

SHOCK AND WATER HAMMER LOADING

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Summary

Transients can introduce large pressure forces and rapid fluid accelerations into a piping system. These disturbances may result in pump and device failures, system fatigue or pipe ruptures, and even the backflow/intrusion of contaminated water. Many transient events can lead to column separation, which can result in catastrophic pipeline failures. Thus, transient events can cause health risks and can lead to increased leakage, decreased reliability and breaches in the pipe system integrity. Transient flow simulation has become an essential requirement for assuring safety and the safe operation of drinking water distribution systems. This chapter introduces the concept and fundamentals of hydraulic transients, including the causes of transients, governing equations, numerical methods for predicting their location, magnitude and duration, and practical guidelines for their suppression and control. Such capabilities greatly enhance the ability of water utilities to evaluate cost-effective and reliable water supply protection and management strategies and safeguard public health.

1. Introduction

Water hammer and shock loading refer to rapid and often large pressure and flow fluctuations resulting from transient flow conditions in pipes transporting fluids. Transient flow analysis of the piping system is often more important than the analysis of the steady state operating conditions that engineers normally use as the basis for system design. Transient pressures are most significant when the rate of flow is changed

rapidly, such as resulting from rapid valve closures or pump stoppages. Such flow disturbances, whether caused by design or accident, may create traveling pressure and velocity waves of excessive magnitude. These transient pressures are superimposed on the steady state (static) conditions present in the line at the time the transient occurs. The total force acting within a pipe is obtained by summing the steady state and transient pressures in the line. The severity of transient pressures must thus be accurately determined so that the pipes can be properly designed to withstand these additional shock loads. In fact, pipes are often characterized by their “pressure ratings” (or pressure classes) that define their mechanical strength and have a significant influence on their cost.

Transient events have been responsible for equipment failure, pipe rupture, separation at bends, and the backflow of dirty liquid into the distribution system via intrusion. High-flow velocities can remove protective scale and tubercles and increase the contact of the pipe with oxygen, all of which will increase the rate of corrosion. Uncontrolled pump shutdown can lead to the undesirable occurrence of water-column separation, which can result in catastrophic pipeline failures due to severe pressure rises following the collapse of the vapor cavities. Vacuum conditions can create high stresses and strains that are much greater than those occurring during normal operating regimes. They can cause the collapse of thin-walled pipes or reinforced concrete sections, particularly if these sections were not designed (i.e., pipes with a low pressure rating) to withstand such strains.

Cavitation occurs when the local pressure is lowered to the value of vapor pressure at the ambient temperature. At this pressure, gas within the liquid is gradually released and the liquid starts to vaporize. When the pressure recovers, liquid enters the cavity caused by the gases and collides with whatever confines the cavity (i.e., another mass of liquid or a fixed boundary) resulting in a pressure surge. In this case, both vacuum and strong pressure surges are present, a combination that may result in substantial damage. The main difficulty here is that accurate estimates are difficult to achieve, particularly because the parameters describing the process are not yet determined during design. Moreover, the vapor cavity collapse cannot be effectively controlled. In less drastic cases, strong pressure surges may cause cracks in internal lining, damage connections between pipe sections, and destroy or cause deformation to equipment such as pipeline valves, air valves, or other surge protection devices. Sometimes the damage is not realized at the time, but results in intensified corrosion that, combined with repeated transients, may cause the pipeline to collapse in the future.

Transient events can have significant water quality and health implications. These events can generate high intensities of fluid shear and may cause re-suspension of settled particles as well as biofilm detachment. Moreover, low pressure transients may promote the collapse of water mains, leakage into the pipes at loose joints, cracks and seals under sub-atmospheric conditions, and back-siphonage and potential intrusion of untreated, possibly contaminated groundwater in the distribution system. Pathogens or chemicals in close proximity to the pipe can become a potential contamination source, where continuing consumption or leakage can pull contaminated water into the depressurized main. Recent studies have confirmed that soil and water samples collected immediately adjacent to water mains can contain high fecal coliform

concentrations and viruses. This is especially significant in systems with pipes below the water table. Locations with the highest potential for intrusion were sites experiencing leaks and breaks, areas of high water table, and flooded air-vacuum valve vaults. In the event of a large intrusion of pathogens, the chlorine residual normally sustained in drinking water distribution systems may be insufficient to disinfect contaminated water, which can lead to damaging health effects. A recent case study in Kenya showed that in the event of a 0.1% raw sewage contamination, the available residual chlorine within the distribution network will not render the water safe.

Transient events that can allow intrusion to occur are caused by sudden changes in liquid velocity due to loss of power, sudden valve or hydrant closure or opening, a main break, fire flow, or an uncontrolled change in on/off pump status. Transient-induced intrusions can be minimized by knowing the causes of pressure surges, defining the system's response to surges, and estimating the system's susceptibility to contamination when surges occur. Therefore, water utilities should never overlook the effect of pressure surges in their distribution systems. Even some common transient protection strategies, such as relief valves or air chambers, if not properly designed and maintained, may permit pathogens or other contaminants to find a "back door" route into the potable water distribution system. Any optimized design that fails to properly account for pressure surge effects is likely to be, at best, suboptimal, and at worst completely inadequate.

Pressure transients in liquid distribution systems are inevitable and will normally be most severe at pump stations and control valves, in high-elevation areas, in locations with low static pressures, and in remote locations that are distanced from overhead storage. All systems will, at some time, be started up, switched off, undergo unexpected flow changes, and will likely experience the effects of human errors, equipment breakdowns, earthquakes, or other risky disturbances. Although transient conditions can result in many abnormal situations and breaches in system integrity, the engineer is most concerned with those that might endanger the safety of a plant and its personnel, that have the potential to cause equipment or device damage, or that result in operational difficulties or pose a risk to the public health.

Transient pressures are difficult to predict and are system dependent, including specific system layout, configuration, design and operation. Engineers must carefully consider all potential dangers for their pipe designs and estimate and eliminate the weak spots. They should then embark upon a detailed transient analysis to make informed decisions on how best to strengthen their systems and ensure safe, reliable operations.

2. Causes of Fluid Transients

Fluid transient events are disturbances in the liquid caused during a change in operation, typically from one steady state or equilibrium condition to another (Figure 1). The principal components of the disturbances are pressure and flow changes at a point that cause propagation of pressure waves throughout the distribution system. The pressure waves travel with the velocity of sound (acoustic or sonic speed), which depends on the elasticity of the liquid and that of the pipe walls. As these waves propagate, they create transient pressure and flow conditions. Over time, damping actions and friction reduces

the waves until the system stabilizes at a new steady-state. Normally, only extremely slow flow regulation can result in smooth transitions from one steady-state to another without large fluctuations in pressure or flow.

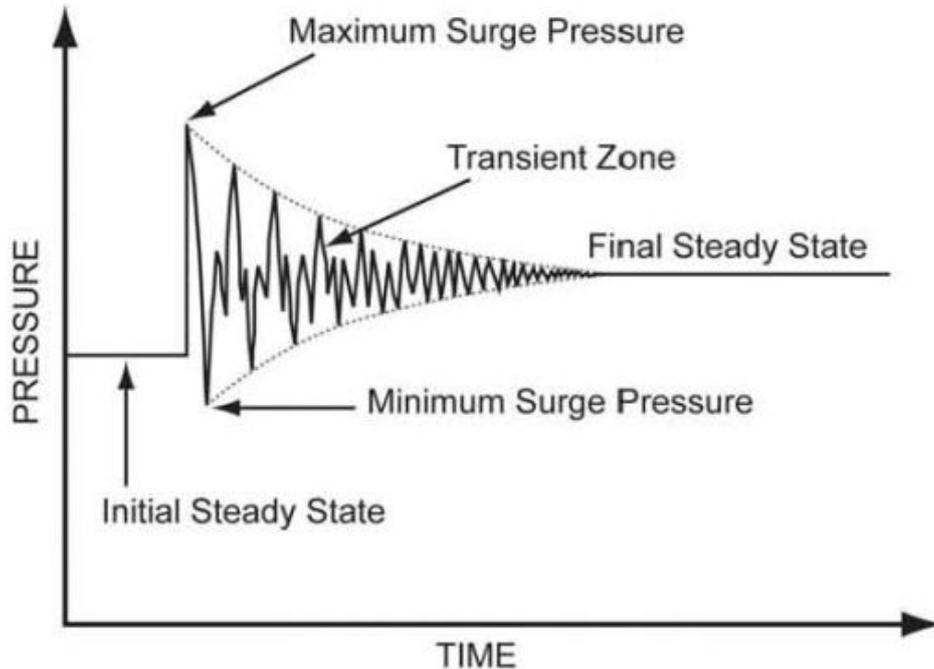


Figure 1. Example steady state transition after a period of rapid transients.

In general, any disturbance in the liquid generated during a change in mean flow conditions will initiate a sequence of transient pressures (waves) in the pipe system. Disturbances will normally originate from changes or actions that affect fluid devices or boundary conditions. Typical events that require transient considerations include:

- Pump shutdown or pump trip (loss of power)
- Pump start-up
- Valve opening or closing (variation in cross-sectional flow area);
- Changes in boundary pressures (e.g., losing overhead storage tank, adjustments in the liquid level at reservoirs, pressure changes in tanks, etc.);
- Rapid changes in demand conditions (e.g., hydrant flushing);
- Changes in transmission conditions (e.g., main break or line freezing);
- Pipe filling or draining – air release from pipes; and
- Check valve or regulator valve action

If special precautions are not taken, the magnitude of the resulting transient pressures can be sufficient to cause severe damage. Figures 2 to 5 describe four typical hydraulic transient problems. The problem of shutting down a pump is illustrated in Figure 2. When the pump is suddenly shutdown, the pressure at the discharge side of the pump rapidly decreases and a negative pressure wave (which reduces pressure) begins to

propagate down the pipeline toward the downstream reservoir. When the negative pressure wave reaches the high point (which already has a relatively low pressure due to the higher elevation) in the pipe, the pressure can drop below atmospheric to reach vapor pressure. At this pressure, gas within the liquid is gradually released and the liquid starts to vaporize (column separation). On subsequent cycles of the transient when the pressure recovers, cavity can collapse generating a large pressure surge spike. On the suction side of the pump, the solid sloping line represents the initial hydraulic grade and the dashed straight line depicts the final hydraulic grade, while start-up transients are not shown.

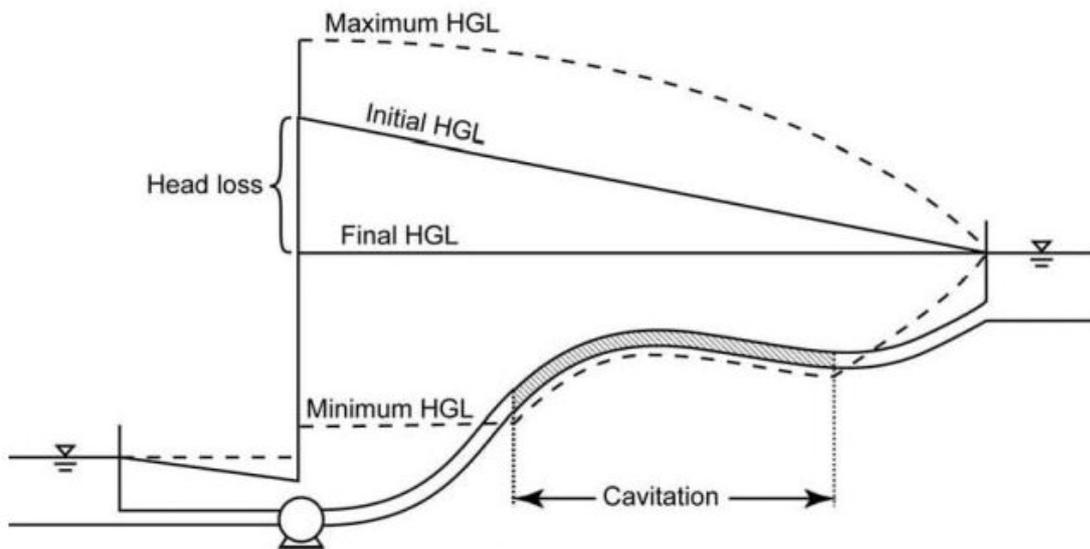


Figure 2. Transient caused by pump shutdown.

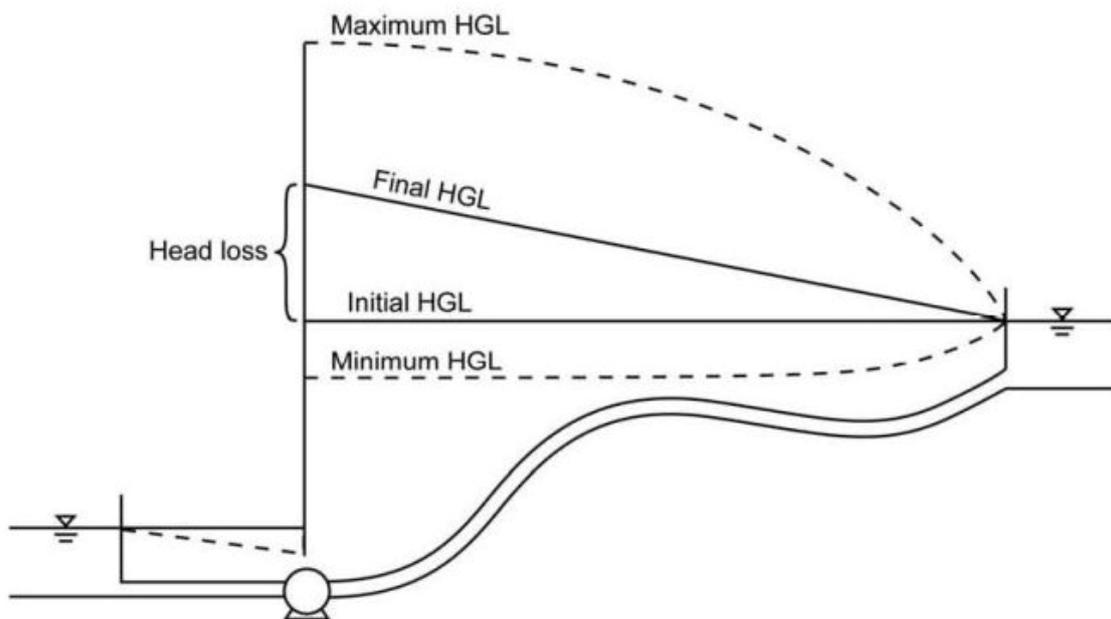


Figure 3. Transient caused by pump startup.

The problem of pump startup transient is illustrated in Figure 3. When a pump is started, the pressure at the discharge side of the pump rises sending a positive pressure wave (which increases pressure) down the pipeline toward the downstream reservoir. The resulting peak pressure can cause the pipe to collapse if the pressure rating of the pipe is less than the maximum surge pressure. When the initial positive pressure wave reaches the downstream reservoir, it is converted into a negative pressure wave which propagates back to the pump and may induce cavitation. On the suction side of the pump, the solid straight line represents the initial hydraulic grade and the dashed sloping line depicts the final hydraulic grade, while shutdown transients are not shown.

Opening and closing a valve too fast can also result in severe hydraulic transients and are illustrated in Figures 4 and 5, respectively. When the valve in Figure 4 is rapidly opened, a negative pressure wave is initiated at the valve and propagates upstream toward the reservoir decreasing the pressure in the pipe. Similar to the pump shut down scenario, the initial negative surge can drop to vapor pressure causing cavitation in the pipe. In the second example (Figure 5), rapidly closing the downstream valve generates a positive pressure wave at the valve that propagates toward the upstream reservoir increasing the pressure in the pipe.

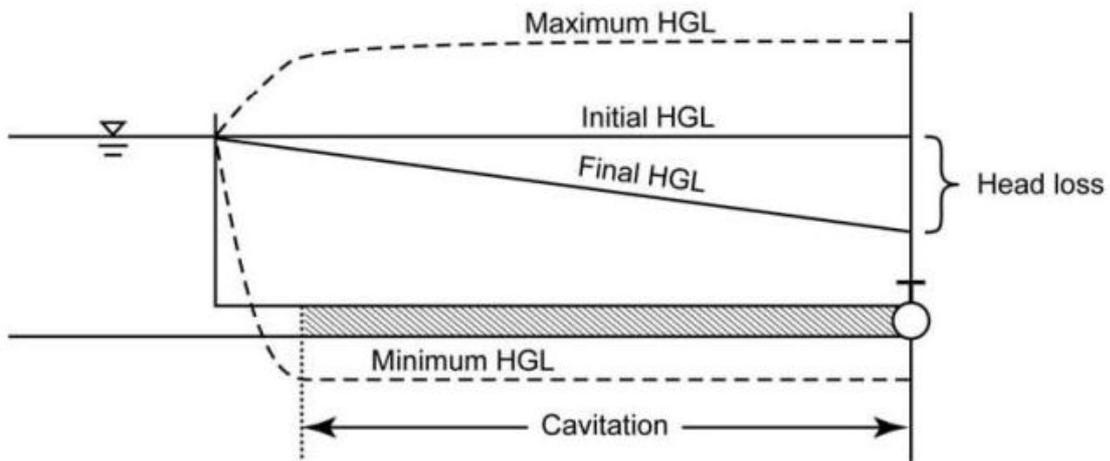


Figure 4. Transient caused by rapid valve opening.

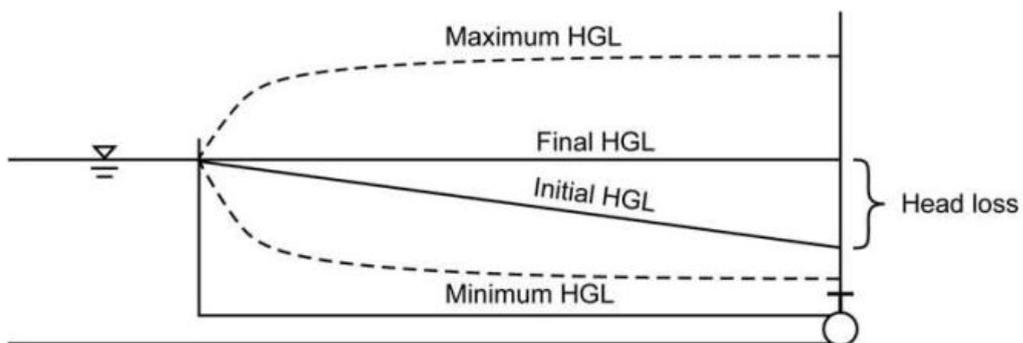


Figure 5. Transient caused by rapid valve closure.

Pipe systems must be designed to handle both normal and abnormal operating conditions. If an analysis indicates that severe transients may exist, the main solution techniques generally used to mitigate transient conditions are:

- Installation of stronger (higher pressure class) pipes;
- Re-routing of pipes;
- Improvement in valve and pump control/operation procedures;
- Limiting the pipeline velocity;
- Reducing the wave speed;
- Increasing pump inertia (e.g., fitting a flywheel between the pump and motor); and
- Design and installation of surge protection devices.

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Biographical Sketches

Paul F. Boulos received his B.S., M.S. and Ph.D in civil engineering from the University of Kentucky in Lexington, KY and his MBA from Harvard Business School, Cambridge, MA.

He is currently serving as President of MWH Middle East (ME) as well as President and Chief Operating Officer of MWH Soft, 380 Interlocken Crescent, Suite 200, Broomfield, Colorado 80021, USA. He has written over 200 technical papers and engineering reports and co-authored eight authoritative books on water and wastewater engineering.

Dr. Boulos has received a range of awards from the American Society of Civil Engineers, the American Water Works Association, and the US Environmental Protection Agency. In 2009, he was awarded the Ellis Island Medal of Honor, one of America's highest honors; and in 2010 he was inducted into the University of Kentucky College of Engineering Hall of Distinction, the University's most prestigious alumni tribute. He is a Fellow of the American Society of Civil Engineers (F.ASCE) and an Honorary Diplomat of the American Academy of Water Resources Engineers (Hon.D.WRE).

Don J. Wood received his B.S., M.S. and Ph.D in civil engineering from Carnegie Mellon University in Pittsburgh, PA.

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Dr. Wood is the recipient of numerous awards including the 2004 Simon Freese Environmental Engineering Award and gave the award lecture on the state-of-the-art in water hammer analysis at the 2004 Environmental & Water Resources Institute (EWRI) Congress.

Srinivasa Lingireddy received his B.E. in civil engineering from Manipal Institute of Technology in Manipal, India, and his M.Tech and Ph.D in hydraulic and water resources engineering from the Indian Institute of Technology in Madras, India.

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