Intro to Centrifugal Pumps

Joe Evans, Ph.D

Pump ED 101

Joe.Evans@Pentairwater.com

http://www.pumped101.com

Script for Power Point Presentation

Part 1 – Elementary Mechanics & Hydraulics

Slide 1 – Introduction

Slide 2 – What is a centrifugal pump

A centrifugal pumps is an extremely simple machine. By definition, a machine is a device that converts one type of energy into another while performing work. The internal conbustion engine and the electric motor ane good examples. One converts chemical energy into mechanical energy and the other produces that same energy from electricity.

The centrifugal pump imparts mechanical or rotational energy to a fluid causing it to flow, rise to a higher level or both. It gets its name from that “center fleeing” force that is supposed to be fundamental to its operation. We will see a bit later that this force does not even exist! But, who cares as long as the pump works and we can understand its operation.

Slide 3 – How does it work

I said before that the centrifugal pump is a very simple machine. If we ignore its bearings and shaft, it has but one rotating part – its impeller. And, a single stationary part – its volute.

Rotation of the impeller forces water from its entry point, at the impeller eye, through the impeller’s vanes and into the volute or diffuser. Lets take a look at what goes on inside a centrifugal pump.

Slide 4 – Centrifugal pump cut away

The figure on the left is an actual cut away of a close coupled centrifugal pump exposing its impeller and the interior of its volute. The one on the right is a drawing that shows a cross section of the volute and the impeller with its vanes exposed.

Water enters the eye (seen at the left) of the spinning circular impeller and is guided by its curved vanes toward the vane exits at the periphery (outside edge of the circle). As the water moves through, its velocity increases and as it exits the vanes this increased velocity is converted to pressure.

The flow and pressure created by a centrifugal pump depends, primarily, upon the design of its impeller and its peripheral velocity. An impeller's peripheral velocity, and therefore the final velocity of the fluid it is pumping, is governed by its diameter and its rotational speed. It is very important that you get a good grasp of peripheral velocity as it is the single most important component in the operation of a centrifugal pump.

Slide 5 – Peripheral Velocity

Circular motion and velocity are often more difficult to visualize than their translational (point to point) cousins. After all if an automobile is traveling at 60 miles per hour, all of its parts travel at the same velocity. Even though the front bumper will reach a point before the rear bumper, both are still traveling at 60 MPH.

Not so with rotational velocity! Although all points on the radius of a spinning circle complete a single rotation in exactly the same unit of time, their velocities will be quite different.

The disc seen at the bottom of the screen shows two points on its radius. One is 6" from its center and the other is at its periphery, 12" from its center. Although both points will complete one rotation together, the point at the periphery travels twice the distance of the point located at 6". If it travels twice as far in the same amount of time, its velocity must be twice as great also.

It is this increasing radial velocity that causes the velocity of the water to increase as it journeys from the center of an impeller to its exit at its periphery. Although we speak of pump speed and impeller diameter when describing a particular pump, remember that it is peripheral speed that governs its operation.

Slide 6 – More about circular motion

Now, I am sure that you won't want to hear this, but that pump that we love so dearly does not operate via centrifugal force! Why – because there is no such animal!

If we were to look at an object traveling in a circle we would find that, at any point in its travel, it is actually traveling in a straight line. Although the sum of its points of travel will describe a circle, each individual point is looking straight ahead.

The figure on the right shows the direction of travel of four points spaced 90 degrees apart. If we were to show the next increment of travel for each, you would notice that the arrows point to their left ever so slightly.

Slide 7 – Centrifugal farce

Centrifugal force is described as "outward fleeing". Suppose, for a moment, you were small enough to climb into a can that is attached to a string and swinging in a circle. What would you feel? Well, you would feel that “centrifugal” force pressing you to the bottom of the can, much the way you feel that same force when you are rounding a sharp curve in an auto.

Now suppose that the person swinging the can releases the string. If there was truly an outward force, you and the can would travel in the direction of the arrow shown in the figure to the left of the screen. But, in actuality, you will not travel in an outward direction but rather in a straight line tangent to the circle as shown by the arrow in the figure to the right. In other words you would travel in the same direction the can was traveling at the instant it was released.

*Demo Swinging Ball on String

Centrifugal force is one of three “apparent” or false forces in physics. Its appearance depends upon one’s point of reference. Inside the can or the car, one would “feel” an outward force but, an observer outside would realize that the force was a result of the can or car restricting you from traveling in a straight line.

In much the same way, the curved vanes of an impeller guide a fluid through an ever increasing radius resulting in some final velocity as it is released.

Slide 8 – The Performance Curve

A pump’s performance curve describes its capabilities and limitations. It unlocks much, if not all, of the information known about it. It provides us with its flow and pressure, the horsepower required to drive it, how well it converts mechanical energy to hydraulic energy, and some outside factors that can affect its performance.

Slide 9 – The Characteristic Curve

Once a pump is designed and built, it is tested and the results of those tests are compiled on a chart known as its characteristic curve. Each set of characteristic curve tests are performed at a single rotational speed and impeller diameter.

The result is a curve that shows head & flow at several points, a power curve that shows the brake HP required at each point, another that illustrates its efficiency at each point, and one that plots the Net Positive Suction Head Required for each point (not shown on this slide). We will address NPSHR a little later.

As you look at the plot on this slide you will see several trends that hold true for all centrifugal pumps. First, the head generated by a centrifugal pump tends to decrease as flow increases. Second, BHP increases as flow increases. And finally efficiency reaches its peak near the center or right center of the curve. It is not within the scope of this introduction to explain why these trends occur, just understand that they always will.

Slide 10 – The Composite Curve

You don’t often see characteristic curves in pump catalogs these days. Instead you will find a plot of a series of curves for a particular pump based on differing impeller diameters or rotational speeds. In this slide we see a more typical Composite curve that shows the performance of a

Berkeley B4GPBH at 1750 RPM and impeller diameters of 9.5” to 12.75”. All of the information seen on the characteristic curve is shown here but a somewhat different manner.

The capacity / head curves are shown in much the same manner and, in this case, the impeller diameter is listed above each. The efficiency and power curves, however, are portrayed as isomers. The BHP isomers are shown as straight, downward sloping lines with the HP for each listed to the right of the line. Any point on a capacity curve that falls between HP isomers must be interpolated. Usually the pump would be sized to incorporate the next larger HP motor. The efficiency isomers are shown as continuous parabolic curves with the efficiency of a particular curve listed each end. Some may not be shown as continuous curves because their values at lower heads may be below the X axis of the plot. Any point on a capacity curve that falls between two efficiency isomers must also be interpolated. Also shown on this plot is the Net Positive Suction Head Required (NPSHR) for both the full size impeller and the smallest diameter. The NPSHR curves for intermediate trims must again be interpolated. We will discuss NPSH in detail a little latter.

Slide 11 – Series and Parallel Operation

A unique feature of the centrifugal pump is that it can be operated in both series and parallel configurations. Positive displacement pumps can operate only in parallel because the fluid compressability needed for series operation is not characteristic of most liquids.

When a centrifugal pump is operated with a positive suction pressure (another pump or an elevated tank) the resulting discharge pressure will be the sum of the suction pressure and the pressure normally developed by the pump. Capacity, however, remains the same as that of a single pump. It is this quality that makes it ideally suited for use of a booster pump. It is also the basis for the multistage centrifugal pump (including submersible turbine pumps).

Conversely, two or more identical pumps may be operated in parallel – taking their suction from a common header or supply. In this case head remains the same as that of a single pump while flows are additive.

The following two slides illustrate these operations.

Slide 12 – Series Operation

Explain. The HP curves for the two pumps are also additive.

Slide 13 – Parallel Operation

Explain . The HP curves for the two pumps are also additive.

Slide 14 – Pressure in Feet vs PSI

Have you ever wondered why pump discharge pressure is usually stated in feet of head rather than pounds per square inch (PSI)? Well, it has to do with something called specific gravity.

Slide 15 – Specific Gravity

The specific gravity of a liquid is defined as the ratio of its weight of a given volume to that of an equal volume of water. For example, if a pint of a certain liquid weighs twice as much as a pint of water its specific gravity (SG) is 2. If it weighs half as much its SG would be 0.5.

The reason discharge pressure is usually stated in feet is because a centrifugal pump will always develop the same head in feet regardless of the liquid's weight. The pressure in PSI, however, will be quite different depending upon the weight or SG of the fluid pumped. Since quite a few pump people work with a broad range of liquids, head in feet (not PSI) is the common denominator.

When pumping liquids of differing SG, pressure in PSI and the BHP required vary directly with the SG.

An example is shown in the next slide

Slide 16 – Effects of SG on PSI

This slide shows three tanks, each filled to a height of 100 feet with different liquids. A pressure gauge is installed at the bottom of each tank. The first contains kerosine, which is lighter than water and has a SG of 0.8. The second is filled with water at a SG of 1.0. And, the third is filled with a brine solution which, at a SG of 1.2 , is heavier than water.

You will note that even though they are all filled to the same elevation, their pressure gauges indicate very different pressures. The brine tank indicates a 20% greater pressure than that of the water tank while the kerosine tank a 20% lower pressure. For water, 1 PSI is equal to 2.31 feet of head.

Although it is not within the scope of this brief introduction to explain why, each of the tanks would show identical pressures regardless of whether their diameter was 1 inch or 100 feet!! You might want to look into that.

Slide 17 – Affinity

The word affinity is of great importance when it is associated with the centrifugal pump. (Read the definition) It is probably important to you too. For example you probably choose your friends based upon certain behaviors that are common to all of them. I bet if you go through your girlfriend (boyfriend) relationships over time you will also find certain characteristics that are shared by all of them.

This characteristic is also true of centrifugal pumps. When their driven speed or impeller diameter changes (peripheral speed) their actions follow three fundamental laws.

Slide 18 – The Affinity Laws

The affinity laws predict a centrifugal pump's performance when its rotational speed or impeller diameter (peripheral velocity) is changed.

Read and explain the three laws.

This another area where the human brain often has a little difficulty understanding some of the implications. When we say flow varies directly with a change in speed we mean that if speed is doubled flow is doubled also. If speed is reduced by half then flow is also. Direct variations are pretty straight forward but when an exponent is involved (as in squared or cubed) the results are often unexpected.

Have the class perform the paper fold exercise.

Slide 19 – Affinity law plot example

This slide shows what happens, based upon the affinity laws, when a Berkeley B3ZPBH's rotational speed is increased from 1800 RPM to 3600 RPM.

Explain the chart with respect to the affinity laws.

Slide 20 – Variable frequency operation

Although this presentation is not designed to cover the AC motor and its operation at various frequencies, the affinity laws offer us a unique opportunity to vary a pump's output based on demand. We will not get into detail but I would like to aquaint you with something we call variable frequency operation.

Explain the slide.

Slide 21 – Performance at different frequencies

This slide shows the same pump operated at frequencies of 60, 55, and 50 hz. The corresponding rotational speeds are 3600 RPM, 3300 RPM, and 3000 RPM. As you can see these speed reductions follow the affinity laws and result in curves that show lower heads and flows.

The beauty of VF operation is that either constant pressure or constant flow can be maintained regardless of existing conditions. If demand decreases a VFD can reduce the motor speed to maintain either based upon some input from a pressure transducer or flow meter. The real pay off of this technique lies in the third law. Note the dramatic drop in BHP even though the speed change was quite small. In times of lower demand the energy savings alone can justify this control technique.

Explain the slide

Slide 22 – Suction Conditions

The "Achilles heel" of any centrifugal pump is its suction and the conditions that exist there. Even submerged pumps such as submersible turbines and sewage pumps are not exempt.

Water has no tensile (pulling) strength so it cannot it cannot transmit tension and be pulled from some level below the pump up to the pump's suction. When a pump creates a "suction" it is simply reducing local pressure in the impeller's eye by creating a partial vacuum. Then atmospheric or some other external pressure acting upon the surface of the water pushes the water up the suction pipe and into the impeller.

Atmospheric pressure at sea level is called absolute pressure (PSIA) because it is a measurement using absolute zero (a perfect vacuum) as a base. If pressure is measured using atmospheric pressure as a base it is called gauge pressure (PSIG or simply PSI). Common pressure gauges are calibrated in PSIG (ie they show 0 PSI).

Atmospheric pressure, as measured at sea level is 14.7 PSIA. In feet of water it is approximately 34 feet.

Slide 23 – Suction Lift

Well, if atmospheric pressure at sea level is 34 feet then a pump operating at sea level should be able to lift water 34 feet. Right? No, 34 feet is the maximum theoretical suction lift for a pump pumping cold water at sea level – and that assumes the pump could create a perfect vacuum. Suction lifts up to 25 feet, however, are common.

Maximum suction lift is dependent upon the design of the pump and its operating point on the capacity curve. Maximum suction lift is also dependent upon the pressure applied to the surface of the water at the suction source. Maximum suction lift decreases as pressure decreases. There is also a third condition. Maximum suction lift is dependent upon the vapor pressure of the liquid being pumped. The vapor pressure of a liquid is the pressure necessary to keep it from vaporizing (boiling) at a given temperature. Vapor pressure increases as its temperature increases and maximum suction decreases with a rise in vapor pressure.

Slide 24 – Net Positive Suction Head

Read slide

Slide 25 – NPSHR

Read slide

Although NPSHR varies with flow, temperature and elevation have no effect. NPSHR increases approximately as the square of capacity since it is a function of the velocities and friction in the pump inlet.

Lets go back to a previous slide and take a look at NPSHR.

Slide 26 – Berkeley composit curve

Explain NPSHR curves

Slide 27 – NPSHA

Read slide

NPSHA = Ha + - Hs – Hvp

Where Ha = Atmospheric pressure in feet, Hs = Suction head or lift in feet, Hvp = Vapor pressure in feet

Suction lift can be easily calculated but the other two are not as apparent. Lets take a look at the effects of elevation and temperature.

Slide 28 – Effect of Elevation and Temperature

This slide shows the effect elevation and temperature has upon the NPSHA of water. The left side of the table illustrates the effect of elevation. As you can see there is very little effect at lower elevations but the effect upon NPSHA in our part of the country can be substantial. In beautiful, flat Denver, for example, we must deduct about 6 feet from the NPSHA found at sea level. As we move into the mountains this deduction becomes even larger.

The right side of the table shows the effect of water temperature. It is not very great at temperatures under 80 degrees but as the temperature increases, so does the pressure required to keep water in its liquid state. The point here is that every foot of pressure that is required to keep water in the liquid state becomes unavailable as NPSHA. When the effects of elevation and temperature are added together, the reduction in NPSHA can grow rapidly.

It’s a bit off the topic but this table also explains why it takes “boiled” food longer to cook in our area than it does in coastal areas. If you look to the right of the chart you will see that water can be heated to 210 degrees and still remain in the liquid state as long as there is 34 feet of atmospheric pressure. Once it reaches 212 degrees it boils.

But the left side of the table shows us that in Denver (el 5500 feet) atmospheric pressure is only 27.8 feet. The right side tells us that, at that pressure, water will remain in the liquid state to about 200 degrees. Once the temperature exceeds 200 degrees it boils. And, its cooking temperature is almost 12 degrees lower than it would be down on the coast.

OK, we are almost finished. I want to touch on just one more topic before we adjourn.

Slide 29 – Liquid Friction

We are not going to delve very deeply into friction but, since I mentioned that it can affect NPSHA, I just wanted to touch on it.

Read the slide
The friction that arises when water flows through a pipe is quite different than that which occurs when two solids come into contact. We actually know very little about it and most of information we have is empirical. It is for this reason we use friction tables rather than equations to determine pipeline friction.

Solid friction is simple – it is all about the force one object exerts on another. For example, the friction that arises between a tire and the pavement depends solely on the tire material and the weight of the car. It has nothing to do with the width of the tire. Those 20” wide tires you see on dragsters produce no more friction than a tire 1" wide. They may handle more power and dissipate heat more quickly but, they do not generate more friction!

Liquid friction, on the other hand, is affected by surface area. When the flow in a pipe increases so does the velocity of the water. With this increase in velocity we also see an increase in the friction between the water and the pipe wall. The only way we can reduce that friction is by increasing the pipe diameter (surface area) and thereby decrease the velocity of the flowing water.

The reason for this is the manner in which water flows in a pipe. Water is a member of the Newtonian fluid family and is said to undergo laminar or viscous flow. The diagram to the right of the slide is a cross section of a pipe and illustrates laminar flow. In a pipe water flows in a series of concentric circles with those nearest the pipe wall flowing more slowly. The vector lengths in the right hand drawing are proportional to the velocity of the flowing water. It is believed that as velocity increases, the circles widen and the "bullet" nose seen in the drawing increasingly becomes "plug" shaped thereby forcing more water towards the pipe walls and increasing friction in the process.

Anyway, that's as far a we are going to go with friction at this point. Just remember – oversize those suction pipes.