Inserting values for the specific gravity and specific weight and adding conversion factors to ensure the final value is in units of horsepower the following relation can be used for calculating the water power.

$$wHp = \frac{GPM \times TDH \times SG}{3960} \quad (9)$$

The efficiency in percent can then be computed by taking the ratio of the water power to the brake power.

$$\eta_{pump} = \frac{wHp}{bHp} \times 100\% \quad (10)$$

Net Positive Suction Head

The parameters considered up to this point have only considered the performance of the pump irrespective of the system the pump is in. When designing or sizing a pump, it is important to understand the state of the fluid at the inlet of the pump. A centrifugal pump is designed to move fluid (increase the flow rate) and does this by increasing the pressure across the pump. In order to draw fluid into the pump, the pressure at the inlet of the pump is typically the low pressure point in the fluid. As discussed earlier, if the pressure at any point in the flow drops below the vapor pressure of the fluid, cavitation may develop reducing the pump performance and possibly causing damage to the pump.

During data acquisition, data was acquired while closing the suction valve allowing us to simulate a change in the supply system. For each data point, the Net Positive Suction Head can be calculated using the following equation.

$$NPSH = h_{P,inlet} + h_{v,inlet} - h_{vp}(T) \quad (11)$$

In a system where there is no pressure gauge at the inlet of the pump, the pressure head must be calculated by starting from a known pressure point on the supply side (usually some point in the flow circuit where there is a fluid surface open to the atmosphere) and then calculating the friction losses and changes in the static pressure due to elevation changes until the pump inlet is reached. However, in the PumpLab™ system, we have a pressure transducer near the inlet of the pump so all pressure changes from the supply tank to the inlet due to elevation changes and friction are accounted for by the pressure measurement. In fact, upon closer inspection of equation 11, we see that the first two terms are identical to the definition of the total dynamic suction head and so equation 11 can be recast in the following form.

$$NPSH = TDSH - h_{vp}(T) \quad (12)$$

The Net Positive Suction Head is therefore simply the suction head minus the vapor pressure head. For proper pump operation, this term should be positive to prevent cavitation on the suction side of the pump and hence the reason for the “Net Positive” portion of the name. When calculating the NPSH for a particular pumping application, it is often quoted as the NPSH available or NPSHa. This is the NPSH that is present for a specific application. A pump manufacturer can’t specify the NPSHa for a pump since it will depend on the system the pump is placed in. The manufacturer can, however, specify the minimum NPSH or the NPSH required (NPSHr) in order for the pump to perform satisfactorily. This minimum will

not be 0 as you may have guessed since the manufacturer will usually calculate the NPSH at the inlet to the pump housing versus the true minimum pressure point at the eye of the impeller. This is done out of pure convenience in that it is easy to measure the pressure at the inlet pipe versus inside the pump housing. There will be further pressure drops due to friction and other losses from the inlet to the minimum pressure point near the eye of the impeller so typically the NPSHr specified by a pump manufacture is greater than 0 and varies with flow rate.

In order to calculate the NPSHr for the PumpLab™ centrifugal pump, we will compare the TDH for the pump when closing the discharge valve (pump curve) and when closing the suction valve. As is customary and specified in standards published by the Hydraulic Institute, the NPSHr is the point in which the TDH of the pump decreases by 3 % of its normal value due to cavitation. Plotting the curves obtained for a single impeller speed when closing the discharge and suction valves separately is a quick way of visualizing this drop off point. Figure 7 shows an example plot using the red impeller at 1800 rpm. The 3 % drop point is clearly visible between the curves created by closing the two valves. Overlaid and plotted on the right y axis is the NPSH for the data obtained when closing the suction valve. Proceeding from the fully open position (far right point of graph) the NPSH drops as the valve is closed. With the valve partially closed, the NPSH is still above the required point since the TDH is following the pump curve exactly. Near a flow rate of 50 gal/min, the TDH for the suction valve test begins to deviate and this point marks the NPSH required for the pump at that flow rate. Further closing of the suction valve causes significant drop in TDH and it is in this operating regime that the pump system is experiencing cavitation.

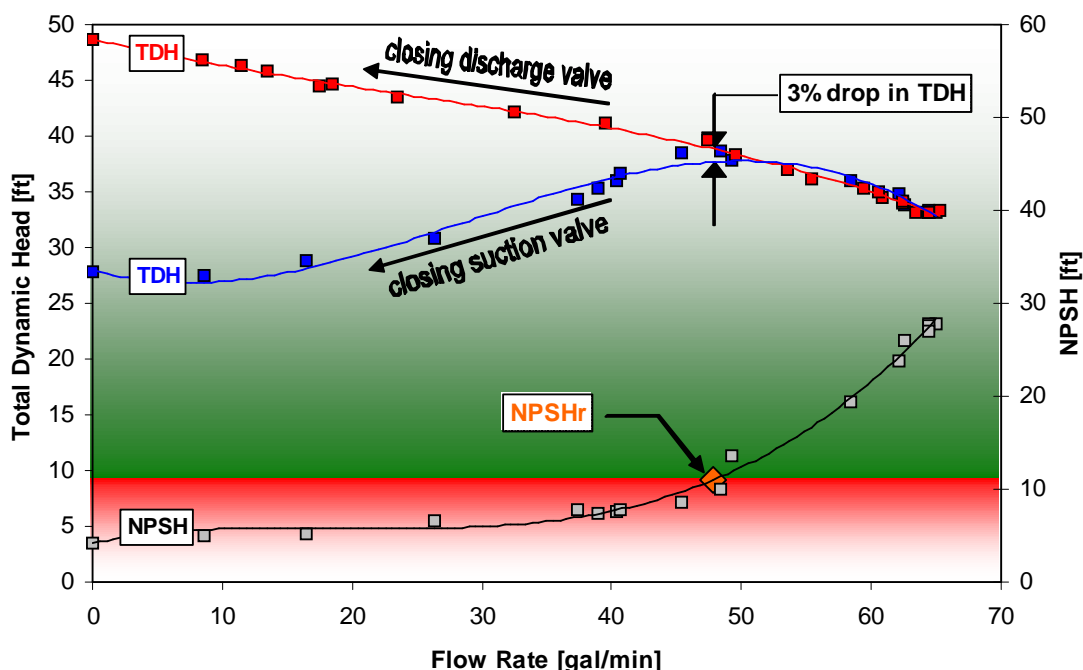


Figure 7: Graphical depiction of finding the net positive suction head required (NPSHr) for the PumpLab™ centrifugal pump system for a single point. In this figure, the pump was run at 1800 rpm and the curves developed by closing the discharge valve and closing the suction valve are compared. The NPSH at which the total dynamic head decreases by 3 % sets the NPSH required by the pump for that particular flow rate and pump speed.

Process Control

Centrifugal Pumps are used extensively in industry to direct the flow of fluids for countless processes. Controlling and integrating this flow is now typically handled by a programmable Variable Frequency Drive (VFD). VFDs can be programmed to control the speed a motor operates, essentially making it a variable speed unit to meet very particular pumping needs. It also can be part of a large control scheme where many pumps are controlled and scheduled automatically to produce a desired final result. Feedback Loops essentially are used to provide information to the VFD regarding adjustments that need to be made to the pump speed that allow it to maintain the desired end result.

The PumpLab™ Centrifugal Flow Process Control System features a programmable VFD that can be used to develop control scenarios for your pump. It also features dedicated feedback loops from pressure and flow transducers, which allow you to program specific process control scenarios. This sample lab will propose some basic process control scenarios for you to accomplish, in order for you to gain a good basic understanding of the process. The goal of this sample lab is to introduce you to programmable process control and step you through some basic exercises that will make you familiar with this process. As a practicing engineer, you may have a need to be involved with process development and having a grasp of the basics of pumping and process control will make your value much greater in terms of designing /expanding effective pumping process systems that get results.

Open Loop Control

If you have a yard light on a simple timer, this is considered open loop control. At a certain time of day, the timer will turn the light on. It could be a bright sunny day outside, but the light will still come on as there is no “feedback” to the timer telling it the light is not needed. You’ve likely seen sprinkler systems operating on a timer system when it’s pouring rain outside. Again, the sprinkler didn’t receive feedback that it wasn’t needed.

Closed Loop Control

If the yard light switch was tied to a light meter or the sprinkler tied to a humidity sensor, they would have “feedback” information which would tell them whether or not they are actually needed when the time came for them to turn on.

The process control we are working with is considered a closed loop control; there is a “feedback” loop which is directly tied to the controller from a sensor and provides status information about the sensor.

An example block diagram of a closed loop control scheme can be seen in Figure 8 below.

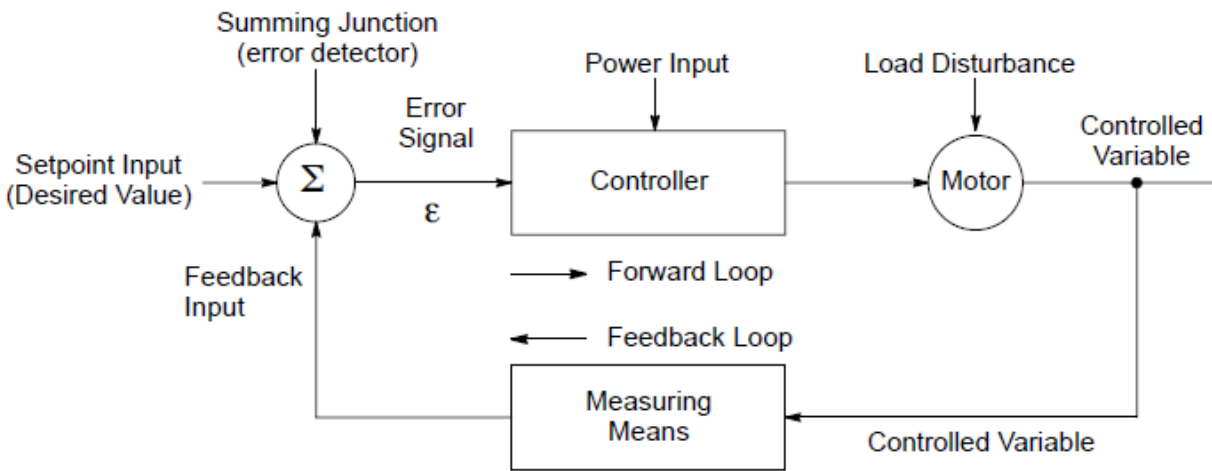


Figure 8: Block diagram of a closed loop control system. The basic premise of this scheme is to adjust the motor conditions in order to minimize the error signal, ϵ .

The process error signal is the result of the subtraction of the process setpoint and the feedback signal.

$$\epsilon = \text{process setpoint} - \text{process feedback} \quad (13)$$

Proportional Control (the P in PID)

Let's use another example regarding a feedback loop;

Your air conditioner is connected to a thermostat. Let's assume the AC unit can vary the amount of cold air it can crank out based upon the temperature information it receives from the thermostat. As your room temperature gets closer to set point, the AC unit reduces its output and tries to crank out just enough cold air to maintain the set point. If the temperature rose, it would increase its output; if it dropped, it would reduce its output or shut itself off. Also, these changes in output would be "proportional" to the change in temperature. A small change in temperature results in a small change in the unit output, while a large change would lead to "proportionally" larger changes in output.

The example above is one of "proportional, closed loop" control and is the P in PID control. Proportional control applies steady state gain; it is always active and is defined as:

$$A_{out} = K_p \cdot \epsilon \quad (14)$$

where :

A_{out} = controller output

K_p = proportional gain

ϵ = error signal

Integral Control (the I in PID)

In pumping applications, proportional control is usually satisfactory to maintain the flow requirements if conditions are fairly steady, with no sudden changes and if small offsets are tolerable. Since proportional

control is time independent, the process usually will reach a steady state condition where the error signal no longer changes with time thus keeping the output of the controller constant. Offsets are steady state errors that proportional control can't overcome alone. Consequently, proportional control must be tempered with elements called integral and derivative control.

Integral gain (like proportional gain) is amplification of the process error signal, but is time dependent. If a steady state error exists for long periods of time, it is known as an offset. Integral gain compensates for this long term error or offset. Generally speaking, if you were to use only proportional control in a process, the controller output would never bring the controlled variable exactly equal to the setpoint. You would always have some small amount of error. This is often called offset. The Integral term senses this long term offset, and corrects the controller output to reduce the effect of offset.

Integral gain is mathematically defined as:

$$A_{out} = K_I \int \varepsilon \Delta t \quad (15)$$

where :

A_{out} = controller output

K_I = integral gain

ε = process error

Δt = increment of time

Derivative Control (The D in PID)

The differential element is proportional to the rate of change of the process error. Differential gain is provided to reduce overshoot of the process control during sudden large disturbances. The differential element is only responsive during transient conditions. The differential gain is not active for steady state errors because their rate of change is zero.

Differential gain is mathematically defined as:

$$A_{out} = K_D \frac{\Delta \varepsilon}{\Delta t} \quad (16)$$

where :

A_{out} = controller output

K_D = derivative gain

$\frac{\Delta \varepsilon}{\Delta t}$ = change in error with time

Putting it all together → PID Control

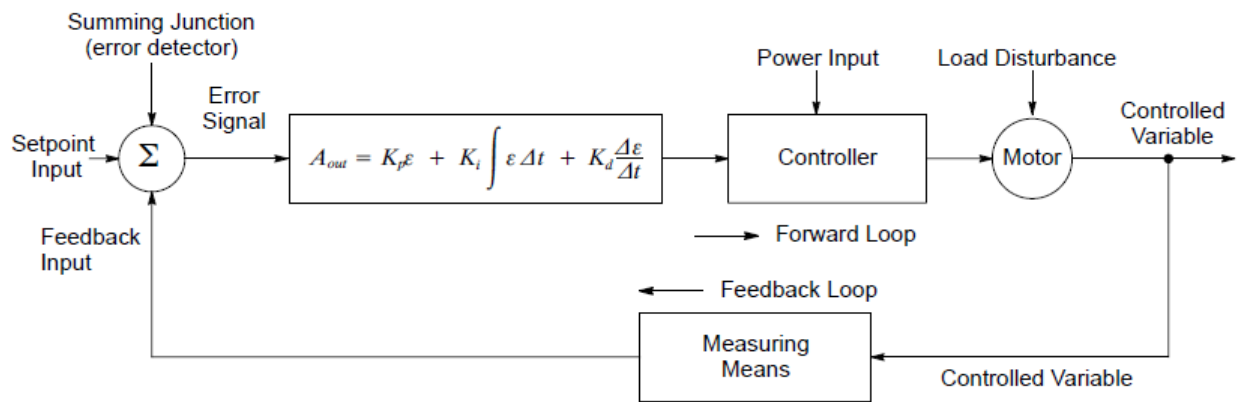


Figure 9: Closed loop control system showing the three components of PID control

In most pump applications, proportional and integral control (PI control) is sufficient for maintaining process control. The proportional control will amplify the output in proportion to the error signal and the integral control amplifies the output based on the accumulation of error with time. Proper selection of the gains for these two control elements is critical to the success of any closed loop control application. **Figure 10** shows the response curves of the PumpLab™ centrifugal pump system when reacting to a step change of the pressure setpoint using differing values of proportional and integral gain. In this figure, the importance of proper gain settings is easily recognized.

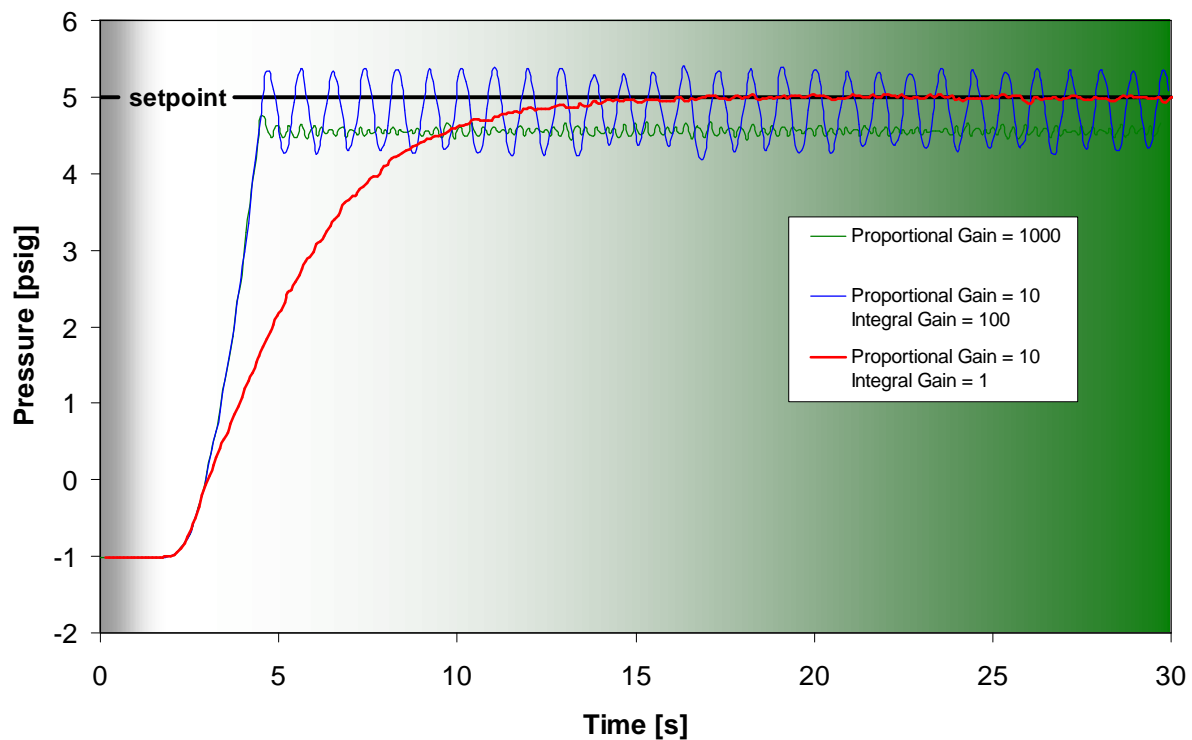


Figure 10: Pressure response of the PumpLab™ to a step change in the pressure setpoint using differing values of the proportional and integral gain.

Process Control Exercise

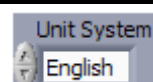
The goal in Process Control is to:

- Maintain a Constant Preset Pressure or Flow output based on fluctuations in pressure or flow.
- Maintaining Constant Pressure with Changing System Conditions

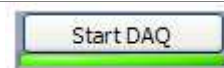
The following procedure offers instructions for performing closed loop PID control using the PumpLab™ centrifugal pump system using the outlet pressure as the control variable.

Software Setup for Process Control

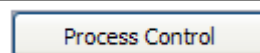
1. Select UNITS on Computer Screen; English or SI



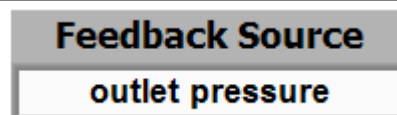
2. Click **START DAQ** Button (data should be flowing on graphs)



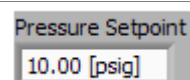
3. Click **Process Control** Button



4. On Feedback Source, click **OUTLET PRESSURE**

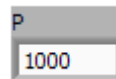


5. On **PROCESS SETPOINT**, Set **PRESSURE SETPOINT** to 10

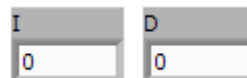


Proportional Gain = 1000**Integral Gain = 0**

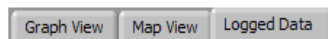
-
1. Set **P** = 1000 (Proportional Gain)



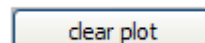
-
2. Leave the **I** and **D** Gains = 0



-
3. Click **LOGGED DATA** Tab



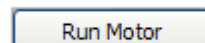
-
4. Click **CLEAR PLOT**



-
5. Click **LOG DATA** Button to start logging continuous data



-
6. Click **Run Motor** for 30 seconds



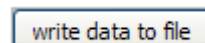
-
7. Click **LOG DATA** Button to stop data logging



-
8. Click **STOP MOTOR** Button



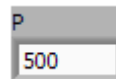
-
9. Click **WRITE DATA TO FILE**



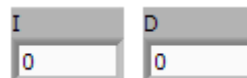
-
10. Save File as: **Red_Pressure_P1000.txt** (Use Black or Gold for other Impellers)
-

Proportional Gain at 500**Integral Gain = 0**

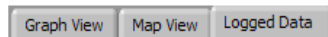
-
1. Set **P** = 500 (Proportional Gain)



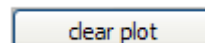
-
2. Leave the **I** and **D** Gains = 0



-
3. Click **LOGGED DATA** Tab



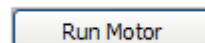
-
4. Click **CLEAR PLOT**



-
5. Click **LOG DATA** Button to start logging continuous data



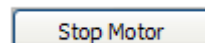
-
6. Click **Run Motor** for 30 seconds



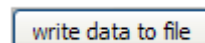
-
7. Click **LOG DATA** Button to stop data logging



-
8. Click **STOP MOTOR** Button



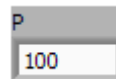
-
9. Click **WRITE DATA TO FILE**



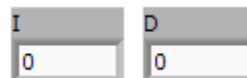
-
10. Save File as: **Red_Pressure_P500.txt** (Use Black or Gold for other Impellers)
-

Proportional Gain at 100**Integral Gain = 0**

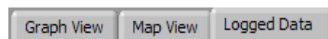
-
1. Set **P** = 100 (Proportional Gain)



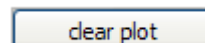
-
2. Leave the **I** and **D** Gains = 0



-
3. Click **LOGGED DATA** Tab



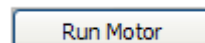
-
4. Click **CLEAR PLOT**



-
5. Click **LOG DATA** Button to start logging continuous data



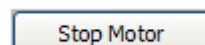
-
6. Click **Run Motor** for 30 seconds



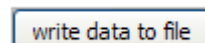
-
7. Click **LOG DATA** Button to stop data logging



-
8. Click **STOP MOTOR** Button



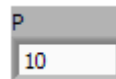
-
9. Click **WRITE DATA TO FILE**



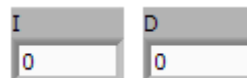
-
10. Save File as: **Red_Pressure_P100.txt** (Use Black or Gold for other Impellers)
-

Proportional Gain at 10 Integral Gain = 0

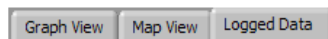
-
1. Set **P** = 10 (Proportional Gain)



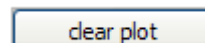
-
2. Leave the **I** and **D** Gains = 0



-
3. Click **LOGGED DATA** Tab



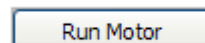
-
4. Click **CLEAR PLOT**



-
5. Click **LOG DATA** Button to start logging continuous data



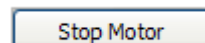
-
6. Click **Run Motor** for 30 seconds



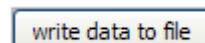
-
7. Click **LOG DATA** Button to stop data logging



-
8. Click **STOP MOTOR** Button



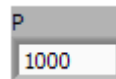
-
9. Click **WRITE DATA TO FILE**



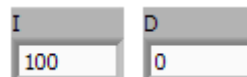
-
10. Save File as: **Red_Pressure_P10.txt** (Use Black or Gold for other Impellers)
-

Proportional Gain at 1000**Integral Gain = 100**

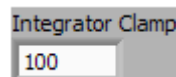
1. Set **P** = 1000 (Proportional Gain)



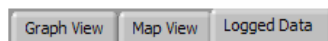
2. Set **I** = 100 and **D** Gain = 0



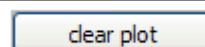
3. Set **Integrator Clamp** = 100



4. Click **LOGGED DATA** Tab



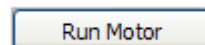
5. Click **CLEAR PLOT**



6. Click **LOG DATA** Button to start logging continuous data



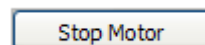
7. Click **Run Motor** for 30 seconds



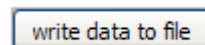
8. Click **LOG DATA** Button to stop data logging



9. Click **STOP MOTOR** Button



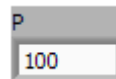
10. Click **WRITE DATA TO FILE**



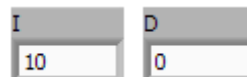
11. Save File as: **Red_Pressure_P1000_I100.txt** (Use Black or Gold for other Impellers)

Proportional Gain at 100**Integral Gain = 10**

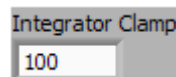
1. Set **P** = 100 (Proportional Gain)



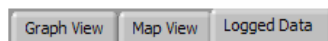
2. Set **I** = 10 and **D** Gain = 0



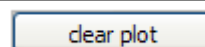
3. Set **Integrator Clamp** = 100



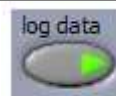
4. Click **LOGGED DATA** Tab



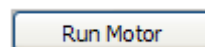
5. Click **CLEAR PLOT**



6. Click **LOG DATA** Button to start logging continuous data



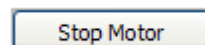
7. Click **Run Motor** for 30 seconds



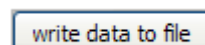
8. Click **LOG DATA** Button to stop data logging



9. Click **STOP MOTOR** Button



10. Click **WRITE DATA TO FILE**



11. Save File as: **Red_Pressure_P100_I10.txt** (Use Black or Gold for other Impellers)

Expanding the PumpLab™ Sample lab

The sample lab outlined in this document provides a starting point for exploring the basics of centrifugal pumping and introduces the concept of closed loop PID control. However, the procedure outlined here only skims the surface of what can be explored with the PumpLab™ centrifugal pump system.

Other possible topics of exploration include:

- Impeller geometry
 - How does a pump actually work?
 - Introducing velocity vector diagrams and pump design
- Specific speed: why do pumps for differing applications look the way they do
- Affinity laws: understanding how a change to a parameter will affect the performance of the pump
- Variable speed pumping: comparing throttling versus varying pump speed in constant pressure/head applications
 - Is one better than the other in terms of efficiency or energy/cost savings?
 - How is the performance curve of a pump used in deciding the choice of impeller for either of these techniques?
- Process Control
 - Modeling the system and comparing this model to real experimental data
- Concepts of closed loop control
 - Under-damped, over-damped, and critically damped systems
 - Frequency and time domain
 - Fourier and Laplace transforms
 - Transfer functions
- Selecting a pump impeller for closed loop control based on the performance curves

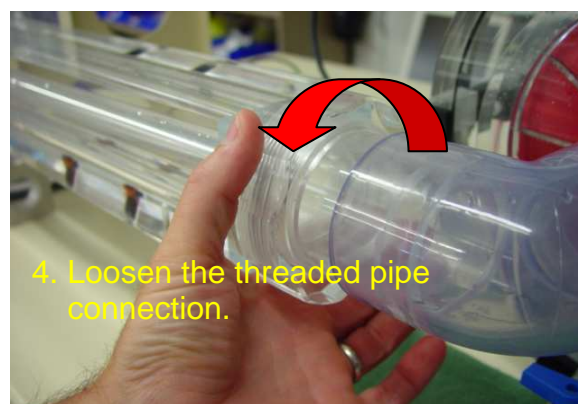
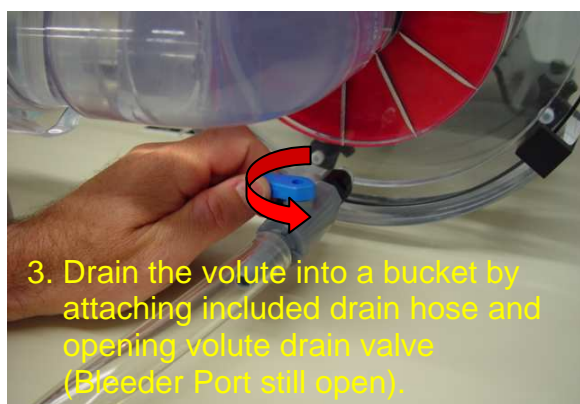
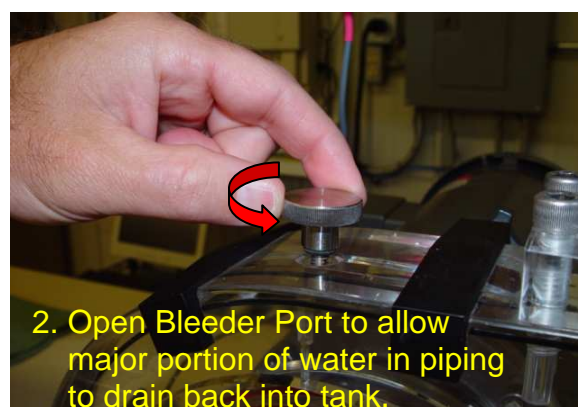
Appendix A

How to change the pump impeller

Your PumpLab™ is supplied with 3 impellers with specific vane profiles;

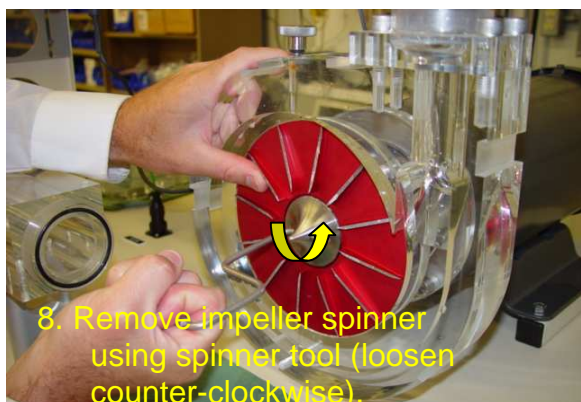
- Black: Forward Swept
- Red: Straight
- Gold: Rearward Swept

Each impeller can be easily changed out to allow testing of the next one.

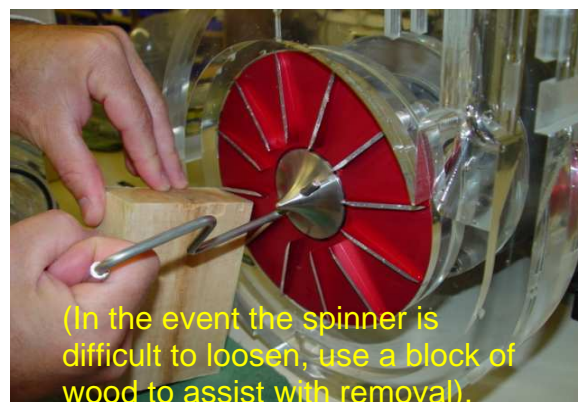




7. Locate Impeller Spinner Tool in Accessory Compartment.



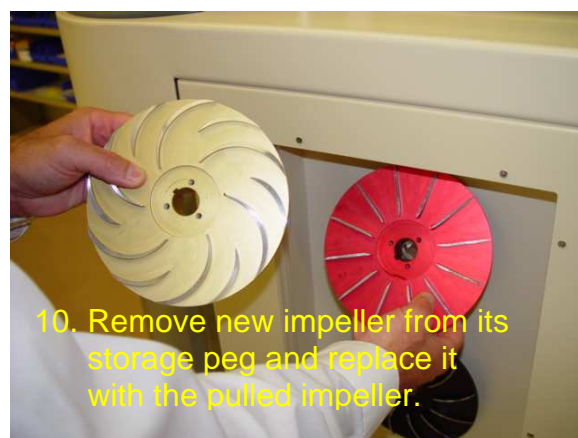
8. Remove impeller spinner using spinner tool (loosen counter-clockwise).



(In the event the spinner is difficult to loosen, use a block of wood to assist with removal).



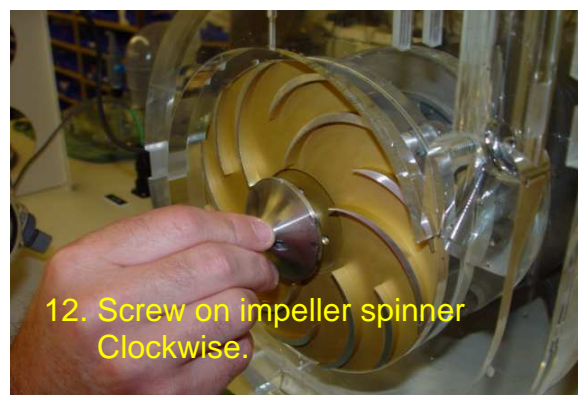
9. Grasp and pull impeller from motor shaft. Retain key that is in keyway.



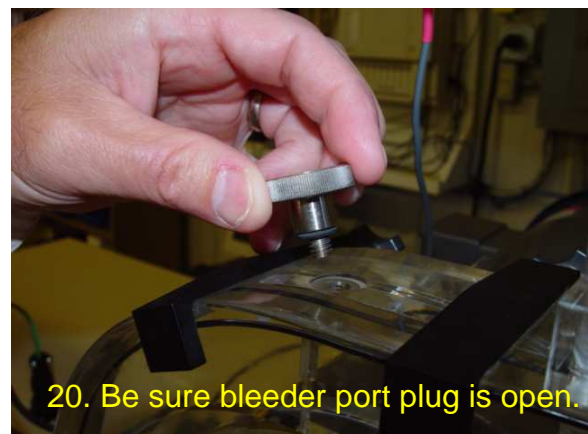
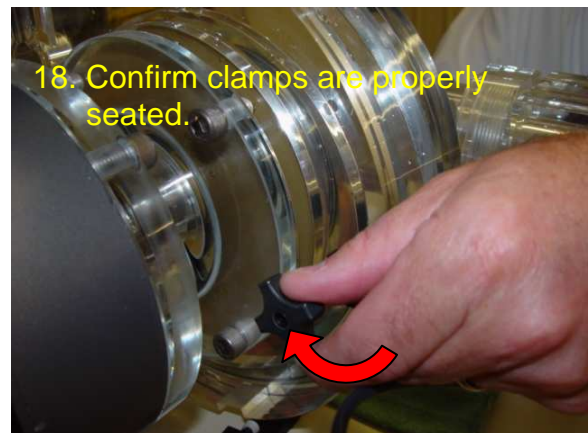
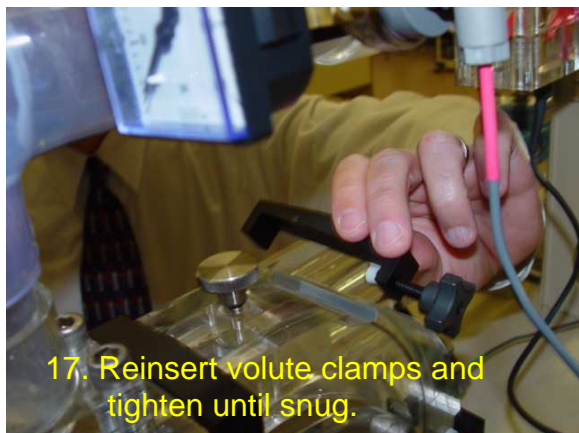
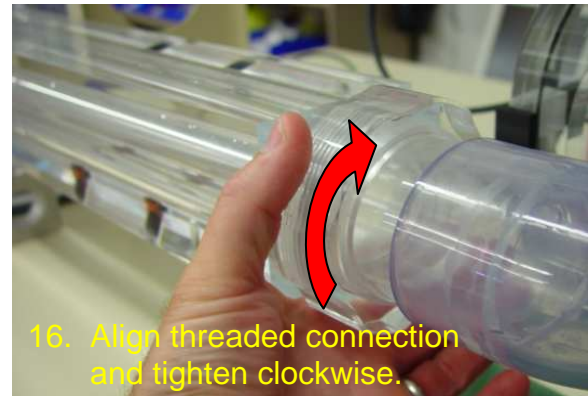
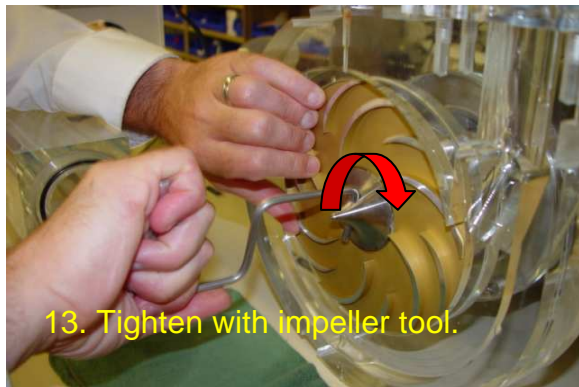
10. Remove new impeller from its storage peg and replace it with the pulled impeller.



11. Slide new impeller onto shaft, carefully aligning it with shaft key and keyway.



12. Screw on impeller spinner Clockwise.



Priming the System

