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Malaysia | **FLUID FLOW
HYDRAULIC LIQUID SURGE

(PROCESS ENGINEERING EQUIPMENT DESIGN GUIDELINE)** | Co Author
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TABLE OF CONTENTS

LIST OF TABLE

LIST OF FIGURE

INTRODUCTION

Scope

This design guideline covers the design elements in the field of hydraulic liquid surge systems in sufficient detail to design a system with liquid surge pressure and velocity considerations. Hydraulic hammering occurs whenever the fluid velocity in a pipe systems suddenly changes, such as a pump stopping, a pump starting up, or valve opening and closing. Hydraulic hammering or dynamic pressure surges may cause piping to jump off its supports, damaged anchors and restraints, and result in leaks and shut downs in process plants and terminal facilities.

To determining how to prevent hydraulic hammering requires a fundamental understanding of fluid properties, governing equations and the design and operation of pipe systems, valves, pumps and pump stations. In the design of pipe systems it is necessary to take into account the magnitudes of pressure surges associated with hydraulic hammering phenomena and, consequently, it is important that these hydraulic hammering effects be calculated with the appropriate accuracy.

The design of liquid surge may be influenced by factors, including process requirements, economics and safety. All the important parameters use in the guideline are explained in the definition section. In the application section of this guideline, two case studies are shown and discussed in detail, highlighting the way to apply the theories of the calculations. These case studies will assist the designer to perform the sizing for liquid surge based on their own plant systems.

INTRODUCTION

General Design Considerations

“Hydraulic transient”, “surge pressure” or, in water applications, “water hammer” is a type of hydraulic transient that refers to rapid changes of pressure in a pipe system that can have devastating consequences, such as collapsing pipes and ruptured valves. It is therefore important to understand the phenomena that contribute to transient formation and be able to accurately calculate and analyze changes as well as maximum and minimum pressures occurring in a pipe system. The term “surge” refers to those unsteady flow situations that can be analyzed by considering the fluid to be incompressible and the conduit walls rigid.

Transient pressures are most important when the rate of flow is changed rapidly, such as resulting from rapid valve closures or pump stoppages. Such disturbances, whether caused by design or accident, may create traveling pressure and velocity waves of large magnitude. These transient pressures are superimposed on the steady-state conditions present in the line at the time the transient pressure occurs. The severity of transient pressures must be determined so that the piping can be properly designed to withstand these additional loads.

Hydraulic hammer causes piping, valves, pipe fixtures, supports, system components, etc. to suffer the added strain of dynamic loads. The term “hydraulic hammer” is used to describe the phenomenon occurring in a closed conduit when there is either an acceleration or retardation of the flow. In contrast to a force, pressure is non-directional; i.e. it does not have a vector. Not until a hydrostatic pressure starts acting on a limiting area, is a force exerted in the direction of the area.

Hydraulic hammer can occurs when the flow of moving liquid is suddenly stopped by a closing valve. Because of the compressibility of liquid and the elasticity of pipes, pressure waves will then propagate in the pipe until they are attenuated at a velocity, which is dependent upon pipe material and wall thickness. This sudden stop causes the whole column of liquid behind the valve to slam into the valve. Rapid pressure changes are a result of rapid changes in flow, which generally occur in a pipe system after pump shut-off, although it may also occur at pump start or at valve opening or closing. The tremendous spike of pressure that is caused, is called hydraulic hammer, and it not only acts like a tiny explosion inside pipes, it can be just as destructive.

Under unfavorable circumstances, damage due to water hammer may occur in pipelines measuring more than one hundred meters and conveying only several tenths of a liter per second. But even very short, unsupported pipelines in pumping stations can be damaged by resonant vibrations if they are not properly anchored.

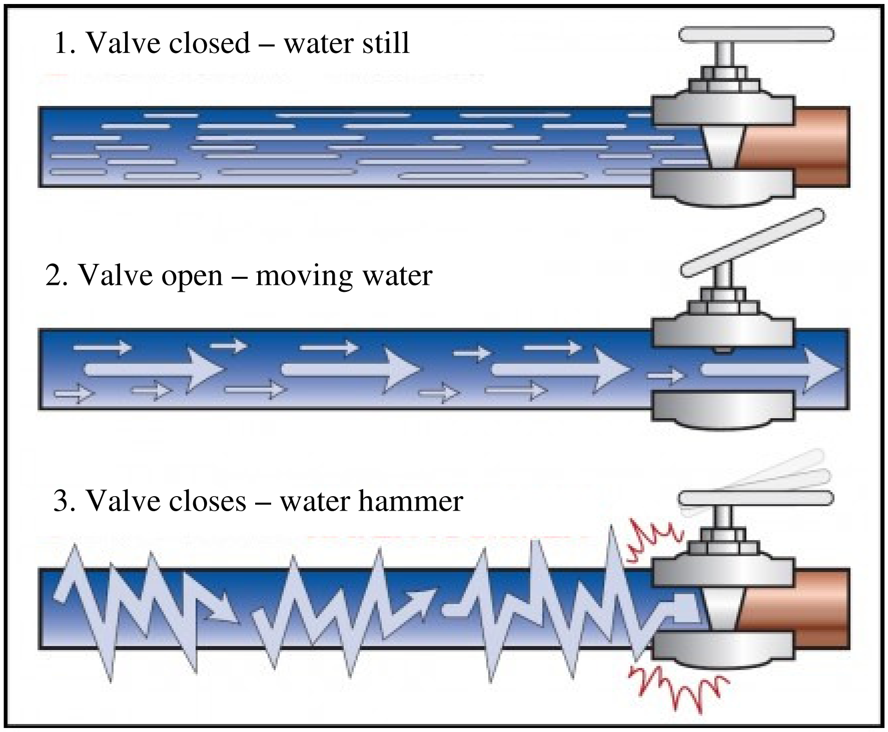


Figure 1: Water Hammer Description

A pumping system can never be operated in steady-state conditions all the time, since starting up and shutting down a pump will change the duty conditions. The term steady state means that volume rates of flow, pressures and pump speeds do not change with time. Generally speaking, every change in operating conditions and every disturbance cause pressure and flow variations or, put differently, cause the flow conditions to change with time.

Flow conditions of this kind are commonly referred to as unsteady or transient state. Referring specifically to pressures, they are sometimes called dynamic pressure changes or pressure transients. The main causes of transient flow conditions are:

- Pump trip as a result of switching off the power supply or a power failure.
- Starting or stopping up one or more pumps while other pumps are in operation.
- Closing or opening of shut-off valves in the piping system.
- Excitation of resonant vibrations by pumps with an unstable H/Q curve.
- Variations of the inlet water level.

Typical events that require transient considerations include the following:

- Pump startup or shutdown;
- Changes in valve settings, accidental or planned Valve opening or closing (variation in cross-sectional flow area);
- Changes in boundary pressures (e.g., losing overhead storage tank, adjustments in the water level at reservoirs, pressure changes in tanks, and so on);
- Rapid changes in demand conditions (e.g., hydrant flushing);
- Changes in transmission conditions (e.g., main break or line freezing)
- Pipe filling or draining.
- Changes in power demand in turbines
- Action of reciprocating pumps
- Changing elevation of a reservoir

- Waves of a reservoir
- Turbine governor hunting
- Vibration of impellers or guide vanes in pumps, fans, or turbines
- Vibration of deformable appurtenances such as valves
- Draft tube instabilities due to vortex
- Unstable pump or fan characteristics

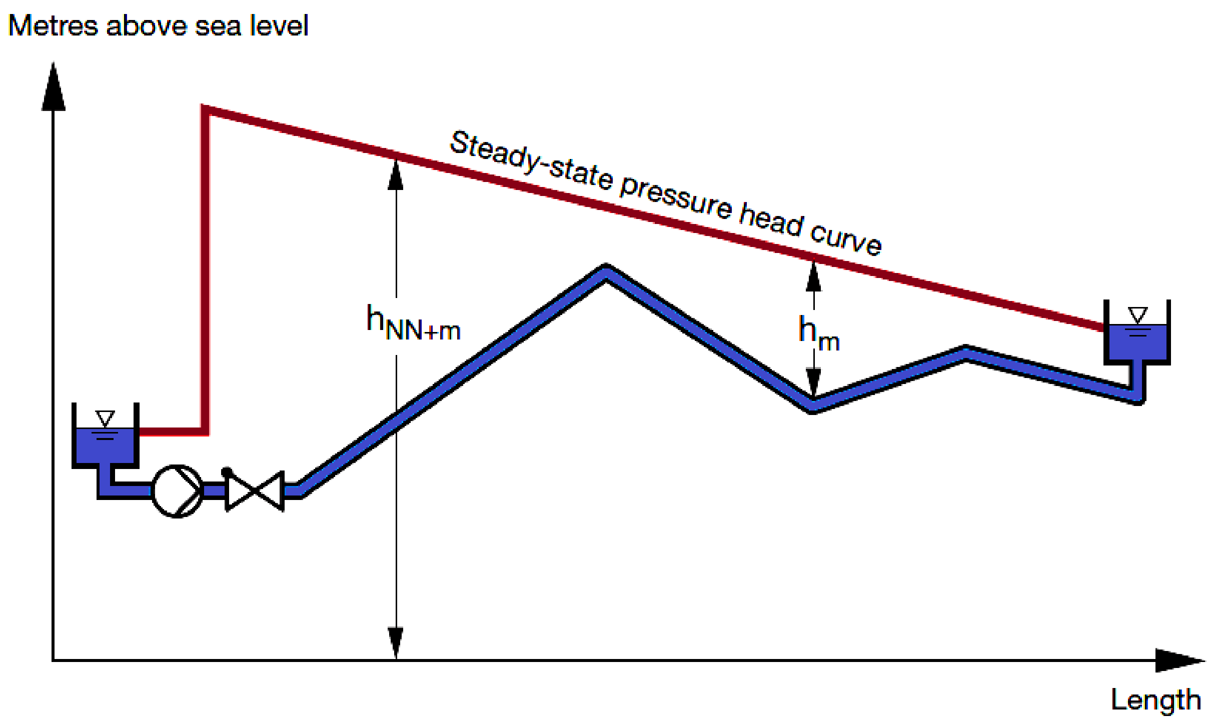


Figure 2: Steady-state pressure head curve of a pumping system

Hydraulic transient events are disturbances in the liquid caused during a change in state, typically effecting a transition from one steady or equilibrium condition to another. The principle 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 (i.e., acoustic or sonic speed), which depends on the elasticity of the liquid and the elastic properties (e.g., material and wall thickness) of the pipe. As these waves propagate, they create a transient adjustment to the pressure and flow conditions throughout the system. Over time, damping actions and friction reduce the waves until the system stabilizes at a new steady state.

It is difficult to determine when the risk of hydraulic hammer exists and calculations are required, there are several factors that generally indicate when taking precautions against water hammer is advisable.

Pipeline profile.

The minimum pressure line (green profile in graph below) depends upon various factors such as the wave speed and the pump's moment of inertia. Therefore the minimum pressure line will retain the same shape regardless of the pipeline profile (dark blue profiles) as long as no vaporization occurs. The magnitude of the sub-pressure that the pipe will experience will therefore depend on the pipeline profile

Pipeline length.

Pipe length will influence the reflection time and the inertia of liquid inside the pipe. The longer the pipe is, the longer the reflection time, that is, the time it takes for the wave to reflect at the outlet and return to the starting point. In addition, the longer the pipe, the larger the mass of liquid that will affect the moment of inertia of the liquid column.

Moments of inertia

A pump's moment of inertia plays a critical role in hydraulic hammer events. The higher the moment of inertia, the longer the pump will continue to rotate after shut-off. A higher moment of inertia minimizes pressure drops before the reflecting wave raises the pressure again.

Pipe material and dimensions

Joukowsky's equation states that the magnitude of water hammer is directly proportional to the velocity of the wave propagation. Wave propagation velocity depends on the elasticity of the pipe walls and the compressibility of the liquid. A typical value for wave propagation velocity in PVC pipes containing water is 300 m/s (985 ft/s) and for steel pipes 1,100 m/s (3600 ft/s). The pipe dimensions will also affect the wave speed.

Filling around the pipeline

The type of filling and packing method used around the pipeline has a direct impact on the external pressure on the pipelines. Due to the pressure changes created by liquid hammer, there will be oscillations of the pipe in the ground, therefore the filling around the pipe will have a great effect on the wear of the pipe. Sharp stones, for example, will tear the pipe exterior.

For submerged pipes, consideration must also be given to the depth of the pipe because the pipe wall is subject to the difference in pressure between the pressure inside the pipe and the external pressure from the surrounding water. If the pressure from the surrounding water is greater than the pressure inside the pipe, there is a risk of collapse or buckling.

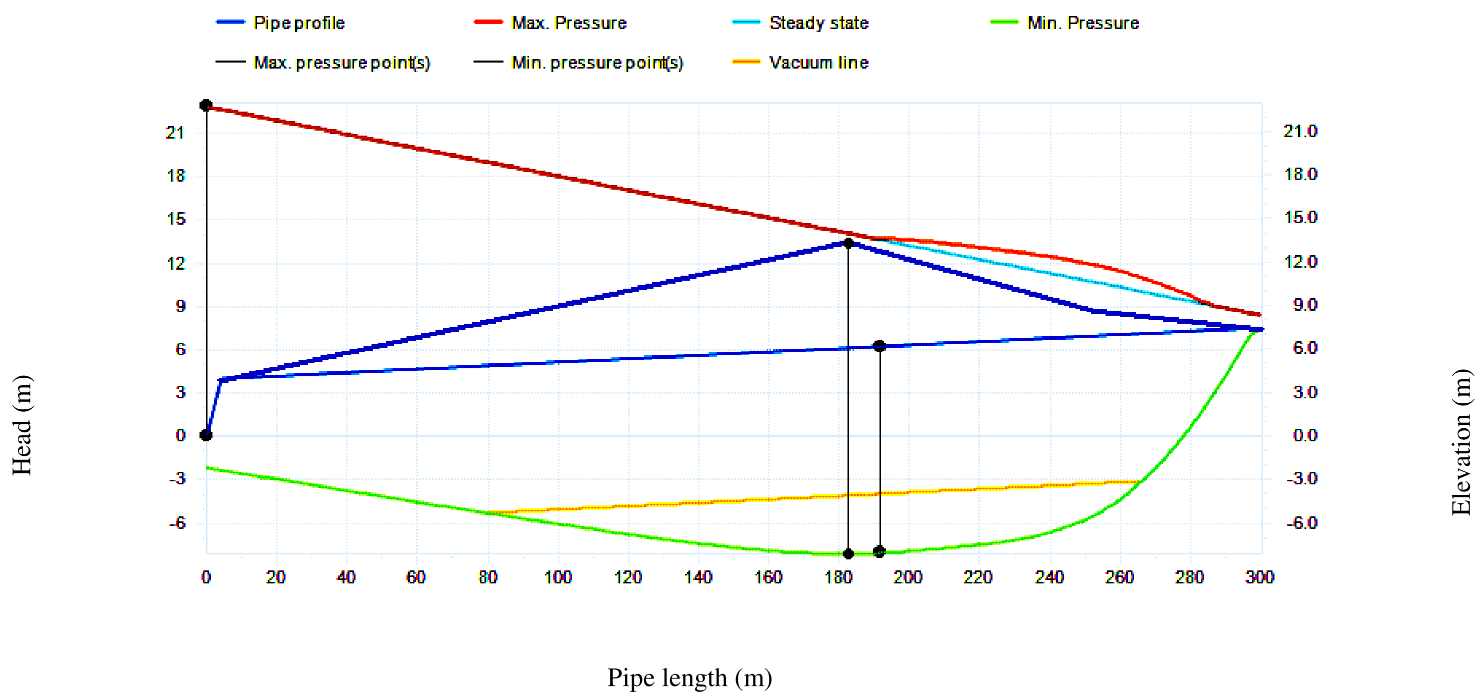


Figure 3: The different maximum sub-pressures due to different pipe profiles.

The effects of the hydraulic hammer vary, ranging from slight changes in pressure and velocity to sufficiently high pressure or vacuum through to failure of fittings to burst pipes and cause pump damage. Pump stopping can create hard-to-handle hydraulic hammer conditions; the most severe conditions results from a sudden power failure that causes all pumps to stop simultaneously.

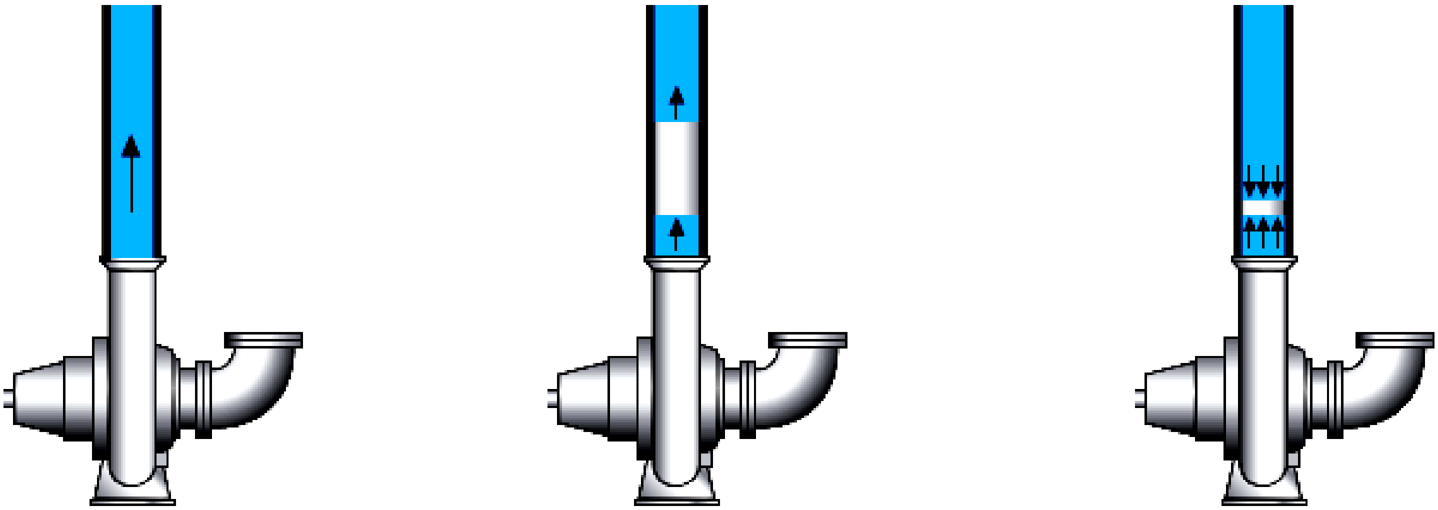
Some representative incidents caused by water hammer are listed in the following:

Pressure rises:

- Pipe rupture
- Damaged pipe fixtures
- Damage to pumps, foundations, pipe internals and valves

Pressure falling:

- Buckling of plastic and thin walled steel pipes
- Disintegration of the cement lining of pipes
- Dirty water or air being drawn into pipelines through flanged or socket connections, gland packing or leaks
- Liquid column separation followed by high increases in pressure when the separate liquid columns recombine (macro-cavitation)



Steady-state condition prior to pump trip

Formation of a vapor pocket (cavitations cavity) following pump trip

High-impact reunion of separate liquid columns accompanied by surge pressures

Figure 4: Macro-cavitation following pump trip

Hydraulic hammer may have devastating effects on the pumping system. These include instant pipe failure, weakening of pipe sections, fatigue and external wear.

- Instant pipeline failure. Pipelines may collapse due to sub-pressure or rupture due to overpressure, Cavitation usually occurs at high points in the pipeline but may also occur in flat areas of the pipe system. The collapse of the vapor pockets can cause dramatic high-pressure transients if the water columns rejoin too rapidly. This, in turn, may cause the pipeline to rupture. Vaporous capitation may also result in pipe flexure, which can damage pipe linings.

- Weakened pipeline section. Pipe failure can also occur after a period of time due to a weakened pipeline section. The weakened section is sensitive to hydraulic hammer, which can lead to pressure up surge, pressure down surge, cracking or rupture.

- Fatigue and external wear. Pipe fatigue and external wear are also common occurrences. Axial pipe movement due to hydraulic hammer causes wear on the pipe, especially in a pump system with frequent starts and stops. Most pipeline materials are more sensitive to fatigue due to sub-pressure rather than overpressure, and pipe fatigue is more pronounced when using plastic pipes. Dimensioning of sub-pressure depends largely on the pipe material and wall thickness

- Slamming valves. Slamming valves are typically the cause of very high water column occurring at pump stop. When the pump is stopped, the water decelerates and reverses direction. Typically slamming valves can be seen in a system with a short pipe length and a relatively high static head while water hammer typically appears in systems with long pipe length and small static head. A high head and a short pipe length will cause a high water column deceleration.

- Maximum pressure in the system; Maximum pressures during transient regimes may destroy pipelines, valves, or other components, causing considerable damage and sometimes loss of human life. Less drastically, strong pressure surges may cause cracks in an internal lining, damage connections and flanges between pipe sections, or destroy or cause deformations to equipment (such as pipeline valves, air valves, or any water hammer protection device).
- Vacuum conditions can create high stresses and strains that are much greater than those occurring during typical operating regimes. Vacuum pressures may cause the collapse of thin-walled pipes or reinforced concrete sections, particularly if these sections are not designed to withstand such strains.
- Occurrence of local vacuum conditions at specific locations and/or cavitation, either within specific devices or within a pipe. Cavitations occur when the local pressure is lowered to the value of vapor pressure at the ambient temperature. At this pressure, gas within the water is gradually released and the water starts to vaporize. When the pressure recovers, water enters the cavity caused by the gases and collides with whatever confines the cavity (i.e., another mass of water or a fixed boundary), resulting in a pressure surge.
- Hydraulic vibration of a pipe, its supports, or in specific devices and/or strong oscillations or rapid movement of the water masses. Oscillations of the water masses between the reservoirs, basins, and water towers may cause noise,

concussions, suction of air into the line, and other serious problems, including temporarily losing control of the system. Strong hydraulic vibrations can damage pipelines, tunnels, tunnel internal linings, or measuring and control equipment, and even crumble concrete. Long-term moderate surges may gradually induce fatigue failures.

- Risk or occurrence of contamination at cross-connections. These events can generate high intensities of fluid shear and may cause re-suspension of settled a pipe particles as well as biofilm detachment. So called “red water” events have often been associated with transient disturbances. Moreover, a low-pressure transient event, for example, arising from a power failure or pipe break, has the potential to cause the intrusion of contaminated groundwater into at a leaky joint or break.

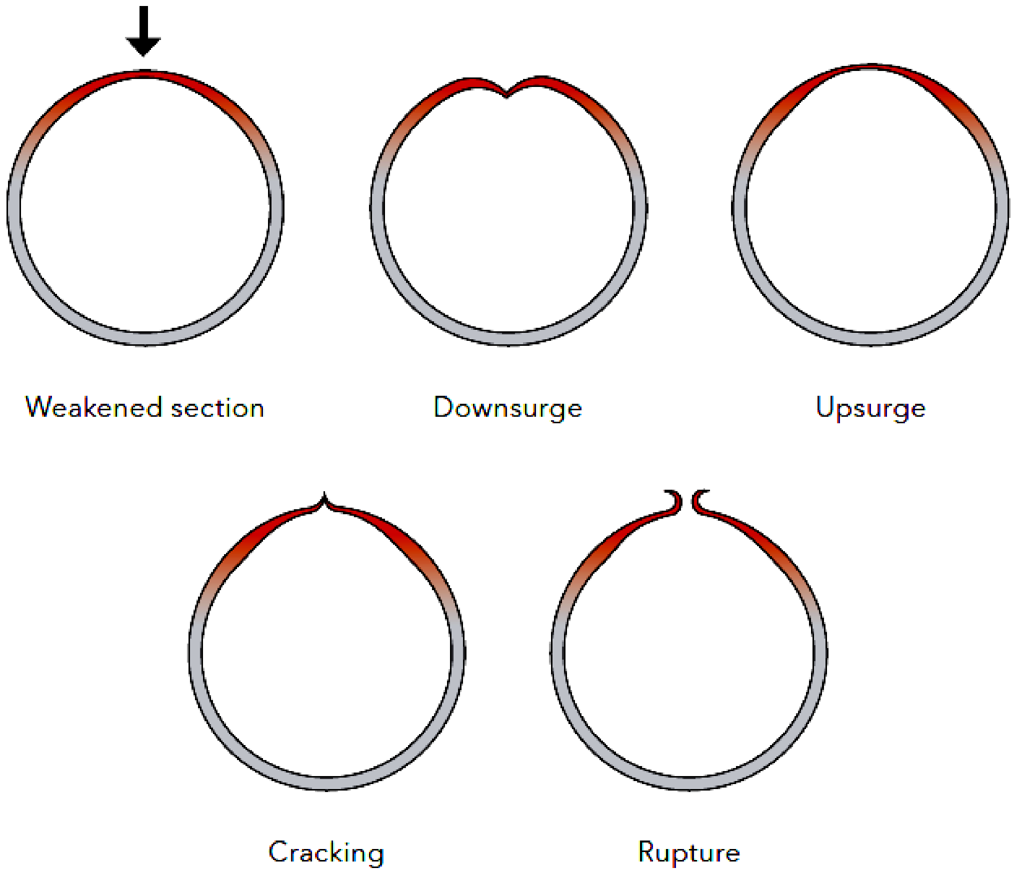


Figure 5: Different effects of a weakened section.

Hydraulic systems must be designed to accommodate both normal and abnormal operations and be safeguarded to handle adverse external events such as power failure, pipeline fracture, and so on. The main design techniques generally used to mitigate transient conditions include:

- Alteration of pipeline characteristics (e.g., pipe diameter),
- Improvement in valve and pump control procedures
- Design and installation of surge protection devices

DEFINITIONS

A variable frequency drive (VFD) is an electric control that can change the frequency of the current to the pump and thereby change the impeller speed.

Air chamber is a reservoir, connected to the pipeline, which is filled with liquid and compressed air.

Bladder tank. This vessel has a bladder that is precharged to a predetermined pressure to maintain the desired air volume under normal operating conditions.

Bypass - any system of pipes or conduits for redirecting the flow of a liquid. Also can be defined as A pipe or channel used to conduct gas or liquid around another pipe or a fixture.

Cavitation - the formation of vapor cavities in a liquid – i.e. small liquid-free zones ("bubbles" or "voids") – that are the consequence of forces acting upon the liquid. It usually occurs when a liquid is subjected to rapid changes of pressure that cause the formation of cavities where the pressure is relatively low.

Cracking - thermal decomposition, sometimes with catalysis, of a complex substance, especially the breaking of petroleum molecules into shorter molecules to extract low-boiling fractions such as gasoline.

Downstream - The downstream stage in the production process involves processing the materials collected during the upstream stage into a finished product.

Fatigue damage is caused when the pipe is subjected to large alternating stresses, for example when the drill pipe rotates in a curved segment (dog-leg) of the well bore, which may be the result of unintentional deviations or which are necessary for directional and horizontal wells

Hydraulic pressure - (transient flow) occurs when the flow of fluid in a pipeline is abruptly changed. Piping systems that use quick acting valves, or use pumps that start up or shut down rapidly, are susceptible to pressure transients (surges). These conditions can result in piping failure, damage to pumps, fittings, instrumentation, and other system components.

Impellers - a rotor used to increase (or decrease in case of turbines) the pressure and flow of a fluid. A rotating component of a centrifugal pump, usually made of iron, steel, bronze, brass, aluminum or plastic, which transfers energy from the motor that drives the pump to the fluid being pumped by accelerating the fluid outwards from the center of rotation.

Moment of inertia - the mass property of a rigid body that defines the torque needed for a desired angular acceleration about an axis of rotation. A larger moment of inertia around a given axis requires more torque to increase the rotation, or to stop the rotation, of a body about that axis.

Pressure drops - the difference in pressure between two points of a fluid carrying network. Pressure drop occurs when frictional forces, caused by the resistance to flow, act on a fluid as it flows through the tube.

Relative Roughness - Ratio of absolute pipe wall roughness ε to inside diameter d, in consistent units.

Relief system - an emergency system for discharging gas during abnormal conditions, by manual or controlled means or by an automatic pressure relief valve from a pressurized vessel or piping system, to the atmosphere to relieve pressures in excess of the maximum allowable working pressure (MAWP)

Reservoir - large tank used for collecting and storing water, esp for community water supplies or irrigation

Specific gravity - Is a relative measure of weight density. Normally pressure has not significant effect for the weight density of liquid, temperature is only condition must be considered in designating the basis for specific gravity.

Steady-state - volume rates of flow, pressures and pump speeds do not change with time) condition all the time, since starting up and stopping the pump alone will change the duty conditions.

Steam Hammer - Steam hammer is excessive pipe vibrations that occur due to the collapse of large vapor bubbles in a cool liquid stream.

Surge control – methods or equipments which are used to prevent pressure surges, which can occur in a hydraulic system when the flow in a pipeline is stopped too quickly.

Surge tower/tank - a standpipe or storage reservoir at the downstream end of a closed aqueduct or feeder or a dam or barrage pipe to absorb sudden rises of pressure, as well as to quickly provide extra water during a brief drop in pressure.

Transient pressures - used to refer to any pressure wave that is short lived (i.e. not static pressure or pressure differential due to friction/minor loss in flow). The most common occurrence of this is called water hammer.

Transition Flow - Flow regime lying between laminar and turbulent flow. In this regime velocity fluctuations may or may not be present and flow may be intermittently laminar and turbulent. This flow type occurs in pipes when 2,100 < Re < 4,000.

Upstream - The upstream stage of the production process involves searching for and extracting raw materials.

Vacuum breaker - A pipe or fixture element in a water supply system that prevents siphon or suction action and the backflow that can result

Vacuum conditions – a condition in which there is no matter or in which the pressure is so low that any particles in the space do not affect any processes being carried on there. It is a condition well below normal atmospheric pressure

Viscosity- Defined as the shear stress per unit area at any point in a confined fluid divided by the velocity gradient in the direction perpendicular to the direction of flow, if the ratio is constant with time at a given temperature and pressure for any species, the fluid is called a Newtonian fluid.

Water hammer - a pressure surge or wave caused when a fluid (usually a liquid but sometimes also a gas) in motion is forced to stop or change direction suddenly (momentum change). Water hammer commonly occurs when a valve closes suddenly at an end of a pipeline system, and a pressure wave propagates in the pipe. It is also called *hydraulic shock*.

Wave propagation velocity - a true speed or velocity in units of distance per time or the speed at which a wave front

NOMENCLATURE

A	Radius-sectional area, ft^2 (m^2)
Ap	cross sectional area based on pipe inside diameter,ft^2 (m^2)
Av	cross sectional area based on valve nominal size, ft^2 (m^2)
C	pipe constraint coefficient (Usually, 1.0 is applicable)
D	pipe inside diameter, in (mm)
D_{IM}	diameter impeller in (mm)
E	pipe material Young's modulus, lbf/ft^2 (kgf/m^2)
F	Funning friction factor)
g	gravity constant, ft/s^2 (m/s^2)
H_{max}	The maximum surge pressure
K	liquid bulk modulus, lbf/ft^2 (kgf/m^2)
L	length of pipeline, ft (m)
N	speed (rev/min)
P	power (kW)
t	pipe wall thickness, in (mm)
Te	effective valve stroking time (s)
Tv	valve stroking time (s)
v_w	wave speed, ft/s (m/s)

Greek letters

ΔH	surge pressure, ft-liq (m-liq)
Δv	change of linear flow velocity, ft/s (m/s)
θ	return number of pressure wave until valve full closure
ρ	liquid density, lb/ft^3 (kg/m^3)
p	pipeline constant
ρ_m	density of the impeller material lb/ft^3 (kg/m^3)