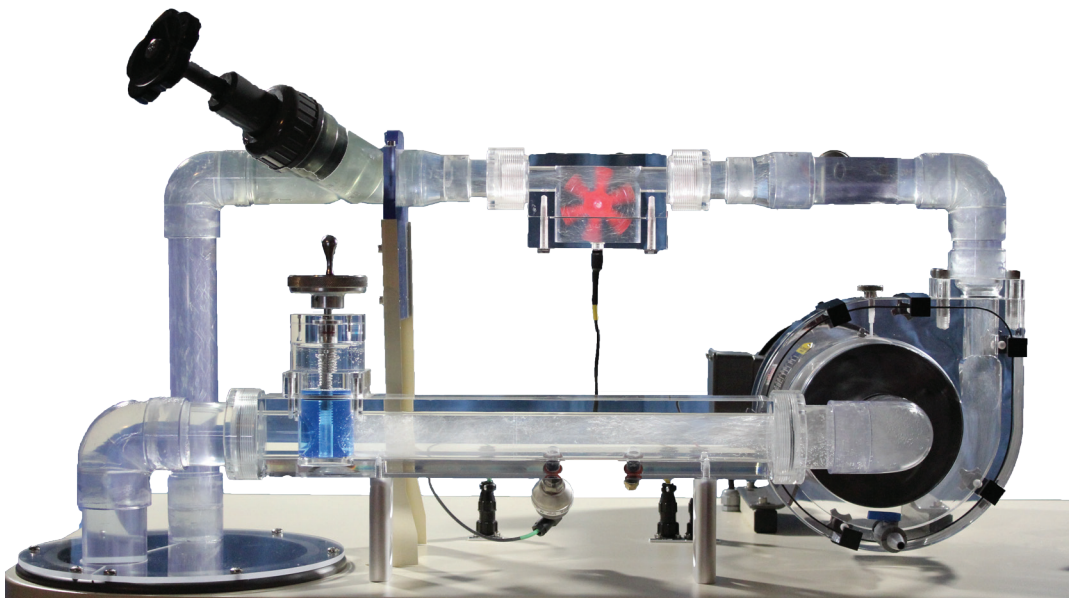


BOOK

1

Classroom Basics

Understanding Centrifugal Pumping



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INTRODUCTION

Upon completion of this book, the student will have a good understanding of important issues related to centrifugal pumping, including; the relationship of gravity and velocity, pressure head, pump impeller sizing, fluid specific gravity and viscosity, system friction head, suction head/lift, Net Positive Suction Head (NPSH) and Cavitation. This knowledge will serve as the foundation for learning to effectively operate a live centrifugal pump system.

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Approximate Lesson
Duration: 25 min.



Lesson 1: Define Centrifugal Pumping

Student will understand what a centrifugal pump is, what the major components of a centrifugal pump are, what pumping head is, and how to size a pump impeller.

Centrifugal pumps are used in many applications including water, sewage, petroleum and petrochemical pumping. They have become a primary component of many industries. A centrifugal pump is a machine that gives energy to a fluid. This energy infusion can cause a liquid to flow, rise to a higher level, or both.

The centrifugal pump is a very simple rotary machine which consists of two major parts: 1) impeller (rotating component) and 2) volute (the stationary structure or casing). The figure shows these two parts (along with the eye, which is the fluid inlet into the volute).

The centrifugal pump's function is as simple as its design. It is filled with liquid and the impeller is rotated (usually with an electric motor). The impeller vanes grab the liquid and “fling” it, giving it energy, which causes it to exit the impeller's vanes at a greater velocity than it possessed when it entered.

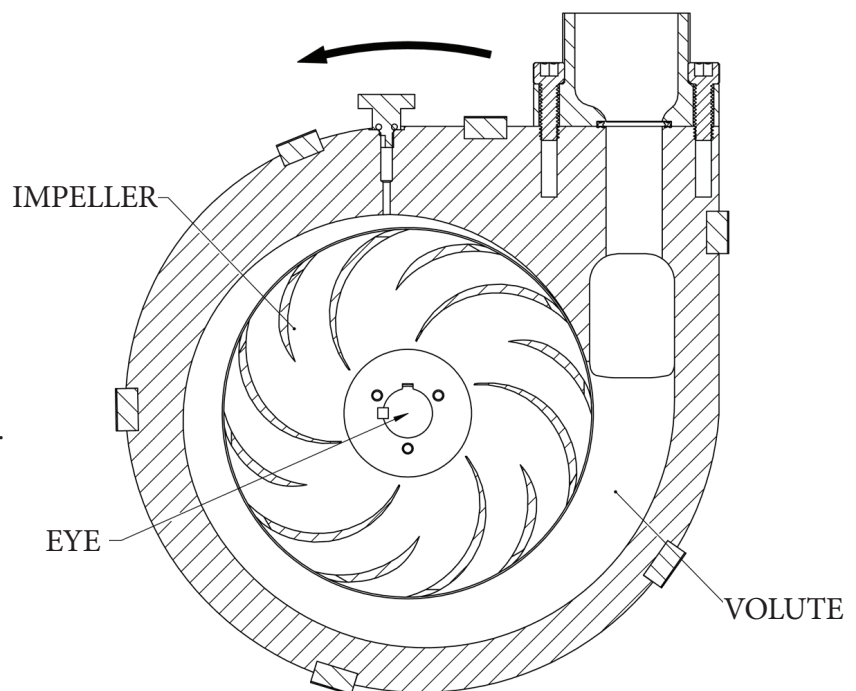
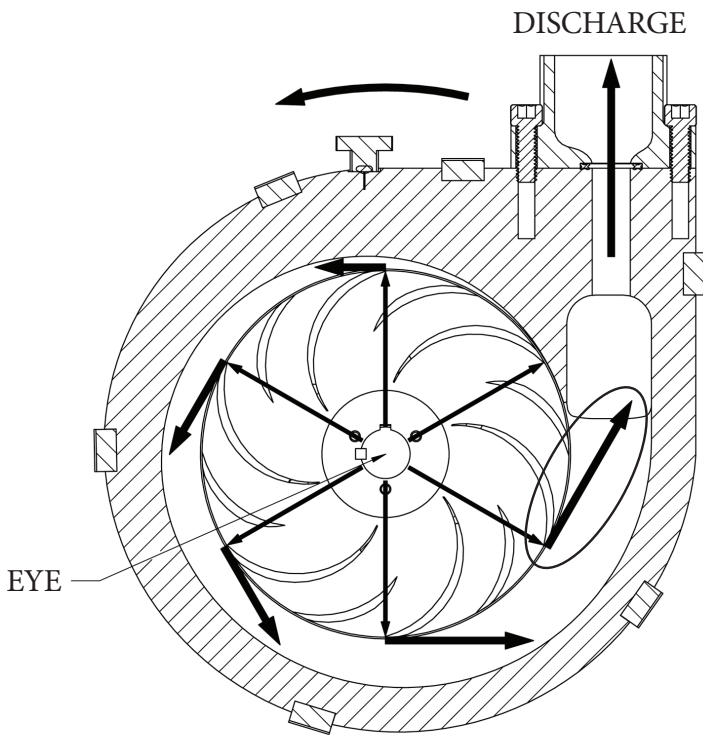


Figure 1.1: Pump Primary Components



This outward flow (flinging) reduces the pressure at the impeller eye (the center where the inlet piping allows the fluid to enter the casing), allowing more liquid to enter. The liquid exits the impeller at its edge (peripheral velocity) and is collected in the casing (volute) where its velocity is converted to pressure before it leaves the pump's discharge.

Figure 1.2: Impeller Outward Flow

What does a real centrifugal pump look like?

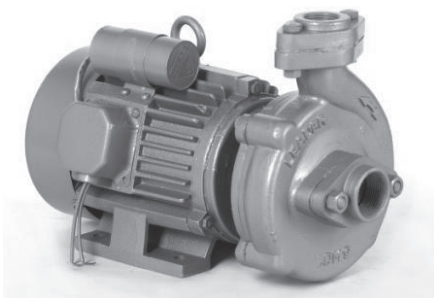


Figure 1.3: Commercial Centrifugal Pump

What does a real centrifugal impeller look like?



Figure 1.4: Centrifugal Pump Impeller

Focus 1: Let's Fling Stones! (How gravity and velocity relate to centrifugal pumping)

Gravity is one of the more important forces that a centrifugal pump must overcome. You will find that the relationship between final velocity, due to gravity, and initial velocity, due to impeller speed, is a very useful one.

Let's use an example that's easy to visualize to better understand what we're talking about.

If a stone is dropped from the top of a building, its speed (velocity) will increase at a known rate of 32.2 feet per second for each second that it falls. This increase in velocity is known as acceleration due to gravity.

If we ignore the effect of air resistance on the falling stone, we can predict the velocity it will hit the ground based upon its starting height off the ground and the effect of acceleration due to gravity (that's 32.2 feet per second PER second).

Now, with help of mathematics and even Sir Isaac Newton himself (you remember that he discovered this thing called gravity), a convenient equation was developed which describes the relationship of velocity, height, and gravity as it applies to a falling body, like that stone as:

$$v^2 = 2gh$$

Where:

v = the velocity of the body in ft/sec

g = the acceleration due to gravity @ 32.2 ft/sec/sec (or ft/sec²)

h = the distance through which the body falls

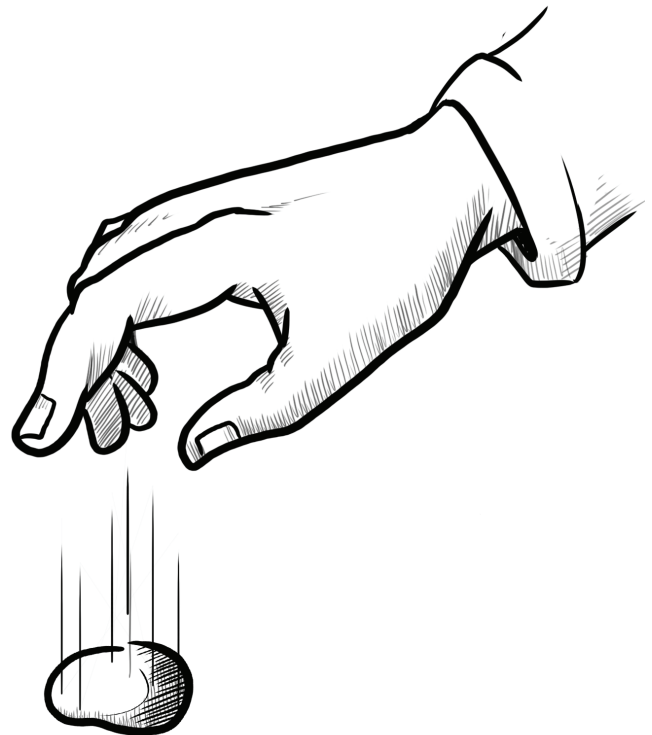
For example, if a stone is dropped from a building 100 feet high:

$$v^2 = 2 \times 32.2 \frac{ft}{s^2} \times 100 ft, \text{ which gives us...}$$

$$v^2 = 6440 \frac{ft^2}{s^2}$$

$$v = \sqrt{6440 \frac{ft^2}{s^2}} = 80.3 \frac{ft}{s}$$

The stone, therefore, will strike the ground at a velocity of 80.3 feet per second (about 55 miles per hour).



Now, let's reverse this scenario. That same equation allows us to figure out how fast we would have to throw that stone (initial velocity) upward from ground level for it to reach the top of the building (100 feet). This is true because the **final velocity** of a falling body **happens to be equal** to the **initial velocity** required to launch it to get it to that same height from which it fell (got that?). Using the example above, the initial velocity required to throw the stone to a height of 100 feet is 80.3 feet per second, the same as its final velocity.

So what does dropping and throwing stones have to do with pumping? Here's the cool part: the same equation we used for the stone applies when pumping water with a centrifugal pump. The velocity of the water as it leaves the impeller determines the head developed. In other words the water is "thrown" to a certain height. To reach this height it must start with the same velocity it would attain if it fell from that height.

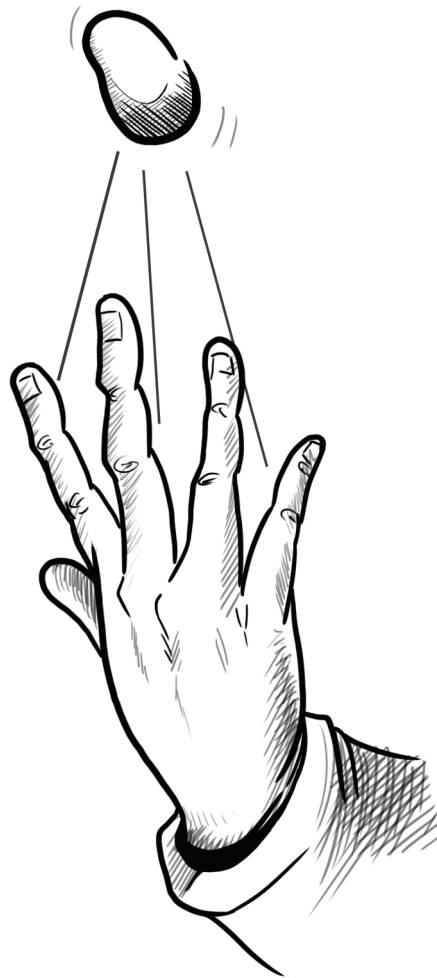
So, if we rearrange the falling body equation we get:

$$h = \frac{v^2}{2g}$$

Now we can determine the height to which a body (or water) will rise given a particular initial velocity. For example, at 10 ft per sec:

$$h = \frac{\left(10 \frac{ft}{s}\right)^2}{2 \times 32.2 \frac{ft}{s^2}}$$

$$h = 1.55 \text{ ft}$$



Lesson 1, Focus 1

1. Calculate the velocity of a marble at impact if it is dropped from a 6 story building (each story is 12 ft. high). Disregard any air resistance.
2. At what speed would we need to launch the marble from the ground level to reach the top of the building?
3. If you were to try this with several different initial velocities, you would find out that there is an interesting relationship between the height achieved by a body and its initial velocity. **This relationship is one of the Affinity Laws of centrifugal pumps which can be studied independently.**

Focus 2: Sizing an Impeller

As a finale to this section, let's apply what we have learned to a practical application. Follow each step carefully and you will gain a good understanding of how this works (you'll feel so smart).

Problem: We have a centrifugal pump that is spinning at 1800 RPM. We need to figure out what impeller diameter would be needed to fling the water up 200 feet (a.k.a. develop a head of 200 feet).

First we must calculate the initial velocity required to develop a head of 200 feet. Using our falling body equation from before:

$$v^2 = 2gh$$

$$v^2 = 2 \times 32.2 \frac{ft}{s^2} \times 200 ft$$

$$v^2 = 12,880 \frac{ft^2}{s^2}$$

$$v = \sqrt{12,880 \frac{ft^2}{s^2}} = 113 \frac{ft}{s}$$

We also need to know the number of rotations the impeller undergoes each second:

$$1800 \text{ RPM} / 60 \text{ sec} = 30 \text{ RPS (Revolutions per Second)}$$

Now we can compute the number of feet a point on the impellers rim travels in a single rotation: 113 ft/sec divided by 30 rotations/sec = 3.77 ft/rotation

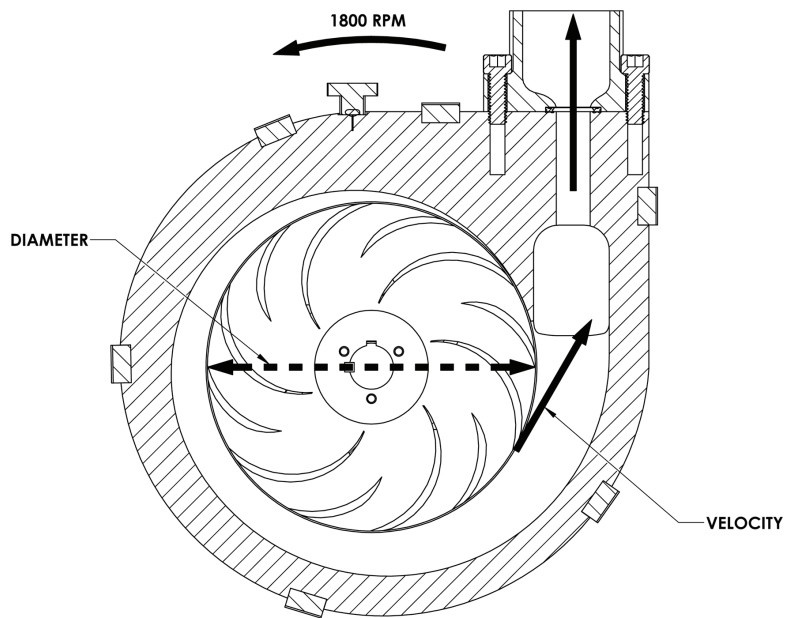
Since distance traveled per rotation is **the same** as the circumference of the impeller we can compute the diameter using the circular relation formula as follows:

$$C = \pi D \Rightarrow D = \frac{C}{\pi}$$

$$D = \frac{3.77 ft}{\pi}$$

$$D = 1.2 ft = 14.4 in$$

Therefore an impeller with a diameter of approximately 14.4" turning at 1800 RPM will produce a head of (fling water up) 200 Feet.



Lesson 1, Focus 2

We have a centrifugal pump that is spinning at 1800 RPM. What impeller diameter would be needed to fling the water up 122 feet (a.k.a. develop a head of 122 feet). _____



Knowledge Certification Quiz: Lesson 1

Please answer all of the following questions without referring to the text (formulas excepted). If you can answer all questions, you are ready for Lesson 2. If not, please review Lesson 1 and retake certification quiz.

1. Name 3 areas centrifugal pumps are used in.
2. What are the 2 main components of a centrifugal pump?
3. What typically drives a centrifugal pump?
4. Calculate the velocity of a cue ball that was dropped from a 100 foot building as it hits the ground.
5. How fast would you need to throw that cue ball upward from ground level for it to reach the top of the 100 foot building?
6. What would the diameter of a pump impeller have to be to throw water up that high?

I certify that I have answered all certification quiz questions correctly and am ready for the next lesson.

Your Signature

Date

Approximate Lesson
Duration: 10 min.



Lesson 2: Specific Gravity of a Fluid (Why head is expressed in feet)

Chances are pretty good that you will be pumping a liquid other than water in your field. The good news is that in pumping, each liquid is compared to water (at a standard temperature and pressure) to get a handle on how a pump will perform when pumping it. This comparison is known as Specific Gravity. This section will explain Specific Gravity and how it relates to head.

The Specific Gravity of a substance is the ratio of the weight of a given volume of the substance to that of an equal volume of water at standard temperature and pressure (STP). Assuming the viscosity of a liquid (see Section 1, Part 3) is similar to that of water, the following statements will always be true regardless of the specific gravity:

- 1) A Centrifugal pump will always develop the same head in feet regardless of a liquid's specific gravity.
- 2) Pressure will increase or decrease in direct proportion to a liquid's specific gravity.
- 3) Brake HP required will vary directly with a liquid's specific gravity.

Figure 2.1 illustrates the relationship between pressure (in psi) and head (in ft).

We can see that the level in each of the three tanks is 100 feet. The resulting pressure at the bottom of each varies substantially as a result of the varying specific gravity. Now, if we keep pressure constant as measured at the bottom of each tank, then it would stand to reason that the fluid levels would vary in a similar way.

Notice that the specific gravity (remember definition) of Jet Fuel is only 82% that of water, while ethylene glycol will be 110% of water. It is very interesting to look up a chart of the specific gravity of a number of liquids. This really gives you a feel for how things compare and may even surprise you. For instance, olive oil has a specific gravity of 91% while glucose is around 140%. One element we'll talk about later is the Viscosity of the liquid.

A centrifugal pump can also develop 100' of head when pumping water, jet fuel, and ethylene glycol. The resulting pressures, however, will vary just as those seen in the figure.

If that same pump requires 10 HP when pumping water, it will require 11 HP when pumping ethylene glycol and only 8.2 HP when pumping jet fuel (based on the specific gravity ratios).

The preceding discussion of Specific Gravity illustrates why centrifugal pump head (or pressure) is expressed in feet. **Since pump specialists work with many liquids of varying specific gravity, head in feet is the most convenient system of designating head.** When selecting a pump, always remember that factory tests and curves are based on water at STP. If you are working with other liquids always correct the HP required for the specific gravity of the liquid being pumped.

Specific Gravity Pressure Variations at Constant Head

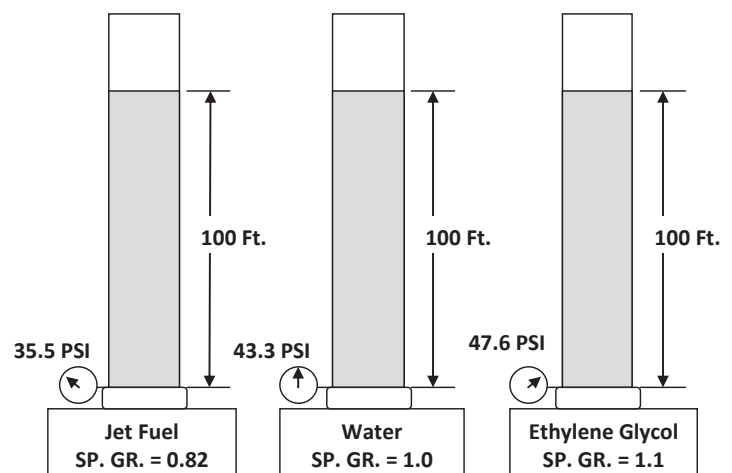


Figure 2.1: Specific Gravity Comparisons
(pressure related to head)



Lesson 2

What is the basic definition of Specific Gravity?

You have a gallon of mercury with a Specific Gravity of 13.5. When you weigh a gallon of water at STP, the scale reads 8.3 lbs (something to keep in mind). What will the scale read when you weigh a gallon of mercury?

A train (yes, a train) leaves Chicago carrying 500 gallons of diesel fuel (specific gravity of 0.82) for its engines, and travels at 50 MPH toward Topeka, which is 400 miles away. The engines combine to burn 50 gallons of fuel per hour. How much less will the train weigh when it gets to Topeka?



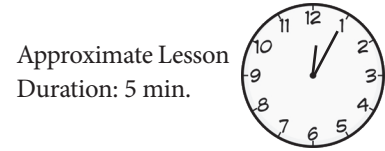
Knowledge Certification Quiz: Lesson 2

1. What is the specific gravity of water at standard temperature and pressure?
2. If 3 identical tanks are filled with 3 mystery fluids to a height each of 50 feet and the pressure readings at the bottom of the tanks all read the same pressure, what does that tell us about the specific gravity of each fluid.
3. The 3 tanks from question 2 are drained. One is filled with water to 100 feet. The second is filled with a Mystery Fluid A to 100 feet. The third is filled with a Mystery Fluid B to 100 feet. If the volume in each tank is 1,000 gallons and Mystery Fluid 1 has a Specific Gravity of 0.8 and Mystery Fluid B has a Specific Gravity of 1.2, how much does each tank of mystery fluid weigh if the water weighs 8.3 lbs/gallon.

I certify that I have answered all certification quiz questions correctly and am ready for the next lesson.

Your Signature

Date



Lesson 3: Viscosity of a Fluid

This lesson will explain the importance of viscosity in fluid pumping and how it changes pump performance.

Viscosity is a fluid property that is independent of specific gravity. Just as resistivity is the inherent resistance of a particular conductor, viscosity is the internal friction of a fluid. The coefficient of viscosity of a fluid is the measure of its resistance to flow. Fluids having a high viscosity are sluggish in flow. Examples include molasses and heavy oil. Viscosity usually varies greatly with temperature with viscosity decreasing as temperature rises.

The instrument used to measure viscosity is the viscometer. Although there are many, the Saybolt Universal is the most common. It measures the time in seconds required for a given quantity of fluid to pass through a standard orifice under STP. The unit of measurement is the SSU or Seconds Saybolt Universal.

Normally, small and medium sized centrifugal pumps can be used to handle liquids with viscosities up to 2000 SSU. Below 50 SSU the Characteristic Curves remain about the same as those of water; however, there is an immediate decrease in efficiency when viscosity increases over that of water. Viscosities over 2000 SSU are usually better suited for positive displacement pumps. This is good to know, especially if you're hired to work in a molasses factory!

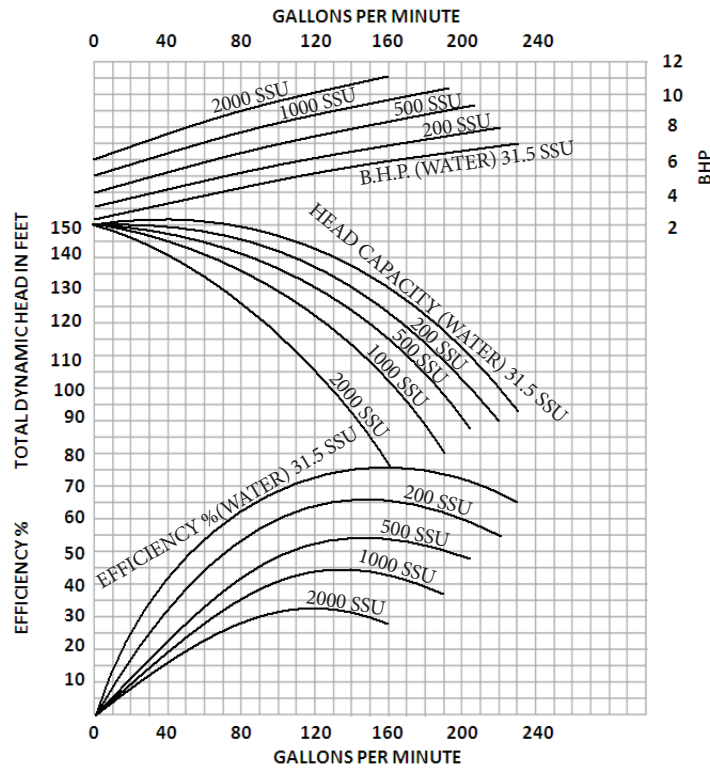


Figure 3.1: Pump Performance at Various Viscosities



Lesson 3

1. What is viscosity?
2. How do you measure viscosity?
3. Using the chart shown on page 12 (Figure 3.1), answer this question: If a fluid has a viscosity of 1000 SSU and is being pumped at 90 gallons per minute, how does the efficiency compare if you were pumping water (SSU of 315)?



Knowledge Certification Quiz: Lesson 3

1. What is viscosity?
2. If you were interested in how much a gallon of fluid weighed, would finding its viscosity be the best way to do this?
3. Name an industry device which measures viscosity.
4. Using the chart in this section: What happens to Pump Efficiency and Total Dynamic head it can produce as the viscosity of the fluids it pumps get larger?

What about the required power to drive the pump?

Why?

I certify that I have answered all certification quiz questions correctly and am ready for the next lesson.

Your Signature

Date

Approximate Lesson
Duration: 10 min.



Lesson 4: Friction and Friction Head

Friction occurs when a fluid flows in or around a stationary object or when an object moves through a fluid. An automobile and an aircraft are subjected to the effects of friction as they move through our atmosphere. Boats create friction as they move through the water. It so happens that liquids create friction as they move through a closed pipe. This lesson will discuss how friction head contributes to centrifugal pumping requirements.

Designers and engineers spend a great deal of money on the design and redesign of aircraft, automobiles and boats to reduce friction (also called drag). Why? Because friction produces heat and where there is heat there is energy, wasted energy that is. Making these vehicles more aerodynamic, or “slippery”, reduces friction, which reduces the energy required to get them from point A to point B.

As water moves through a pipe its contact with the pipe wall creates friction. As flow (or more correctly velocity) increases, so does friction. The more water you try to cram through a given pipe size the greater the friction and thus the greater the energy required to push it through. It is because of this energy that friction is an extremely important component of a pumping system.

Laminar flow describes the flow of a liquid in a smooth pipe. Under conditions of laminar flow, the fluid nearest the pipe wall moves more slowly than that in the center. Actually there are many gradients between the pipe wall and the center. The smaller the pipe diameter, the greater the contact between the liquid and the wall thus the greater the friction. The figure below shows laminar flow through two cross sections of a pipe. The vector lengths (arrows) in the right hand drawing are proportional to the velocity of the flowing liquid.

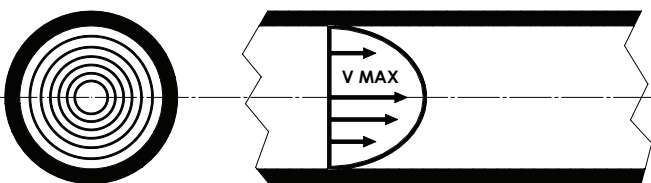


Figure 4.1: Laminar Flow through Pipe Cross Section

Friction or Friction Head is defined as the equivalent head in feet of liquid necessary to overcome the friction caused by flow through a pipe and its associated fittings.

Friction tables are universally available for a wide range of pipe sizes and materials. They are also available for various pipe fittings and valves. These tables show the friction loss per 100 feet of a specific pipe size at various flow rates. In the case of fittings, friction is stated as an equivalent length of pipe of the same size. An example is shown in Figure 4.3 on the following page.

PIPING FRICTION FACTOR DATA									
LOSS OF HEAD IN FEET, DUE TO FRICTION,									
PER 100 FEET OF 17 YEAR OLD STEEL PIPE									
For New Pipe, Multiply Readings by 0.6									
For 25 Year Old Pipe, Multiply Readings by 1.2									
U.S. GPM	PIPE SIZE								
	1	1 1/4	1 1/2	2	2 1/2	3	4	5	6
10	11.7	3.1	1.4						
15	25	6.6	3	1.1					
20	42	11.2	5.2	1.8					
25	64	16.6	7.9	2.7					
30	89	23.5	11	3.8	1.3				
35	119	31.2	14.7	5.1	1.7				
40	152	40	18.8	6.6	2.2				
50		60	28.4	10	3.3	1.4			
60		85	39.5	13.9	4.7	1.9			
70		113	53	18.4	6.2	2.6			
80		145	68	23.7	7.9	3.3			
90		180	84	29.4	9.8	4.1	1		
100			102	35.8	12	5	1.2		
120			143	50	16.8	7	1.7		
140			190	67	22.3	9.2	2.3		
160				86	29	11.8	2.9		
180				107	35.7	14.8	3.6	1.2	
200				129	43.1	17.8	4.4	1.5	
220				154	52	21.3	5.2	1.8	
240				182	61	25.1	6.2	2.1	
260					70	29.1	7.2	2.4	
280					81	33.4	8.2	2.8	1.1
300					92	38	9.3	3.1	1.3
325					107	44	10.7	3.6	1.5
350					122	50.3	12.4	4.2	1.7
375						57.7	13.7	4.8	1.9
400						65	16	5.4	2.2
425						73	17.5	6	2.4
450						80	19.8	6.7	2.7
475						89	22	7.4	3
500						98	24	8.1	3.3
550							28.7	9.6	4
600							33.7	11.3	4.7
640							39	13.2	5.5
700							44.9	15.1	6.3
750							51	17.2	7.1
800							57	19.4	8
850								21.7	9
900								24	10
1000								26.7	12

Based on Williams & Hazen Formula with Constant C = 100

Figure 4.2: Pipe Friction Table

Fitting	Equivalent Pipe Length EX: 20D = 20 x pipe diameter
90 degree elbow	30D
45 degree elbow	20D
T straight through	16D
T through side	60D
Swept 90 bend	4-8D
Open gate valve	9D
Open globe valve	275D
Full-bore non-return valve	6D
Butterfly valve	20D

Note: Various reference books publish detailed charts for values of friction loss in various pipes. It is important to become familiar with these tables for accuracy. Friction Loss Constants (the C in the Friction Head Table) should be determined for your specific piping material to better determine the loss factors. Note that the supplied chart uses a C=100 and magnitude factors for the pipe age.

Figure 4.3: Fitting Equivalent Pipe Length Table

It is evident from the tables that friction increases with flow. It is also evident that there is an optimum flow for each pipe size, after which friction can use up a disproportionate amount of the pump output. For example, 100 GPM for short lengths of 2" pipe may be acceptable; however, over several hundred feet the friction loss will be unacceptable. 2 1/2" pipe will reduce the friction by 66% per 100 feet and is a much better choice for a 200 foot pipeline. For systems that operate continuously, 3" pipe may be the appropriate choice.

Many friction tables show both friction loss and fluid velocity for a given flow rate. Generally it is wise to keep fluid velocity under 10 feet per second. If this rule is followed, friction will be minimized.

The friction losses for valves and fittings can also add up (see fitting chart). 90 degree turns and restrictive valves add the most friction. If at all possible, straight through valves and gentle turns should be used. The chart gives you equivalent lengths for each fitting, which adds to the piping length that the head loss chart must take into account.

Consider this problem: What head must a pump develop if it is to pump 200 GPM through a 2.5" pipe, 200 feet long, and to an elevation of 75'? Use the table in Figure 4.2.

Elevation = 75'

Friction 2.5" Pipe = 43' per 100 feet or 86' for 200 feet of pipe.

Total head = 75' + 86' = 161' TDH

Use of 3" pipe in the above problem will reduce friction head by 30% and although it will cost more initially, it will pay for itself in energy savings over a fairly short period of time.

If we place 5-90° elbows in the system (see Figure 4.3), you can see that the equivalent pipe length increases by $5 \times 30 \times 2.5" = 31.25$ feet.



Lesson 4

1. What is friction in fluid flow?
2. Based upon the supplied chart on page 14 (Figure 4.2), what would be the added friction head to your system calculations for a 17 year old, 2 inch diameter, 200 foot long pipe that is being used to pump 120 GPM of water?



Knowledge Certification Quiz: Lesson 4

1. When fluid moves through a pipe, does the fluid move at the same speed across the cross-section of the pipe?

Why?

2. If you are pumping 10 gallons per minute through a 1 inch diameter pipe and also pumping this same amount through a 2 inch diameter pipe, which pipe offers the most friction or drag?

Why?

3. Using the chart on page 14, please answer the following:

A brand new 2 inch pipe is installed right next to a pipe that has been in service for 25 years. Each pipe has to deliver 100 GPM of output at the end of a 100 foot run. How much friction head does each pump have to overcome for each pipe?

I certify that I have answered all certification quiz questions correctly and am ready for the next lesson.

Your Signature

Date

Approximate Lesson
Duration: 15 min.



Lesson 5: Introduction to Suction Conditions

Suction conditions are some of the most important factors affecting centrifugal pump operation. If they are ignored during the design or installation stages of an application, they will probably come back to haunt you. In this lesson, you will learn about condition factors which affect pump suction.

Focus 1: Suction Lift

A pump cannot pull or “suck” a liquid up its suction pipe because liquids do not exhibit tensile strength. Therefore, they cannot transmit tension or be pulled. When a pump creates suction, it is simply reducing local pressure by creating a partial vacuum. Atmospheric or some other external pressure acting on the surface of the liquid pushes the liquid up the suction pipe into the pump.

Sucking your Drink through a Straw

(How does the sucking action of a straw actually work?)

When you are drinking water from a glass with the help of a straw, you suck at the straw; essentially drawing air out of it. This decreases air pressure right above the level of the water in the straw. In the mean time the air pressure around your glass of water is constantly pushing the drink level to go down (the surface of your water). And the water pressure of your drink is pushing the water level to go up. Since you just helped decrease the air pressure in the straw, the water finds an outlet (path of least resistance) and thus goes up the straw until it reaches your mouth. Think of that the next time you're sipping on that drink with a straw. And now, back to our lesson...



Now, read this slowly and understand it—it's really important!

Atmospheric pressure at sea level is called absolute pressure (PSIA) because it is a measurement using absolute zero (a perfect vacuum) as a comparison or base. When we walk around outside, we are walking in the atmosphere, which is at a certain pressure (this can fluctuate, but it maintains a relatively constant value). For things we do where we raise the pressure greater than atmospheric pressure (like pumping up a basketball), we can measure and display that pressure increase above Atmospheric Pressure on a pressure gauge. Again, that reading shows the pressure in that ball above atmospheric pressure. Guess what that pressure is called? Indeed; Gauge pressure. It is labeled as PSIG (pounds per square inch gauge) or simply PSI. Do you have a good feel for that? Let's move on with more details.

Atmospheric pressure, as measured at sea level, is typically 14.7 PSIA. A formula to convert it to feet of head is:

$$\text{Head} = \text{PSI} \times 2.31 / \text{Specific Gravity}$$

For Water it is:

$$\text{Head} = 14.7 \times 2.31 / 1.0 = 34 \text{ Ft}$$

Thus 34 feet is the theoretical maximum suction lift for a pump pumping cold water at sea level. Now, no pump can actually attain a suction lift of 34 ft.; however, well designed ones can reach 25 ft. quite easily (Hmm...knowing what you know to this point, what might be causing that?)

You will note, from the equation above, that specific gravity can have a major effect on suction lift. For example, the theoretical maximum lift for brine (Specific Gravity = 1.2) at sea level is 28 ft.

In real applications, a realistic maximum is around 20 ft. Remember to always factor in specific gravity if the liquid being pumped is anything but clear, cold (68°F) water. In addition to pump design and suction piping, there are two physical properties of the liquid being pumped that affect suction lift;

1) Maximum suction lift is dependent upon the pressure applied to the surface of the liquid at the suction source. Maximum suction lift decreases as pressure decreases. For instance, the higher in elevation you get, the lower the atmospheric pressure. So, if you are sucking your drink at the beach (sea level-highest atmospheric pressure), it will take less suction power by you since the atmospheric pressure pushing down the surface of your drink is greater than it would be if you tried this same thing on top of a mountain (less atmospheric pressure up there pushing on the surface of your drink—you have to suck harder to make it happen).

2) 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 the liquid from vaporizing (boiling) at a given temperature. Vapor pressure increases as liquid temperature increases. Maximum suction lift decreases as vapor pressure rises.

Whoa! What? Let's add a little perspective with something you're familiar with. When you place an open kettle of water on the stove and bring it to a boil to cook something, the boiling part is the water changing over from its liquid state to its vapor state (you watch those bubbles pop and steam rise). When we are at standard atmospheric pressure, water boils at 212°F. Remember, pressure and temperature are directly related; if we were to drop the atmospheric pressure acting on that kettle, the water would boil at a lower temperature (keep in mind that a fluid's "vapor pressure" is pressure value that allows a fluid to turn in to a vapor at a related temperature). Drop the pressure enough and you can boil water at room temperature (think about that). How do you lower the pressure enough to do that? You keep lowering or "drawing" the pressure down until it goes negative, at which time you are in a vacuum. Caution—you will need to wear a space suit to actually do that. Now, back to our story...

So, it follows then, that the maximum suction lift of a centrifugal pump varies inversely with altitude (the higher you go, the less atmospheric pressure you have pushing down on it). Conversely, maximum suction lift will increase as the external pressure on its source increases (for example: a closed pressure vessel). The following figure 5.1 shows how altitude and atmospheric pressure relate to each other.

SUCTION LIFT CORRECTIONS AND ATMOSPHERIC PRESSURES AT DIFFERENT ALTITUDES

Altitude [Ft]	Atmospheric Pressure [Ft of H ₂ O]	Deduction [Ft of H ₂ O]
0	34	0
500	33.3	0.7
1,000	32.8	1.2
1,500	32.2	1.8
2,000	31.6	2.4
2,500	31	3
3,000	30.5	3.5
3,500	29.8	4.2
4,000	29.4	4.6
4,500	28.7	5.3
5,000	28.2	5.8
5,500	27.8	6.2
6,000	27.3	6.7
6,500	26.6	7.4
7,000	26.2	7.8
7,500	25.7	8.3
8,000	25.2	8.8
8,500	24.8	9.2
9,000	24.3	9.7
10,000	23.4	10.6

Figure 5.1: Suction Lift Corrections for Altitudes

PROPERTIES OF WATER AT VARIOUS TEMPERATURES
Based on water at 68°F, weighing 62.4 lbs/ft³

Temperature [Ft]	Vapor Pressure Lbs. P.S.I.Gauge	Vapor Pressure Feet Absolute	Specific Gravity
50		0.41	1.002
60		0.59	1.001
70		0.84	1
80		1.17	0.998
90		1.62	0.997
100		2.2	0.995
110		2.96	0.993
120		3.95	0.99
130		5.2	0.988
140		6.78	0.985
150		8.74	0.982
160		11.2	0.979
170		14.2	0.975
180		17.85	0.972
190		22.3	0.968
200		27.6	0.965
210		34	0.961
220	2.49	41.45	0.957
230	6.07	50.35	0.953
240	10.27	60.75	0.948
250	15.12	73	0.944
260	20.72	87.35	0.939
270	27.15	103.3	0.935
280	34.48	122	0.93
290	42.85	144	0.925
300	52.3	169	0.92

Figure 5.2: Water Properties at Various Temperatures

A pumping application located at an elevation of 5000 feet will experience a reduction in atmospheric pressure of approximately six feet of head. This will result in a reduction in NPSHA (discussed in the next section) by the same amount. Elevation must be factored into a pumping application if the installation is more than a few hundred feet above sea level. Keep that in mind.

As we already mentioned, the maximum suction lift of a liquid varies inversely with the temperature of the liquid. The higher the temperature, the higher the vapor pressure and thus suction lift is decreased. Think about that. If a centrifugal pump is used to pump a liquid that is too hot, the liquid will boil or vaporize in the pump suction side. This condition is called cavitation and will be discussed in more detail later.

Figure 5.2 shows the relationship between vapor pressure and temperature for clear, cold water.

At a temperature of 70°F, a pressure of only one foot is required to keep water in the liquid state. As its temperature rises, however, more and more pressure is required. At about 210 degrees, a pressure of 34 feet or, sea level atmospheric pressure, is required. As it rises to 212 degrees the water will boil unless some additional pressure is applied. When pumping liquids at elevated temperatures, the liquid's vapor pressure at that temperature must be included in the NPSHA calculation. So, if you are working in a soup factory, pumping hot chicken broth to a processing area, you have to be aware of the vapor pressure of the broth. Just keep this in mind as you continue putting all this together.

Lesson 5, Focus 1

1. When you are sitting outdoors, what is the physical pressure called that is acting on you (no, it's not peer pressure)?

What is that pressure based on?

2. If you had a basketball with a pressure indication gauge on it, and pumped it up to 15 psig, what is this pressure called?

How does that relate to atmospheric pressure?

How does that relate to absolute pressure?

3. When you suck on a straw in a drink, what are you doing to the pressure in the straw?

4. Which requires a higher suction pressure when drinking through a straw; cola or thick milk shake?

5. What is the vapor pressure of water open to the atmosphere that is boiling at a temperature of 220°F? (use chart).

6. Will water “boil” at a lower temperature if we lower its vapor pressure?

Focus 2: Capacity and Suction Lift

The suction lift of a centrifugal pump also varies inversely with pump capacity. This is shown in Figure 5.3. It illustrates how the head - capacity curve falls off quickly at various suction lifts. You will notice that maximum suction lift increases as pump capacity decreases. For this reason pumps used in high suction lift applications are selected to operate in a range considerably to the left of their peak efficiency.

Remember: manufacturers run their pumps through testing and publish these charts to show the characteristics. There is much to remember, but if you use the published charts along with what you will learn in these lessons, you will have a much greater capacity in making the right decisions for pumping applications.

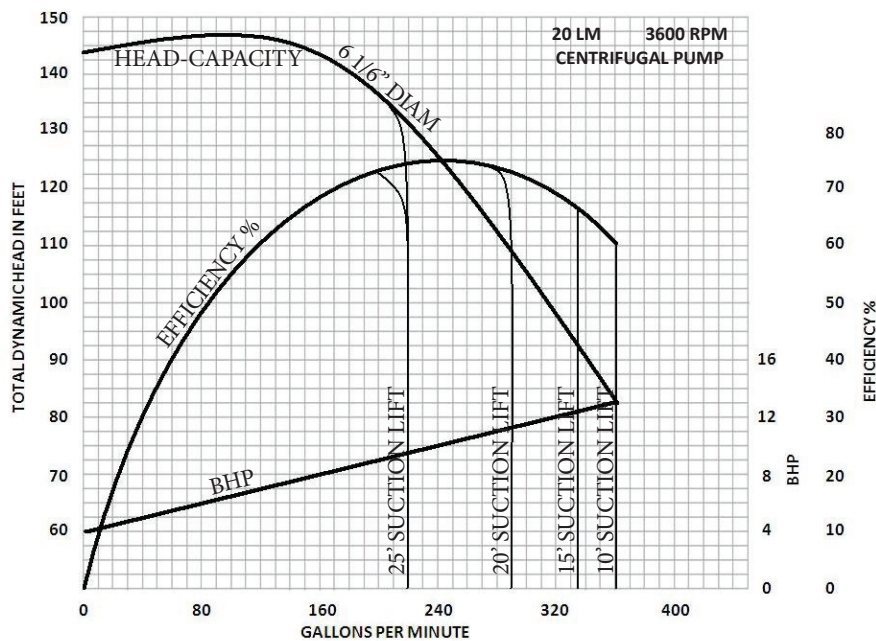


Figure 5.3: Head Capacity for Various Suction Lifts



Lesson 5, Focus 2

1. What happens to the suction lift of a centrifugal pump the more GPM it pumps?
2. If you want to maximize your suction lift, do you want to reduce the GPM?



Knowledge Certification Quiz: Lesson 5

1. You are drinking a glass of water with a straw inside a building that is pressurized above atmospheric pressure. If you go outside, will it be easier, harder, or make no difference on how hard you have to suck on the straw to drink the water?

Why?

2. If you were playing basketball with a pressure indication gauge on it in your pressurized building and then went outside to play, what would your pressure gauge indicate outside?

3. When you suck on a straw in a drink, what are you doing to the pressure in the straw? (Yes, you did answer this before; did you answer the same this time?)

4. Which requires a higher suction pressure when drinking through a straw; water or molasses?

5. What happens to the specific gravity of water as it goes up in temperature? (Use chart).

6. Will water “boil” at a lower temperature if we lower its vapor pressure?

7. Does suction lift of a centrifugal pump improve or deteriorate the more GPM it pumps? (Use chart).

8. Did you remember that pump manufacturers publish performance graphs and charts for their pumps?

I certify that I have answered all certification quiz questions correctly and am ready for the next lesson.

Your Signature

Date

Approximate Lesson
Duration: 20 min.



Lesson 6: Net Positive Suction Head (NPSH) & Cavitation

This lesson covers Net Positive Suction Head (required and available) and their relationship to a system problem called Cavitation.

The process of boiling is not as simple as it may seem. We tend to think that it is all about temperature and often forget that pressure has an equal role in the process. The point at which water boils is proportional to both its temperature and the pressure acting upon its surface (remember that when you're boiling water for spaghetti). As pressure decreases, so does the temperature required to initiate boiling. The onset of cavitation also follows this rule.

When water, at some ambient temperature, travels through an area of low pressure, it can undergo a change in state from liquid to vapor (boiling). As it progresses into an area of higher pressure it will return to the liquid state (cavitation). The bubbles that form and collapse during this process are those of water vapor -- not air. Although dissolved or entrained air can affect pump performance, it produces a totally different kind of bubble than the one produced by boiling. The vapor bubbles form a vapor "cavity" in the liquid (thus the name cavitation). **These bubbles can spell trouble for system operation and efficiency and will be covered more thoroughly in Lesson 7 of this series.**

The fact that boiling is proportional to both temperature and pressure is the reason cavitation is such a persistent problem. Simply stated, water can boil at virtually any temperature. At sea level, where atmospheric pressure is about 14.7 PSI (34'), it takes 212 deg F to boil. Increase that elevation to 6000' and it drops to around 200 deg F because the corresponding atmospheric pressure decreases to 11.7 PSI (27'). If we introduce a vacuum and continue to reduce pressure to about 0.2', it will boil at its freezing point. Well, so what? We don't usually operate a pump in a vacuum and even at the top of Mt. Everest we still have almost 5.2 PSI (12') of atmospheric pressure!

Well, it turns out that all centrifugal pumps produce a partial vacuum. If they did not they would be unable to pump water from a lower level. During normal operation, the area of

lowest pressure occurs near the impeller vane entrances and if the pressure in this area drops to about 1', water will boil at 75 deg F! In order for a pump to operate cavitation free, an excess of pressure energy is required of the water entering this area. We typically refer to this requirement as **NPSHr** -- or the **Net Positive Suction Head required**.

Where does this pressure energy come from? It is a combination of several different forms of energy that exist, at various levels, on the suction side of the pumping system. We refer to this available pressure energy as **NPSHa** -- or the **Net Positive Suction Head available**.



Focus 1: Net Positive Suction Head Available (NPSHa)

NPSHa is a characteristic of the system in which the pump operates (remember that “available” is about the system the pump is operating in). It depends upon the elevation or pressure of the suction supply, friction in the suction line, elevation of the installation, and the vapor pressure of the liquid being pumped (all things we’ve covered).

The NPSH available to a centrifugal pump combines the effect of atmospheric pressure, water temperature, supply elevation, and the dynamics of the suction piping. The following equation illustrates this relationship. All values are in feet of water and the sum of these components represents the total pressure available at the pump suction.

$$\text{NPSHa} = \text{Ha} \pm \text{Hz} - \text{Hf} + \text{Hv} - \text{Hvp}$$

Where:

Ha is the atmospheric or absolute pressure (the difference is covered below)

H_z is the vertical distance from the surface of the water to the pump center line

H_f is the friction formed in the suction piping

H_v is the velocity head at the pump’s suction

H_{vp} is the vapor pressure of the water at its ambient temperature

Ha is the atmospheric or absolute pressure exerted on the surface of the water supply. Atmospheric pressure is the pressure due to the density of the earth’s atmosphere at some elevation. It develops its greatest pressure (14.7 PSI) at sea level (where it is most dense) and approaches zero at its upper boundary.

We seldom think about this pressure because, out of the box or on the work bench, the typical pressure gauge reads 0 PSI. These gauges are calibrated to something we call “gauge” scale (PSIG) and totally ignore atmospheric pressure. Gauges calibrated to the “absolute” scale (PSIA) include atmospheric pressure and will read 14.7 PSI at sea level. Figure 6.1 compares these two pressure scales. On the absolute scale, 0 PSI equates to a perfect vacuum but on the gauge scale it equates to atmospheric pressure.

If the water source is a reservoir or an open (or vented) tank, **Ha** is simply the measured atmospheric pressure. It takes on another dimension if the supply is an enclosed, un-vented tank. In this case **Ha** becomes the absolute pressure or the sum of the measured atmospheric pressure plus or minus the actual gauge pressure of the air in the tank.

H_z takes into account the positive or negative pressure of the water source due to its elevation. If it is above the pump **H_z** is a positive number and if it is below, **H_z** is negative.

H_f is simply the friction generated due to flow in the suction piping and is always a negative number. It is a function of the pipe length and diameter plus the fittings and valves it incorporates.

H_v and **H_{vp}** may be a little less familiar to some of us. **H_v**, or velocity head, is the kinetic energy of a mass of water moving at some velocity **V**. It is the equivalent of the distance that water would have to fall in order to reach that velocity.

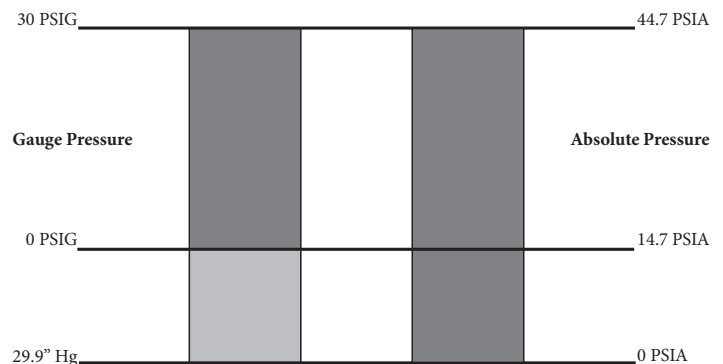


Figure 6.1: Gauge / Absolute Pressure Relationship

It can be calculated by determining the velocity in the suction piping from a velocity table and substituting that value for V in the equation “ $h=V^2/2g$ ” (where g is the universal gravitational constant @32 ft/sec²). It is usually small; at a velocity of 7 fps, Hv is just 0.765’, and is often ignored if Ha and Hz are sufficiently large. Hvp represents the pressure that is required to keep water in the liquid state at some ambient temperature and is obtained from a vapor pressure table. At 50 deg F, just 0.41’ is required but at 160 deg F that requirement increases to 11.2’. Since this pressure must be reserved for its stated purpose, Hvp is always a negative number.

At first glance, the equation for NPSHa looks pretty static but, it is actually quite dynamic. All of the variables can be in a continuous state of change. Velocity head and suction line friction vary as a function of flow. Likewise, atmospheric pressure can vary by several feet depending upon weather conditions. And, water supply elevation and temperature can vary seasonally. Usually the “worst case” values for each of these components are used when calculating NPSHa.

For example: A pump installed at an elevation of 2500 ft is pumping 30 GPM. The water level of the tank feeding the pump is 10’ below the pump inlet and piping to the pump is 20’ of 2” steel with a sweeping elbow into the pump. The water is 60 OF. What is NPSHa?

As indicated earlier, $NPSHa = Ha +/- Hz - Hf + Hv - Hvp$. Check back to the definitions spelled out earlier.

$Ha = (14.7 \text{ PSIA}) \times 2.31 - 3' = 30.95'$ (3’ comes from a head correction due to altitude chart).

$H_z = -10'$ (water level is below pump).

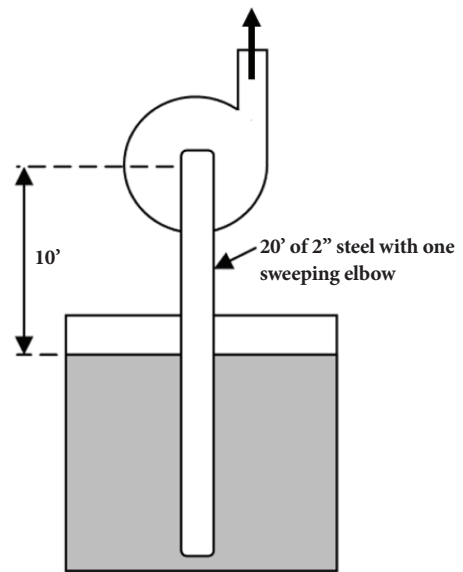
$H_f = -1'$ (friction factor estimate using friction factor charts for 2” steel pipe)

$H_v = 0.1'$ (velocity Head; typically very small and usually disregarded if flow velocity is less than 7 ft/s.)

$H_{vp} = 0.6'$ (vapor pressure based on chart data).

$NPSHa = 30.95' - 10' - 1' + 0.1' - 0.6' = 19.45'$

Often a two foot safety margin is subtracted from NPSHA to cover unforeseen circumstances. When selecting a pump for the conditions above, the NPSHR as shown on the pump’s published characteristic curve should be 17.45 ft or less (19.45’ - 2’).



Lesson 6, Focus 1

1. For a centrifugal pump, define what NPSHa means.

Focus 2: Net Positive Suction Head Required (NPSHr)

NPSHr is a function of a specific pump design (remember that “required” is about the pump design itself). In simple terms it is the pressure, measured at the center line of the pump suction, necessary for the pump to function satisfactorily at a given flow. Although NPSHR varies with flow, temperature and altitude have no effect.

As mentioned earlier NPSHr is the suction pressure necessary to insure proper pump operation. It is purely a function of the pump design and, although it could be calculated, it is more accurately determined by actual testing. Why does a pump require a positive suction head? Quite simply, it is impossible to design a centrifugal pump that exhibits absolutely no pressure drop between the suction inlet and its minimum pressure point, which normally occurs at the entrance to the impeller vanes. Therefore, all pump systems must maintain a positive suction pressure that is sufficient to overcome this pressure drop. If the pressure is not sufficient, some of the water will change state (liquid to vapor) and cavitation occurs. Like NPSHa, NPSHr is also a dynamic quantity and increases substantially with pump flow.

You would think that the NPSHr, measured by the pump manufacturer, would be the suction pressure required to prevent cavitation. That used to be the definition but, it is currently defined as the suction pressure at which a particular pump’s hydraulic performance is degraded by 3%. This raises some concern since this degradation is actually due to cavitation and, at the 3% level, it has the potential to be damaging. The Hydraulic Institute’s standards stipulate that each of the points on a pump manufacturer’s NPSHr curve must reflect this 3% value. There are rumors that the term NPSHr will eventually be changed to NPSH3 which more accurately describes its true meaning. Depending upon the pump design, HI recommends an NPSHa / NPSHr margin of 1.1 to 2.5. Some pump experts recommend even more. It is a good idea to check with your pump manufacturer for their specific margin requirement as it relates to a particular pump model and its application.

In recent years a new term, NPSHi (inception), was developed to define the suction pressure required that will suppress all cavitation. The cavitation that occurs between NPSHi and the point where damage occurs is called incipient cavitation.

This form of cavitation appears to cause little, if any, damage in normal pumping applications. There is some ongoing debate as to whether the cavitation that occurs due to a 3% performance degradation should be regarded as incipient cavitation.

The preceding has dealt only with water. The same general principles apply to other liquids; however, vapor pressure must be factored into the equations. For rough approximations where the vapor pressure is unknown, a pump will usually operate satisfactorily if the NPSHa is equal to or greater than that required for water under similar conditions. This method may be used only when the viscosity of the liquid is approximately the same as water.

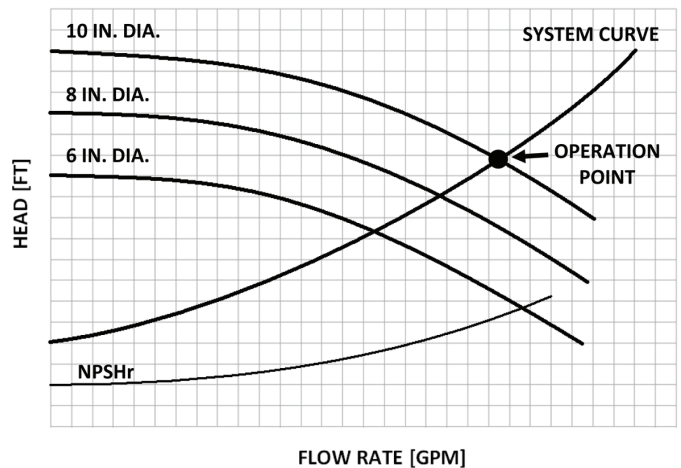


Figure 6.2: Simplified view of manufacturer’s pump performance curves, featuring NPSHr, as a result of factory testing

Lesson 6, Focus 2

1. For a centrifugal pump, define what NPSHr means.
2. What is the best way to determine NPSHr?
3. What is the name of the phenomena we are trying to avoid by maintaining desired NPSH values?
4. You need to bring a gallon of water to a boil two days in a row. The barometric pressure on the first day is much higher than the second day. Will the water come to a boil quicker on one of the two days, or will it take the same amount of time if heat addition is at the same rate?



Knowledge Certification Quiz: Lesson 6

1. Can water boil at virtually any temperature?
2. If we are able to boil water at a lower temperature than what we normally experience at atmospheric pressure, what could be the reason?
3. Net Positive Suction Head (NPSH) for a centrifugal pump focuses on required and available. Briefly explain each.
4. True or false; centrifugal pumps create a partial vacuum in their inlet piping during operation.
5. A pump is installed at an elevation of 1000 ft and has a suction lift of 8 ft while pumping 60 degree water. What is NPSHA?
6. What is the most accurate way to get a NPSHr curve for a centrifugal pump?

I certify that I have answered all certification quiz questions correctly and am ready for the next lesson.

Your Signature

Date

Approximate Lesson
Duration: 5 min.



Lesson 7: Cavitation – Another Word for Trouble

When vapor bubbles in a boiling pot of water rise to the surface and burst, the “explosion” releases a small amount of energy. When the same bubbles form in the vanes of a centrifugal pump impeller, that energy release is much larger. Let’s find out more about this harmful condition.

Cavitation (from the word cavity) is the rapid formation and collapse of vapor bubbles, due to dynamic action, creating cavities on the surfaces of solid boundaries (displaced water in the form of a bubble). These solid boundaries can exist in any number of structures, but our focus will be on centrifugal pump impellers.

Suction cavitation is the most common form of cavitation. It occurs when the NPSHa (available) at the pump suction inlet falls below the minimum NPSHr (required) by a particular pump. The areas that are the most sensitive to this type of cavitation are the low pressure sides of a centrifugal pump impeller, near the inlet/outlet shroud, where the vane curvature is the greatest. When water flows over these surfaces, the pressure near the surface is lowered and the flow can separate from the surface. If the pressure is low enough, water bubbles can form in the separated areas and then collapse (implode) when they enter an area of higher pressure. This implosion has a much stronger concentration of energy released than a bubble would have from an open boiling container. When the bubble collapses, water rushes in to fill the void, emitting a shock wave. When thousands of these bubbles are collapsing every second, the effect of the shock wave can be damaging to the impeller. It also creates noise and pump performance/

efficiency drops off rapidly, which can be very disruptive. Furthermore, as the bubbles that are impinging on the impeller grow in number, the more water is replaced by water vapor, effectively pumping more vapor and less of the needed water in the process at hand.

Now, other factors can add to the cavitation probability. Entrained air in the system can be a factor, as well as vortices. **However, the biggest contributor most often is improper suction piping. Remember this, if you remember nothing else about this section. This usually means the piping leading up to the pump has too many bends, valves, etc. too close to the pump inlet.** All of these “impediments to flow progress” cause slight pressure drops which can add up to drop the vapor pressure low enough to cause the liquid to start changing to a vapor state (start boiling). As we discussed earlier, NPSHa becomes less than what is required, which are a major cause of this problem.

There are other types of cavitation in a centrifugal pump system, including; recirculation cavitation, suction recirculation and discharge recirculation. While they can contribute in a small fashion to our problem, it is the improper inlet piping that gives us the most problem.

Skill
Builder

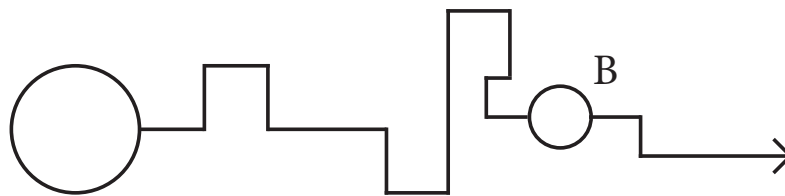
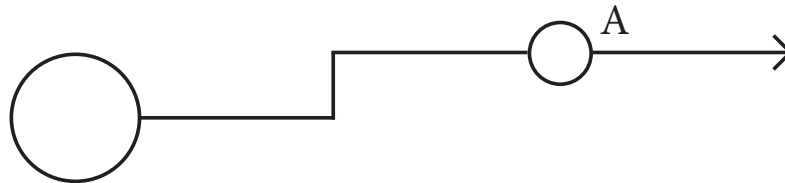
Lesson 7

1. Give 3 problems cavitation creates for a centrifugal pump operator.
2. Does cavitation occur on the discharge side or intake side of the pump?
3. True or False: To help eliminate cavitation, it is best to put a sharp 90 deg. elbow in the piping system right before the piping goes into the pump.



Knowledge Certification Quiz: Lesson 7

1. Define cavitation in a centrifugal pumping system.
2. Cavitation bubbles collapse in the system, rather than burst like those in a boiling pot of water. Which transmits more energy by their action?
3. Does cavitation occur when the NPSHa (available) at the pump suction inlet falls below the minimum NPSHr (required) by a particular pump?
4. You are working in a dairy processing plant. Your boss points to 2 pumps which are each transferring milk from individual holding tanks to a process area. He tells you pump B doesn't seem to be getting the milk to the processing area as well as pump A. What might be the problem and what could you do to change the situation?



I certify that I have answered all certification quiz questions correctly and am ready for Book 2.

Your Signature

Date

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