# Waterhammer – Its All About Conserving Energy

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## Introduction

In his 1963 book, *The World of Elementary Particles*, Kenneth Ford introduced the topic by saying: "It is easy to talk about the incredibly short lifetime of an elementary particle or about the fantastically small size of atomic nucleus. But, it is not so easy to visualize these things". A similar statement could be made about waterhammer.

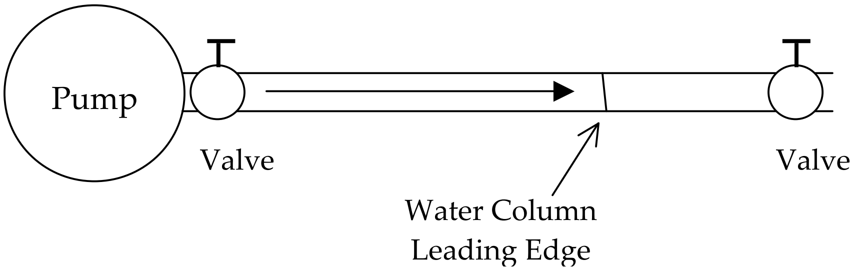
Most of us are familiar with the phenomenon known as waterhammer but few realize how destructive its force can be. Neither can we visualize some of the events that lead to its inception and those that occur afterwards. Oddly enough, it can be more of a concern in low head applications but its potentially damaging effects show no prejudice. In this tutorial we will investigate both the cause and effect of waterhammer. We will also look at several methods of mitigating its damage and inception.

## What Is Waterhammer ?

Waterhammer is a real life example of one of the fundamental laws of Physics - - the conservation of energy. It is a force that can arise in any pumping system that undergoes abrupt changes in its rate of flow. These flow changes can result from pump starts and stops, the opening and closing of valves, and water column separation and closure. The piping design does have an effect upon waterhammer but, these three conditions are the primary reason it occurs. We will take a look at each of these causes.

Waterhammer occurs when an abrupt change in flow creates a shock wave that travels back and forth between the barrier that created it and some secondary barrier. The creating barrier could be a valve, located downstream of the pump, and the secondary barrier could be a pipe "Tee", an elbow, or even the pump itself. Perhaps the best way to visualize this action is to use a hypothetical example because it is, sometimes, difficult to comprehend its inception in a piping system where flow is continuous.

The figure below shows a pump that is pumping water into an empty pipe connected to its discharge. The two valves located at the pump discharge and the far end of the pipe are fully open and both have the ability to close instantaneously. The valves and the pipe are entirely inelastic and no volume change can occur regardless of the pressure. Also, the column of water flowing through the pipe has a leading edge that is nearly flat and matches that of the cross sectional ID of the pipe. By this, I mean that the area of the pipe just a fraction of an inch behind the leading edge of the water column is entirely full - - there are no air gaps. Just as the leading edge of the water column reaches the downstream valve, it closes at nearly the speed of light and entraps no air ahead of the water column. Even though the leading edge has struck the closed valve, flow into the pipe continues for the next few milliseconds. Just as flow ceases, the upstream valve closes (this time at the true speed of light) and the water column is completely isolated between the two valves. What events occur as the column strikes the closed, downstream valve and why does water continue to enter the pipe?



Well, if this moving column was a column of metal instead of water (did I mention that this is a hypothetical example?), a couple of things could occur. Depending upon its coefficient of restitution (its ability to avoid permanent damage) the kinetic energy due to flow (motion) could be transformed into mechanical energy as the leading edge of the metal column is crushed. If this occurred, the column would remain motionless at the valve. Or, if its restitution is very high, that same kinetic energy could be used to reverse its direction in the form of a bounce. Regardless of the outcome, the “entire” metal column would either come to rest or bounce in the opposite direction. Neither of these cases could occur when water is involved.

You have probably heard that water is a “nearly noncompressible” liquid. But, the flip side of that statement would indicate that it is “slightly compressible”. At ambient temperature one pound of pressure will decrease its volume by a factor of about 0.0000034. That seems pretty small but the larger the volume, the easier it is to see the effect. For example, if water did not compress, sea level would be more than one hundred feet higher than its current level! At higher pressures, say 40,000 PSI, its compressibility is increased to about 0.1. But, most water is not just “water” - - it also contains air which is mostly nitrogen, oxygen, and carbon dioxide. If this were not the case there would be no fish! Dissolved air composes about 2% of a given volume of unprocessed water and adds, substantially, to its compressibility.

It is the water’s (and that of the dissolved air) compressibility that causes it to act differently than the slug of metal. Were it not compressible its leading edge would be permanently crushed or the entire column would bounce backwards. When the leading edge of a water column strikes the closed valve it comes to a halt, but the water behind it is still in motion and, since it has nowhere to go, it begins to compress. This compression along the entire length of the column allows a small amount of water to continue to flow into the pipe even though the leading edge has halted. When flow ceases, its kinetic energy of motion and that due to compression is transformed into pressure and energy is conserved.

Compression begins at the leading edge of the water column and since the additional energy it produces cannot continue on past the closed valve, a pressure or shock wave is generated and travels back upstream. The inception of this shock wave is very similar to the “echo” that is produced when a sound wave, traveling through air, strikes some barrier. When the wave hits the upstream valve it is reflected back downstream but with a diminished intensity. This, back and forth, motion continues until friction and reflection losses cause the waves to disappear. The speed at which a wave travels and the energy it loses during travel depends upon the density and compressibility of the medium in which it is traveling. It turns out that the density and compressibility of water make it a very good medium for shock wave generation and transmission.

The pressure waves created by hydraulic shock have characteristics similar to those of sound waves and travel at a similar velocity. The time required for a waterhammer pressure wave to negotiate a length of pipe is simply the pipe length divided by the speed of sound in water (approximately 4860 ft/sec). In waterhammer analysis, a time constant that is often used is one that describes the progression of the wave from its inception to secondary barrier and back again ($Tc = 2L / \alpha$ where $L$ is the pipe length and $\alpha$ is the speed of sound). For a 1000 foot length of pipe it would require less than half a second for the wave to make a complete round trip.

Although the equation at the top of the following page does not take into account the effect of pipe size and elasticity on waterhammer, it will provide some insight as to the additional pressure that is created by a waterhammer pressure wave.

P(additional) = $\alpha V / 2.31g$

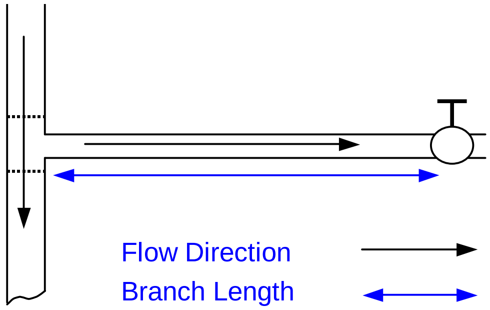
Where P is the additional pressure created by the shock wave, $\alpha$ is wave velocity (in this case the speed of sound), V is the velocity of the flowing water in the pipe in feet per second (fps), and g is gravitational constant @ 32 ft/sec$^2$. At a pipeline velocity of 5 fps the additional pressure created by the shock wave is about 329 PSI. Increase that velocity to 10 fps, and that pressure increases to about 658 PSI. Obviously, systems that are not designed to accommodate such an increased pressure are often damaged or even destroyed.

## Waterhammer Causes

In the previous section, we used a hypothetical example to illustrate the onset and effects of waterhammer. Lets take a look at a practical example.

### Valve Closure & Opening

The figure below shows a main pipeline with a branch circuit that is fed by a "Tee". Further down the branch is a valve. The black arrows show the flow direction in the primary and branch lines and the blue arrow is the length of the branch line. As in the earlier example, the valve acts as the primary barrier but this time the secondary barrier is the "Tee" itself. If the valve is closed quickly, waterhammer could occur in the branch line and its inception would follow the same sequence of events seen in our hypothetical example. One small difference is that some of the intensity of the shock waves will be lost in the "Tee" as it is open to the main pipe line on either side. Still, a significant portion will be reflected back towards the valve.



A major difference, in this example, is that we have some control over the valve closure time (in our previous example the valves closed at the speed of light). And, closure time has a significant effect on the inception and intensity of waterhammer. In addition two other variables, flow velocity and pipeline length, are also major factors. The equation below shows the relationship of these three variables and their effect.

$$P(\text{additional}) = 0.07\ (VL\ /\ t)$$

Where $P$ is the additional pressure generated, $V$ is the flow velocity in fps, $L$ is the pipe length before valve in feet, and $t$ is the valve closing time in seconds. The additional pressure created by the shock wave is directly proportional to flow velocity and pipeline length and inversely proportional to closure time. In other words higher values of $V$ and/or $L$ will increase pressure while higher values of $t$ will result in a decreased pressure. The table below shows the results we obtain from this equation when using differing velocities, pipe lengths, and closure times. For $V$ we will use 5 & 10 fps, for $L$ we will use 100 & 1000 ft, and for $t$ we will use 1 & 2 seconds. In each example we will keep two of the variables constant.

| | |
|---|---|
| $P = 0.07\ (5\text{x}100)\ /\ 1 = 35$ | $P = 0.07\ (5\text{x}100)\ /\ 2 = 17.5$ |
| $P = 0.07\ (10\text{x}100)\ /\ 1 = 70$ | $P = 0.07\ (10\text{x}100)\ /\ 2 = 35$ |
| $P = 0.07\ (5\text{x}1000)\ /\ 1 = 350$ | $P = 0.07\ (5\text{x}1000)\ /\ 2 = 175$ |
| $P = 0.07\ (10\text{x}1000)\ /\ 1 = 700$ | $P = 0.07\ (10\text{x}1000)\ /\ 2 = 350$ |

Both columns of the table illustrate the proportional influence of velocity and length - - pressure increases as they increase. The lower values seen in the right hand column illustrate the inverse relationship of time - - these pressures are half those seen in the left hand column because the closure time has doubled. As I mentioned earlier, pipe diameter and the elasticity of its material also influence the pressure generated. Larger diameters and more elastic materials absorb some of the intensity of the shock waves and therefore reduce the pressure generated. You will find that most pipe manufacturers publish curves or tables that show the potential pressure increase, that can be generated by waterhammer, for various pipe diameters and materials of composition.

We have very little control over the length of a pipeline regardless of the application. Therefore, our ability to decrease the value of $L$ in our equation is extremely limited. We can, however, control the other two variables and, in doing so, eliminate or greatly reduce the effect of waterhammer.

Suppose, for a moment, that the branch line valve is closed. If it is opened quickly, we can get an effect similar to that of quick closing. When the valve is opened quickly, the branch line sees an immediate drop in pressure and the static water column (and its dissolved air) expands slightly from its compressed state. Incoming water from the main line adds velocity to column and also increases it pressure. If the pressure increases quickly, the forward water column will act as the primary barrier and waterhammer can occur. Usually its effect is much smaller than that of valve closure and is often referred to as a "surge". Still, under certain conditions, this surge can be damaging.

## Pump Starts and Stops

In most pressure booster applications, a "spring loaded" check valve is installed at or near the pump discharge and remains closed when the pump is idle. When the pump is started, flow does not begin until the pressure it generates exceeds the pressure on the downstream side of the closed valve. If the downstream pressure is not allowed to decrease below a certain minimum, flow increases slowly and waterhammer inception is avoided or reduced significantly. When the pump stops, an unexpected event occurs - - a quick closing valve actually prohibits, rather than initiates, waterhammer! In this particular instance, the spring provides quick closure of the valve and thus prevents the water column from changing direction due to the higher downstream pressure. Even though there is an abrupt change in flow, pressure remains relatively constant throughout the downstream column. If a standard check valve was installed the water column would have enough space to change direction, accelerate backwards, and slam the check closed thus initiating waterhammer.

In many large pumping plants it is normal procedure to start a pump against a closed discharge valve. Once the pump is up to full speed the valve is opened slowly, flow is initiated, and then increases to its maximum as the valve continues to open. This procedure is reversed when a pump is stopped. Starting and stopping against a valve that is opened or closed slowly will prohibit the initiation of waterhammer or reduce its effect to a, virtually, immeasurable quantity. Depending upon the installation the discharge valve may be operated manually or by some automatic mechanism.

One of the short comings of manually operated valves occurs when during a power outage. When a pump motor loses power, the reduction in pump speed and flow from its discharge occur rapidly. The resulting change of kinetic energy to that of pressure will produce waterhammer waves in the discharge line. Additionally, as the water column reverses direction, the impeller will begin to accelerate backwards. When it reaches it maximum reverse speed, backwards flow is reduced and an additional pressure surge is created.

In the introduction, I mentioned that the effects of waterhammer can be more significant in low pressure systems.  The pressure of the shock wave is proportional to the length of the pipe and velocity of the water flowing in it and is independent of its operating pressure.  Therefore the shock wave created in a one mile pipe flowing at 10 fps will be the same whether the operating pressure is 20 PSI or 200 PSI.  There is a difference though.  The ratio of shock pressure to operating (design) pressure is quite a bit higher in the low pressure system - - thus the potential for damage can be greater in the lower pressure system.

## Water Column Separation & Closure

So far our discussion of waterhammer has dealt with something  we call single phase systems.  In these systems, water remains in a single state (liquid in this case) regardless of the changes in the hydraulic conditions.  The shock waves generated by single phase systems are due to an abrupt change in flow and the resulting transformation of kinetic energy.

The waterhammer generated by water column separation and closure is a two phase process.  In a two phase system, water changes state and can exist both as a liquid and a vapor within the same confined volume.  This phase change can take place whenever the pressure in a pipeline is reduced to that of the vapor pressure of the water.  When this pressure drop occurs, the water column can become separated, in one or more locations, by a pocket of vapor.  When the pressure rises above the vapor pressure the column rejoins or closes and can create a high pressure wave (not unlike that of an imploding cavitation bubble but on a much larger scale).  Water column separation, by itself, can cause problems in very large diameter or thin wall pipes (they can collapse), but the waterhammer that arises during closure is the more common problem.

Water column separation can occur when a pump is stopped and the water column reverses direction or in condensate lines where high temperatures can mitigate the need for a large pressure drop.  Although both forms can be extremely damaging, condensate lines tend to be far more dangerous.  The shock waves generated by column closure can travel in opposite directions and if they hit secondary barriers they can be redirected back towards one another.  Although I have found nothing in the literature to support this, I would suspect that these reflected waves may increase in intensity when they collide.  This is certainly the case with water and voltage waves and it may account for the often greater damage resulting from closure initiated waterhammer.

## Eliminating or Reducing Waterhammer

You will find numerous articles on the web and in the literature that cover the available methods for reducing or even eliminating waterhammer in various pumping applications. I will mention just a couple. (By the way, if you use a web search engine be sure to search for both waterhammer and water hammer.)

Two of the simplest methods of controlling waterhammer include the two variables seen in our branch line pumping example. As I mentioned, we usually have little control over pipeline length but, we have total control over flow velocity and valve closing time.

Although a conservative (read correctly sized) pipeline design will increase its first cost, the lower flow velocity will reduce the effect of waterhammer. But this, first cost, issue could be a moot point because waterhammer control devices, and their associated costs, may not be required if the pipeline is sized correctly in the beginning. Proper pipeline sizing makes good sense from both a waterhammer and a friction loss perspective.

Manual valves pose few problems as long as the humans who control them are in control of their actions. You have probably noticed that the manual closure or opening of a gate valve seldom, if ever, gives rise to waterhammer. The reason is that it is almost impossible to close or open a gate valve too quickly. Ball valves, on the other hand, seem to “want” to open and close quickly and extreme care must be used in their operation. Butterfly valves fall somewhere in between. Automatic valves can pose a different problem. Since they are not human controlled (sometimes a good thing), they must be selected correctly. Often small, fast closing, solenoid valves will not cause waterhammer because of their low flow rate. Larger ones, however, can cause significant problems. Almost all valve designs can be automated and most automation systems allow selection of opening and closing times. Many of the automatic valves used in irrigation systems now offer this feature and pipe rupture due to waterhammer is becoming a thing of the past.

The variable frequency drive has been a major player in controlling waterhammer during pump starts and stops. The ability to ramp the frequency, and thus the motor speed, over a period of time significantly reduces the differential force that is normally encountered. A secondary benefit of this so called “soft start” is a similar reduction in both electrical and mechanical stress on the motor and pump.

Joe Evans, December 2005