UNUSUAL ASPECTS OF PUMP SYSTEMS

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There are many unusual aspects to pump systems. It is some of these aspects that make pump systems fascinating for some and complicated to others. I will be discussing three unusual aspects of pump systems in this article.

The first is the attitude of the pump suppliers. Many purchasers require assurance that the pump they are about to buy will satisfy their requirements. This assurance is hard to come by.

A second aspect that has long fascinated me is the bizarre behavior of fluids. For example, the ability of a fluid to move upwards (the siphon) without a pump or any external source of energy is remarkable. Another interesting aspect is the large variation in pressure that can be seen throughout certain systems, this variation is not directly linked to the amount of energy required of the pump.

The third aspect is the effect of fluid properties (density, viscosity and vapor pressure) on the pump's performance. The effect of these properties on the proper operation of the pump is considerable.

1. The attitude of pump suppliers

When the time comes to make the final determination of the pump size required for your application, few manufacturers will offer assistance. Let's say you were shopping for a new car and asked a car salesman to suggest something suitable, I think you would be surprised to hear him say "Sorry, I can't make a recommendation, you must choose yourself".

No doubt each manufacturer has valid reasons for adopting this attitude possibly there is a fear of being sued if the pump does not operate as predicted, or that the work required to properly size a pump would go unpaid, etc. If we look at it from the manufacturer's point of view, he only supplies the pump and not any of the other elements of the system and there is the possibility that these might interfere with the proper operation of the pump.
To order a pump, you need to specify the complete operating details of the pump: the operating total head, the flow, and the fluid properties such as temperature, density, viscosity, vapor pressure and the nature and size of suspended particles if any. Determining these details requires a certain expertise that the buyer must have or that he must obtain by hiring an engineer specialized in this field. This is the equivalent of saying to the car salesman that you need a car that can negotiated a 30 degree slope at 60 km/h which has rocks that protrude 6 inches from the surface whose dimensions are…I have may friends in the pump world, please don't take this wrong but I still find this attitude unusual.

2. Low pressure areas in a pump system

Figure 1 shows the large amount of pressure variation that can occur in a pump system. This figure shows where the pressure is low (lower than atmospheric pressure) and higher. There is a relationship between the pressure, the elevation, the velocity and the friction loss due to fluid viscosity. This relationship provides us with a method for calculating the pressure anywhere within the system. Normally we are interested in the pressure at the outlet and the inlet of the pump, the difference between these two pressures is proportional to the total head or energy of the pump.

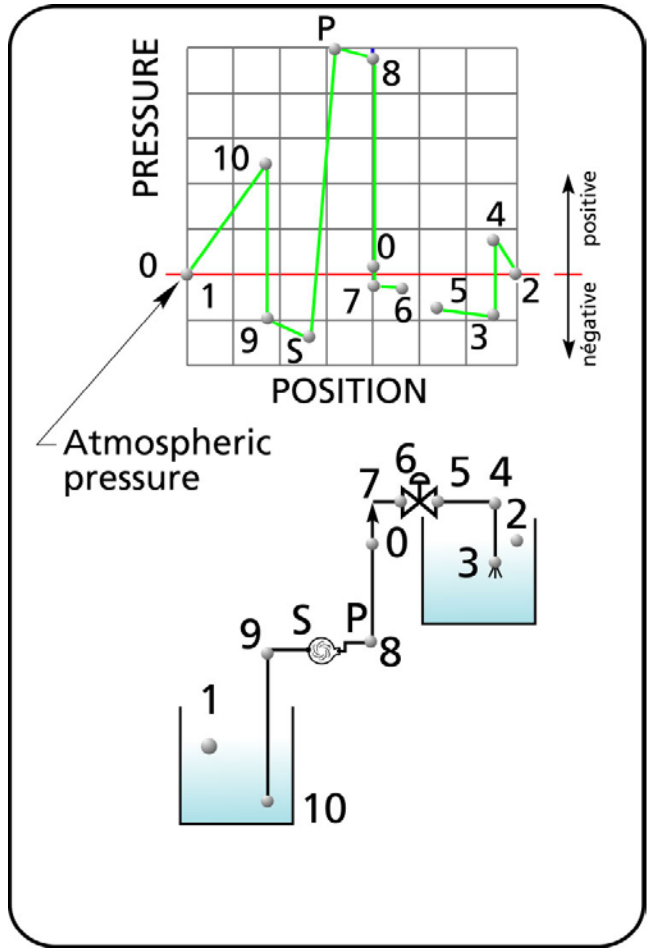

Figure 1 Pressure variation within a system.

Low pressure is possible at the pump suction if the level in the suction tank is low. The pump may not be capable of pumping its rated flow under these conditions.

In this next figure, we can see the variation in the pressure level at the pump suction as the fluid level in the suction tank is lowered. When the tank is partly full, the pressure reading at the pump suction is 5 psig. As the level drops to the same level as the pump suction pipe, the pressure drops to 0 psig. When the level drops further, the pressure drops to –3 psig or 3 psi lower than atmospheric pressure. This pressure may be too low for the proper operation of the pump.

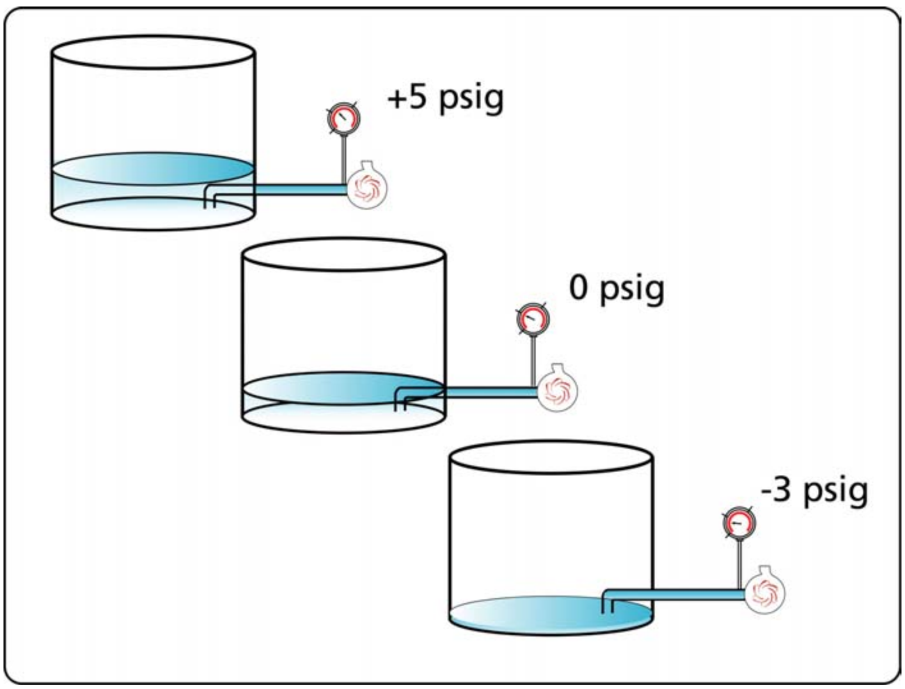

Figure 2 The pressure level at the pump suction for different fluid levels in the suction tank.

Fluids suspended within a tube

Imagine that we have fluid in a tube; we disconnect the fluid source, and lift one end up vertically. What happens to the fluid in the tube? It falls. Why, because there is no net upward force to support the weight. The fluid in the tube is subjected to atmospheric pressure on each side. The forces generated by atmospheric pressure are equal and there is no overall upward net force to support the fluid's weight therefore it falls.

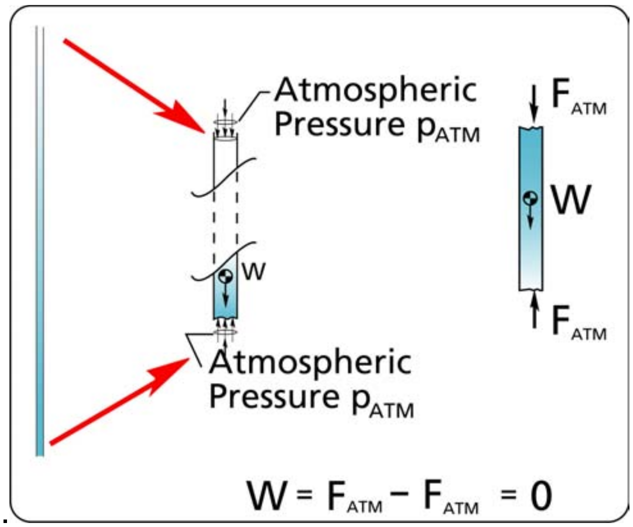

Figure 3 Fluid in an open tube falls due to lack of support.

When we draw fluid up into a straw, we do it by creating low pressure at the top end of the straw. Find a straw and try it. If we keep providing the low pressure, we can remove the straw from the glass and keep the water suspended in the straw. The low pressure we generate at the top end of the straw holds the fluid in place. Try this experiment and the next one on the following page.

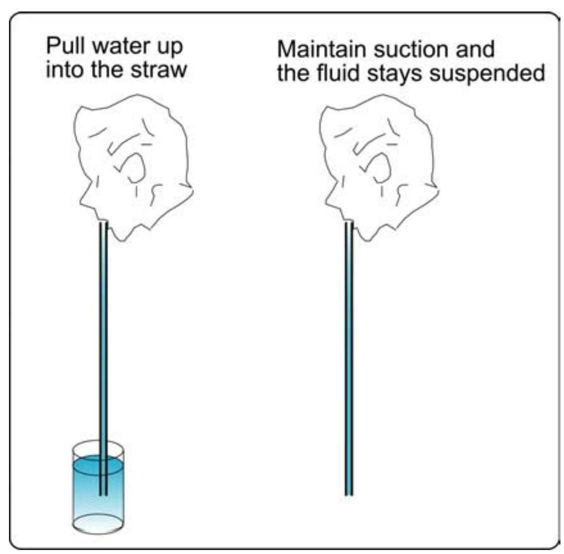

Figure 4 Fluid suspended in a straw while applying suction at the top end.

For the second experiment, seal the bottom end of the straw with your finger and turn the straw upside down.

What happens? When we turn the fluid upside down low pressure is generated at the top end of the straw, the low pressure helps suspend the fluid. The low pressure is created by the weight of the fluid that tends to pull the fluid away from the top end or the finger. As the fluid tries to pull away, it creates a low pressure at the top end that tends to keep it in place.

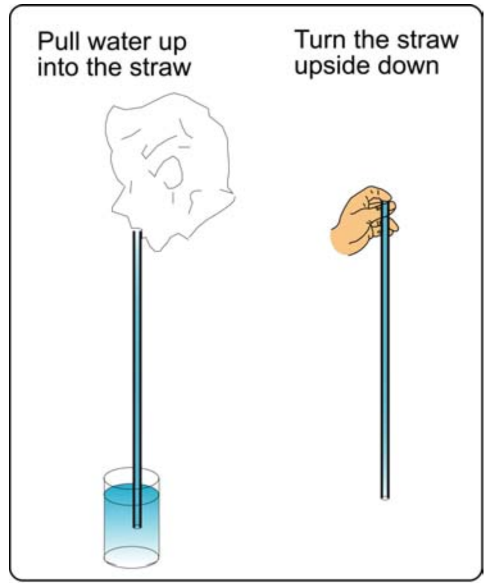

Figure 5 Fluid suspended in a tube with the top end sealed.

Fluids can be suspended in a vertical tube if the top end is sealed. The pressure is lower on the sealed side vs. the open side of the tube. This difference in pressure generates a difference in the forces on each side of the fluid such that there is a net upward force to support the fluid.

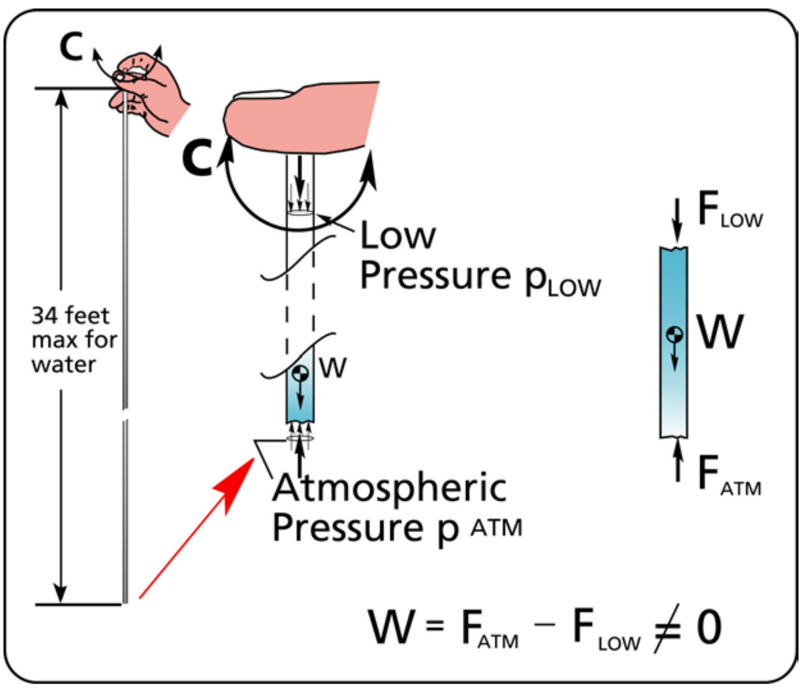

Figure 6 Fluid suspended with no apparent means of support within a tube.

Let’s do one more experiment with the straw. Using a straw with a flexible neck, pull some water up and seal the bottom. Now turn the top part downward. Will the fluid stay suspended in the top part or will it fall out of the straw? Let’s find out.

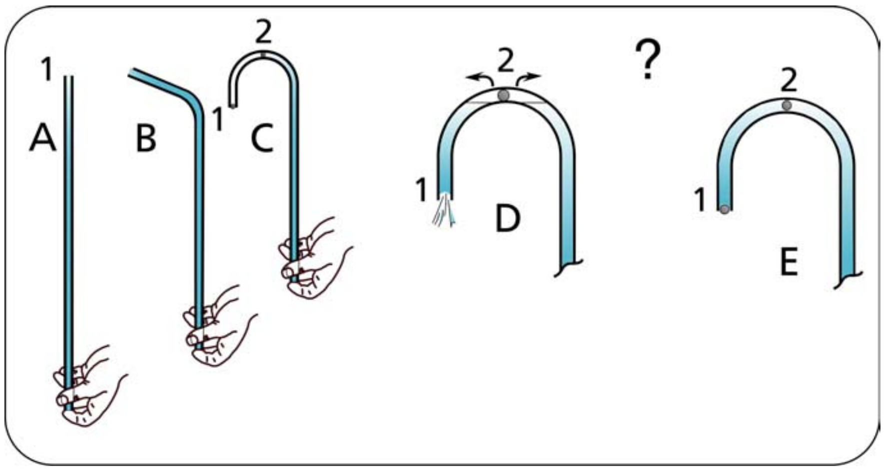

Figure 7 The straw experiment.

What’s happening? When the tip of the straw is turned downwards low pressure is created at point 2, the high point of the straw. This low pressure helps support the fluid between points 1 and 2.

Imagine that the fluid particles are beads strung on an elastic (see Figure 8). At position A, the pressure at point 2 is proportional to the height of fluid above point 2. When the straw tip is at position B, the pressure at point 2 has dropped because there is less fluid weight above point 2. At position C, the bent straw neck is horizontal; there is no pressure at point 2 since there is no fluid or weight above point 2. The pressure at point 2 is the same as the pressure in the atmosphere at the open tip of the straw. Here’s where it becomes interesting. When the tip of the straw goes below the horizontal as in position D, what happens to the pressure at point 2? Keeping with our analogy that the fluid particles are connected between themselves as beads on an elastic, the water particles that are below the horizontal at the open end of the straw pull on the water particles that are at the top and this has the effect of lowering the pressure. If we lower the pressure below the level in the atmosphere, the pressure becomes negative with respect to the atmosphere. How much water can be suspended on the open side of the straw? As much as 34 feet before the elastic breaks. This analogy helps us to visualize how low pressure can be created at a high point that is sealed. The elastic in real fluids is actually very stiff so that there is little or no movement between the fluid particles.

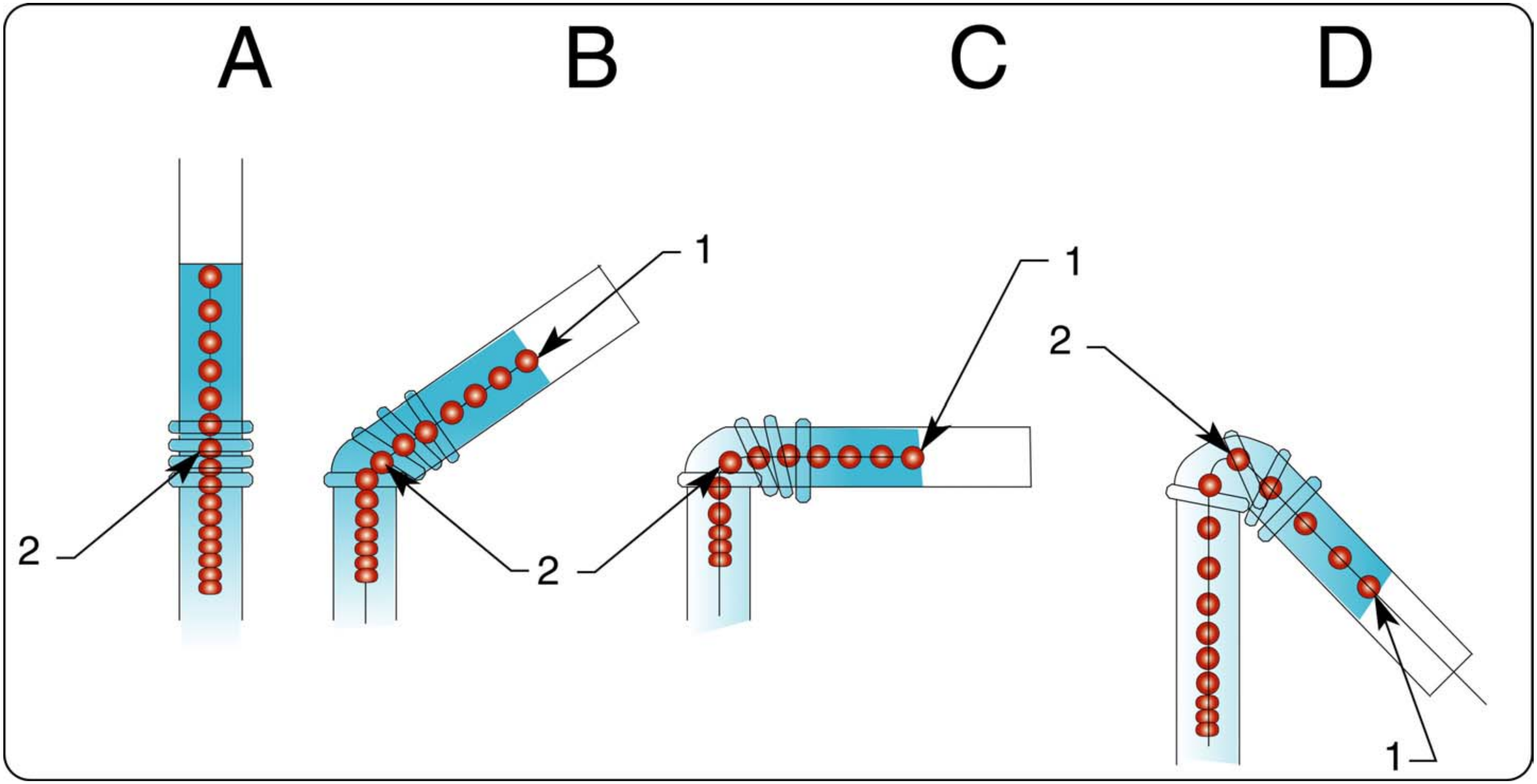

Figure 8 The bent neck straw experiment done step by step.

This brings us to a remarkable behavior of fluids, the siphon effect.

Two conditions define a siphon:

1. the inlet is higher than the outlet
2. a portion of the pipe is higher than the inlet.

A siphon has the ability to lift fluids higher than its inlet point without the use of a pump.

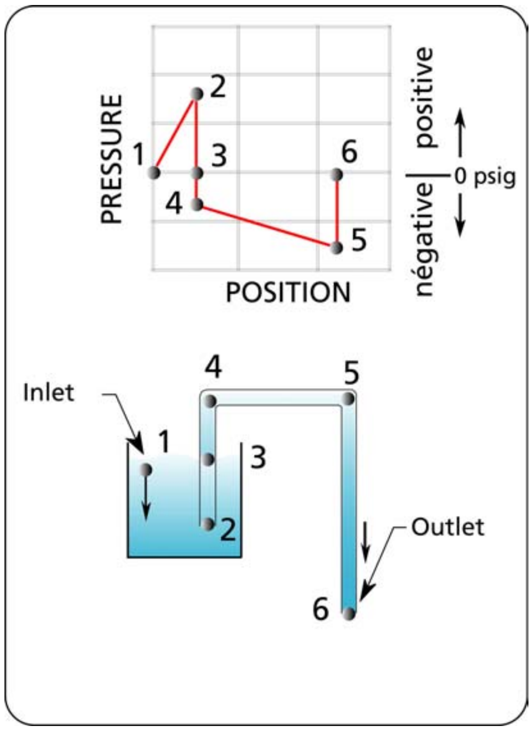

Figure 9 The siphon effect.

This remarkable behavior is due to low pressure at the top portion of the pipe. How so? The fluid is drawn into the pipe at point 2, and moves upwards to point 4. We know from the straw experiment that the only way for the fluid to stay suspended is if we have low pressure at point 4. The only difference between the siphon and the straw experiment is that the fluid in the siphon is moving. The pressure stays low all the way until we get to point 6, the outlet, where it becomes equal to the atmospheric pressure.

The difference in height between points 1 and 6 provides the energy to move the fluid. How high can the top part of a siphon be above its inlet (point 1)? Approximately 34 feet for water at the atmospheric pressure corresponding to sea level.

A siphon provides a mechanism by which we can empty a tank to a lower level. If a pump is connected to the lower part of a siphon we can transfer fluid from a lower level to a tank at a higher level. This is the same situation as the siphon except that flow is reversed. The pressure level in the top part of the pipe will be the same as in the siphon. Therefore expect low pressures in the top part of a pipe when it enters a tank from above.

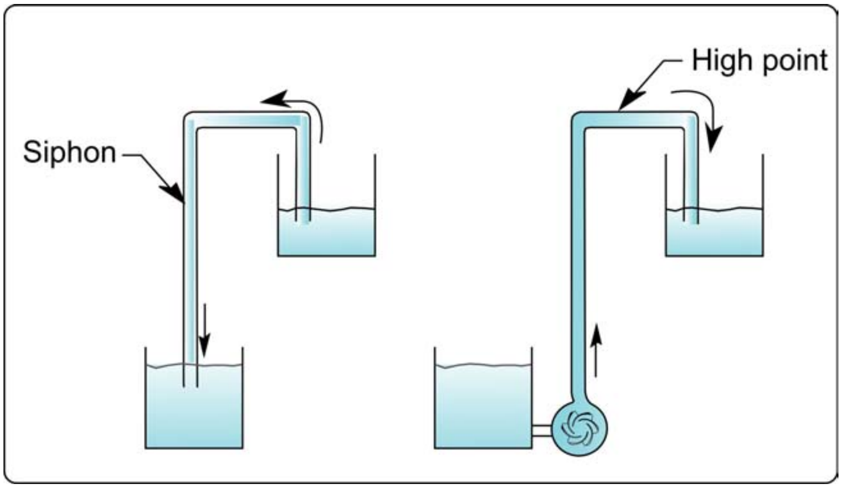

Figure 10 The similarity between a pump system and a siphon.

You are probably thinking: well of course there is low pressure at the top, the end of the pipe is submerged. That's true, but there will be low pressure at the top whether the pipe is submerged or not. There is low pressure at the top because there is a portion of the fluid that is higher than the outlet that is at atmospheric pressure.

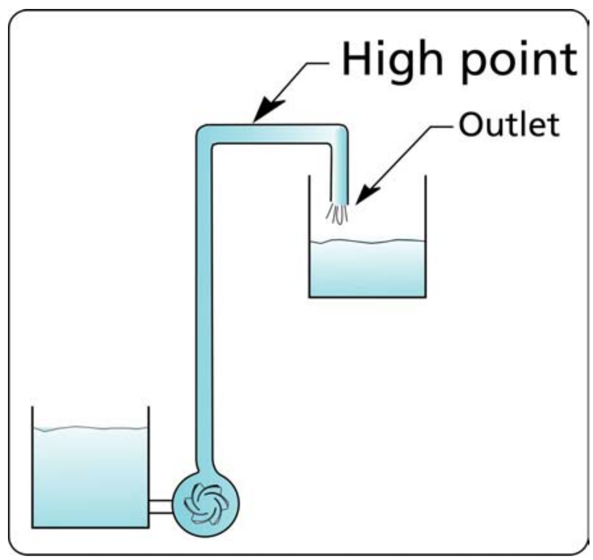

Figure 11 Low pressure at the high point of a typical pump system even when the pipe end is not submerged.

Why this preoccupation?

As mentioned before low pressure can cause air to be sucked into the system if that area is damaged or cracked.

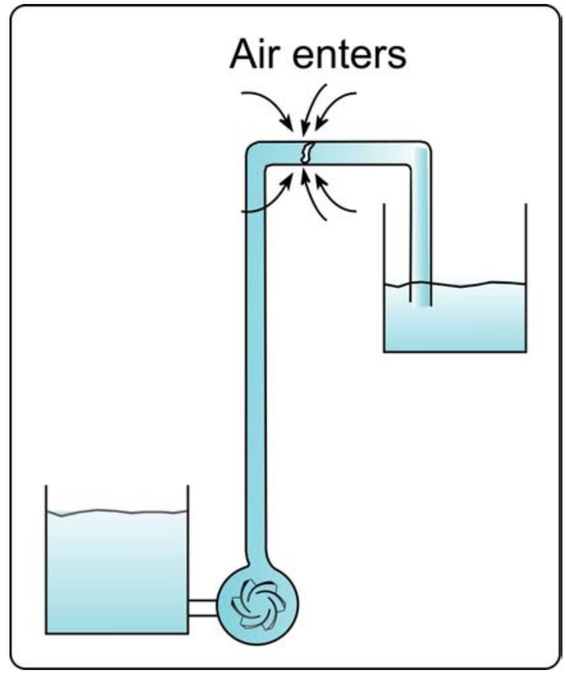

Figure 12 A cracked pipe at a low pressure area allows air to enter the system.

Also, if you try to add a connection at this point to supply fluid to another area of the plant, you will find that no fluid will ever leave that connection because of the low pressure.

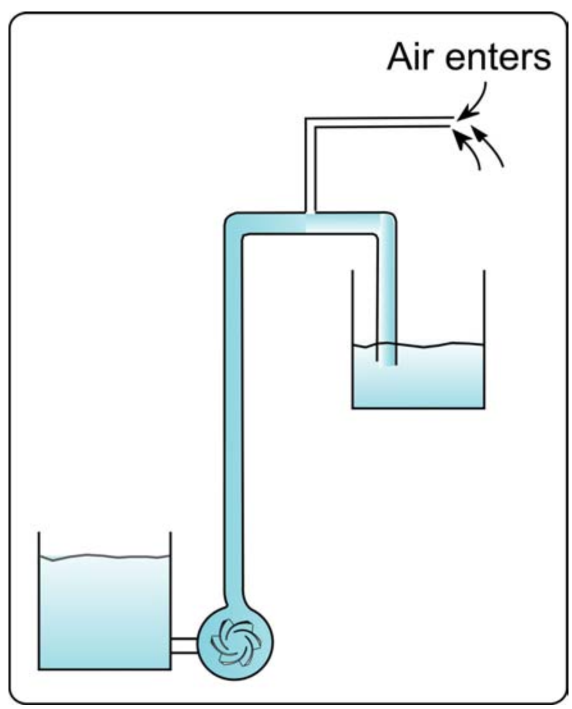

Figure 13 A new branch at a low pressure area does not allow fluid out.

Identifying the correct outlet point of the system

People who are new to pump systems sometimes choose the wrong pump system outlet point. Choosing the right outlet point is critical to establishing the correct static head of the system In figure 14, several situations are presented for where choosing the correct outlet point may trip some people up.

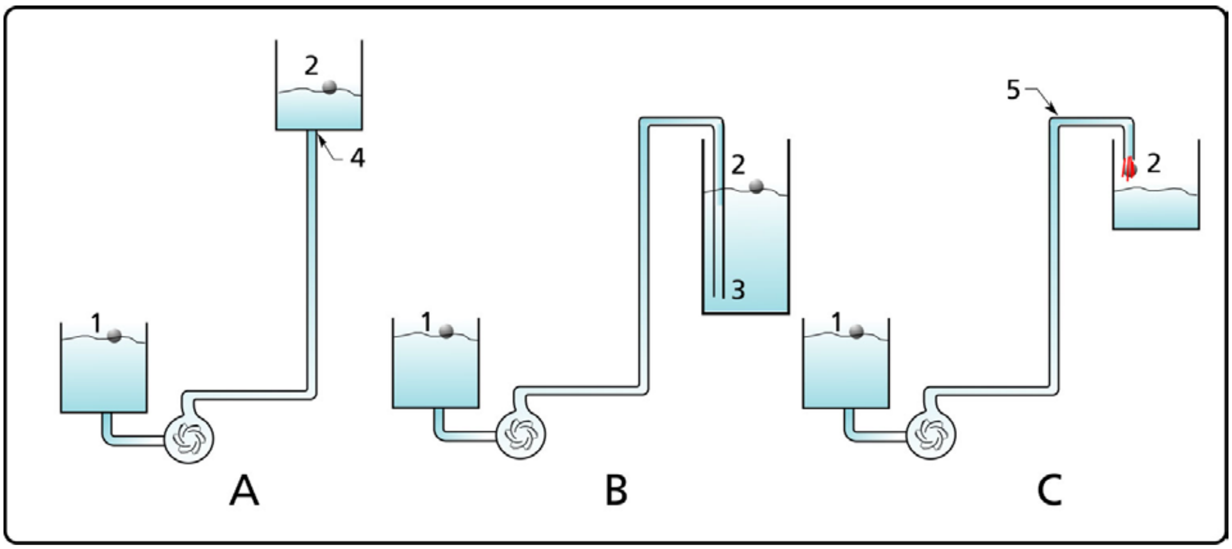

Figure 14 Various outlet configurations.

The outlet point in case A of figure 14 is point 2 so that the static head will be the difference between the elevations of points 2 and 1.

In case B, one might be tempted to say that the outlet point is point 3, the argument being that there is some pressure at the level of point 3 which we need to take into account. If we use point 2 then we will neglect this effect and the pump will not generate sufficient pressure to overcome the pressure at point 3. It is a good argument but incorrect. Let's take case A, there is pressure at point 4 but that does not stop us from using point 2 for the outlet. In case C, the pressure at point 5 is less than the atmospheric pressure meaning that at point 5 the fluid is under vacuum which helps suspend the fluid at that point. This does not stop us from using point 2 as the outlet in case C.

The way to view this is to follow the fluid particles from start to finish. The force that connects fluid particles together is that generated by pressure and pressure can vary considerably throughout the system (see Figure 1). Follow the fluid particles from point 1 all the way through the system to the furthest point that we can go while maintaining continuity between the particles. We know that the fluid particles must all reach point 2, therefore the pump will have to supply sufficient energy to overcome the static head due to the elevation difference between points 1 and 2 in all these cases. Yes, in case B the pressure at point 3 is high but the pressure that is critical for the pump is the pressure at the outlet (point 2) vs. the inlet (point 1) of the system. In Figure 14, the pressures at these points is the atmospheric pressure, the forces that are generated by this pressure on the liquid surfaces of the tanks balance each other and therefore have no net effect on the pump. What would happen if the outlet reservoir were pressurized (see Figure 15)? In this case, the forces generated by pressure on the liquid surfaces would be unbalanced and the pump would have to supply an additional head of 10 x 2.31 = 23.1 feet.

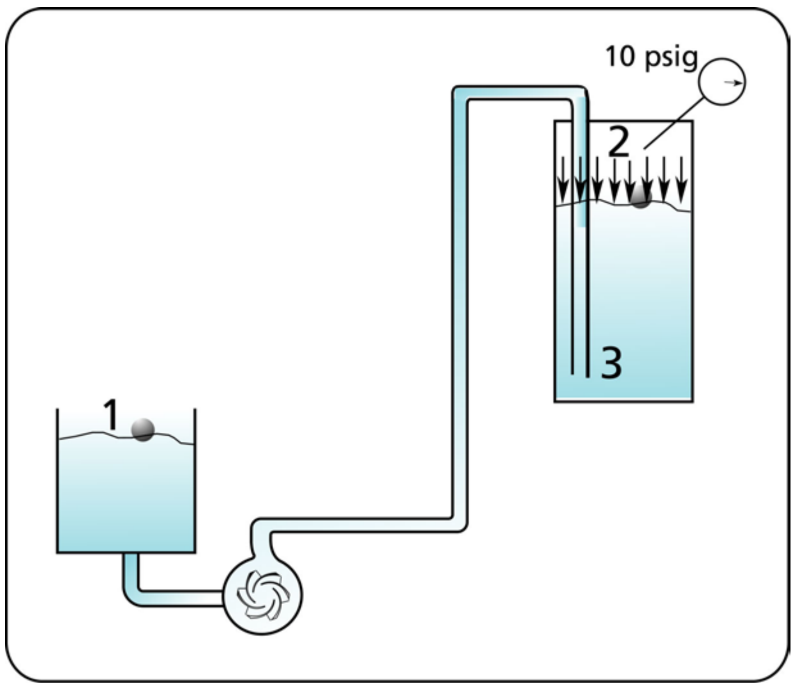

Figure 15 Accounting for a pressurized outlet.

Why do I use the term outlet when there are not too many outlets to be seen in any of these images? The term outlet may not be the best term to use but it is better than: the point at which there are no more fluid particles.

3. The effect of fluid properties on pump performance

There are three fluid properties that are important because of their effect on pump performance.

1. Density or specific gravity has a direct effect on power consumed and no effect on total head;
2. Viscosity because of its effect on friction losses and its effect on the pump's ability to pressurize the fluid;
3. Vapor pressure because of its effect on the N.P.S.H. available and cavitation.

Fluid density or specific gravity

Density is the measure of the mass of a fluid per unit volume, for example in pounds per cubic foot (lbm/ft^3).

Specific gravity (SG) is often used as a means of stating the fluid's density, since we know the density of water at standard conditions (62.34 pounds per cubic feet) we can relate the density of a fluid to that of water. Specific gravity is the ratio of the fluid's density to that of water.

$$SG = \frac{density \quad of \quad fluid}{density \; of \;\; water}$$

Some examples of fluid density and specific gravity are:

Fluid	Density (lbm/ft^3)	Specific gravity (SG)
Water	62.34	1.0
Automobile oils	53-59	0.85-0.95
Beer	62.34	1.0
Gasoline	46.7	0.75
Mercury	848	13.6
Milk	62.34	1.0
Molasses	87	1.4

Table 1 Examples of fluid density and specific gravity.

Specific gravity is used to convert a pressure measurement to pressure head, for example when we measure the total head of the pump with pressure gauges.

When we need to convert a pressure measurement (p) to the corresponding pressure head (h) we use this formula:

$$h(ft\ \ fluid) = \frac{2.31 \times p(psi)}{SG} \qquad [1]$$

If we need to convert the pressure head (h) to the corresponding pressure (p) we use the same formula with the pressure term isolated on one side of the equation (see equation [2]) :

$$p(psi) = \frac{1}{2.31} \times SG \times h(ft\ \ fluid) \qquad [2]$$

The power consumed by the pump is proportional to the specific gravity and is given in equation [3] :

$$P(hp) = \frac{SG \times \Delta H_P(ft\ \ fluid) \times q(USgal/\min)}{3960 \times \eta} \qquad [3]$$

where ΔH_P : the total head of the pump in feet of fluid
q : the flow rate through the pump in US gallons per minute
η : the efficiency of the pump
P : the power consumed by the pump

Why is the total head of the pump independent of specific gravity or density of the fluid?

This is a surprising statement; one would expect that the specific energy requirement or head would be greater for a fluid that is denser assuming that all the other properties of the fluid are identical. The solution to this problem is simple and is hidden in the definition of the term "head". Head is specific energy or energy per unit of fluid weight displaced. Typical units would be foot-pounds (lbf-ft) that is energy, divided by pounds (lbf) of fluid displaced that equals feet (ft).

$$specific\ \ energy\ \ or\ \ head = \frac{Energy}{weight} = \frac{lbf - ft}{lbf} = ft \qquad [4]$$

The specific energy or head of a pump will be the same for fluids of different density because it takes the same amount of specific energy to transfer one pound of a dense solution vs. one pound of a lighter one because they are both still one pound.

Viscosity

Viscosity is the ability of a fluid to resist shear forces. As viscosity increases, the fluid's ability to resist a shear force also increases. Examples of fluids which have increasing viscosity are: water, molasses and jello. Clearly jello has the higher viscosity and can resist a small shear force.

Viscosity is the relationship between the shear force F that is applied and the displacement d.

Imagine a fluid between two plates where the bottom plate is fixed and the top plate is moving with a certain velocity. Because the fluid is viscous, the shear force F is required to move the top plate. The top layer of fluid moves a certain distance d and the bottom layer is fixed. Viscosity is the relationship between the shear force F and the movement of the top fluid layer d.

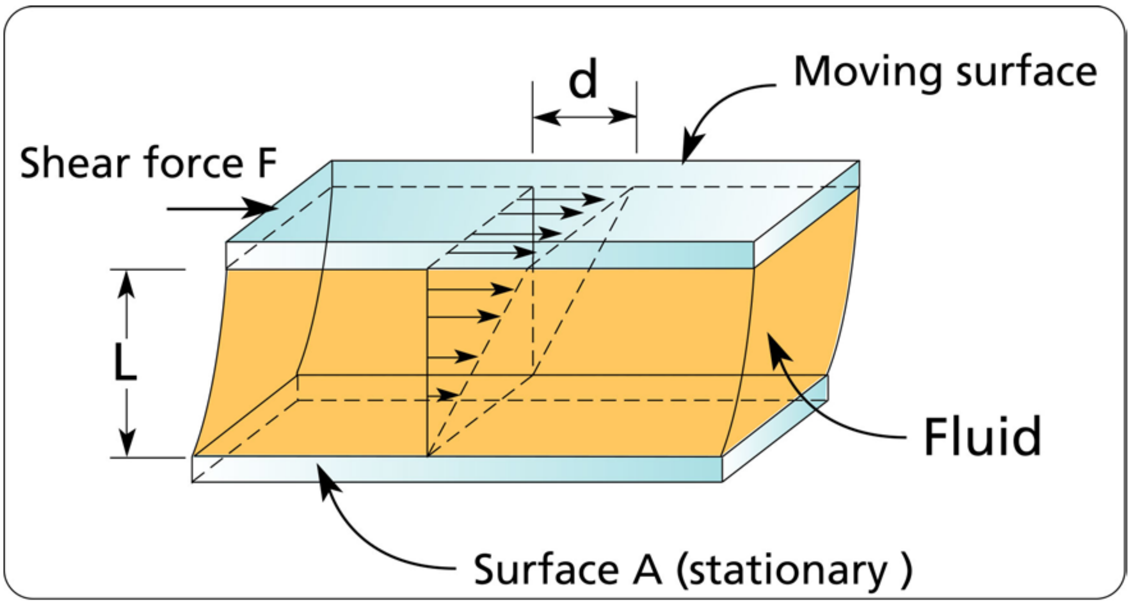

Figure 16 A fluid that is sheared between two plates.

Viscosity is often represented by the greek letter μ (mu). The shear force is F and the displacement of the top layers of fluid is d . Viscosity is simply the multiplying factor that relates these two quantities.

$$\frac{d}{L} = \mu \times F / A \qquad [4]$$

The movement of fluids through pipes and fittings produces friction which can be related to viscosity. The higher the viscosity, the higher the friction head required to displace the fluid from one location to another. Try pulling cold molasses through a straw. The effect of an increase in viscosity can be reduced by decreasing the velocity or flow rate of the fluid.

Here are some examples of typical fluid viscosities:

Fluid	Viscosity (centipoises) (cP)
Water	1.0
Automobile oils	3-10000
Beer	2
Gasoline	0.5
Mercury	1.4
Milk	1
Molasses	350-7000

Table 2 Examples of viscosities of different fluids.

As you can see, viscosity and density are unrelated properties. Oils are usually lighter than water but can have a wide range of viscosity values, usually much greater than water. Mercury is much denser than water yet has about the same viscosity as water.

An increase in viscosity increases the friction losses throughout the system which increases the amount of energy required to displace a fluid at a given flow rate. The higher the viscosity, the higher the energy requirement or total head of the pump for the same flow rate.

The effect of fluid viscosity on the pump's ability to pressurize fluids

Centrifugal pumps are tested with water and this is the basis of the performance of the pump or the pressure level can be obtained for a given flow rate. The rotation of the impeller vanes forces the fluid particles to conform to the shape of the blade giving them an optimal path from the eye of the impeller to the discharge. When the fluid viscosity increase the fluid particles cannot follow exactly this path resulting in more friction and performance loss.

The resultant effect will be to decrease the total head, the flow and the efficiency of the pump. The Hydraulic Institute has tested this effect using standard centrifugal pump volutes and has published a chart that quantifies this effect (see Figure 17). The performance drop can be severe enough that for fluid of 300 centiStokes or more a different type of pump should be considered, a positive displacement pump for example.

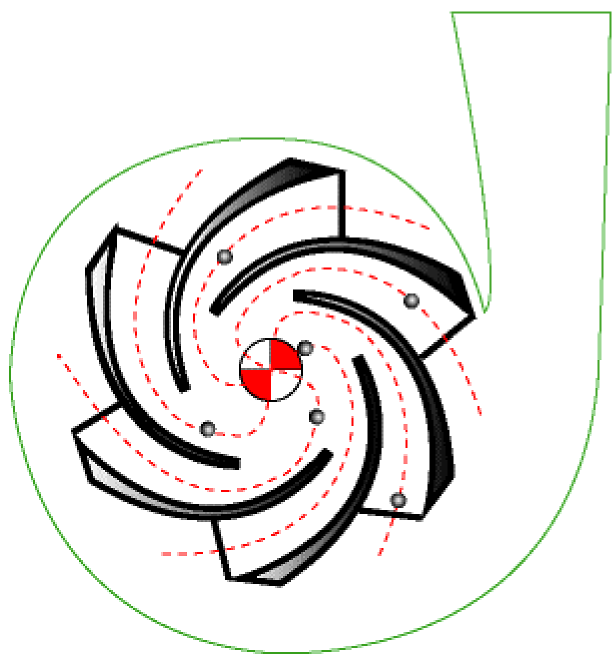

Figure 17 The rotary motion of a pump impeller pressurizes the fluid (see animation at http://www.lightmypump.com/pump_glossary.htm#gl11_1).

centrifugal pumps applications

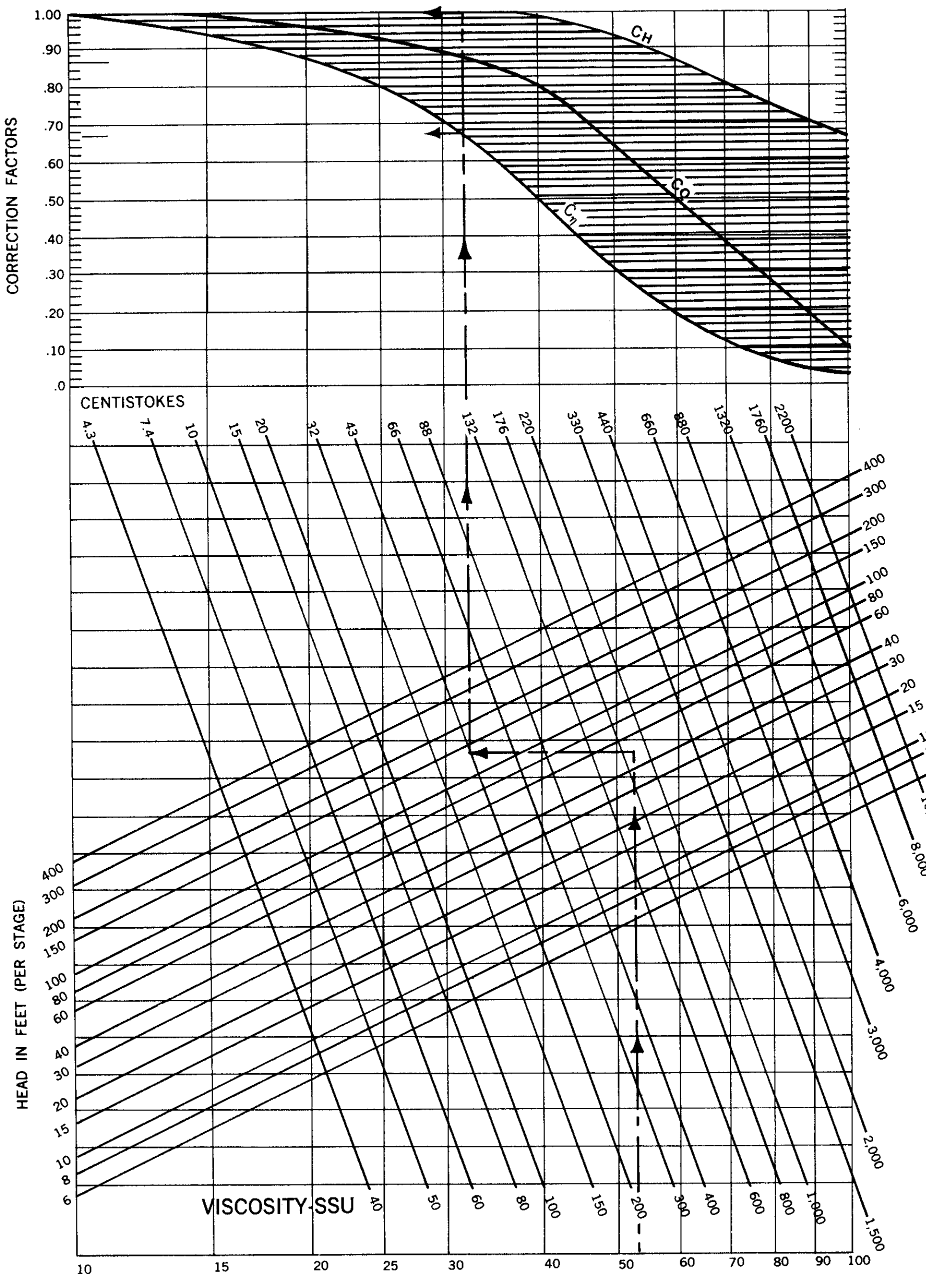

Figure 18 Correction factors to be applied on total head, flow and efficiency vs. viscosity (source le Hydraulic Institute, www.pumps.org).

Vapor pressure

If you were ever in high altitude areas, say 5,000 feet or higher, you may have noticed that water boils at a lower temperature than it does at a lower altitude or sea level for example.

Vapor pressure is the pressure at which a liquid boils for a given temperature. There are two ways to make a liquid boil. The liquid can be heated at constant pressure, as on a stove for example, and brought to a boil by increasing its temperature or we can make a liquid boil by lowering the pressure. For example, if we boil water on a stove in an open pot, in a normal kitchen where the pressure around us is constant at 14.7 psia, the temperature will have to reach 212 °F for boiling to occur. In this case, the vapor pressure is 14.7 psia. In our normal every day life the pressure in our environment does not vary significantly therefore water always boils at the same temperature. However, we know that in pump systems, the pressure can vary drastically and in some cases be significantly lower than the atmospheric pressure. This brings us to the other way to boil a liquid.

If we lower the pressure, we can also boil a liquid, but in this case the boiling temperature will be lower. Let's say the water in our pump system has a temperature of 120 F, if the pressure is lowered to 1.5 psia, then the water will boil. The vapor pressure of water at 120 F is 1.5 psia. If the temperature of the water was 180 F, then the pressure required for boiling would be 7.5 psia. The vapor pressure of water at 180 F is 7.5 psia.

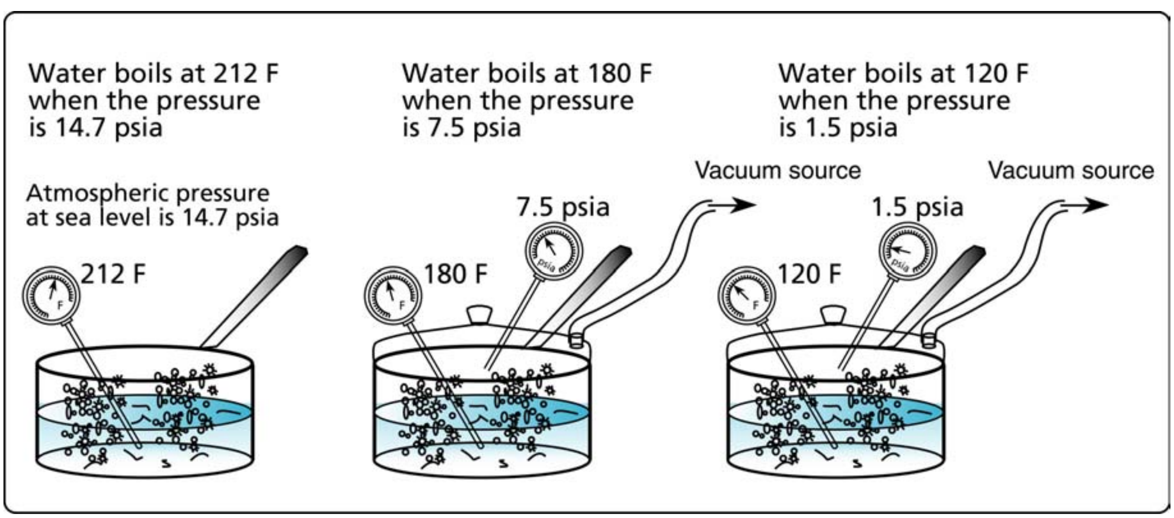

Figure 19 The relationship between vapor pressure and temperature.

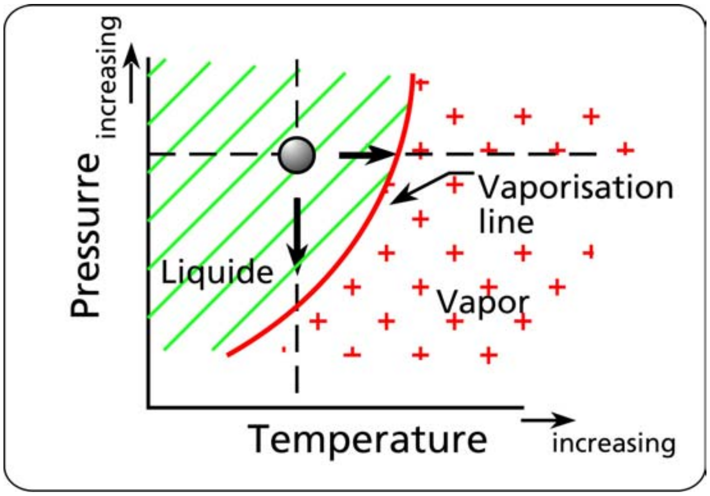

Figure 20 Vapor pressure vs. temperature.

Cavitation begins as the formation of vapor bubbles at the impeller eye due to low pressure. The bubbles form at the position of lowest pressure at the pump inlet (see Figure 21), which is just prior to the fluid being acted upon by the impeller vanes, after which they are then rapidly compressed. The compression of the vapor bubbles produces a small shock wave that impacts the impeller surface and pits away at the metal creating over time large eroded areas and subsequent failure. The sound of cavitation is very characteristic and resembles the sound of gravel in a concrete mixer. You can hear this sound at www.lightmypump.com http://www.lightmypump.com/downloads-free.htm#download12.

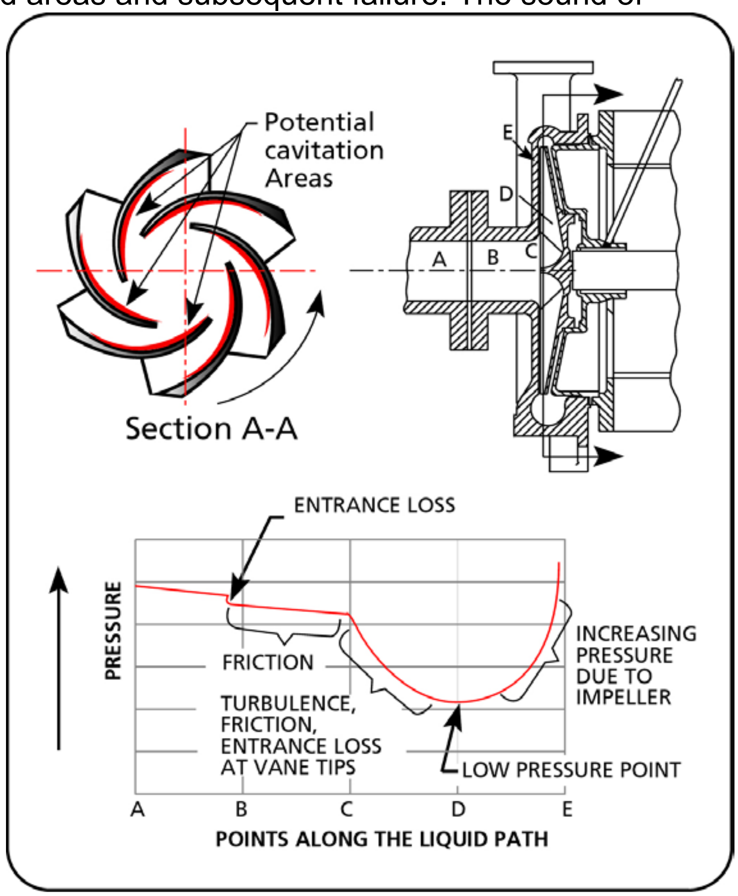

Figure 21 Pressure profile at the pump entrance.

As you can see from Figure 21 the pressure available at the pump inlet can be reasonably high but still drop considerably as it makes it way into the pump. The pressure may be lowered enough that the fluid will vaporize and will then produce cavitation. The same effect can sometimes be seen in control valves because they have a similar pressure drop profile, if the pressure is insufficient at the control valve inlet cavitation will also occur.

HOW TO AVOID CAVITATION? CAVITATION CAN BE AVOIDED IF THE N.P.S.H. AVAILABLE IS LARGER THAN THE N.P.S.H. REQUIRED.

Net Positive Suction Head Available (N.P.S.H.A.)

The Net Positive Suction Head Available (N.P.S.H.A.) is the total energy per unit weight, or head, at the suction flange of the pump plus the atmospheric pressure head less the vapor pressure head of the fluid. This is the accepted definition that is published by the Hydraulic Institute's Standards books (see the HI web site at www.pumps.org). The Hydraulic Institute is the organization that formulates and promotes the use of common standards used for the pump industry in North America. The term "Net" refers to the actual head at the pump suction flange, since some energy is lost in friction prior to the suction.

Why do we need to calculate the N.P.S.H.A.? This value is required to avoid cavitation. Cavitation will be avoided if the head at the suction is higher than the vapor pressure head of the fluid. In addition, the pump manufacturers require a minimum N.P.S.H. to guarantee proper operation of the pump at the values of total head and flow rate indicated on the pump`s characteristic curves. They call this the N.P.S.H.R., where "R" stands for required.

To determine N.P.S.H.A., calculate or measure the pressure head H_S at point S (the pump inlet) add the atmospheric pressure head and subtract the vapor pressure head (see equation [5]). If the pressure head at the inlet is measured then the velocity energy $V_S^2/2g$ must be included.

$$N.P.S.H._{avail.}(ft\ \ fluid\ absol.\ ) = H_S + \frac{v_s^2}{2g} + H_A - H_{va} \qquad [5]$$

where H_S : the pressure head at the pump inlet
v_S : the fluid velocity at the pump inlet
H_A : the atmospheric pressure head
H_{va} : the vapor pressure head

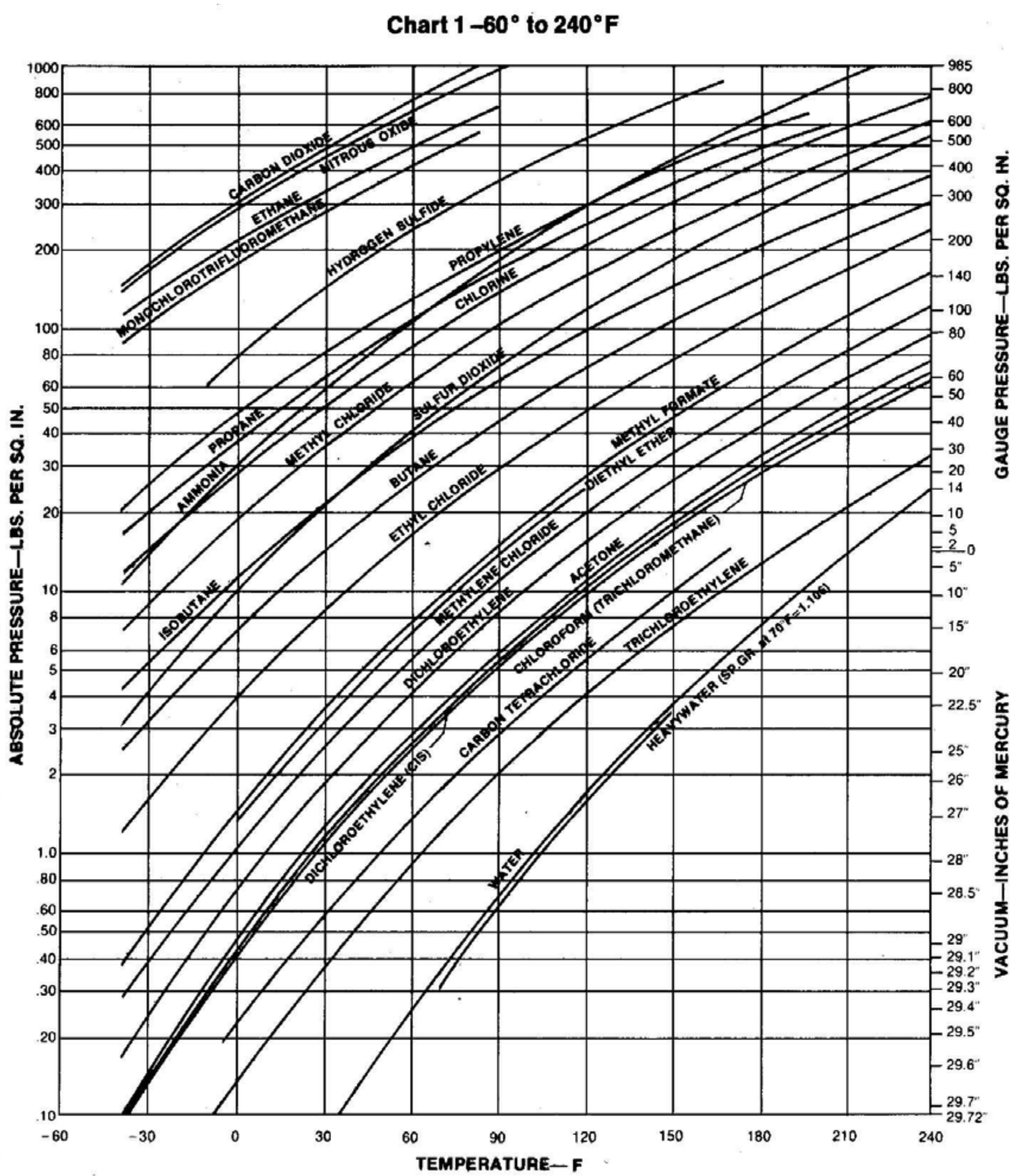

Figure 22 Vapor pressure of different fluids at different temperatures (source: Goulds pump catalog, technical section).

The venturi effect

You can boil water at room temperature with the following experiment. But before, a few words about the venturi tube. A venturi is a tube or pipe than has a reduction. Because of the nature of fluid flow, the pressure in the reduced portion of the tube is less than in the upstream larger portion. Why? It is clear that all the flow must pass from the larger section to the smaller section. Or in other words, the flow rate will remain the same in the large and small portions of the tube. The flow rate is the same, but the velocity changes. The velocity is greater in the small portion of the tube. There is a relationship between the pressure energy and the velocity energy, if velocity increases the pressure energy must decrease. This is the principle of conservation of energy at work. This is similar to the situation of a bicycle rider at the top of a hill. At the top or point 1 (see Figure 23), the elevation of the cyclist is high and the velocity low. At the bottom (point 2) the elevation is low and the velocity is high. Pressure and velocity behave in the same way. In the large part of the tube the pressure is high and velocity is low, in the small part, pressure is low and velocity high.

If the reduction in diameter is great enough it will be possible to reduce the pressure dramatically, well below atmospheric pressure, this will provide us with a source of vacuum that you can use to boil water at room temperature. The venturi tube is available at a modest price at Fisher or Cole Palmer who both provide laboratory devices and supplies.

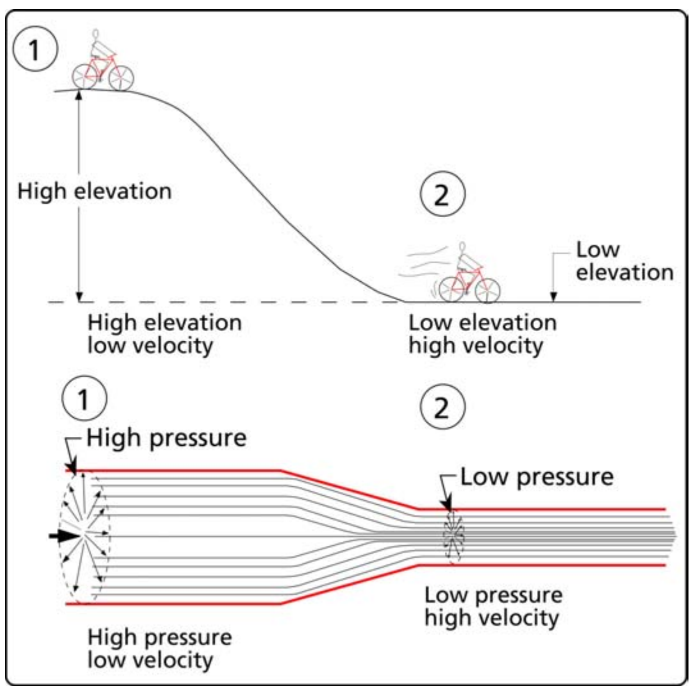

Figure 23 The relationship between pressure energy and velocity energy.

A venturi tube is also called an eductor. I use this device as a source of vacuum for the following experiment. Put room temperature water in a sealed reservoir, hook up the suction line, turn the tap on and watch water boil at low temperature. Water boils at room temperature when the pressure is approximately 1 psia which is equal to –28 inches of mercury.

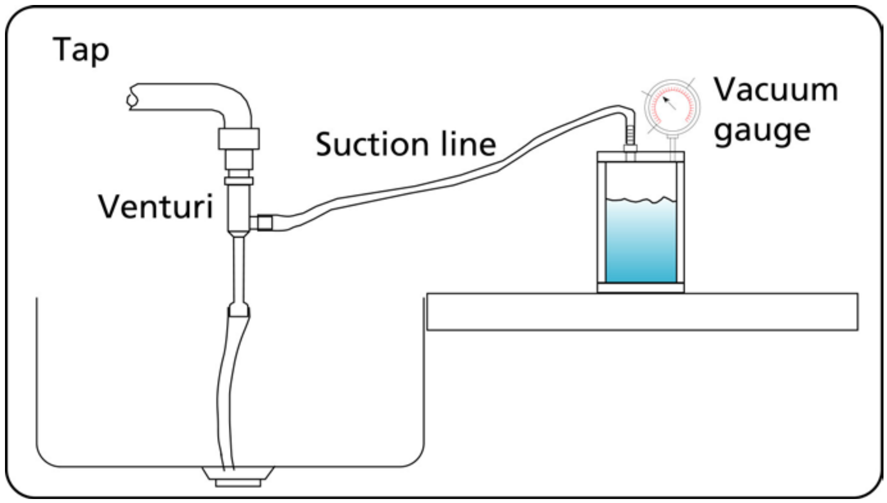

Figure 24 The venturi tube used as a source of vacuum.