The interesting and strange behavior of liquids

Jacques Chaurette, May 31, 2018

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"Water seeks its own level". It's an unusual saying, not sure what the origin is. It is what follows when you connect 2 bodies of water that are at different levels together by some means such as a pipe or a channel. The result is that the body with the higher level will drain into the body with a lower level. Sounds perfectly natural. But why? Once these two bodies are connected they form a system, one part of the system is then higher than the other part. There is no way to keep the higher water particles at their high level, there is no source of energy to do that. Therefore, the higher particles all fall as far as they can go. Of course, because of the volume being transferred the final level will be some intermediate level between the previous levels. *When water finds its own level sometimes it likes to journey upwards first.*

"You can't get water to go up without a pump". Sounds very much like "You can't move an object up without a push". While this is true for solids, it is not for liquids. It can be done very easily by using a tube that connects 2 reservoirs at different heights. The important condition is that one part of the tube must be higher than the highest level. Another important and essential condition is that the tube must be full of water, no air bubbles or gaps between parts of the liquid in the tube. <u>This is called a siphon</u>. The higher reservoir wants to empty itself into the lower. To do that it needs to go up first, that's not difficult for a liquid. The water that is in the tube at the high point is under low pressure, this low pressure or vacuum acts as a force holding the liquid up. How can there be vacuum in the tube? The same way you can pull up water in a straw, you create vacuum with your mouth pulling the water up and then use your finger to seal the top of the straw. The water stays nicely suspended between a low pressure at one end and a higher pressure at the other. Since the liquid in the siphon tube is completely suspended there is nothing stopping it moving from the high reservoir to the lower one. It seeks its own level.

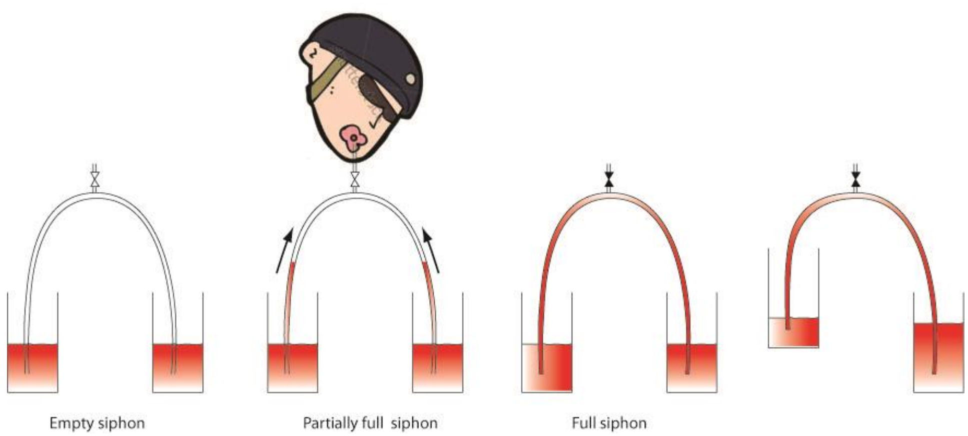

Figure 1

How to you move liquids and how fast can you move them? Liquids are moved most often because of pressure. Pressure will cause a liquid to move from a high-pressure area to a low-pressure area. For example, from the discharge connection of a pump (high pressure) to the outlet of a pipe (low pressure). In the case of the siphon the driving force is not pressure but elevation or potential energy.

Prior to the invention of pumps, the only way to move water in large quantities was to take advantage of elevation difference. You had to find a body a water at a high elevation and convey this water through clay pipes or channels to a lower elevation and you would get water forever as long as the upper lake was replenished by its tributaries.

There are other ways to move water? You can put it in buckets and move it from place to place, assuming of course you have no ready source such as a pressurized municipal water outlet as you would have for your backyard hose connection. We move solids (i.e. bricks, two by fours, shingles) with simple means such as buckets, wheelbarrows and trucks all the time. But not so for water, our civilization has made water ubiquitous, available everywhere. Why? Because it's difficult to move and its so important. It is difficult if not impossible to have a concentration of people without readily available fresh potable water. It is needed to sustain us, to cook, to wash and it's a means to remove sewage which breeds pathogens that make us sick.

We're not the first to think about providing running water. The civilization of Petra and of course the Ancient Romans were great builders of water transportation and foul water removal infrastructure thousands of years ago. The vestiges of the great aqueducts which span valleys in Italy and many other European countries are a testament to these vast undertakings. What else did the Ancient Romans use water for? For one, it was used for sophisticated communal baths, hot and cold water; and another, joy of joy, for underfloor heating. Maybe this is an example of what is meant by the saying; "There is nothing new under the sun".

Still there is a need to be able to handle water regardless if there is a handy municipal water supply available or not. The proof is the large quantity of small to medium size pumps available in the market place. However, buying a pump is not like buying a car, we have to select it using terminology that is not familiar such as: head, pressure and flow. Pumps come in a bewildering variety of types and sizes. We also have to appreciate that water although it appears to be non-viscous and will basically flow at the drop of a hat, is not quite that accommodating. You have to get it from A to B through a pipe or tube, and if you want the correct flow rate at the other end you need to select the right size of tube.

Solid objects are moved with a force, a push, pull, lift, etc, liquids are moved with pressure. Pressure as a distributed force, a familiar example is a syringe. On the syringe is a plunger to which you apply a force, that force creates pressure inside the syringe cylinder, pressure pushes the liquid through the needle. A similar effect occurs when you puncture your bicycle tire, the pressure that is contained within the tube is suddenly in contact with an environment of lower pressure and the air under pressure is expelled from the tube.

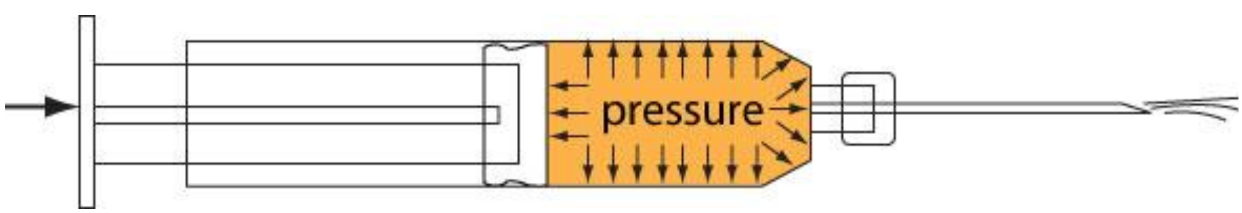

Figure 1 Developing pressure in a syringe.

Any device that moves water has to create pressure in one way or another. There are two big classes of pumps: centrifugal and positive displacement. Centrifugal types are the most widely available to consumers and for industrial use.

The pump world uses a specific terminology. It's not the terminology that a scientist would use but it is effective and simplifies many pumping issues.

For example, the term head used for pumping systems is equivalent to pressure, not identical. You can use either one but it's much simpler to use head in the pump system context. The head of a pump tells you how high you can pump a liquid, it's equivalent to pressure and will tell you essentially the same thing but since the goal of many pump systems is to raise a liquid to a certain height, knowing that height already gives you an important parameter for the pump, and that height is head. If all you knew was the pressure the pump could develop, you would have to figure out the height that pressure would provide. Don't resist the terminology, it's a significant benefit.

How do you figure out the height that a given amount of pressure can provide? We don't need a pump to figure this out, it's done by analogy. Imagine a tank full of water and you put a pressure gauge at the bottom. What will the pressure gauge read for a given height? Or in other words what is the weight on the bottom of the tank and what is the surface area of the bottom. You divide the weight by the surface and you get the pressure. The pressure gauge doesn't do any calculations, it is designed to measure pressure and pressure is provided by the water. Here's where the analogy part comes in. If a pump can provide pressure it can move a liquid vertically up to a certain height. You can replicate that height in any tank and create pressure at its bottom which you can confirm by measuring it. Therefore, we don't need to use pressure as a term in pump systems because height or head will do much better.

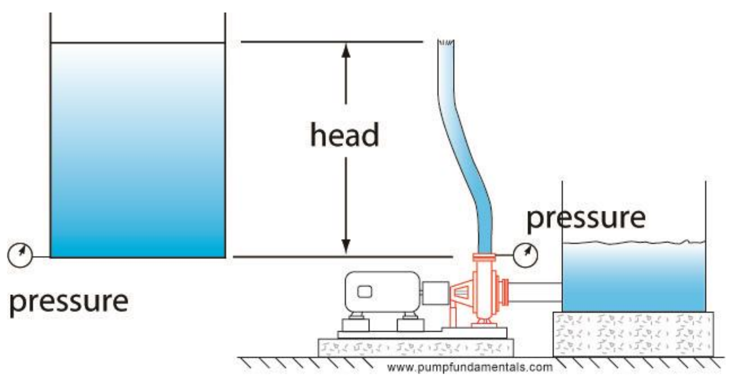

Figure 2 Head and pressure.

Flow rate is something we live with everyday but we don't pay much attention to it unless we don't have enough. Water comes out of your tap effortlessly usually at a rate higher than you need which is why you need a tap that can control the flow rate appropriately. Flow rate is typically defined as gallons per minute or meters cube per hour in the metric system.

As an example, let's take the pump system shown in Figure 3 item 1. The flow *rate* is dictated by the height (i.e. head) of the highest fluid particle and the size of the tube that will carry the water. The height we can measure and it is called static head. As the water moves over the inner surface of the tube it will impede the flow by creating friction. The smaller it is for a given flow rate the higher the friction. How is this friction assessed and how will we relate it to the pump? We measure the pressure drop that occurs when we run a liquid in a tube of a given size for a given flow rate. This has been done for many tube sizes and many flow rates and many tables and charts have been produced to show this data. The pressure drop is converted to head in the same fashion that we converted static pressure to static head. Now we can do a simple addition of the height required to move the liquid (static head) plus the head required because of friction (friction head), and we get the head required of the pump.

See this web app to do pipe friction calculations: http://www.pumpfundamentals.com/web-apps.htm

As you can see the pump does not operate on its own, it is part of a system. That's why it's so difficult to buy the right pump without having carefully analyzed the system.

One element is missing, where is the pump getting its water. It's very rare that the pump's suction intake is at the same level as the water source. Typically, the source of water is a suction tank and the water will be at a certain level in the tank. This water is therefore providing pressure to the pump suction, this is pressure or energy that the pump does not have to supply. Therefore, we must subtract this head (suction static head) from the pump discharge static head to select the right pump otherwise the pump will be too large for our needs.

Here are some typical pump systems that shows how the total static head will vary depending of the configuration of the system on the discharge and suction side of the pump (see Figure 3).

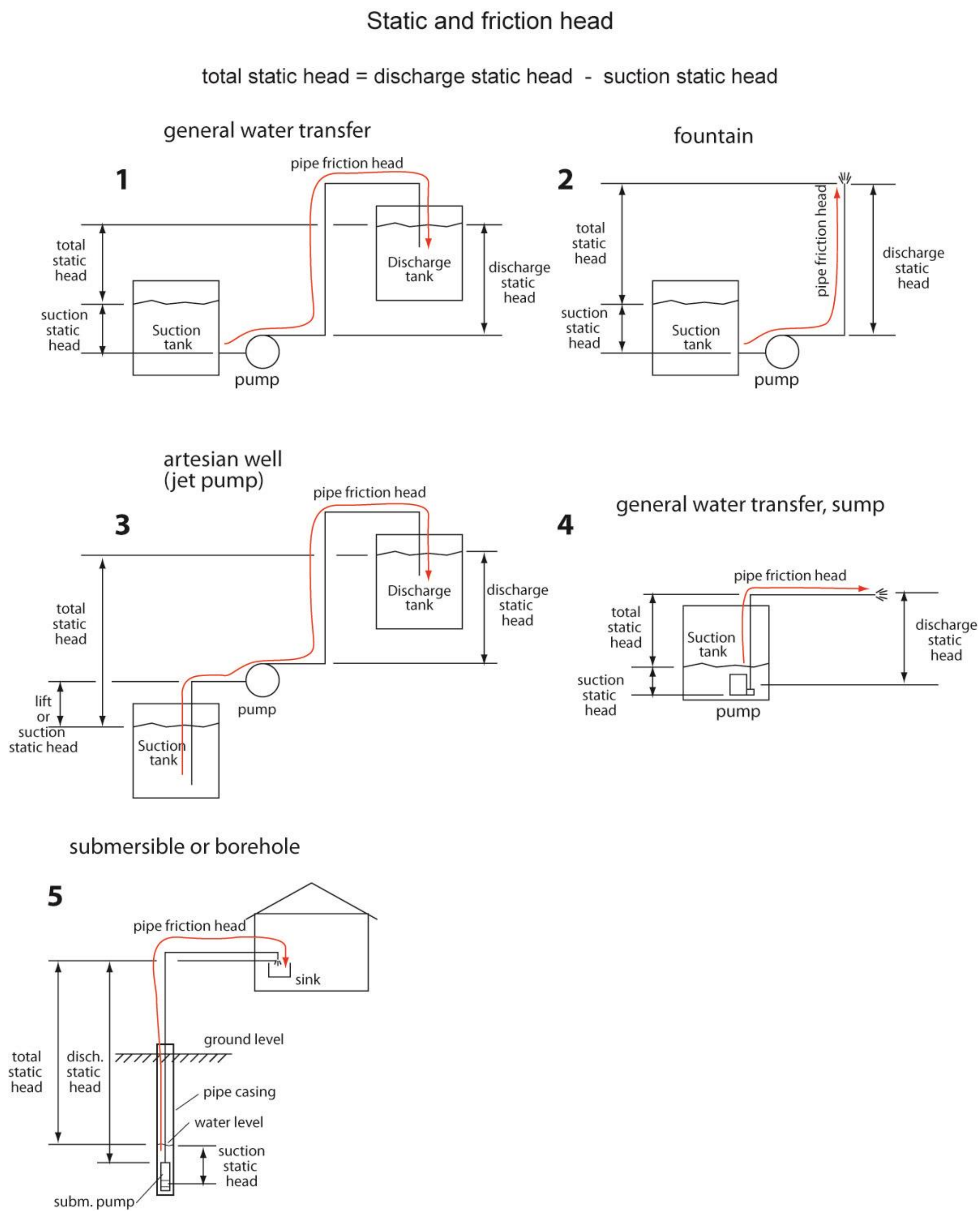

Figure 3 Typical pump systems

These figures show that the highest point that the liquid goes does not determine the static head (Figure 3 examples 1 and 3). Because we have to look at the whole system full of liquid from one end to the other it would be better to say that the discharge static head is determined by the height of the remotest part of the liquid with respect of the pump discharge; and the suction side is treated in a similar fashion.

“There’s not enough pressure at the end of this hose”. We’ve all said this or something like it. It’s a misconception, there is no pressure at the end of the hose, there will never be any pressure no matter how big a pump you put at the other end. What we are really saying is the pump is not supplying enough pressure for the flow I want.

Why? The liquid is coming out into the air, there is no pressure in that environment. What feels like pressure is the water hitting your hand with a certain velocity, if it hits harder it feels like more pressure, if it trickles out it doesn’t feel like anything at all.

Pressure will vary from it’s maximum at the pump outlet and decrease according to the height the liquid goes up and according to the friction produced by the moving water. At the end of the open pipe the pressure will always be zero.

Pressure acts very differently than a force. With a force you can push or pull. Pressure doesn’t have a direction, it pushes against the boundary of the container within which a liquid is contained. Pressure will cause a liquid to move from a high-pressure area to a low-pressure area. For example, from the discharge connection of a pump (high pressure) to the outlet of a pipe (low pressure).

Pressure drops when a liquid moves from a large diameter pipe to a smaller one. Pretty strange and counter-intuitive. It seems like the pressure should increase. After all, when you try to stuff something into a smaller pipe it requires more force. Once again liquids can surprise us.

A cyclist arrives at the top of a hill and he just wants to cruise down. At the top he has elevation energy (potential energy) and at the bottom he will have velocity energy (kinetic energy). His elevation energy is transformed into velocity energy as he barrels down the hill. This is the law of conservation of energy in action. Energy cannot be destroyed but it can be traded off for a different type of energy, in this case velocity energy. As friction is always present some of the energy will also be traded off to friction energy or energy loss.

In the case of a fluid going into a smaller pipe, the fluid starts with pressure energy, keep in mind that the flow rate is constant and somewhere upstream is a pressure source providing this flow rate constantly. As fluid particles enter the smaller pipe the velocity increases, it has to increase, if the flow rate is constant the liquid has to speed up to maintain the flow rate. Because of the law of conservation of energy if the velocity energy increases the pressure energy must decrease, therefore the pressure drops. It can drop so low as to create a vacuum if the small pipe section is much smaller than the larger one. This is known as a venturi, Daniel Bernoulli was the first to explain fully this phenomena, that’s why it is sometimes called the Bernoulli effect.

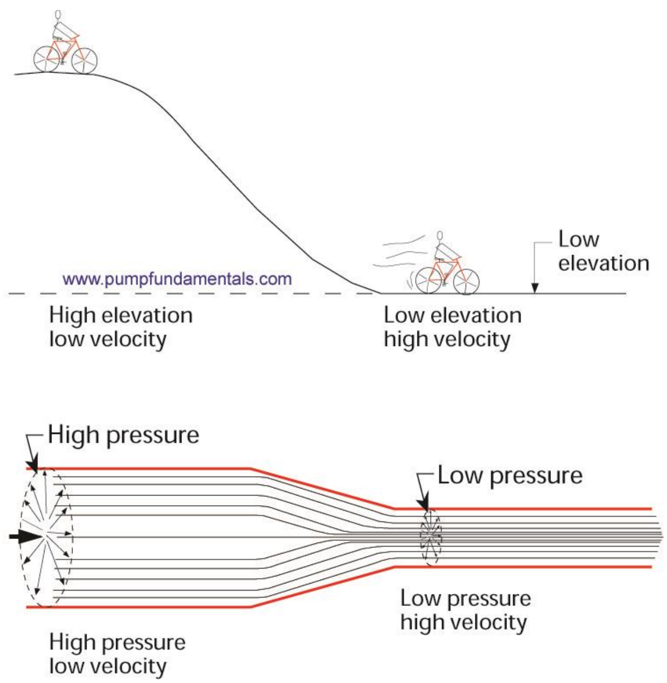

Figure 4 The venturi effect.

You can create yourself a powerful vacuum with a simple plastic venturi attached to your water tap that is worth a few dollars. Many labs use this to remove air from solutions prior to further testing.

Figure 5 The Nalgene vacuum pump

Boiling water at room temperature. Sound impossible? I am using a strict definition of boiling that means getting water to go from a liquid phase to a gaseous phase in particular without using heat and instead using low pressure or vacuum.

There is no such thing as negative pressure, a better term to use is vacuum or low pressure. By low pressure I mean a pressure that is lower than atmospheric pressure. The atmospheric pressure is 14.7 psia, this is pounds per square inch absolute. Pressure can vary from any high number say 100 psia, down to that of the surrounding atmosphere at 14.7 psia or lower, lower than 14.7 psia means we are under vacuum and this continues down to 0 psia. That's it, we can't go any further. The pressure in outer space is 0 psia, there is no matter to create any pressure.

Often instead of psia we use psig, 14.7 psia is equal to 0 psig. This is because very often the systems we deal with have an interface or connection with the local atmosphere (i.e. the system is not sealed) and it is more convenient to use the local atmospheric pressure as a reference.

There is two ways to boil a liquid, you can apply heat, as in boiling a pot of water on a stove, and when the temperature reaches 212 °F the liquid will boil. This corresponds to moving on a horizontal line in the image below. Alternatively, you can leave the heat constant, say room temperature and apply low pressure. This corresponds to moving on a vertical line in the image below. For this you need a sealed container. You can use the venturi mentioned above as your vacuum source.

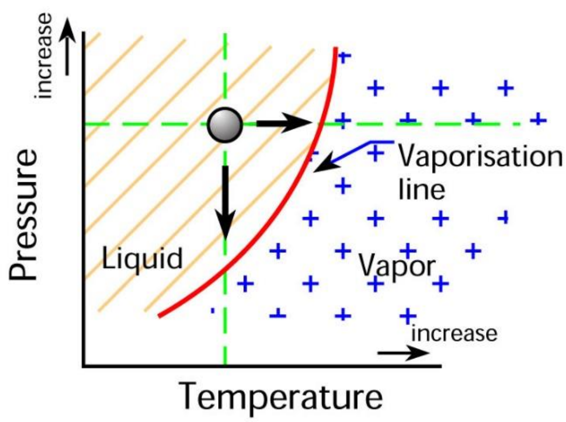

Figure 6 Vapor pressure of a liquid.

Terminology

Friction head: the head required to overcome friction. It will depend on the flow rate (i.e. velocity, the pipe diameter, the viscosity of the liquid, the roughness and length of the pipe;

Head: the height at which a liquid is raised, it is a convenient term used in the pump industry because pumps typically move water from a low level to a higher level. Head is related to pressure, for example a tank full of water will exert pressure at the bottom. The pressure will be proportional to the height of the water above the tank. It takes a certain amount of energy to move a liquid and this is best expressed in terms of head; terms that are derived from head and useful to the user are: static head, rated head, maximum and minimum head; the units of head are feet in Imperial units and meters in the metric system.

Impeller: is a disk the has curved blades, it is the prime mover of liquids in a pump, it generates pressure at the outlet or discharge of the pump. Figure T-1 shows a typical small pump impeller.

Figure T1 Typical small pump impeller

Lift: is the ability of pump to lift a liquid from a lower elevation compared to the pump suction (see Figure 1); it is an abbreviation of lift head;

Maximum flow: the flow at which the pump will operate at minimum head (see Figure T2);

Maximum head: the head at which the pump will operate at zero flow (see Figure T2), also known as shut-off head;

Minimum head: the head at which the pump will operate at maximum flow (see Figure T2);

Performance curve: this is the curve that shows the pump's ability to create head at a given flow rate (see Figure T2), it is provided by the pump manufacturer. For small pumps the manufacturer will often produce a table of flow vs. head (see Figure T3) instead of a performance curve;

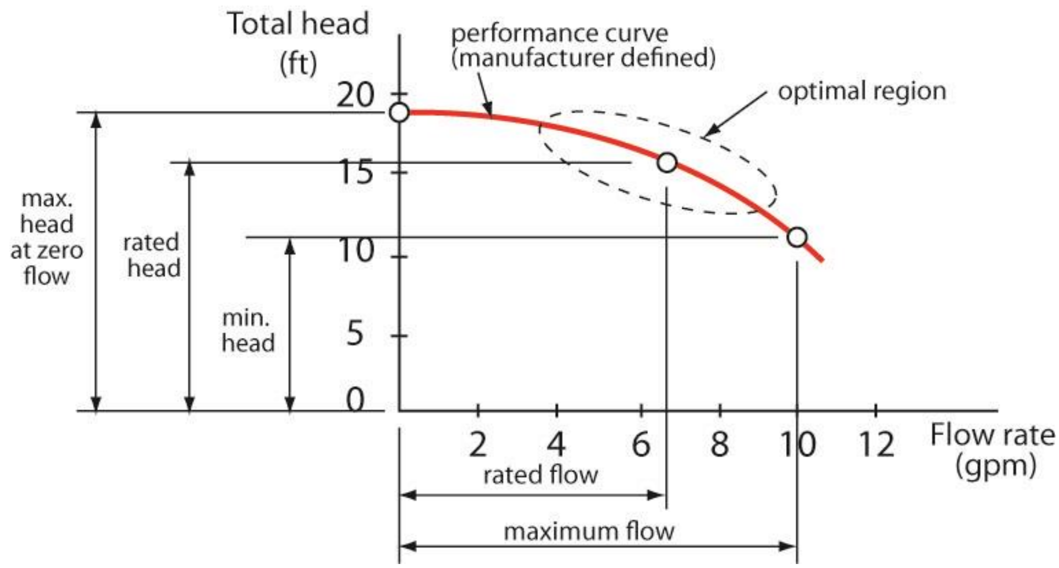

Figure T2 Pump performance curve

PERFORMANCE (GPH)							FLOAT SWITCH		SOLIDS HANDLING
DISCHARGE HEIGHT ABOVE PUMPING LEVEL	0'	5'	10'	15'	20'	MAX. LIFT	ON	OFF	
FPCI5050	4,700	4,200	3,540	2,820	1,800	24'	7.5"	3"	1/4"
FPCI3350	4,200	3,660	3,000	2,160	960	22	7.5"	3"	1/4"

Figure T3 Head vs flow rate table

Pressure: is defined as a force divided by a unit of area; you can feel pressure when you swim to the bottom of a pool on your eardrums, you put pressure in your tires, pressure will move liquids from one place to another; you can measure pressure with a pressure gauge, the unit is psi in the Imperial system and kPa in the metric system; pressure is directly related to head, pump manufacturers prefer to use the term head because it more directly relates to the activity of the pump and it’s ability to move water or any liquid upwards at a given flow rate.

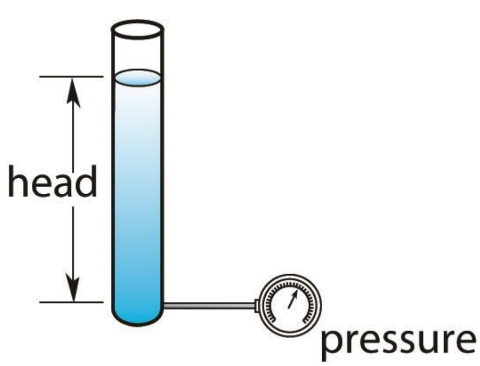

Figure T4 Pressure vs. head

Rated flow: the flow at which the pump will be most efficient (see Figure T2);

Rated head: the head at which the pump will be the most efficient (see Figure T2);

Static head: can be any difference in level depending on the context; to be more precise use total static head, suction static head or discharge static head (see Figure T5 and Figure 3).

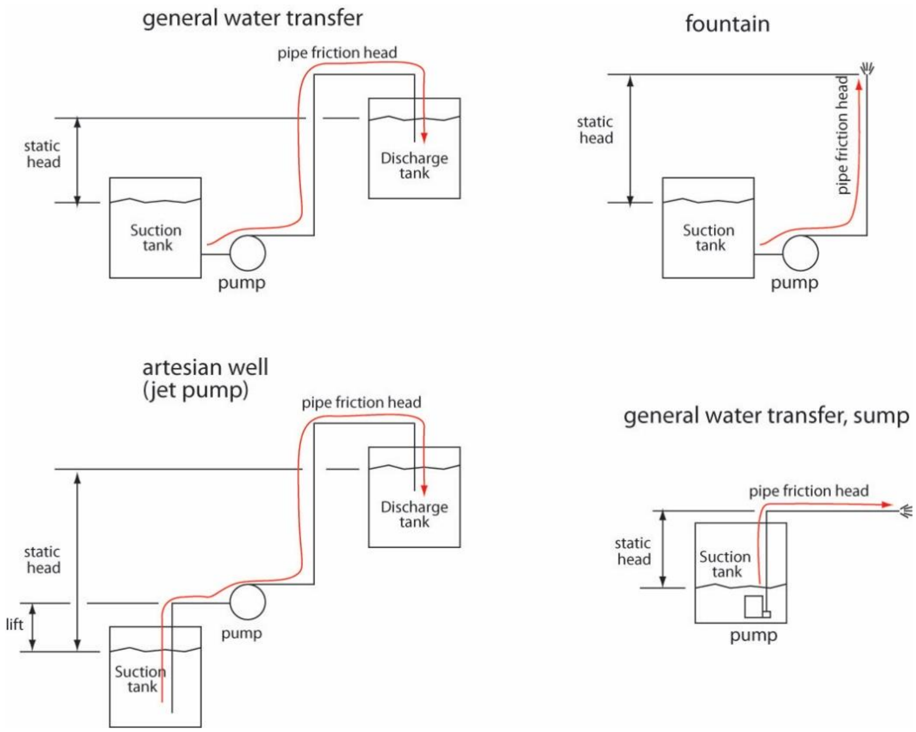

Figure T5 Static head

Total static head: is used to describe the elevation difference between a suction tank level and the discharge tank level or in the case of an open pipe the height of the open pipe end (see Figure 3).

Total head: is the difference in head between the discharge and suction side of the pump that can be delivered at a given flow rate (see Figure T2); it is the vertical axis on the pump. The user's head requirement will be the sum of the friction head loss and the total static head and that should match the total head of the pump..

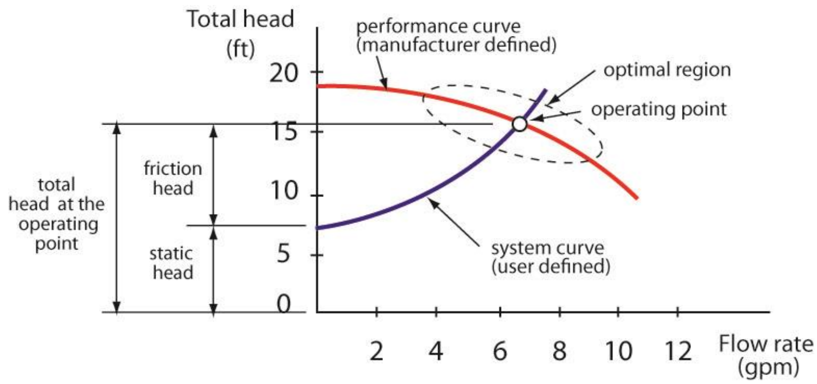

Figure T6 Pump performance curve

This sounds like the user has to do allot of work to select the right pump for his application. That's true! The reason is the manufacturer has no way of knowing what the user's system looks like.

That's why static head is always a difference of levels, it can be determined for any system. Where the user runs into the most trouble is in trying to determine the friction head. There are many tables, charts and formulas to do this, but that is not always available to the user. (se this source for the Cameron Hydraulic book friction tables http://www.pumpfundamentals.com/Cameron%20pipe%20friction%20tables.pdf

Using a bigger pipe than required will minimize this concern but at a cost. The user does not normally calculate and plot a system curve. She will calculate the total head required based on her required flow. Then she will look for a pump that can meet this condition at an optimal location on the performance curve.

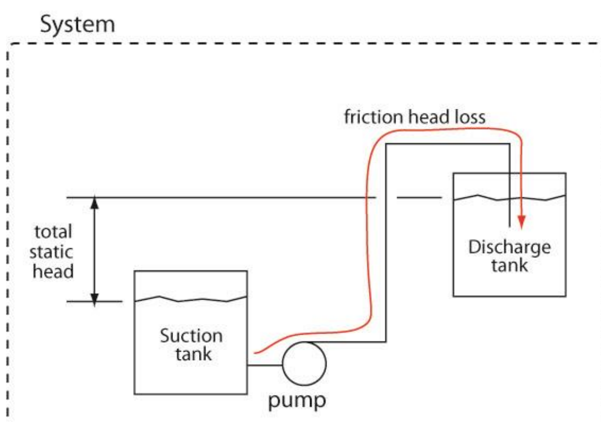

Figure T7 Pump system

The pump will operate at the intersection of the performance and operating curve. This point is called the operating point (see Figure T6). The user is charged with finding a pump that will meet her criteria in the optimal operating area of the pump. The system curve represents what the user requires. To plot the curve, the user calculates the total head based on the static head (assumed constant) and calculates the friction head based on a given flow rate, the sum being the total head, repeat for different flow rates until a complete curve is plotted.

Vapor pressure: the pressure (in absolute terms) at which a liquid will boil at a given temperature;