1. Introduction

Pipeline design and pipeline operation should address both safety and minimum cost of operation. Pipeline design mainly concerned with pipeline sizing, equipment sizing and equipment location, whereas system operation is concerned with pipeline system or facility startup and shutdown, flowrate change, emergency shutdown and equipment failure.

A pipeline state is defined as a condition of a pipeline expressed in terms of pressure and flowrate at given location and time. steady state is a condition of a pipeline system that flow variable doesn't change with time, whereas transient state is an unsteady condition that changes with time between two steady states. A surge or water hammer is a transient that occurs abruptly during flow changes from normal steady state flow. Positive surge or upsurge occurs if the pipeline pressure increases above the steady state pressure in the pipeline. A down surge occurs if the pipeline pressure decreases below the steady state pressure in the pipeline.

In steady state, pressure and flowrate are independent of time. Generally a pipeline system can be based on a steady state operation. This assumption is applicable only when the system is not subjected to sudden changes in the flowrates. Steady state conditions are not applicable to test capability of the system to test the level of safety. The steady state is not valid during transient state because flowrates and pressures are changing therefore the following problems cannot be addressed.

(1) Positive and negative surges
(2) Pump tripping
(3) Column separation

Why transient analysis is required for water pipelines?

1. Many pipeline failures occur because of improper provisions are made to manage transient related problems such as pump trip, check valve slam.
2. The following operating conditions should be taken into account in design and operational analysis
   (a) Changes in valve settings
   (b) Power failures
   (c) Pump startup and stopping
   (d) Air entrainment

Transient analysis is beneficial because

1. Steady state design for water pipeline systems tends to give larger pipe diameter, high capacity pump requirement, and incorrect booster pump location.
2. Steady state design is based on peak load whereas transient state design may be based on average load.

Transient (Dynamic) model

Transient model calculates time dependent flow and pressure behavior by solving the time dependent flow equations. Transient model generates hydraulically more realistic results than a steady state model, it predicts system behavior such as effect of changes in supply flow rates, supply pressure and delivery demands.

Transient (Dynamic) model capabilities

Analyze startup or shutdown procedure, i.e., different combinations of startup or shutdown procedures. A transient model can be used to study demand changes. Transient model is used to evaluate corrective strategies by modeling pump failures, pipe rupture and stoppage of flow. Transient model is required to study when a leak or rupture occurs. A transient model is more complex to use and execution time is longer than that of a steady state model. It requires extensive data particularly equipment and operational data.

Governing laws and equations

Dependent variables Q , P, independent variables x, t

Equations: continuity equation and momentum equation

Continuity equation:

Mass cannot be created or destroyed. For incompressible flows in a pipeline, inflow = outflow.

Momentum equation:

The rate of change of momentum equals to the sum of external forces. Newton's second law of motion is applied to the fluid element in pipelines to derive the momentum equation.

A general form of the one dimensional continuity and momentum equations are given below.

$$\frac{\partial P}{\partial t} + \rho a^2 \frac{\partial V}{\partial x} = 0 \qquad (1.1)$$

$$\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} + \frac{1}{\rho} \frac{\partial P}{\partial x} + g \frac{\partial h}{\partial x} + \frac{fV|V|}{2D} = 0 \qquad (1.2)$$

Where f = friction factor, h = elevation, g = gravitational acceleration, x = displacement, t = elapsed time, V = cross sectional average velocity, P = pressure, a = wave velocity, ρ = mass density.

In the momentum equation, the first time represents a force due to acceleration, second term is a force due to convective acceleration 'or' force due to kinetic energy. These two terms together called as inertia force. The third term is a force due to pressure difference between two points in a pipe segment. The fourth term is gravitation force and the last term is frictional force, or Darcy Weisbach equation which is nothing but viscous force opposing the flow in the pipeline.

Reynolds number

Reynolds number relates density, viscosity, fluid velocity and pipe diameter. Reynolds number is dimensionless.

$$R_e = \frac{\rho V D}{\mu} = \frac{VD}{\nu}$$

Where D = inside diameter; V = fluid velocity; μ = absolute or dynamic viscosity; ν = kinematic viscosity; ρ = fluid mass density.

If R_e < 2000, flow is laminar, flow is in transition (critical) for 2000 <R_e< 4000, and flow is fully turbulent for R_e> 4100.

Friction factor (f)

Friction factor f is a function of R_e for laminar flows. Friction factor is a function of (R_e, and pipe relative roughness) for smooth turbulent flow. For highly turbulent flows, friction factor is function of only relative roughness. The moody diagram (Fig. 1.1) relates the friction factor in terms of Reynolds number and relative roughness.

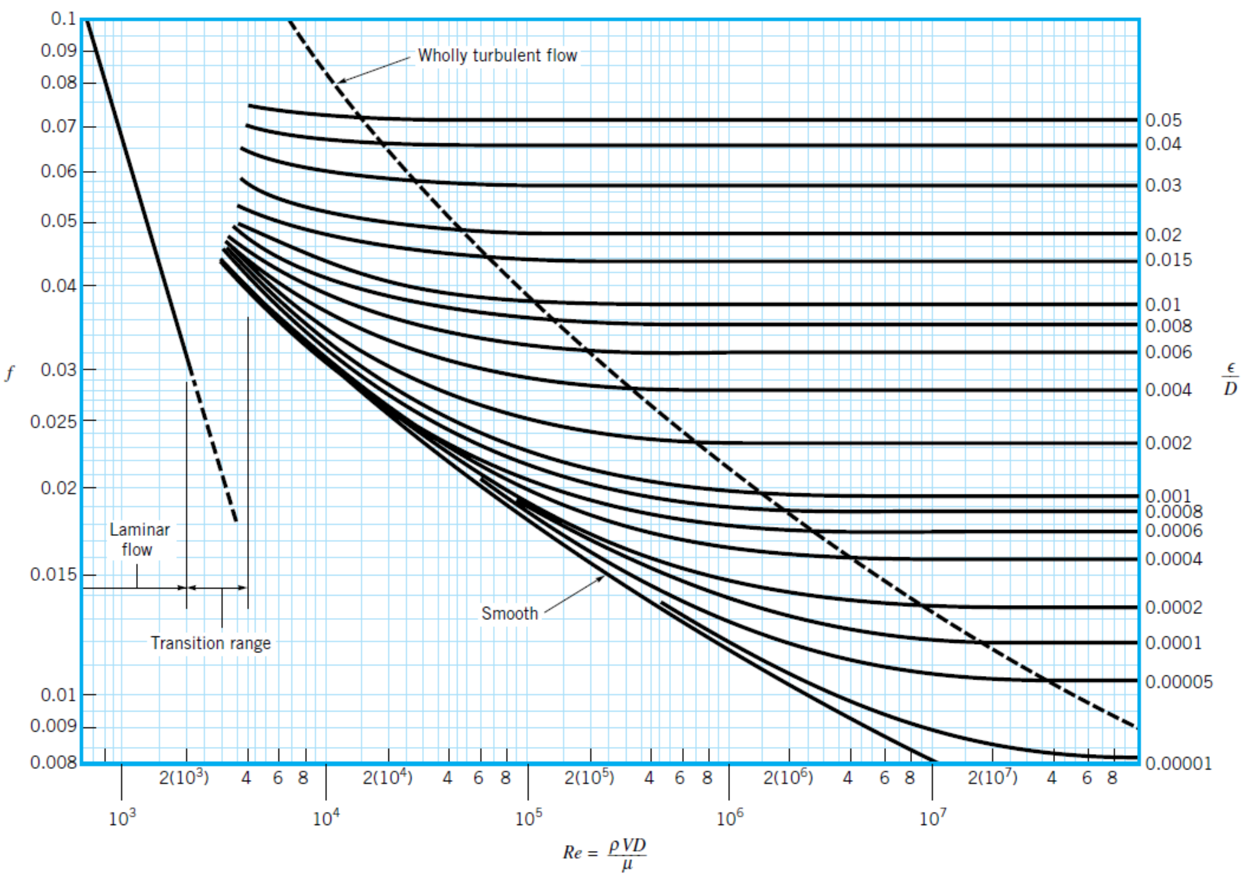


Fig 1.1: The Moody Diagram

In laminar flows friction factor decreases with increasing Reynolds number. Similarly, in smooth turbulent flows, for a given relative roughness, friction factor decreases with increasing Reynolds number. However, for highly turbulent flows (R_e> 1000000), friction factor is function of only relative roughness. Fluid rheological property viscosity is a measure of fluid resistance to shear force, expressed in absolute or kinematic viscosity.

Solution methods

The continuity and momentum equations are non-linear so they can be solved only in a numerical approach using a computer. The set of these equations are discretized dividing pipelines into finite intervals. The discretized equations are numerically solved for pressure and flowrate over a time step. Common solutions approaches are explicit solutions, implicit solutions and method of characteristics.

Assumptions

Flow in a pipeline can be represented in 1-D equations and angular momentum is negligibly small.

Explicit methods

The values at the current time are explicitly calculated from the values at the previous time step with the boundary conditions at current time. An explicit FD method converges only when distance and time steps are small. These methods are subjected to CFL (Courant Frederik Law) stability criteria.

Implicit Solutions

The values at the current time are implicitly calculated from the values at the current time and previous time and boundary conditions at the current time. The implicit FD method equations are expressed in large matrices which are solved simultaneously for pressure and flowrate at every discretized point. The large matrices are solved by a sparse matrix technique. Implicit solution techniques are flexible with time steps and inherently stable always.

Method of Characteristics

The characteristic method converts the continuity and momentum equations into four total differential equations. The four characteristic equations are solved explicitly for pressure and flowrate. The solution methodology is simple for a single fluid pipeline. Time step is constrained by Δx and acoustic speed of the fluid a.

$$\frac{\Delta x}{\Delta \mathrm{t}} \geq a$$

Boundary and initial conditions

1. Pressure and Pressure boundary condition
2. Pressure and flow boundary condition

The initial conditions can be

(1) A steady state
(2) Transient state available from a previous simulation run

Causes of transients

Transients are basically two types (1) pressure transients (2) flow transients. Pressure transients occur when a change in pressure occurs in the pipeline which adds or remove energy from the pipeline. Flow transients occur when there is a change in flowrate by change in energy.

The main causes of transients in a pipeline are

(1) Change in the valve settings (open or close)
(2) Startup or shutting down the pump
(3) Changes in pump speed or head
(4) Pipeline rupture, column separation or trapped air
(5) Vibration of impeller in a radial pump

Transient properties

1. A transient (surge or water hammer) is a pressure wave.
2. Pressure wave propagates at the sound velocity of the fluid and velocity of fluid in a pipe.
3. Initial magnitude of pressure wave is proportional to acoustic velocity and fluid velocity.
4. The magnitude attenuates as the pressure wave moves away from the source of the transient.
5. Small amount of air entrained in the liquid can alter acoustic velocity.

Water hammer

1. Water hammer occurs because the fluid mass before the stoppage is still moving forward with its fluid velocity, building up a very high pressure.
2. On the other hand when an upstream flow in a pipe is suddenly stopped, the fluid downstream will attempt to continue flowing which creates a vacuum that may cause the pipe to collapse. This problem particularly occurs if the pipe is on a downhill slope.
3. Other causes of water hammer are (i) pump failure and (2) check valve slam.

Acoustic speed

The acoustic speed in a buried pipe can be calculated by following formula. Acoustic speed is a function of void fraction in the water as shown in Fig. 1.2.

$$a = \frac{\sqrt{K/\rho}}{\sqrt{1 + (K/E)(D/e)(1 - \upsilon^2)}}$$

Where K = bulk modulus of fluid; E = Young's modulus; D = inside diameter of pipe; e=thickness and υ= poison ratio = 0.3.

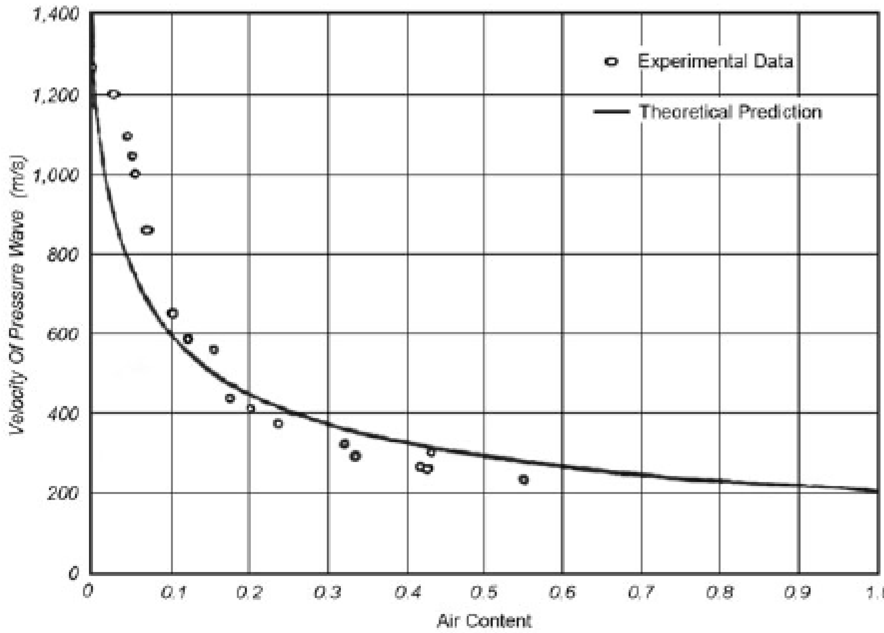


Fig 1.2: Acoustic speed as a function of void fraction.

Potential surge

The initial pressure increase following flow stoppage is referred to as the potential surge.

$\Delta P = -\rho a V;\ \Delta H = -\frac{aV}{g}$; V=change in velocity.

Where ΔP and ΔH are change in pressure; ρ=mass density of water; a = acoustic wave velocity.

Pressure wave propagates away from the transient location. The wave reflects back at a boundary point and the reflected wave has a negative head.

Critical period (t_c)

The critical period is defined as the time that an acoustic wave travels from the transient location to the end point and travels back to the transient location.

$$t_c = \frac{2L}{a}$$

L= pipe length.

Attenuation of surge

The magnitude of the potential surge decreases as it travels, this reduction is called attenuation. At high pressures, increase of fluid stored occurs, which is called as line packing. The pressure increases, the pipe wall expands and the fluid is compressed.

Colum separation

1. On the downstream side of the closed valve, the pressure drops as given by the Joukowsky equation. If the pressure drops below the vapor pressure, the liquid vaporizes and column separation occurs.
2. Column separation is a phenomenon that results from water hammer. It happens when part of the pipe is subjected to low pressure.
3. Column separation accompanies the down surge. It is more likely to occur at high points or knees (sharp changes in slope) in the pipeline.
4. Column separation can buckle the pipelines and should be prevented from happening through proper design and operation.

Column separation and rejoining of water columns is shown in Fig. 1.3

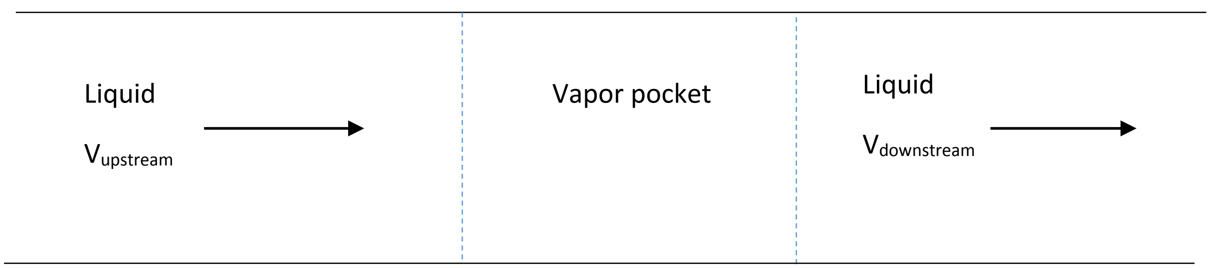


Fig 1.3: Schematic of column separation

The head increase which results from the collapse (ΔH):

$$\Delta H = \frac{a\left(V_{upstream} - V_{downstream}\right)}{g}$$

a = acoustic velocity.

Collapse of vapor column

The upstream column will be accelerated and the downstream column is decelerated if the back pressure increases, and the upstream column overtakes the downstream column. If the process occurs quickly, the vapor column collapses. When the vapor column collapses, it can be destructive, this head increase may be sufficient magnitude to rupture the pipe.

Consequences of transients

1. Unstable pressures
2. Column separation
3. Check valve slam or control valve oscillation

4. Resonance in pipe system
5. Pipeline shutdown due to pipe rupture or collapse.

Objectives of surge control

1. The main objective of the surge control is to limit the magnitude of the surge to within the allowable limits of the pipe system, including joints and equipment on the pipeline system.
2. There are two ways of managing pressure transients
   (a) Control the surge
   (b) Extra protection of the pipeline

Surge control is important for the following operations

1. Pump startup and shutdown
2. Valve operations sudden opening and sudden closure
3. Changes in supply and demands of flow

Protection of the pipeline and equipment

The main objective of pipeline and equipment protection is to preserve the integrity of the pipeline and to prevent system failure. When events occur beyond the control of operations such as power failure, valve failure and operation error.

Transient control

1. Control strategies include timing of control of pumps and valve operations.
2. Surges expected to be severe, the magnitudes of surges should be determined.
3. Pipeline should be reinforced with proper joints and anchoring system.
4. Computer simulations are necessary to select reliable and responsible control system.
5. The continuous pounding of small surges can cause leaks and eventually lead to pipe failure.
6. Knee points are avoided, thicker pipes need to be installed and surge control devices are installed.

Operation phase

1. Open and close valve gradually.
2. Fixed speed drives for automatic control valves which open and close control valves gradually
3. Variable speed drives for pumps which ramp speed up and ramp down the speed in a controlled way.

Mechanisms to control surges in the pipeline systems

(1) Valve movement (2) check valve (3) pump startup/shutdown (4) power failure

Surge control devices

1. Pressure relief valves

2. Pressurized surge tanks
3. Rupture disks
4. Control valves

Valve movement

Surge magnitude depends on the (1) type of valve (2) valve movement (3) elastic restraint properties of the pipeline system (4) valve coefficient.

It is safe to close the valve in time longer than $2L/a$

Check valve

1. Check valves can cause large transient pressure if the flow reversal through them can occur before the valve closure is complete.
2. Modern check valves closes gradually
3. Some check valves closes at the instant forward flow stops.
4. Check valve must close quickly before reverse flow is considerable or close gradually, i.e., more than critical time ($2L/a$)

Pump Startup

As the pump starts up and comes "online" a positive surge is created in the downstream line. The magnitude of the surge depends on the sudden increase in speed which occurs when the check valve is forced open and the liquid in the line begins to move. When there is no entrapped air, the pressure increase is generally not large. If there is a vapor in the delivery line, substantial transient pressure can be developed. In general upsurges are followed by down surges and vice versa. Upsurges and down surges are shown in Fig. 1.4.

Pump power failure

1. Severe transients occur upon power failure where the static lift is large, where pipeline profile rises rapidly immediately downstream of the pump.
2. If power is cutoff, the pressure just downstream of the pump drops rapidly and this pressure drop propagates downstream at the wave speed.
3. The drop in pressure can cause extensive column separation and lead to subsequent cavity collapse and shock of large magnitude.
4. Moreover a flow reversal in the system occurs and lead to significant overpressures in the vicinity of the pumps.

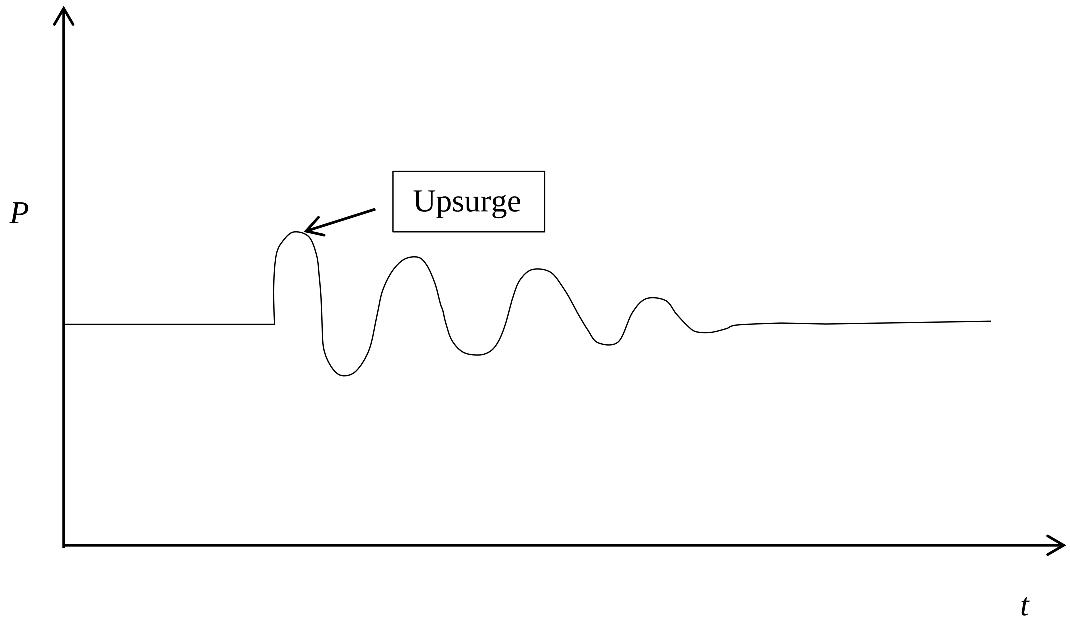
Pressure relief valve (PRV)

1. PRVs are mechanical devices that are used to protect the pipeline system from excessive pressures. They are installed along the pipeline where maintenance is easy.

2. PRV opens when the pressure exceeds a specified preset pressure. The valve closes when the pressure in the line decreases below the set value.
3. PRV can release some of the flow during pump startup to avoid over pressurizing the system.
4. PRV installed in the pump discharge line between the pump and the discharge control valve acts like a bypass valve during pump startup to prevent a pump from operating near shutoff head.
5. PRVs can be used only to control upsurges and not suitable to control down surges.
6. PRVs are very useful in short and steep pipe profile where reversal of flow quickly follows power failure or pump trip.

Limitations of PRV

1. Upsurge and downsurge (Fig 1.4) travel at acoustic speed, a PRV may not open that quickly therefore ineffective.
2. PRV is designed for a certain flowrate, undersized PRV may not be able to discharge at a high enough flowrate.



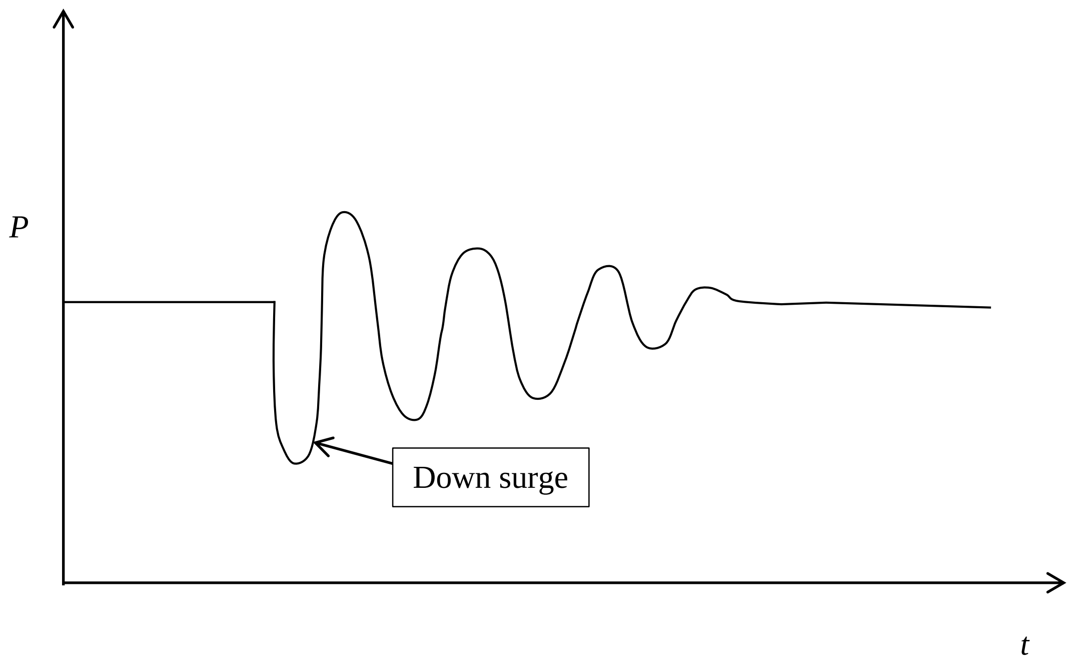


Fig 1.4: Upsurge and downsurge

Pressurized surge tank (Air vessel or accumulator or hydrophore tank)

An accumulator (air vessel) contains a gas that absorbs the pressure surges and prevents the transfer of pressure waves that arise in one section to other parts of the pipeline system. Pressurized surge tank (air vessel) are reliable and require no repairs because there are no moving parts. They are expensive, regular maintenance is required to maintain the volume of gas in the tank.

Rupture disks

Rupture disks are non-mechanical pressure surge control devices which consists of bursting membrane designed to rupture at preset conditions of pressure. Rupture disks are inexpensive and they work similar to PRVs, they need storage tanks to accept relief flow. Rupture disks must be replaced after being ruptured therefore they must be available in stock.

Transient control (pump startup)

Pump startup operations can cause a rapid increase in fluid velocity that may result in undesirable surge, but they seldom cause a problem in actual operation.

(1) If there are several pumps, start them one at a time at intervals at least two times the critical period.
(2) Open a control valve slowly after the motor starts (at least two times the critical period)
(3) Use a variable speed drive for each pump ramped upto full speed slowly enough to avoid high surges.

(4) Pumps and control valves should be operated in systematic to greatly reduce the transients.
(5) Upon start-up of pump, pump operates against a closed valve. As the valve opens, the flow into the pipeline gradually increases to the full capacity of the pump.

Transient control pump shutdown

1. Normal pump shutdown may also cause surges. They can be controlled to keep the pressures within acceptable limits.
2. Turn pumps off one at a time at intervals at least two times the critical period.
3. Close a control valve slowly (at least two times the critical period) before the stopping the motor.
4. If pumps are equipped with variable speed drives, motor is completely stopped in ramp down approach.
5. At the time of pump shutdown, the control valve must be closed slowly to give gradual deceleration to the flow, after the valve is fully closed after which power to the pump is shutoff.

Transient control after power failure

Power failure at a pumping station causes pump tripping, and results in an initial rapid down surge in the discharge header and piping close to the pump station. The power failure cannot be fully avoided but its effect can be reduced by increasing the inertia of pump and motor with a fly wheel.

Important note: Control valves cannot prevent down surge on power failure

Uses of Transient Analysis

1. Determine pipe wall thickness by locating high pressure points in steady and unsteady flow situations (especially worst case scenarios).
2. Determine the location and sizing of pressure relief valve and air vessel.
3. Determine maximum and minimum working pressures (worst case scenarios).
4. To design ramping up and down of pumps (variable speed).

Worst case scenarios must be studied

1. Pump trip, 2. Check valve slam, 3. Control valve sudden closure