Fundamentals 0f Flow in pipelines
Part II – Water Hammer

Dr. Ahmed Elmekawy

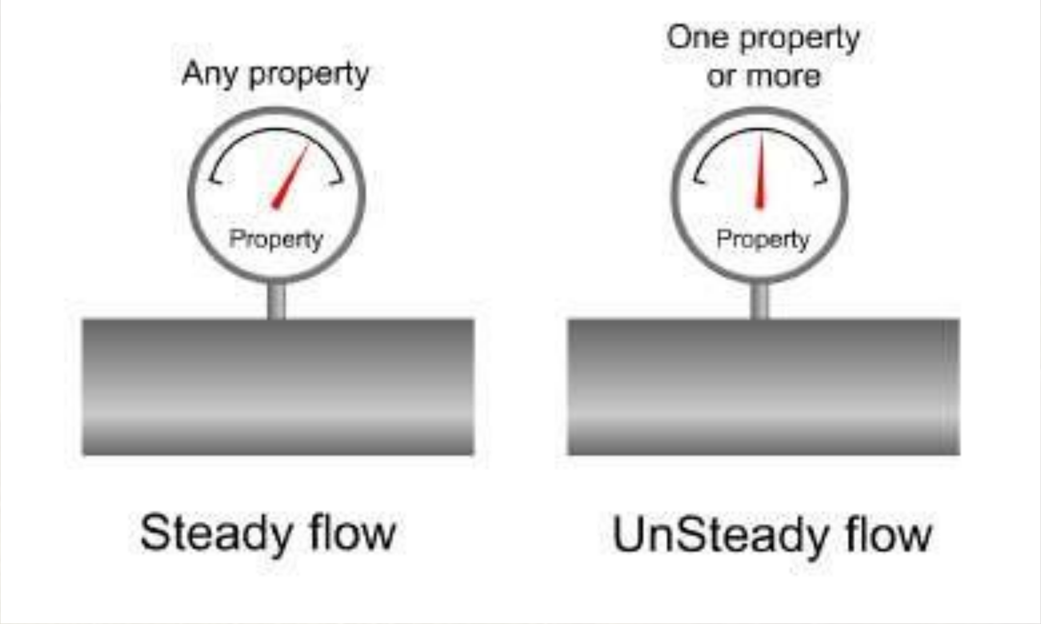
2017-2018

Unsteady Flow

- Fundamental of unsteady flow
- Practical approach
- Transitional wave principle
- Water hammer
- Water hammer effect
- Water hammer protection
- Unsteady flow equations
- Rigid water column theory
- Elastic Theory

Fundamentals of unsteady flow

- **Steady flow**: the value of all fluid properties, as well as flow properties at any fixed point, are independent of time.
- **Unsteady flow**: a fluid or flow property – or more - at a given point in space (locally) varies with time.



Fundamentals of unsteady flow

Unsteady flow may be:

1. **Non-Periodic flow**: shut down, start up, closure processes for hydraulic components.
2. **Periodic flow**: periodic injection of the Air-Gasoline mixture in spark ignition engines.
3. **Random flow**: occurs in turbulent flow and is absent from laminar flow.

Fundamentals of unsteady flow

Mathematically

For steady flow $\partial\phi / \partial t = 0.0$

For Quasi-steady flow $\partial\phi / \partial t \approx 0.0$

For unsteady flow $\partial\phi / \partial t \neq 0.0$

- **Quasi-steady flow**: the change of any property at any point with respect to time is so small or behaves in slow rate and could be neglected.
- For simplicity of flow analysis, it could be assumed as steady (or quasi-steady) flow in some applications.

Fundamentals of unsteady flow

- **Application in practice**

1. Start up operations

   (transition from zero velocity to steady state operation)

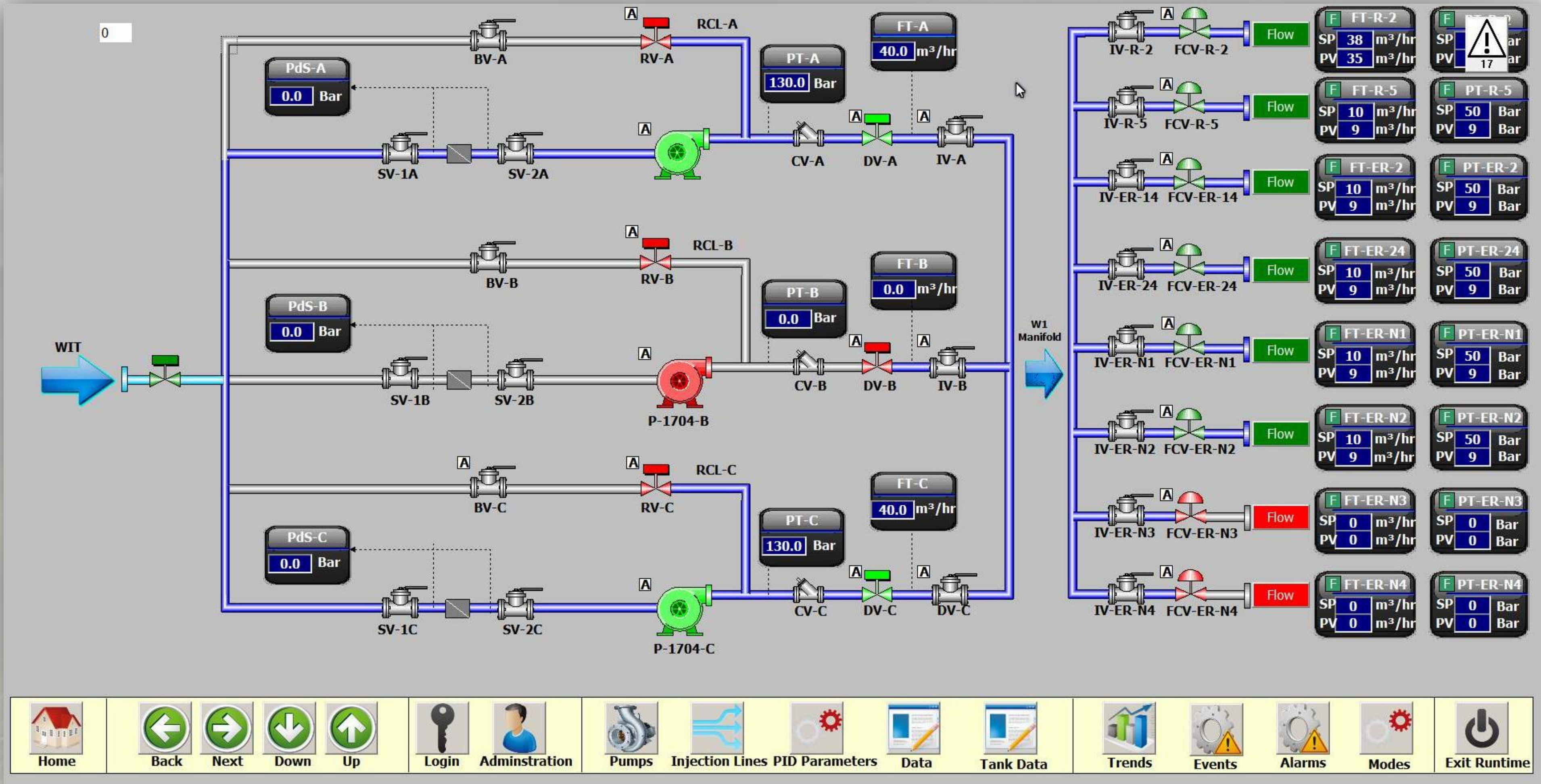
2. Shut down operations

   (transition from steady state velocity to static equilibrium state (v=0.0))

3. Hydraulic component closure (valves)

   (transition from steady state operation to zero velocity in small periods)

Water Injection System



Calm Buoy System

- Calm Buoy
- In a typical SPM buoy / terminal application, the loading buoy(s) is anchored offshore and serves as a mooring point for tankers to load / offload their gas or fluid product for transfer between the onshore facility and the moored tanker. Although the SPM buoy is clearly a key component, a number of other components are integral to such a system

CALM Buoy Body

CALM Buoy Body

Pipe Line End Manifold

- Installed on the seabed and which interfaces the terminal under buoy hoses with the sea line .

CALM Buoy Body

- A Buoy body
- Turn table
- The buoy fluid product circuit
- The anchoring system
- The floating hoses
- A Pipeline End Manifold (PLEM)
- Onshore/offshore pipeline
- Main bearing
- Central pipe swivel

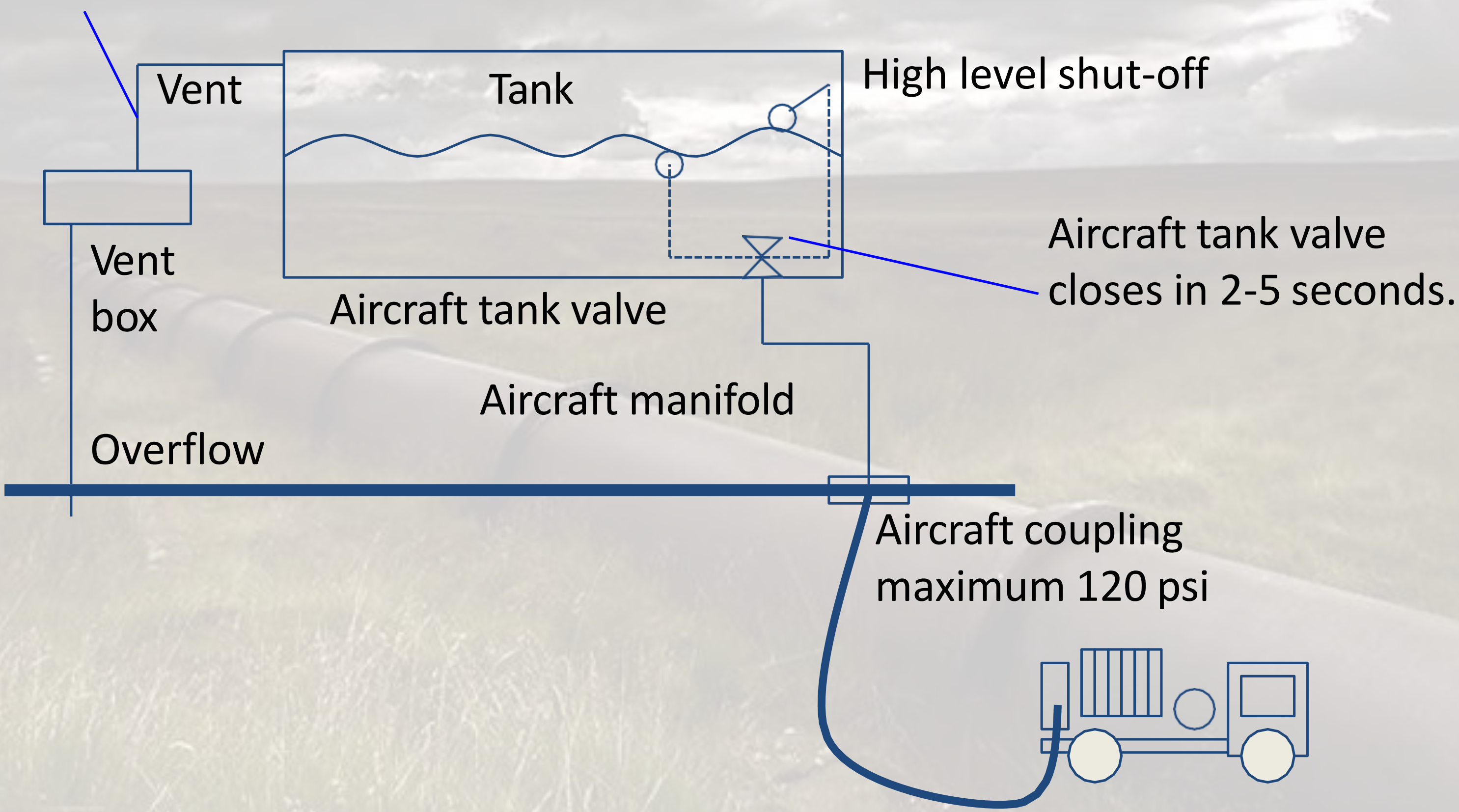
Water Hammer

- is a pressure surge or wave resulting when a fluid in motion is forced to stop or change direction suddenly (Momentum Change).
- Water hammer commonly occurs when a valve is closed suddenly at an end of a pipeline system, and a pressure wave propagates in the pipe.

Water Hammer

Practical approach

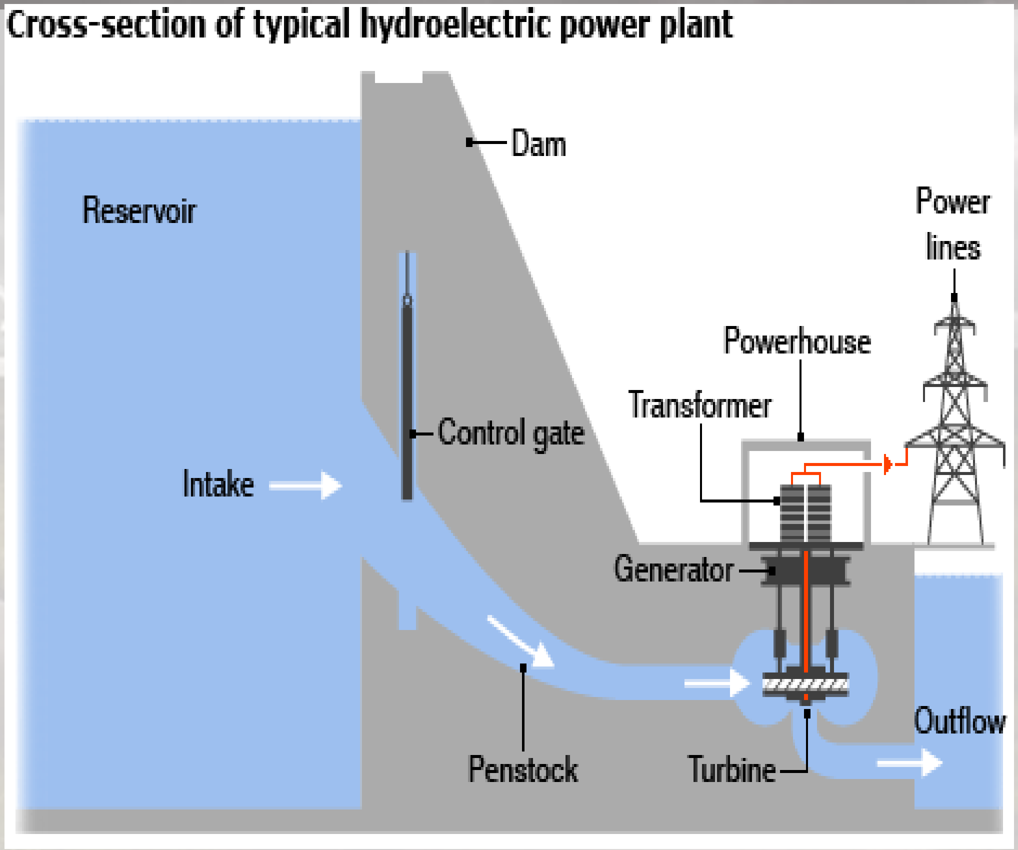
If aircraft tank valve fails to close, vent line is designed to handle 50 psi



Practical approach

- Necessary to protect aircraft fuel systems from excessive fuelling pressure and surge pressures.

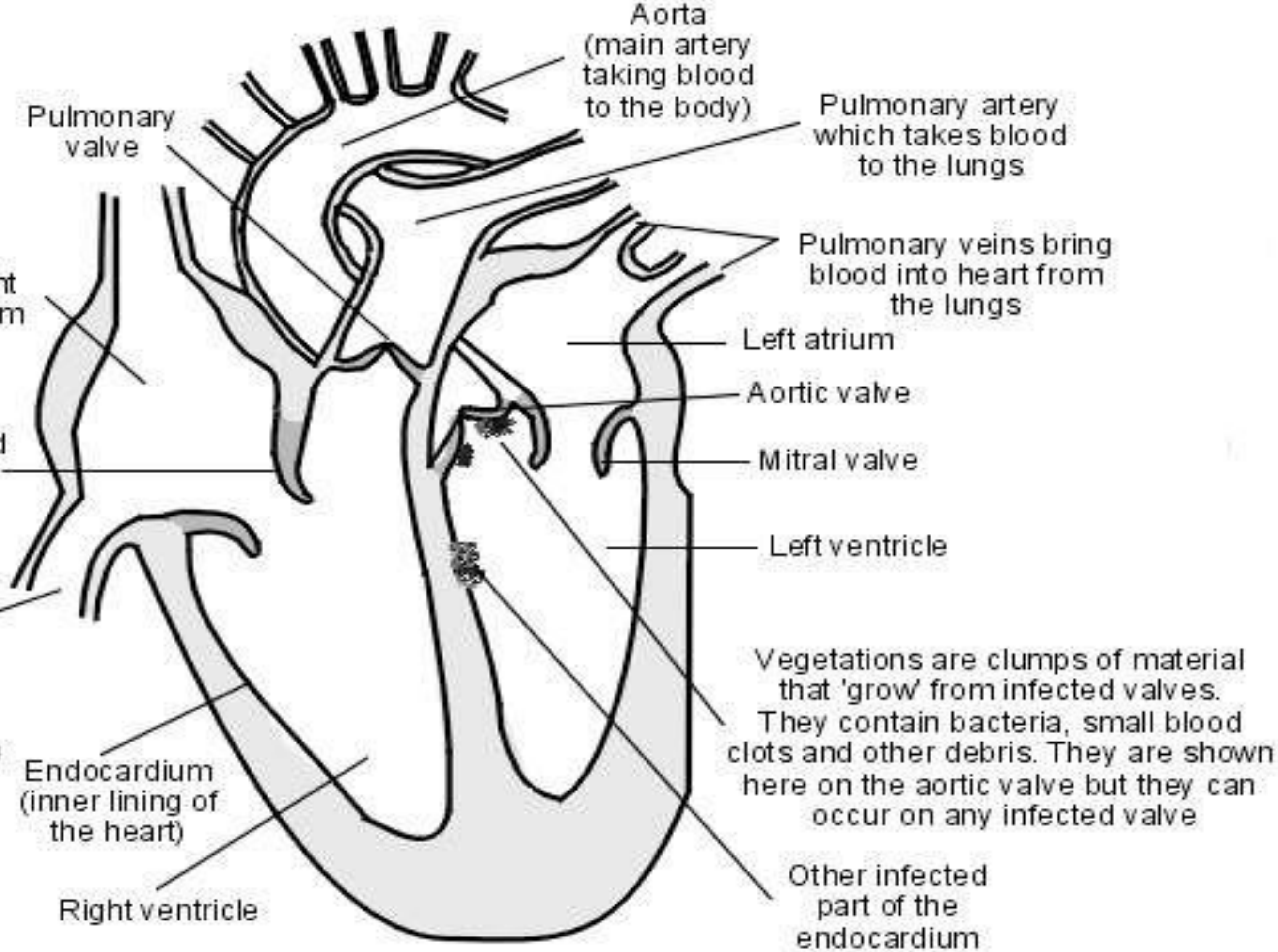
► When the generator of a water turbine is disconnected from a power network, the turbine speed starts to increase. Consequently, the turbine controller closes the inflow to the turbine, thus creating water hammer in the penstock. Water hammer effects in the penstock are created by any changes in discharge through the turbine, caused by changes in the connected power network, by the operators, or by breakdowns. Sometimes, the entire system becomes unstable due to the mutual influence of a turbine equipped with a controller and to an unsteady flow in the penstock. In such case, even small variations in pressure in the penstock may increase steadily and perilously.



[Accident at Russia's Biggest Hydroelectric - Rev 00.pps]

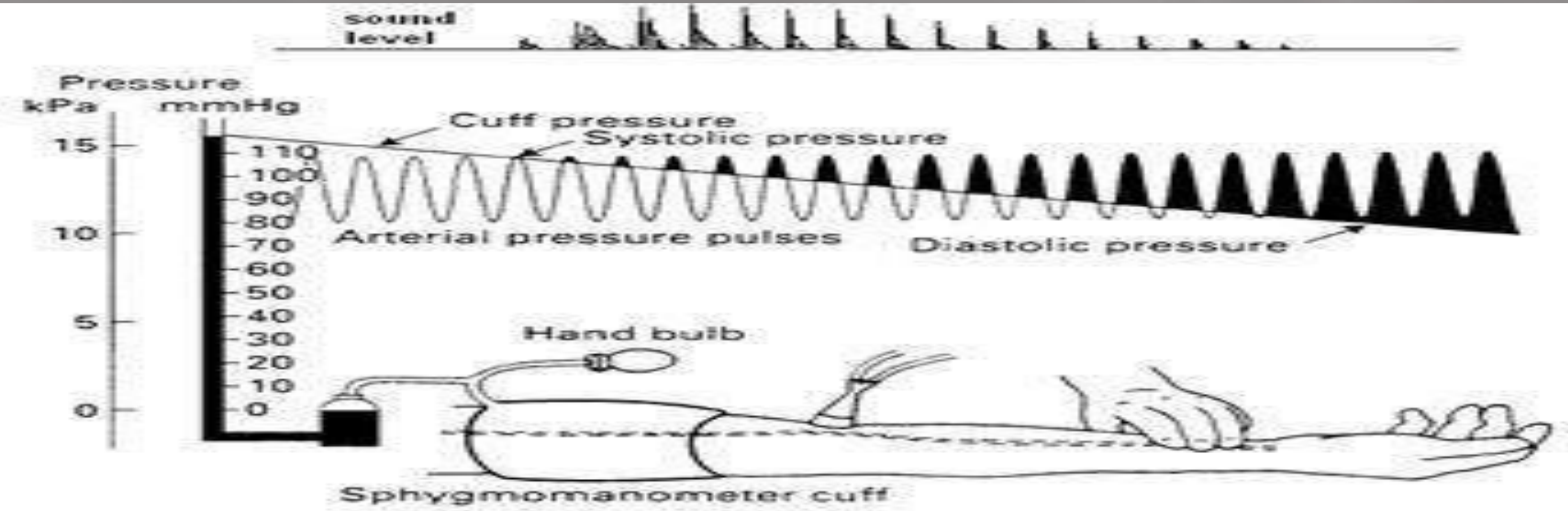
Blood Hammer phenomenon

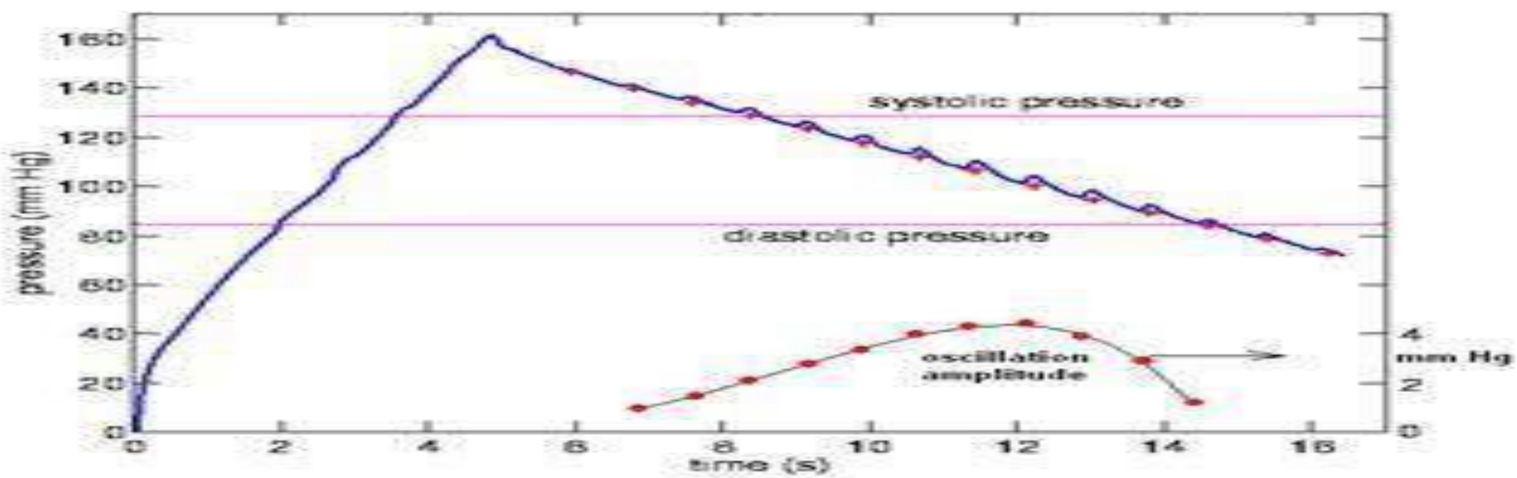
- The Blood hammer phenomenon is a sudden increase of the upstream blood pressure in a blood vessel (especially artery or arteriole) when the bloodstream is abruptly blocked by vessel obstruction. The term "blood-hammer" was introduced in cerebral hemodynamics by analogy with the hydraulic expression "water hammer", already used in vascular physiology to designate an arterial pulse variety, the "water-hammer pulse".



Heart With Infective Endocarditis

Watson's water hammer pulse is a characteristic medical sign first described by Thomas Watson, M.D. in 1844. The water hammer pulse is a pulse that is powerfully pulsating, similar in nature to the pounding of a water hammer. This hyperdynamic pulse occurs when an increased amount of blood is pumped with each stroke of the left ventricle, the largest chamber of the heart. There is also a decreased resistance to outflow of the blood, leading to a widening of the range between the highest and lowest numbers of a blood pressure reading, called the pulse pressure. The Corrigan's pulse, named for Sir Dominic Corrigan, M.D., refers to a water hammer pulse that is detected in the carotid artery, whereas a Watson's water hammer pulse pertains to a water hammer pulse detected peripherally in an arm or leg.


sound level
Pressure
kPa
mmHg
Cuff pressure
Systolic pressure
Arterial pressure pulses
Diastolic pressure
Hand bulb
Sphygmomanometer cuff
15
10
5
0
110
100
90
80
70
60
50
40
30
20
10
0

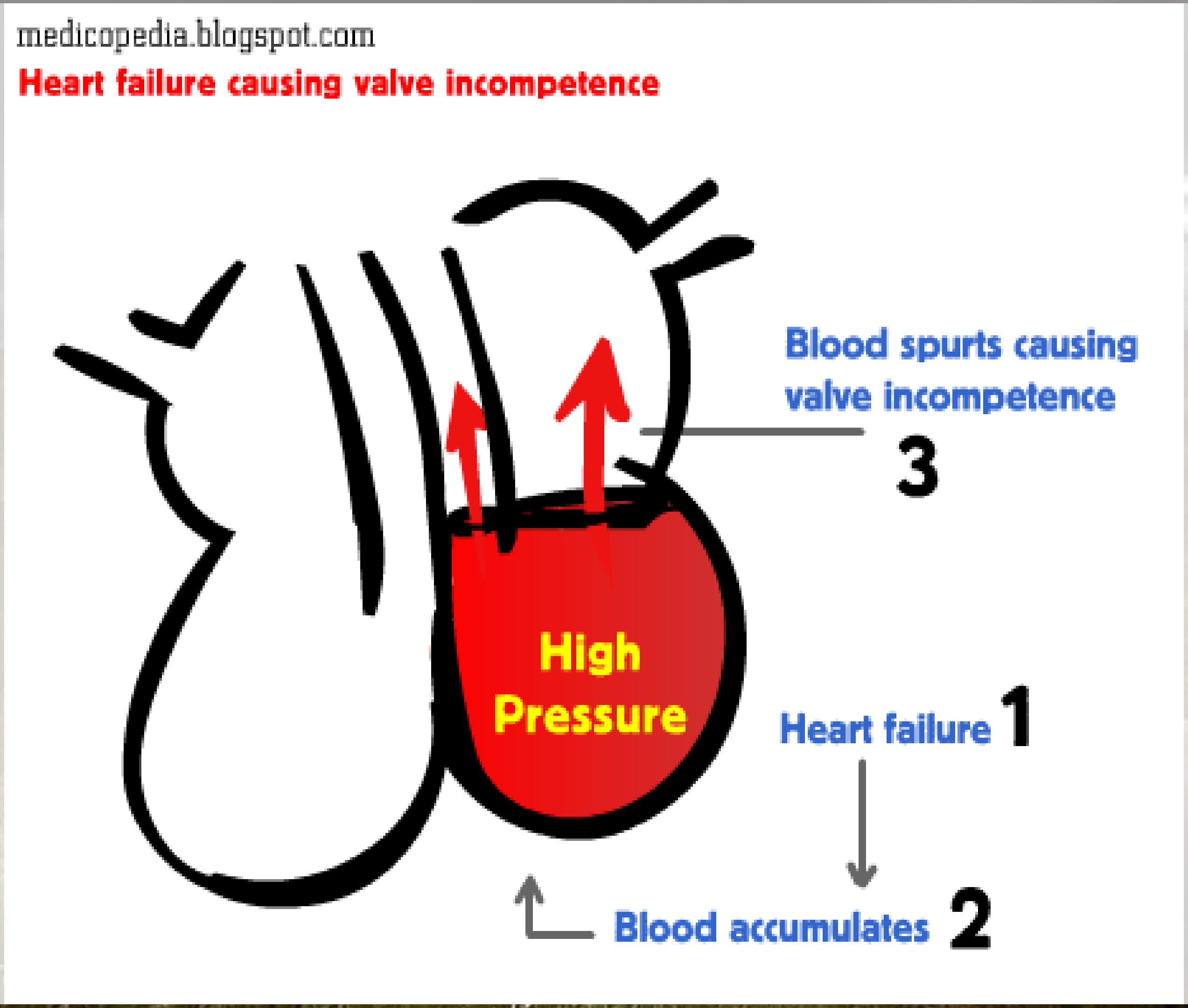

systolic pressure
diastolic pressure
pressure (mm Hg)
time (s)
oscillation amplitude
mm Hg
0
20
40
60
80
100
120
140
160
2
4
6
8
10
12
14
16

A pulse is the rhythmic throb of blood flow due to the heartbeat. The pulse can be felt in many sites on the human body. Common sites for checking a pulse include in the neck, at the wrist, on the inside of the elbow, behind the knee, and near the ankle joint. It can also be ascertained by assessing the heartbeats directly using a stethoscope. Both pulse rate and quality reveal the underlying status of the heart and blood vessels.

Systolic and diastolic readings constitute the numerical boundaries of blood pressure. They represent opposite ends of the cardiac cycle and the highest and lowest levels of blood pressure for a given individual. The pulse pressure is an indicator of the force that the heart generates each time it contracts. In healthy adults, the pulse pressure in a seated position is approximately 40, but can rise to 100 during exercise. Some studies indicate that the pulse pressure may be a better prognostic indicator of clinical outcome than either the systolic or the diastolic blood pressure alone.

There are many symptoms associated with water hammer pulse, the most common of which are muscle weakness and fatigue. Other associated symptoms include shortness of breath, lower extremity swelling, and headache. Patient may experience chest pains and palpitations. Cardiac arrhythmia, irregular heartbeat, may occur due to impaired electrical conduction in the heart chambers.

•A water hammer pulse is most often associated with a leaking aortic valve. The aortic valve is the valve that normally keeps blood that has been pumped out of the heart from flowing backward into the heart again. Aortic regurgitation or leakage occurs when the valve does not close properly, allowing blood to leak backward through it. As a result, the left ventricle has to pump more blood than usual, with progressive expansion due to the extra workload. The symptoms of aortic regurgitation can range from mild to severe, with some patients having no symptoms for years.


medicopedia.blogspot.com
Heart failure causing valve incompetence
Blood spurts causing valve incompetence
3
High Pressure
Heart failure 1
Blood accumulates 2

Water hammer effect

Assume:

- The difference between the energy gradeline (EL) and the hydraulic gradeline (HGL) will be neglected
- Horizontal, constant-diameter pipe.
- Neglect friction.

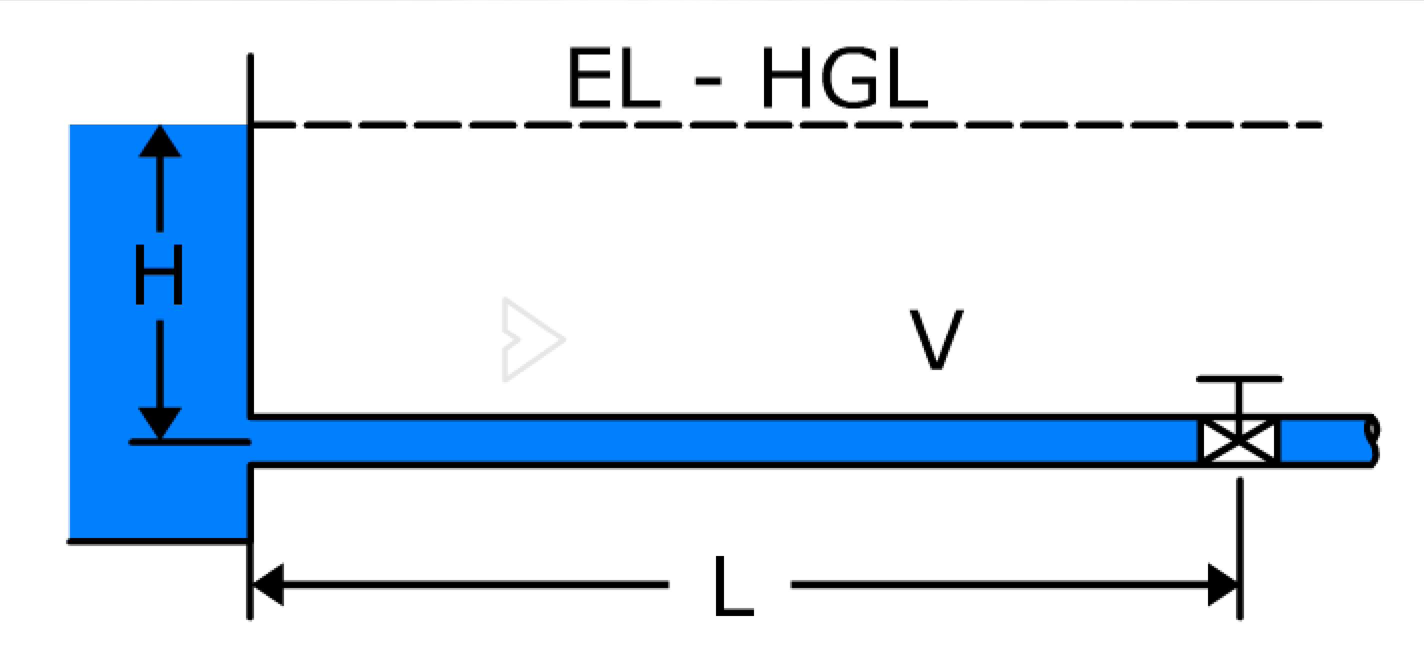


Illustration of Water Hammer

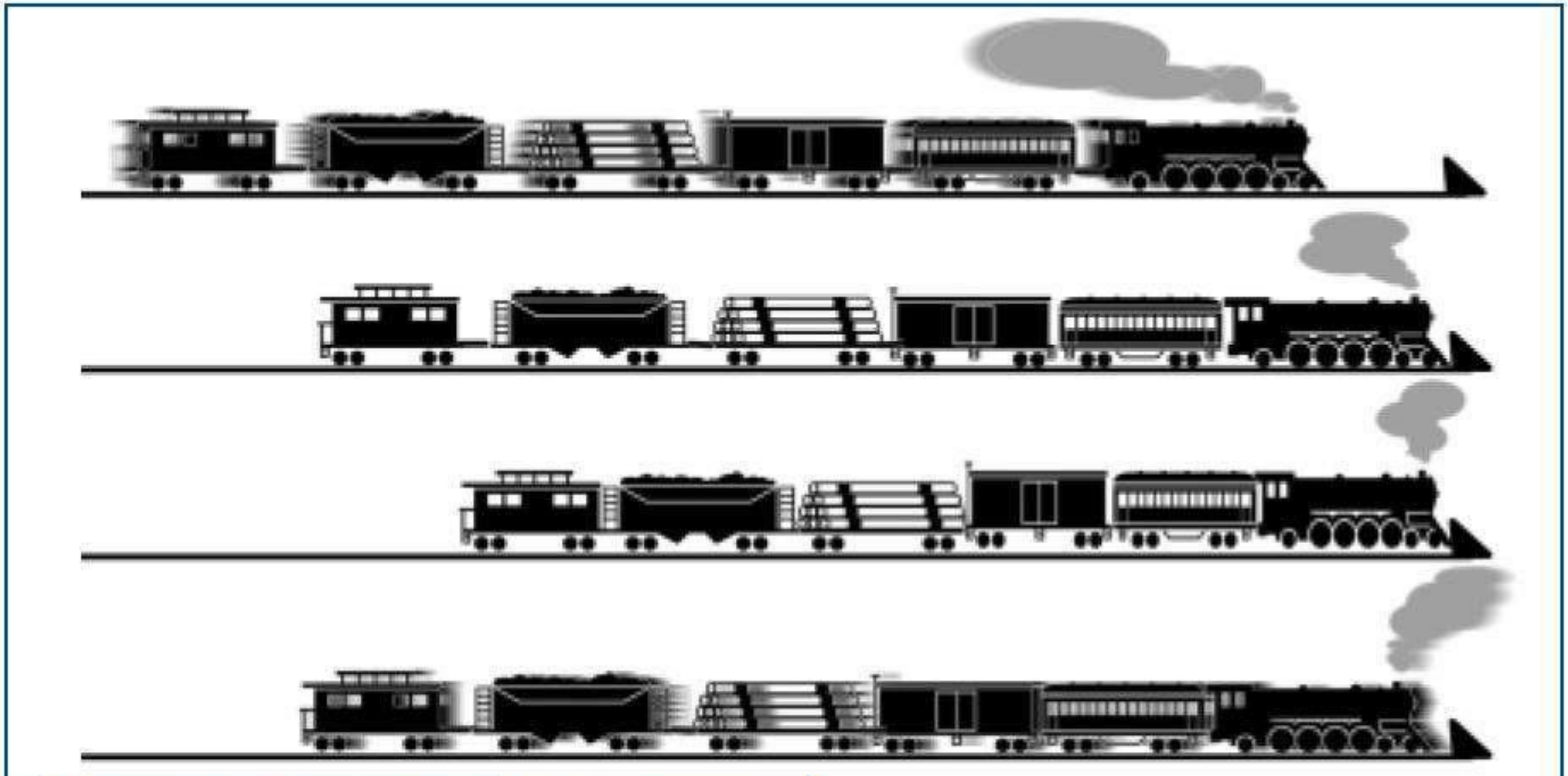
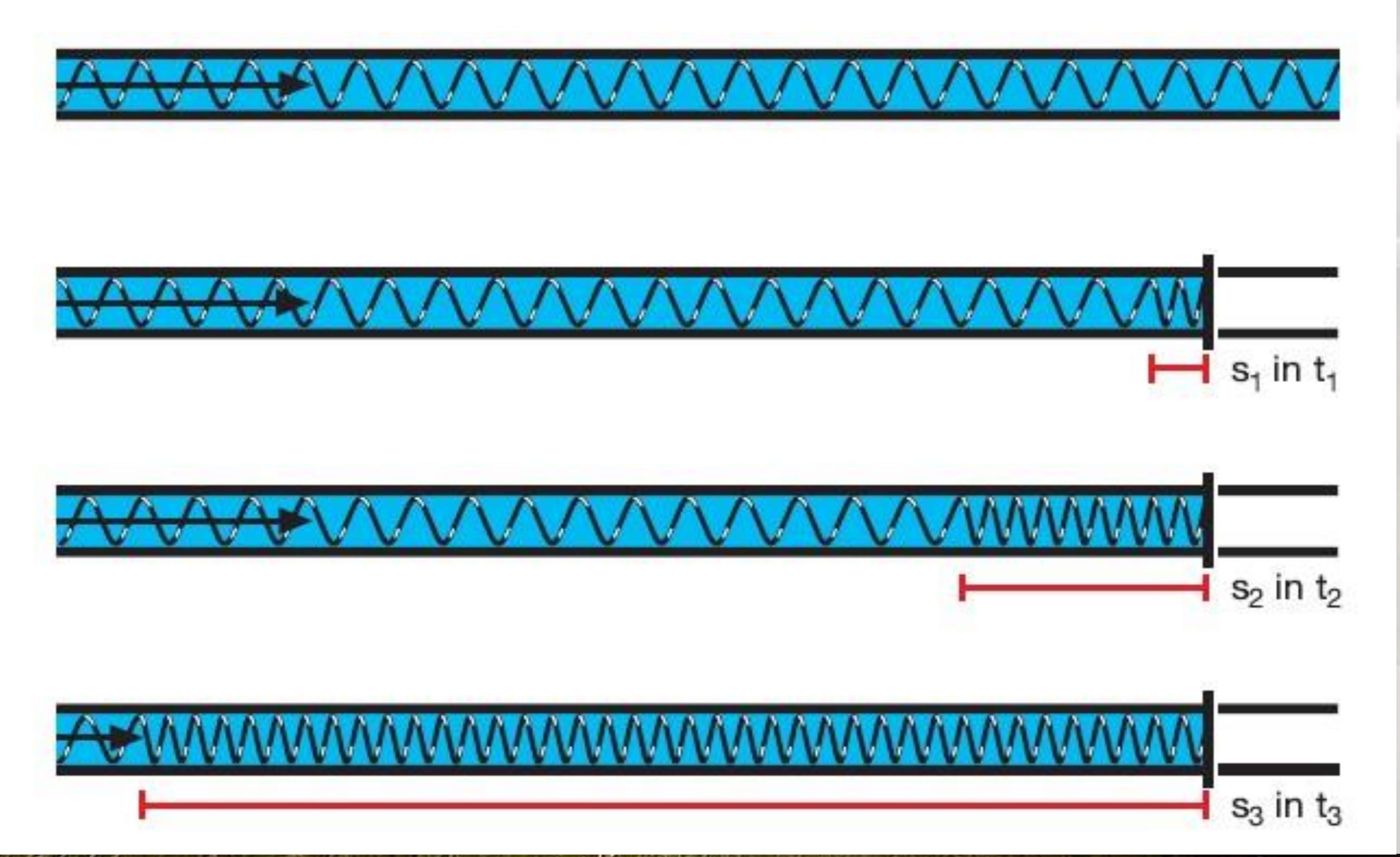


Figure 1 - Illustration of Water Hammer

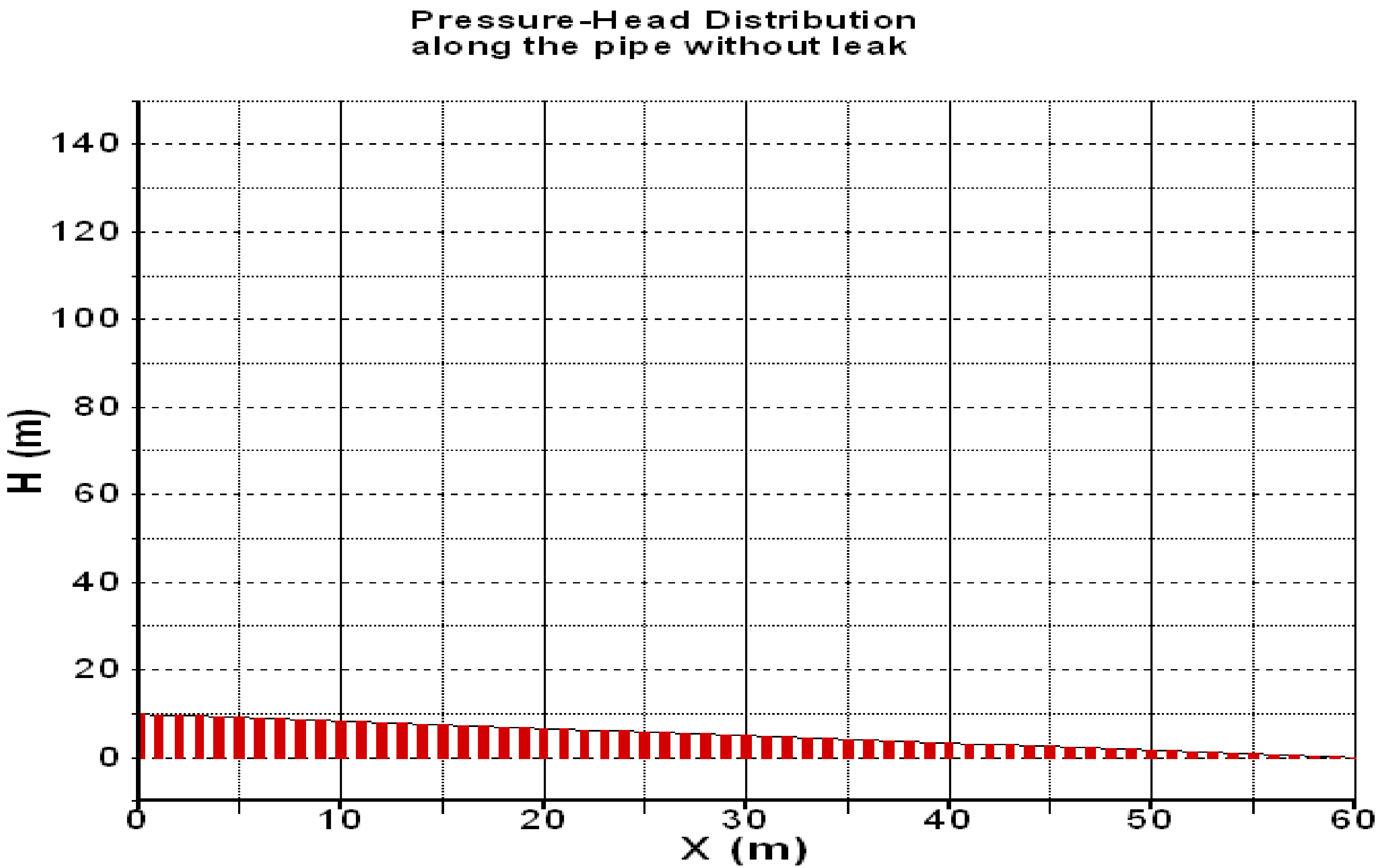
Source: Pickford, John. 1969. *Analysis of Water Surge*. Gordon and Breach Science Publishers.

A column of water acts like a freight train suddenly stopping when an outlet valve is suddenly closed.

Sudden Closure of gate valve, visualized by a heavy steel spring



Wave propagation after Valve Closure



Transitional wave principle

- **Wave**: is the substance reaction against any change in an exerted phenomena and differs according to the substance itself.

Pressure wave → Substance reaction due to pressure change
Thermal wave → Substance reaction due to Thermal change
Surface wave → Substance reaction due to Height change

- **Shock wave**: is a produced wave due to very large change in the exerted phenomena in the substance.

Transitional wave principle

Pressure waves

1. **Pressure waves**: Transmits the effect of pressure rise/increase.
2. **Expansion waves**: Transmits the effect of pressure drop/decrease.

Water hammer effect

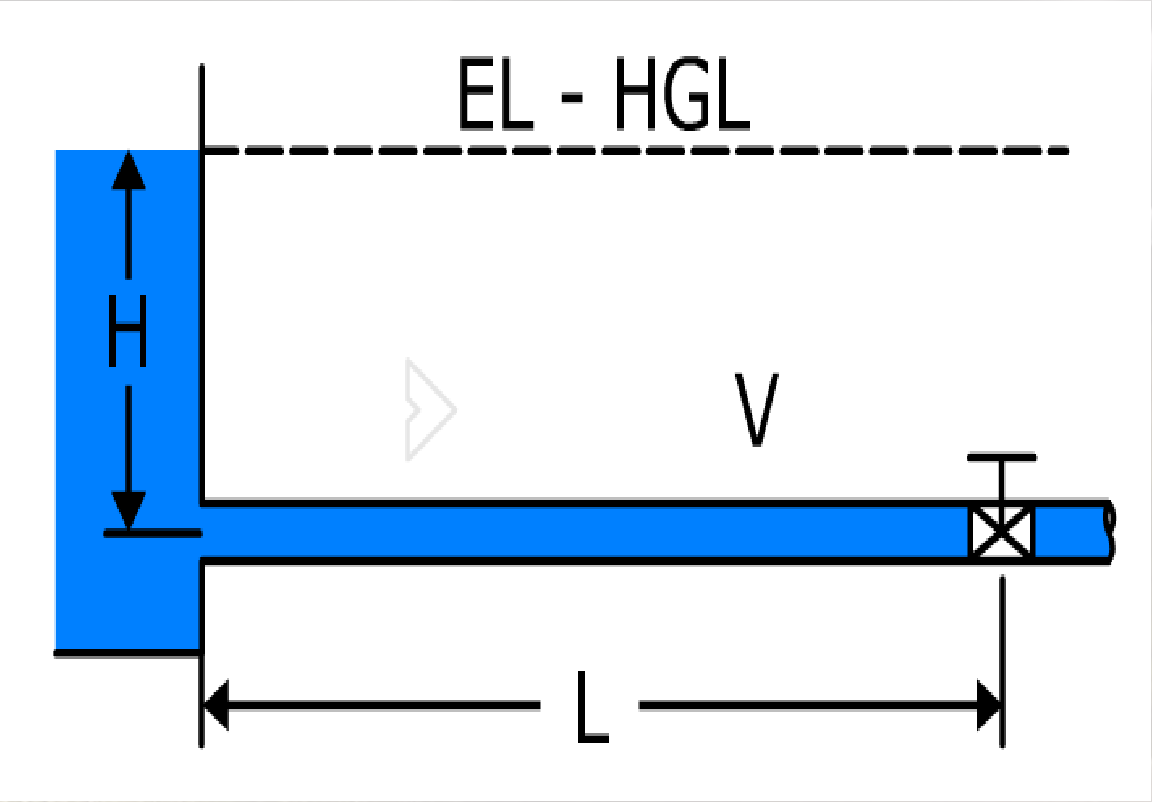
- Where

  t : time since valve was closed

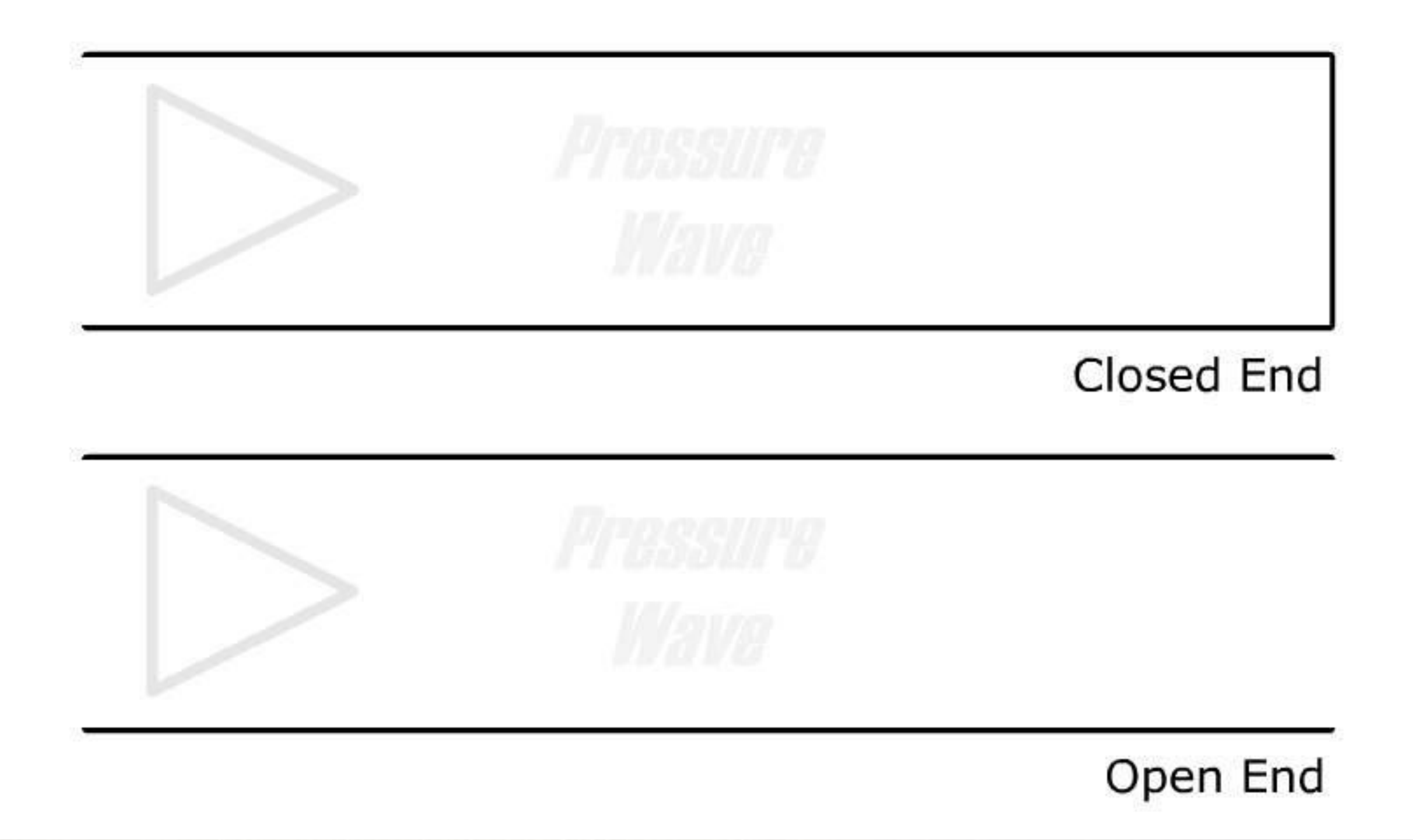
  a : velocity of pressure wave

  L : Length of the pipe

  ΔH : increasing in pressure head



Transitional wave principle



Transitional wave principle

Closed End

Open End

What is water hammer?

Water hammer (or hydraulic shock) is the momentary increase in pressure, which occurs in a water system when there is a sudden change of direction or velocity of the water.

When a rapidly closed valve suddenly stops water flowing in a pipeline, pressure energy is transferred to the valve and pipe wall. Shock waves are set up within the system. Pressure waves travel backward until encountering the next solid obstacle (or change in density), then forward, then back again. The pressure wave's velocity is equal to the speed of sound; therefore it "bangs" as it travels back and forth, until dissipated by friction losses.

Anyone who has lived in an older house is familiar with the “bang” that resounds through the pipes when a faucet is suddenly closed. This is an effect of water hammer.

A less severe form of hammer is called surge, a slow motion mass oscillation of water caused by internal pressure fluctuations in the system. This can be pictured as a slower “wave” of pressure building within the system. Both water hammer and surge are referred to as transient pressures.

If not controlled, they both yield the same results: damage to pipes, fittings, and valves, causing leaks and shortening the life of the system. Neither the pipe nor the water will compress to absorb the shock.

Investigating the Causes of Water Hammer

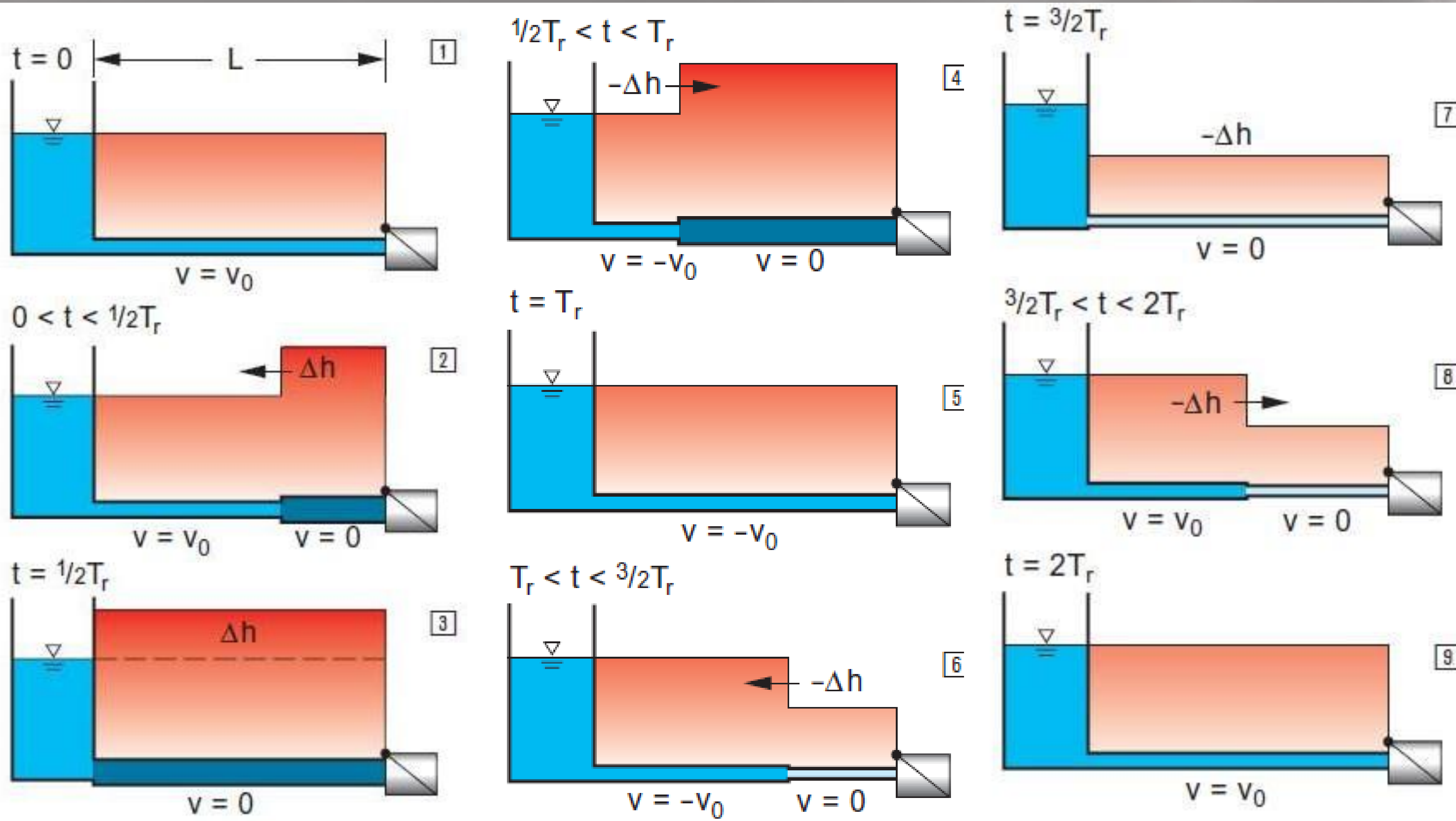
A water transport system's operating conditions are almost never at a steady state. Pressures and flows change continually as pumps start and stop, demand fluctuates, and tank levels change. In addition to these normal events, unforeseen events, such as power outages and equipment malfunctions, can sharply change the operating conditions of a system. Any change in liquid flow rate, regardless of the rate or magnitude of change, requires that the liquid be accelerated or decelerated from its initial flow velocity. Rapid changes in flow rate require large forces that are seen as large pressures, which cause water hammer.

Entrained air or temperature changes of the water also can cause excess pressure in the water lines. Air trapped in the line will compress and will exert extra pressure on the water. Temperature changes will actually cause the water to expand or contract, also affecting pressure. The maximum pressures experienced in a piping system are frequently the result of vapor column separation, which is caused by the formation of void packets of vapor when pressure drops so low that the liquid boils or vaporizes. Damaging pressures can occur when these cavities collapse.

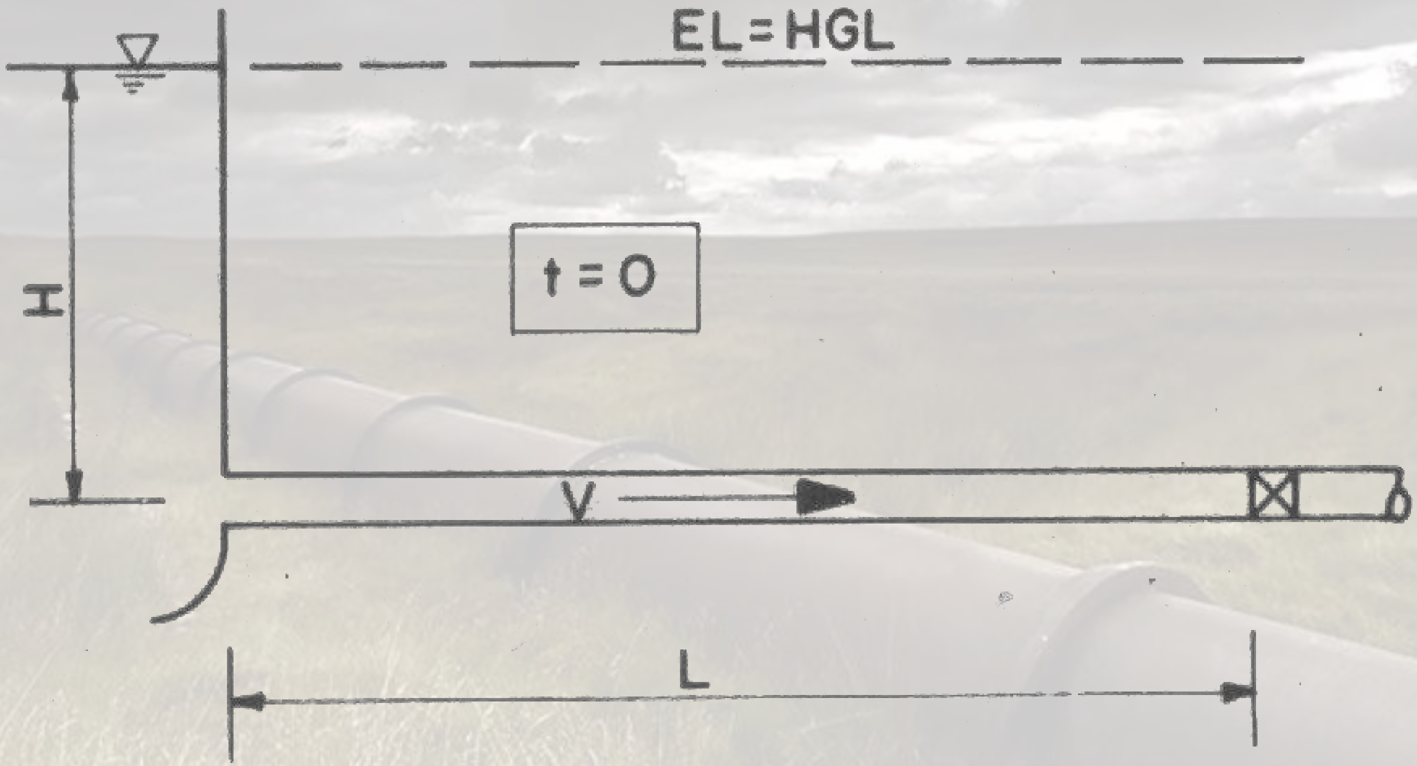
Summary

Water hammer refers to fluctuations caused by a sudden increase or decrease in flow velocity. These pressure fluctuations can be severe enough to rupture a water main. Potential water hammer problems should be considered when pipeline design is evaluated, and a thorough surge analysis should be undertaken, in many instances, to avoid costly malfunctions in a distribution system. Every major system design change or operation change—such as the demand for higher flow rates—should include consideration of potential water hammer problems. This phenomenon and its significance to both the design and operation of water systems is not widely understood, as evidenced by the number and frequency of failures caused by water hammer.

Pressure and velocity waves in a single-conduit frictionless pipeline following its sudden closure.

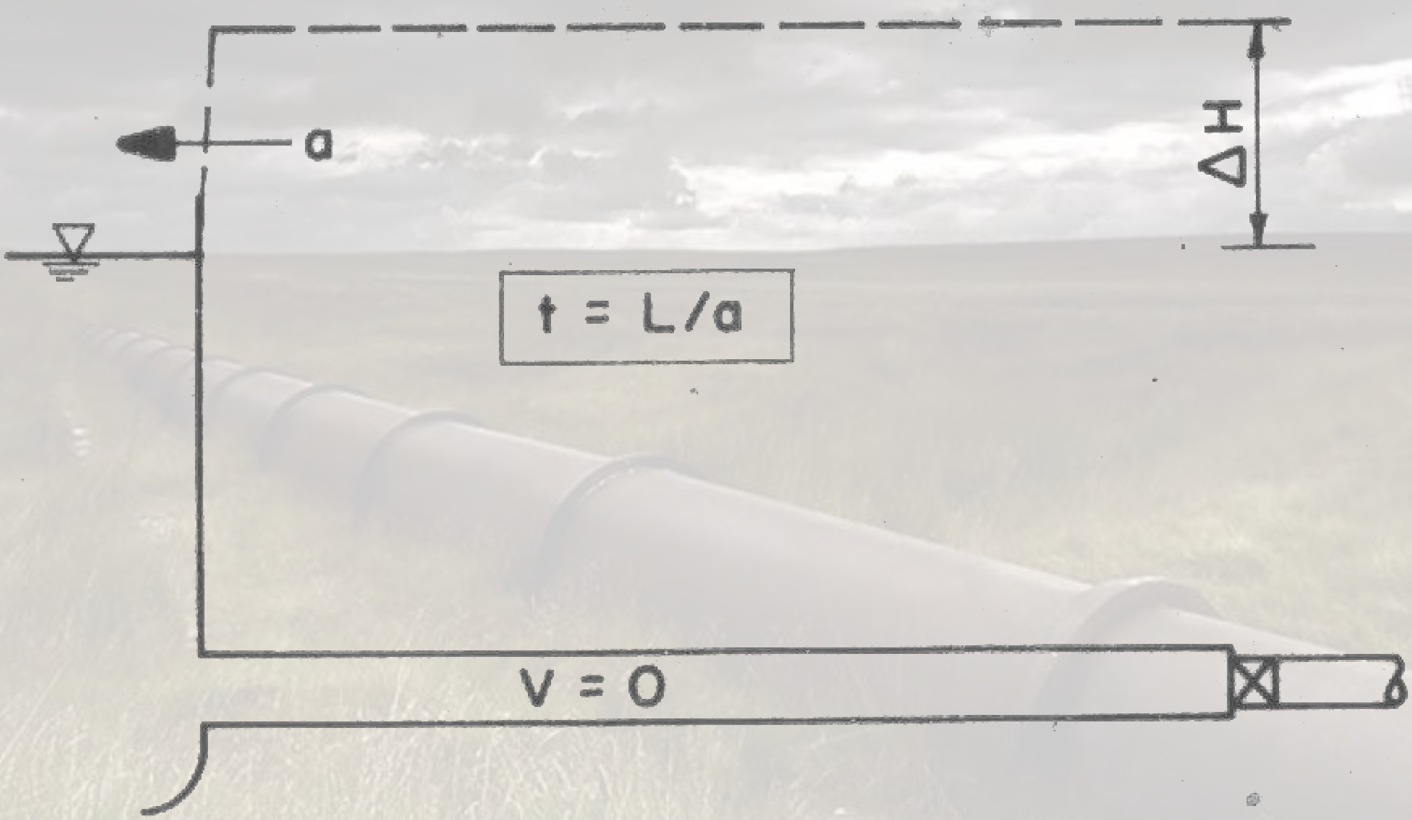


Water hammer effect

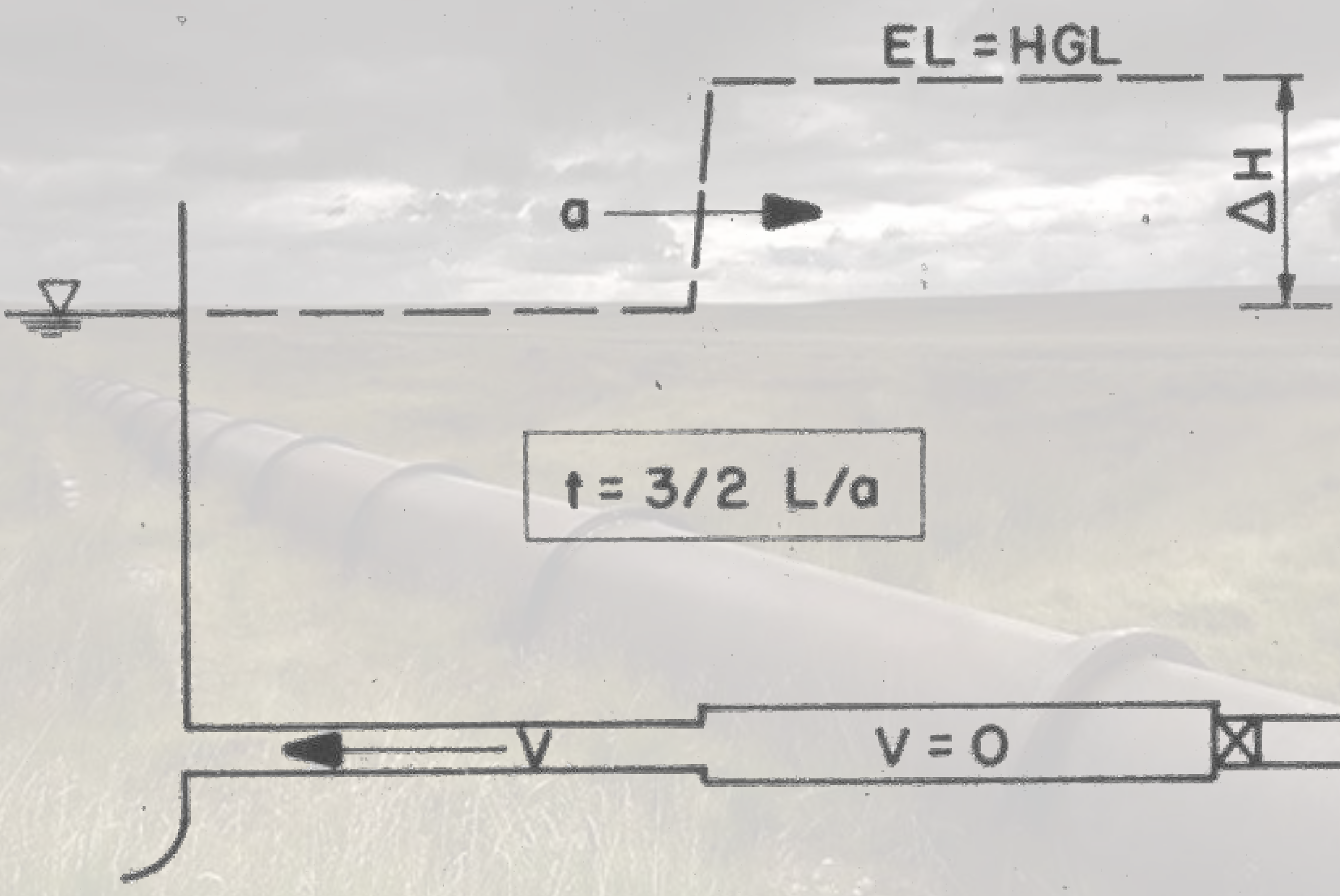


Water hammer effect

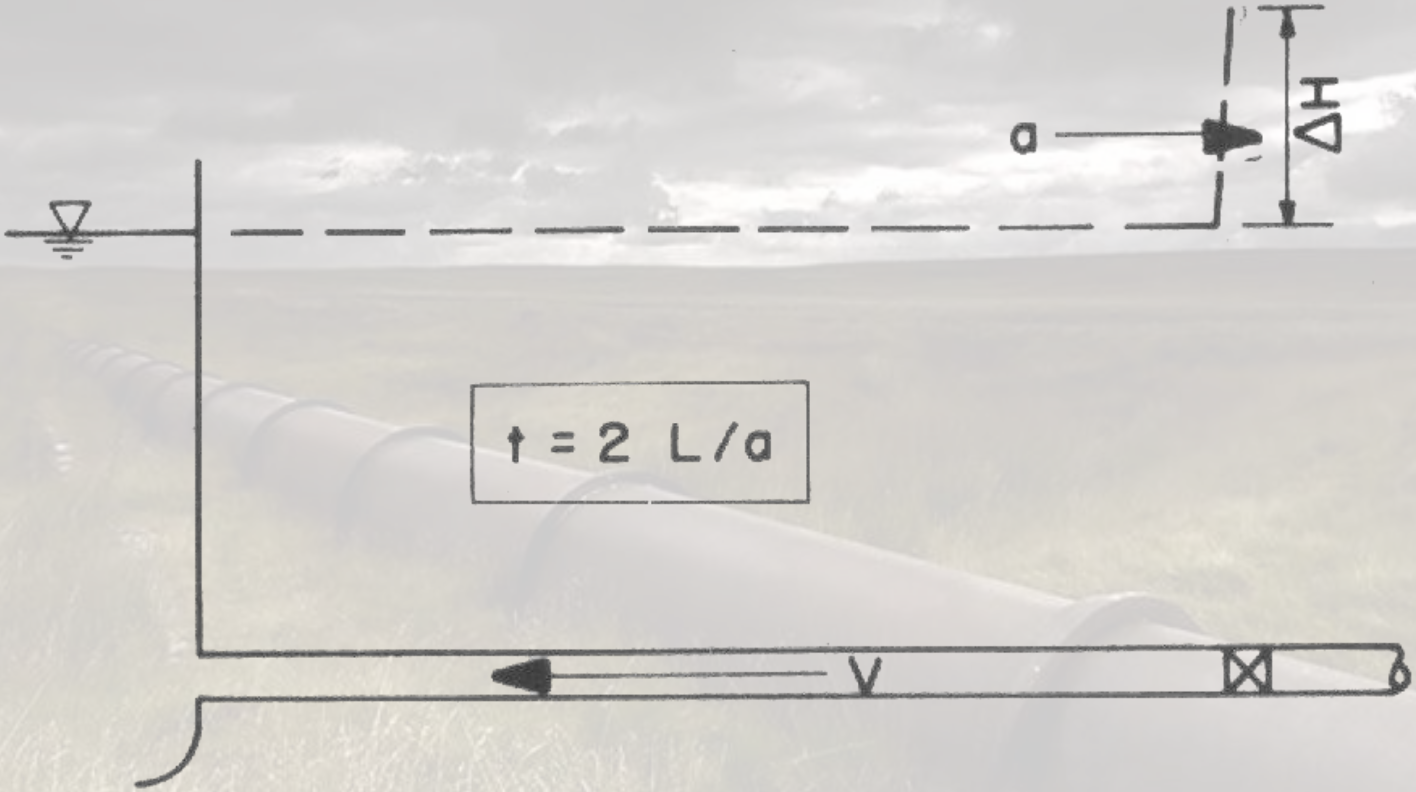
Water hammer effect



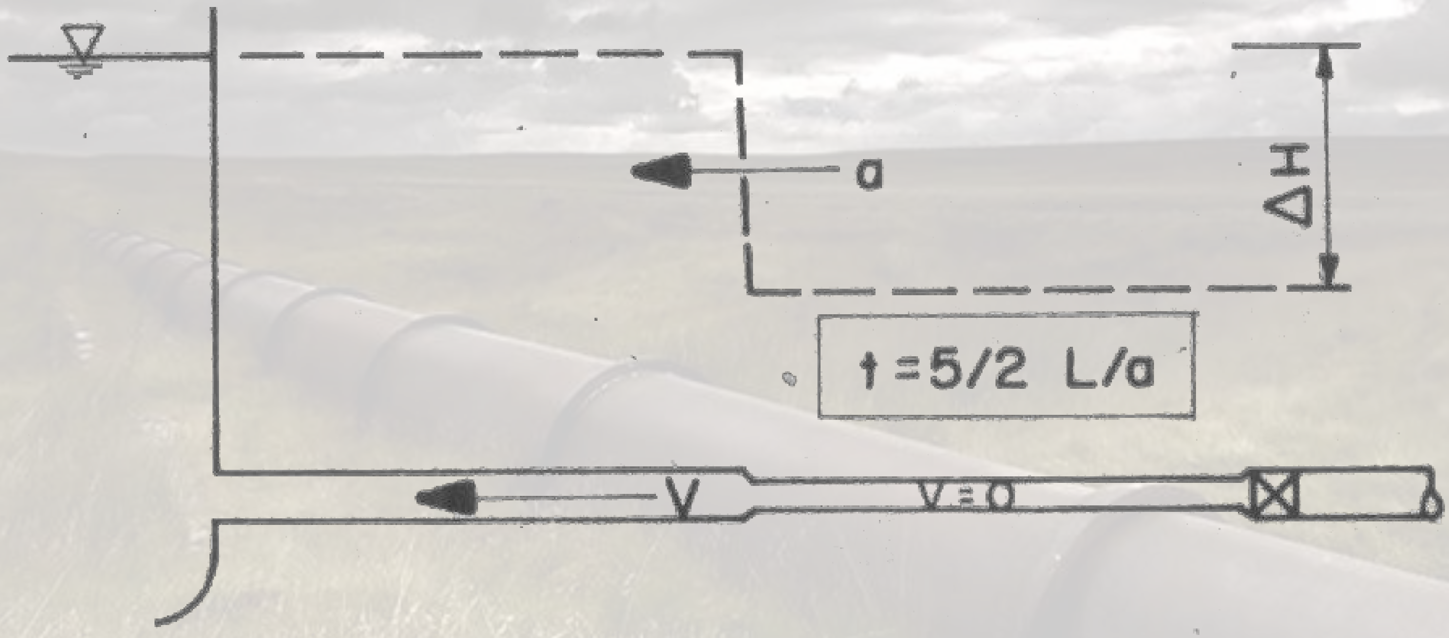
Water hammer effect



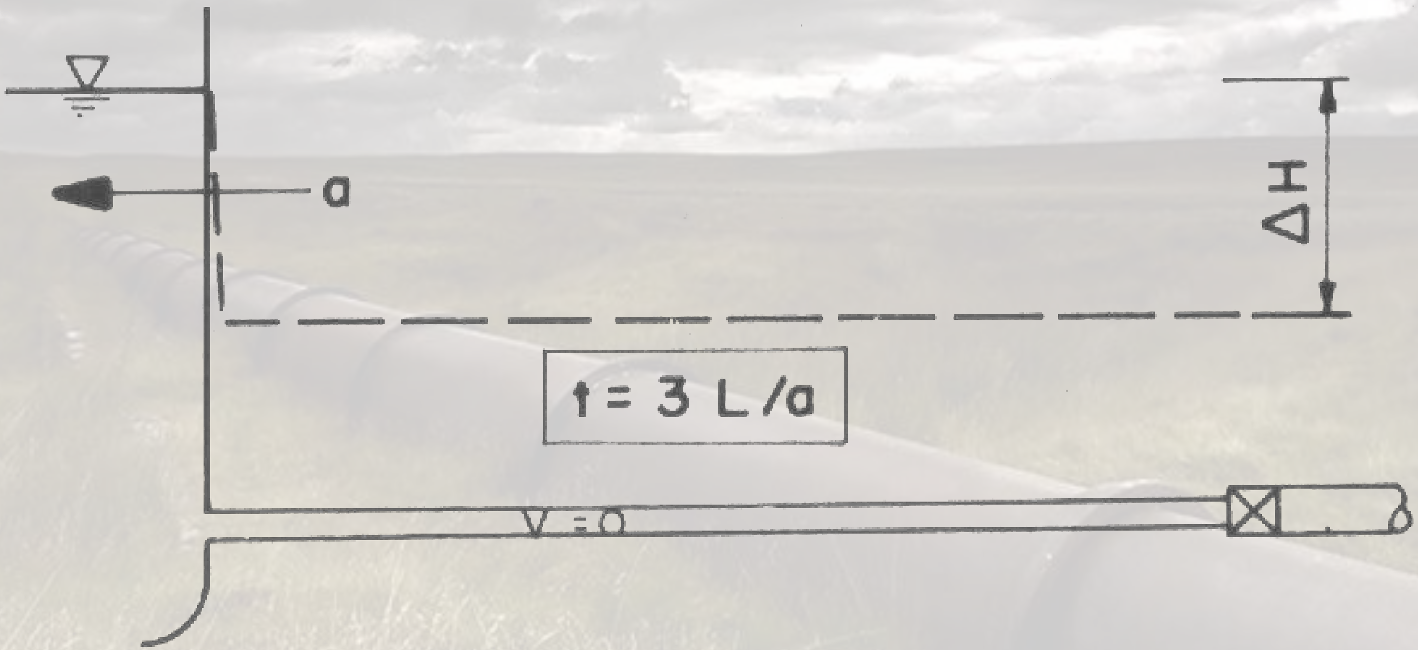
Water hammer effect



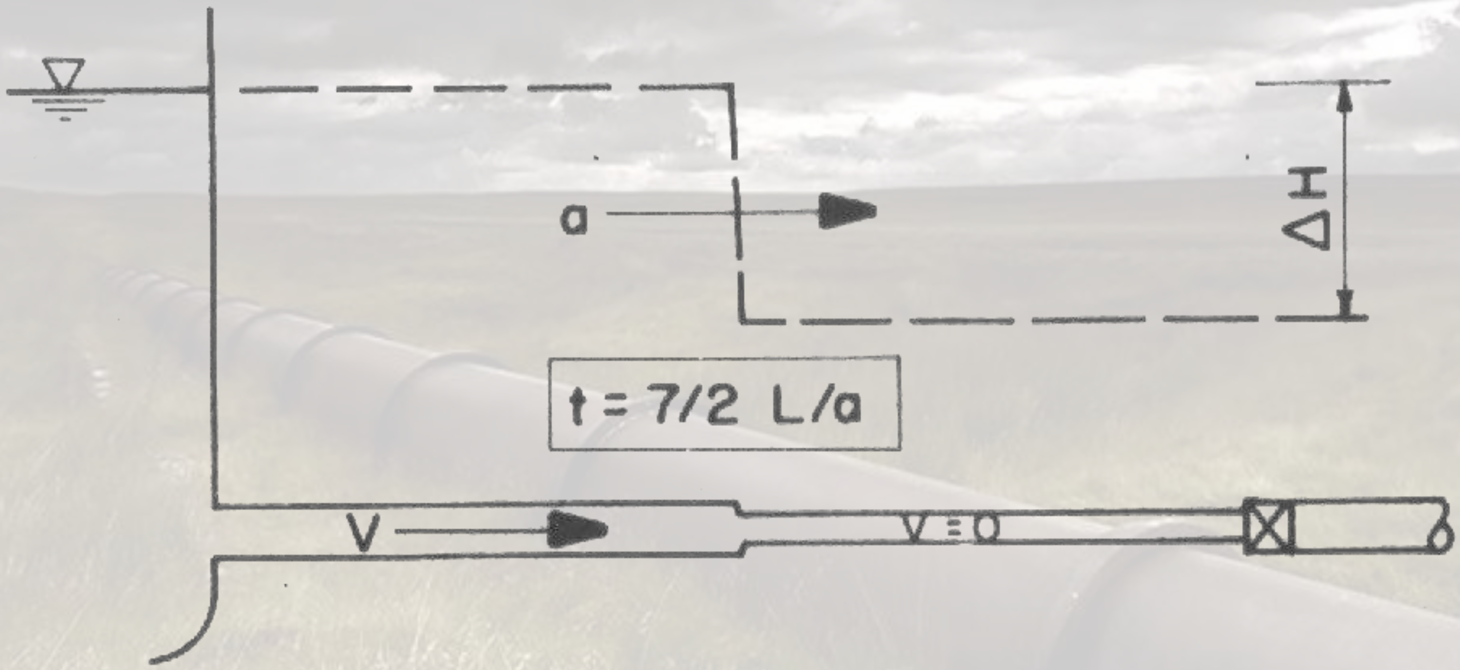
Water hammer effect



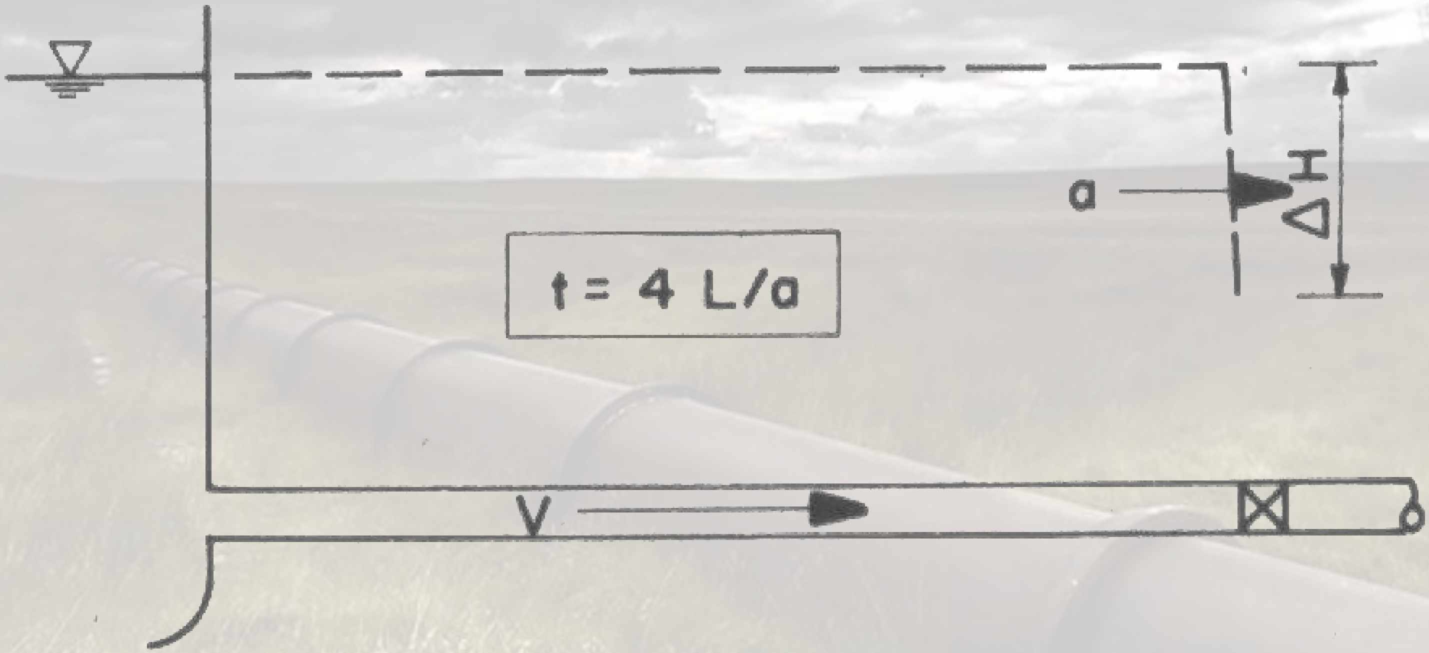
Water hammer effect



Water hammer effect

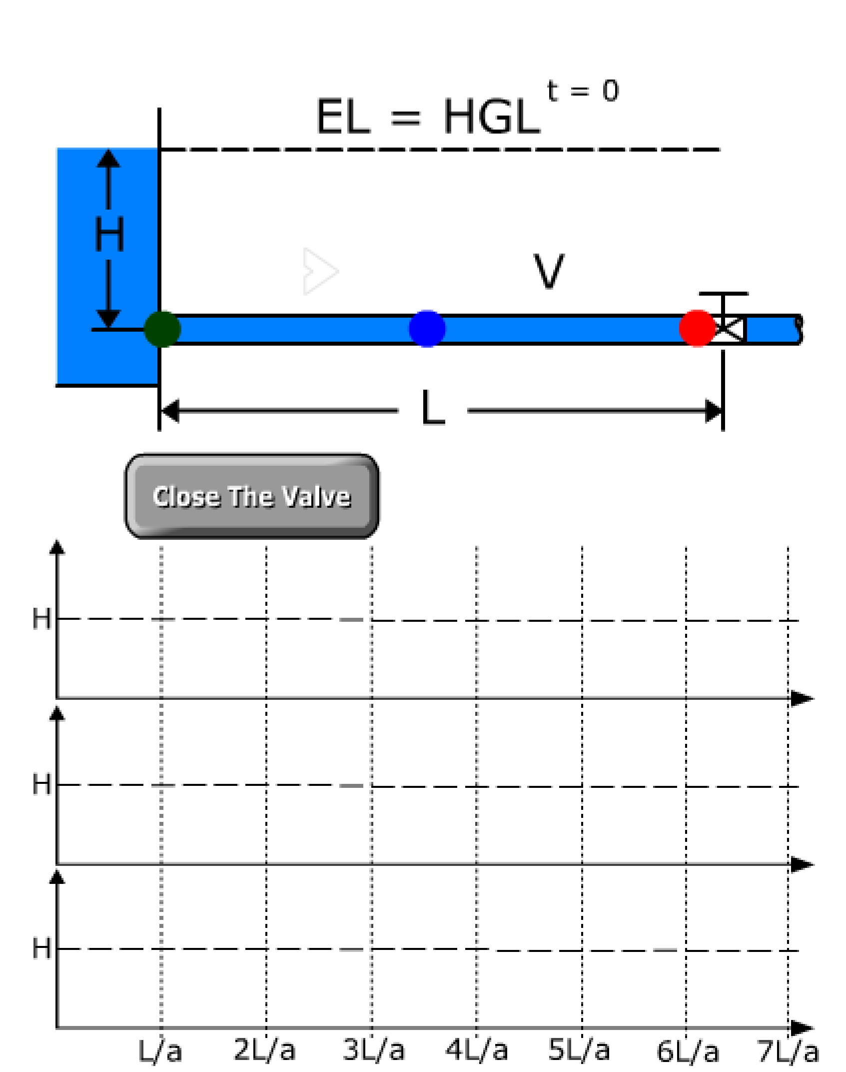


Water hammer effect

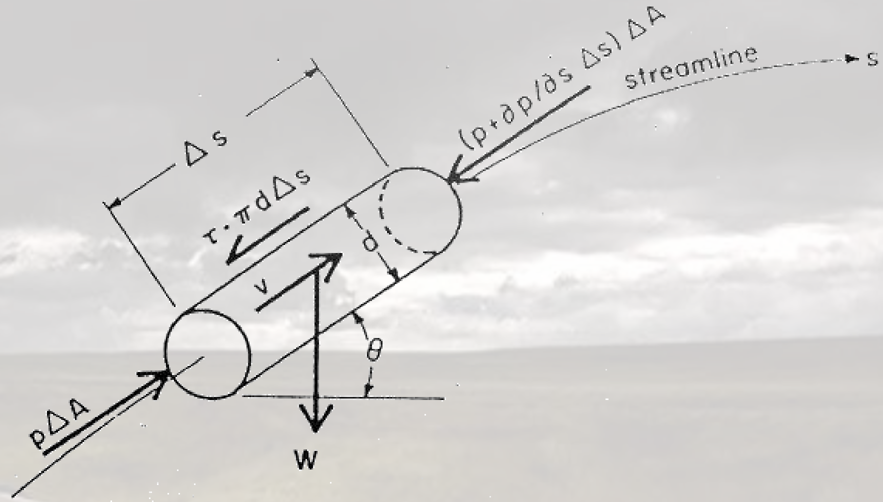


Water hammer effect

- Pressure head at the valve
- Pressure head at the midpoint
- Pressure head at the reservoir



The unsteady flow equations



Considering only the streamline direction, Newton's second law gives

$$\sum F_s = ma_s = m\frac{dv}{dt}$$

Where m = fluid particle mass, and s signifies the streamline direction.

Substituting the force components and mass from the figure into this equation results in

$$p\Delta A - \left(p + \frac{\partial p}{\partial s}\Delta s \right)\Delta A - W\sin\theta - \tau\Delta s\pi d = \frac{W}{g}\frac{dv}{dt}$$

The unsteady flow equations

After some manipulation, we end up with the one-dimensional Euler equation

$$-\frac{1}{\omega}\frac{\partial p}{\partial s}-\frac{\partial z}{\partial s}-\frac{4\tau}{\omega d}=\frac{1}{g}\frac{dv}{dt}$$

Expanding the particle diameter to the size of the pipe cross-section and introduction the average velocity gives a more useful equation

$$-\frac{1}{\omega}\frac{\partial p}{\partial s}-\frac{\partial z}{\partial s}-\frac{4\tau_0}{\omega D}=\frac{1}{g}\frac{dv}{dt}$$

Where D is the pipe diameter and τ_0 is not directly useful, we will substitute a relation between τ_0 and the Darcy-Weiscach friction factor f. The result of this substitution is

$$-\frac{1}{\omega}\frac{\partial p}{\partial s}-\frac{\partial z}{\partial s}-\frac{f}{D}\frac{V^2}{2g}=\frac{1}{g}\frac{dv}{dt}$$

The unsteady flow equations

Recognizing that z is a function only of s and represents the elevation above some datum of the pipe centerline, we can change the partial derivative to a total derivation. Finally, the equation has the form

$$-\frac{1}{\omega}\frac{\partial p}{\partial s}-\frac{dz}{ds}-\frac{f}{D}\frac{V^2}{2g}=\frac{1}{g}\frac{dv}{dt}$$

<u>This equation is valid for:</u>

1- Compressible/ incompressible flow,

2- Steady/ unsteady flow,

3 Real/ Ideal flow,

4 Rigid and elastic pipe.

The unsteady flow equations

- Assuming

1. Ideal flow

   Neglect viscous force

$$-\frac{f}{D}\frac{V^2}{2g} = 0.0$$

$$-\frac{1}{\omega}\frac{\partial p}{\partial s} - \frac{dz}{ds} = \frac{1}{g}\frac{dv}{dt}$$

2. Steady flow

$$\frac{dv}{dt} = 0.0$$

$$\therefore V = fn(s,t)$$

$$\therefore dv = \frac{\partial v}{\partial s} ds + \frac{\partial v}{\partial t} dt$$

$$\therefore \frac{dv}{dt} = \frac{\partial v}{\partial s}\frac{ds}{dt} + \frac{\partial v}{\partial t} \qquad \frac{\partial v}{\partial t} \cong 0.0$$

$$\therefore \frac{dv}{dt} = V\frac{\partial v}{\partial s}$$

The unsteady flow equations

$$\therefore \frac{1}{\omega}\frac{\partial p}{\partial s} + \frac{dz}{ds} + \frac{1}{g}\frac{dv^2}{2ds} = 0.0$$

Euler equation for steady ideal flow

- For incompressible flow ($\gamma = \text{constant}$)

$$\therefore \frac{p}{\omega} + Z + \frac{v^2}{2g} = E$$

Bernoulli's equation

Rigid Water Column Theory

$$\frac{1}{\omega}\frac{\partial p}{\partial s}+\frac{dz}{ds}+\frac{1}{g}\frac{dv^2}{2ds}=0.0$$

- **1- Neglect compressibility of the fluid i.e.,**

ρ = Constant

- **2- neglect Elasticity of the pipe,**

D = Constant

Flow establishment in horizontal pipe

$$-\int_L \frac{1}{\omega}\frac{\partial p}{\partial s}\,ds - \int_L \frac{dz}{ds}\,ds - \int_L \frac{fV^2}{2gD}\,ds = \int_L \frac{1}{g}\frac{dV}{dt}\,ds$$

(dz/ds) = 0, and V is a function of time only, assume the f-value in unsteady flow is the same as for a steady flow at a velocity equal to the instantaneous value.

$$\frac{p_1}{\omega} - \frac{p_2}{\omega} - \frac{fL}{2gD}V^2 = \frac{L}{g}\frac{dV}{dt}$$

Because the pressure head p_1/ω = constant = H_0 and because $p_2/\omega = 0$ for t>0

$$H_0 - \frac{fL}{2gD}V^2 = \frac{L}{g}\frac{dV}{dt}$$

Integration is performed by separating the variables to form

$$\int dt = \frac{L}{g}\int \frac{dV}{H_0 - \frac{fL}{2gD}V^2}$$

Flow establishment in horizontal pipe

The integration gives the following equation for the time necessary to accelerate the flow to given velocity V

$$t = \sqrt{\frac{LD}{2gfH_0}} \log \frac{\sqrt{\dfrac{2gDH_0}{fL}} + V}{\sqrt{\dfrac{2gDH_0}{fL}} - V}$$

Where log denotes natural logarithm. Recognizing that $V_0 = \sqrt{2gH_0 D / fL}$, the steady state velocity, the equation for t becomes

$$t = \frac{LV_0}{2gH_0} \log \frac{V_0 + V}{V_0 - V}$$

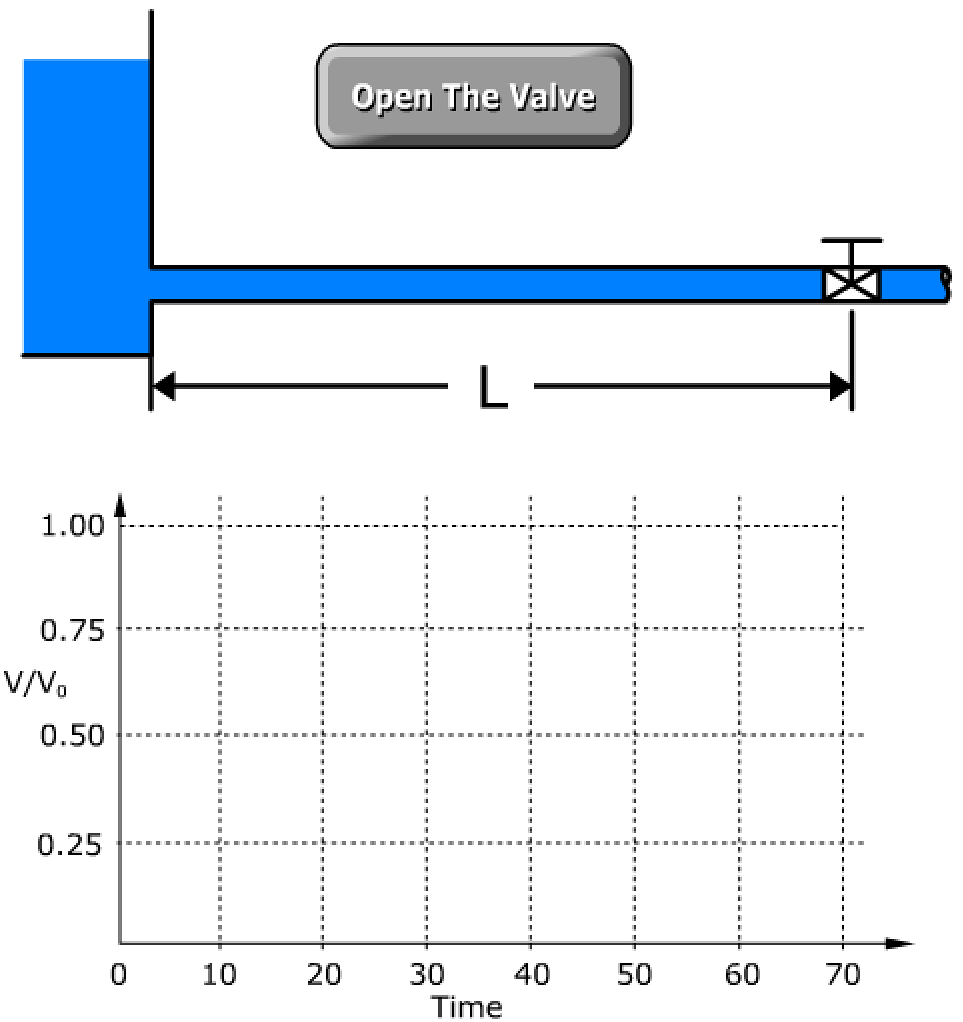
Flow establishment in horizontal pipe

- It is important to note that as steady flow is approached, $V \rightarrow V_0$ and as a consequence $t \rightarrow \infty$. Of course this answer is unacceptable so we propose that when $V = 0.99\ V_0$, we have essentially steady flow. With this interpretation,

$$t = 2.65 \frac{LV_0}{gH_0}$$

Flow establishment in horizontal pipe

- When the valve is closed pressure is everywhere equal to H_0.
- When the valve is suddenly opened. The pressure at the valve drops instantly to zero and the fluid begins to accelerate.



Example.1

A horizontal pipe 24" inside diameter, 10,000 ft long leaves a reservoir 100 ft below surface and terminates with a closed valve. If the valve opens suddenly. How long would the velocity takes to reach 99% of its final value, neglecting minor losses valve. Friction factor of 0.018 is to be assumed constant during the acceleration phase

- Given:

d = 24" = 2 ft	L = 104 ft	Ho = 100 ft	F = 0.018= const

- Required:

t for a velocity of $0.99V_o$

Example.1

- Solution

$$V_o = \sqrt{\frac{2gdH_o}{fl}}$$

$$= \sqrt{\frac{2\times 32.2\times 2\times 100}{0.018\times 10^4}} = 8.45 \quad ft/s$$

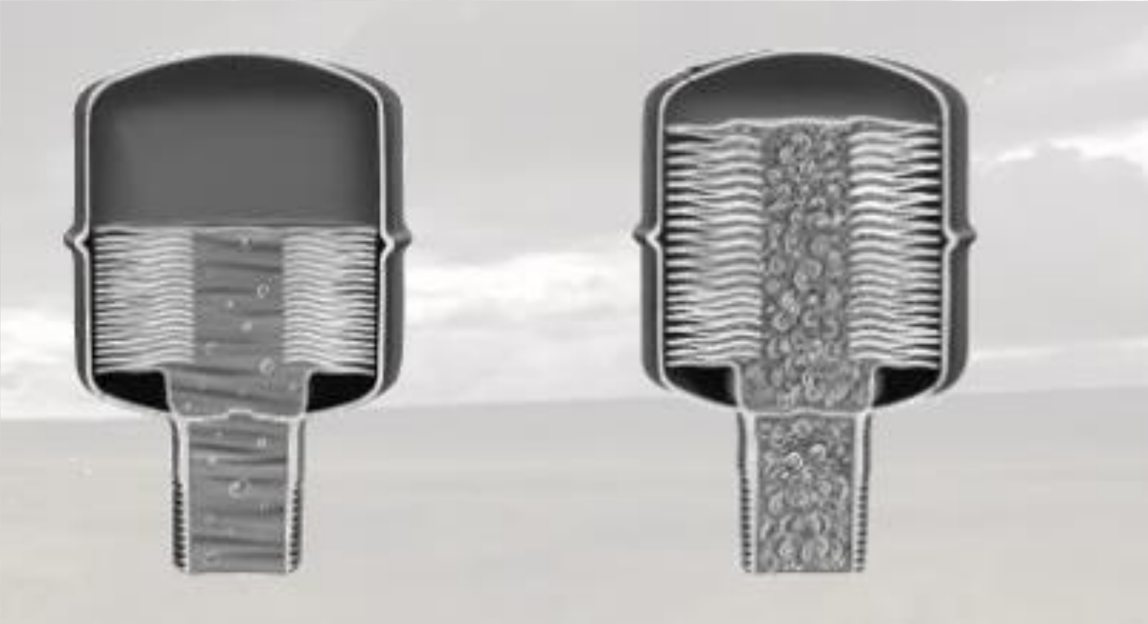
$$\therefore t = \frac{lV_o}{2gH_o}\ln\frac{V_o+V}{V_o-V}$$

$$\therefore t = \frac{10^4\times 8.46}{2\times 32.2\times 100}\ln\frac{8.46\times(1+0.99)}{8.46\times(1-0.99)}$$

$$\therefore t = 70 \text{ second}$$

Water Hummer Protection

Using Accumulators and Air Chambers



Water Hummer Protection

1. Automatically controlled valves which close slowly
2. Pumps: Increasing the flow slowly during startup and shut down
3. Using Accumulators and Air Chambers