

HYDRAULIC TRANSIENTS: PERIL FOR PUMPS AND PIPES

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One of the essential features of a modern urban society is the ability to efficiently distribute potable water to end users and collect and transfer wastewater away from them. These transfer operations depend on a complex network of pumps and pipes. Properly estimating the necessary community flows and appropriately sizing the pumping systems, reservoirs and piping network are primary tasks of civil and environmental engineers.

These design efforts can be challenging. Engineers are taught to perform these computations based on **steady-state** flow assumptions. In simple language “steady-state” means that the mean (average) velocity of water flowing through the system is constant. The purpose of this approach is two-fold: (1) provide the desired flow and pressure at specific locations within the system, and (2) configure the delivery components so as to minimize the expense. Guidelines and techniques based on this approach have allowed engineers to reliably design facilities for communities they serve.

But what happens in a system that experiences **unsteady flow** during the course of its operations? Unsteady flow, of course, refers to situations where the mean velocity in the pipes is not constant. This, in fact, occurs routinely (if not constantly) in fluid systems. Unsteady flow gives rise to **hydraulic transients** (also known as waterhammer or surge). Transients consist of pressure waves that very quickly move through the system. These would be of little interest if the transient waves were small and inconsequential. However, many times this is not the case and, in certain situations, transients can have catastrophic consequences. Interestingly, analysis of transient conditions is all too often neglected in the design process. This article will explore the basic characteristics of hydraulic transients, their analysis and some of the routine methods of controlling them. Transients can occur in both open channel and pressure flow situations. Only pressure pipe transients will be addressed here.

Basic Factors Affecting Transient Formation

Transients can be described by basic state equations, which result from the physical characteristics of water and the fundamental relations of physics. In essence, the mathematical effort attempts to model a system where the energy from the changing velocity is simultaneously trying to compress the water and stretch the conduit circumferentially. Water has a couple of properties that accentuate its ability to create these pressure waves.

First, water has a high density. Because pipelines are typically long relative to diameter, the water column (volume) is significant. Due to water density, this means that the mass, momentum and kinetic (active) energy can be quite large.

Second, water is, for all intents and purposes, incompressible. This makes water a very effective energy transfer medium. Therefore, whenever a pressure wave is formed, there is negligible dampening due to water compression.

Given these characteristics, when a moving column of water is abruptly stopped or started, a pressure wave is formed. The magnitude and speed of the pressure wave is mathematically defined by two differential equations that satisfy the Conservation of Mass and Conservation of Momentum criteria. While computer simulations are required for actual design, some simplified equations can provide an indication of the magnitude for non-complex systems.

The **Joukowski equation** is many times used as a rough estimate of the magnitude of the pressure rise in the pipe. It is given by:

$$\Delta H = \frac{a}{g} \Delta v$$

where: ΔH = change in pressure
 a = pressure wave propagation speed
 g = acceleration of gravity
 Δv = change in velocity

To compute this, the propagation speed of the transient must be calculated. The equation governing this takes several forms depending on the pipe material and construction characteristics. A general form of this equation is:

$$a = \sqrt{\frac{\frac{K}{\rho}}{1 + \left(\frac{KD}{Ee}\right)}}$$

where: K = bulk modulus of elasticity of water
 ρ = mass density of water
 E = Young's modulus of elasticity for the pipe material
 e = pipe wall thickness

After performing these computations over time, what one finds is that it is not unusual to see a pressure rise in the hundreds of pounds per square inch (psi) in unprotected systems (for reference the typical water system pressure is between 55 to 75 psi). The wave speed is incredibly fast, traversing the system at a speed on the order of 3,000 to 4,500 feet per second (roughly equivalent to 3,000 miles per hour).

With the intensity of these pressure swings, significant damage can occur to pipes, pumps, valves, as well as end user equipment and appurtenances if left unmanaged. In addition, recent studies have shown that water quality can actually deteriorate in systems that have significant transient problems. This is hypothesized to occur as a result of disturbance of biofilms within the distribution system, and possibly even aspirating small volumes of external (contaminated) water during negative pressure phases of the transient wave.

What Causes Hydraulic Transients?

Waterhammer can result from a wide array of system events that makes it difficult to completely eliminate from occurring. Per the definition, anything that causes a change in the mean velocity of the water column in a pipe will develop a pressure wave. The magnitude of the transient, then, is a result of the magnitude of the velocity change, the volume (mass) of water in movement, and the characteristics of the pipe. Typical operating conditions that result in changes in the water column velocity include:

1. Changes in valve settings. Opening or closing a valve within the pipeline system will obviously change the velocity within a pipe.
2. Starting or stopping a water supply or booster pump. It's common to associate waterhammer with stopping fluid flow, but it must be remembered that surge effects also result from starting or introducing a flow.
3. Change in demand conditions. User demand changes result in adjustment within the distribution system to meet the demand. A clear example of this is the large flow demand change that might occur at the start or conclusion of firefighting.
4. Changes within the transmission system. This occurs whenever a pipe ruptures or a new pipe is first put into service, causing a re-leveling of pressures within the system.
5. Changes in storage tank operation. Whenever an elevated storage tank begins to fill or drain, transients can occur. Normally, these pressure gradients are more gradual, but occasionally they can cause concern.
6. Air accumulation within pressure pipes. While this might not seem like much of an issue, air can in fact cause many problems. Air can actually restrict flow in variable ways and, in certain conditions, can cause column separation that can result in vacuum development. Depending on the situation, this vacuum can collapse pipes and attached storage tanks if not properly vented.

It is clear from looking at this list that pressure waves can occur almost continuously within a water or wastewater pressure system because system changes are constantly occurring. Since hydraulic transients can't be eliminated, designers and operators must look for ways to minimize their magnitude and effect.

How Can Hydraulic Transient Effects Be Minimized?

The first step in minimizing transient effects is to recognize that they will occur in most every pipe system to one extent or another. With that knowledge, during the design process, one should look for situations where the magnitude and/or frequency of these pressure waves can be deleterious to the system. For example, it is prudent to

look for situations where large changes in elevation or pressure occur. When this condition arises it is likely that a change in flow condition will create a pressure wave due to the energy associated with the water. Conversely, when one sees a long, flat pipeline care must be exercised in this situation too. These pipelines can have a considerable amount of energy associated with them due to the mass of the water column and the pumps driving the flow may require considerable power to overcome the pipe friction to meet the design flow condition. Turning those pumps off and on (not to mention valve closures) can create the potential for hydraulic transients.

Another red flag is design of systems within hilly terrain. Actually, the hills don't have to be extremely large to be an incipient transient generator. Pipe systems should be designed to minimize the ability for air pockets to form, thus, they should be laid with an eye toward them being as horizontal as practicable. Where this is not possible, the profile should be examined to cause the air to collect in a controlled location, then removed by an appropriate device such as an air or air/vacuum relief valve.

In an operational setting, workers should be trained to never quickly open or close valves, especially on large pipes. This would include firefighters, operational personnel at large water users, etc. that can cause significant changes in the demand upon a pressure system through changes in valve settings. Actually, for specified conditions, it is possible to compute the allowable valve closure rate to keep a transient within acceptable range.

A number of techniques and devices have been developed to assist the designer or operator to manage transient events. Examples of devices commonly encountered include surge tanks, air cushioned surge tanks, air/vacuum relief valves, pressure relief valves, and by-pass lines. In addition, there are various pump and valve controllers that have been shown to effectively minimize the formation of pressure waves when properly designed and implemented.

The take away message of this article is that water and wastewater pressure systems are not static entities. Anything that changes the velocity of flow in the piped system (a pump is engaged/disengaged, a valve closes, a significant new demand occurs, etc.) creates an opportunity for a hydraulic transient to form. Mathematical analysis and field experience indicates that these transients can result in situations that are destructive, if not appropriately managed. Therefore, the design phase should be based not only upon the steady state conditions but should also consider the likelihood of unsteady flow regimes and consider their implications. The design should seek to configure the system in such a way as to minimize the transients but, if that is not possible, utilize the appropriate devices to suppress the waterhammer to levels that are not harmful. Further, operational practices should be enforced which protect the system from functional damage (ex. quick valve closure after firefighting, water main repair, etc.). These efforts will pay for their consideration many times over, especially as our utility systems age.

Additional Reading:

Jung, B.S., B.W. Karney, et al. (2007). "The Need for Comprehensive Transient Analysis of Distribution Systems." JAWWA **99**(1): 112-122.

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