Effect of air entrainment on wave speed

When free air (or any other gas) is present in a pipeline, either as small bubbles or in larger volumes, the wave speed in the pipeline is decreased dramatically. As a consequence, the wave propagation patterns and the resulting pressures are substantially changed

If the air water mixture is assumed to be uniformly distributed throughout the pipeline, the wave speed can be computed as

$$a = \sqrt{\frac{K/\rho}{1 + \frac{KD}{eE}\psi}}$$

$\psi =$ restraing type

however $K = K_{mix}$

$\rho = \rho_{mix}$

$$K_{mix} = \frac{K_{liq}}{1 + \alpha\left(\frac{K_{liq}}{K_{air}} - 1\right)}$$

$$\rho_{mix} = (1 - \alpha)\rho_{liq}$$

$$\alpha = \text{void fraction} = \frac{\text{Volume of air}}{\text{total volume of mixture}}$$

then

$$a = \sqrt{\frac{\dfrac{K_{mix}}{\rho_{mix}}}{1 + \dfrac{K_{mix} D}{e E} \psi}}$$

for $\dfrac{K_{liq}}{K_{air}} >> 1$

$$K_{mix} = \frac{K_{liq}}{1 + \alpha \dfrac{K_{liq}}{K_{air}}}$$

$$a = \sqrt{\frac{\dfrac{K_{liq}}{\rho_{mix}}}{\left(1 + \alpha \dfrac{K_{liq}}{K_{air}}\right)\left(1 + \dfrac{K_{mix} D}{e E} \psi\right)}}$$

~~Denominator~~

$$a = \sqrt{\frac{\dfrac{K_{liq}}{\rho_{mix}}}{1 + \dfrac{K_{liq}}{E}\dfrac{D}{e} + \alpha \dfrac{K_{liq}}{K_{air}}}}$$

It is clear from above equation, the wave speed in the pipeline depends on the pressure in the pipeline because the values of α and K_{air} depend on the pressure.

As a consequence the wave speed varies with the passage of a pressure wave. This factor greatly complicates an analysis and makes accurate prediction of water hammer pressure most difficult.

<u>Isothermal process</u>. $K_{air} = p$

<u>isentropic process</u>. $K_{air} = 1.4p$

<u>Polytropic process</u>. $K_{air} = 1.2p$

adiabatic process $K_{air} = 1.4p$

<u>Isothermal process</u>: Temperature is constant ($\Delta T = 0$) and there may be energy flowing into and out of the system. Energy is dissipated here.

<u>Isentropic process</u>: Entropy remains constant since no energy is dissipated. Isentropic process is both adiabatic and reversible.

<u>Adiabatic process</u>: No heat is transferred from system to surroundings and vice versa. Irreversible process.

polytropic process $\quad pV^n = \text{constant}$

Numerical

Compute the wave velocity in the steel penstock of

$D = 6.78\,m$, $e = 19\,mm$, $L = 244\,m$,

$E = 207\,GPa$, $\rho = 1000\,kg/m^3$, $K = 2.19\,GPa$.

The penstock has longitudinal expansion joints. $\psi = 1.0$

The air fraction in water $= 0.1\%$ $(\alpha = 0.001)$

Assume: isothermal process

$H = 50\,m$

$$a = \frac{\sqrt{K_{liq}/\rho_{mix}}}{\sqrt{1 + \frac{K_{liq}}{E}\cdot\frac{D}{e}\psi + \alpha\frac{K_{liq}}{K_{air}}}}$$

$$\alpha\frac{K_{liq}}{K_{air}} = \frac{(0.001)(2.19\times10^9)}{6\times10^5} = 3.65$$

$$\rho_{mix} = (1-\alpha)\rho_{liq} = 1000(1-0.001) = 999$$

$K_{liq} = 2.19\,GPa$, $K_{air} = p = 5\,bar + 1\,bar$

$= 6\,bar$ (absolute)

$= 6\times10^5$ (abs)

$$\sqrt{\frac{K_{liq}}{\rho_{mix}}} = \sqrt{\frac{2.19\times10^9}{999}} = 1480.6$$

$$\frac{D}{e} = 353, \quad \frac{K_{liq}}{E} = \frac{2.19\times10^9}{207\times10^9} = 0.0106$$

$$\frac{K_{liq}\,D}{E e}\,\psi = (353)(0.0106)(1.0) = 3.7418$$

$$a = \frac{1480.6}{\sqrt{1+3.74+3.65}} = 511 \text{ m/s}$$

try with $\alpha = 0.5\%$, 1% 5%

3. Transient Analysis

Surge: the term surge has been associated with the concept of mass oscillations constant along pipeline but changes with time. Generally surge is used for longer period transients or slow transients. Surges are numerically modeled with large time steps. Surges are also called mass oscillations, whereas water hammer is used for faster transients. Water hammer is numerically modeled with shorter time steps. The term pressure surge and hydraulic transients are considered to be interchangeable.

Factor of safety (FOS): In the past when numerical programs were not available, the FOS was high thus increasing the cost of the system. At present, wide variety of numerical programs are available for WDNs with complex components thereby reducing FOS and optimizing the system.

A mathematician without understanding practical aspects developed a water hammer program and which caused costly repairs and several months delay in commissioning the system. Therefore it is very important to take care of practical difficulties while coding the program. For example, a high head turbine runner was fabricated with even number of runner blades where wicket gates are also even number. This is against the principles laid down. The result was that a large number of blades were cracked in a couple of months of operation leading to expensive repair.

Initial transient study along with steady flow modeling should be carried out to reduce overall cost by installing suitable equipment at the initial construction phase.

American school of practice	European school of practice
Involves extensive use of surge protection devices relying more on cure rather than prevention.	Believes prevention is better than cure, i.e., avoiding the unacceptable surging in the first place.

Rigid column theory is used for finding preliminarily dimensions for pressure vessels and surge tanks. Selection of appropriate check valve is very important.

Motivation for hydraulic transient analysis

Strengths of pipes and pipeline fittings are of paramount importance in determining whether a design is safe.

Knowing pipe materials and allowable internal pressure is very important before transient analysis of the system.

Why transient analysis is required?

1. Flow behavior with regard to a safe operating environment.
2. Analysis is designed to predict max and minimum pressures which may develop within the pipe system during its life time and their probability of occurrence of each extreme event.
3. Unplanned or accidental changes in flow.
4. Time scale of the transient event such as time taken to establish steady state flow after a pump startup therefore suitable pump can be selected.
5. Time taken to establish steady state after an alteration of valve setting governs the selection of suitable valve.

Permitted pressures

Permitted pressure is maximum allowable pressure in a pipeline which depends on (1) strength of pipe, (2) nature of the liquid, (3) type of pipelining. For example, a brittle lining may break if pipe deforms too great. Any crack in the lining may aggravate the attack of liquid on pipe.

Maximum Pressures

Maximum pressures with respect to pipe can be obtained from the manufacturer literature. Similarly, for fittings the permissible pressures is readily obtainable from suppliers.

Pipe materials two types (1) rigid pipes, (2) flexible pipes.

Important decision variables in pipe selection is (1) design lifetime of the system (2) allowance for extensions and upgradations.

Rigid pipes

(1) Gray Cast Iron (GI pipes)

Gray Cast Iron is being used from year 1455. It is a strong pipe which can take earth pressure loadings, traffic impact and transient pressures.

Types of joints: spigot and socket, flanged and rubber gasket.

Unlined Cast Iron pipes subjected to tuberculation without lining.

Unlined pipes subjected to maximum allowable pressures as given in following table

Dia (mm)	Type	Maximum allowable pressure (bar)	Maximum allowable pressure (water head)
80-500 mm	Class-1	10	100
80-500 mm	Class-3	16	

Test pressure = 2* working pressure

CI pipes fail catastrophically.

Asbestos cement pipes

1. Pipes are usually manufactured in diameters upto 900 mm.
2. Susceptible to attack by acid, or Sulphate bearing water.
3. Brittle material which fails catastrophically

Type	Working pressure	Test pressure
Class-B	6 bar g	12
Class-C	9 bar g	18
Class-D	12 bar g	24

Concrete pipes

1. Bigger diameter (700-1200 mm) pipes available.
2. Working pressures for small diameter pipes 15 bar (g)
3. Working pressures for bigger diameter pipes 18 bar (g)
4. Pipes are very high and available in short lengths requiring more joints
5. Rubber gaskets are used to joints.

Type	Work pressure	Test pressure
Class-15	7.5 bar g	15
Class-20	10 bar g	20
Class-25	12.5 bar g	25

Flexible pipes

1. **Ductile Iron pipe**

   Working pressure is 15 bar

   Test pressure = working pressure + transient pressure=15+7 = 22 bar (g)

   Pipe diameters can go up to 1600 mm.

   Typically allowable pressure fall with increasing diameter.

   For cement lined Ductile Iron pipe, allowable deflection must be under control.

   Allowable deflection (Δ) by diameter (D) is $2 < \frac{\Delta}{D} < 4$.

2. **Steel pipe**

   Yield pressure is very high 1760-2950 bar

   Working pressure = 50% of yield stress

   Typical diameters= 150-3600 mm

   For higher grades, working pressure is more than 70 bar for diameters of 400 mm

   For lesser diameter pipes, working pressure is 20 bar (g)

Overpressure allowance

DI pipes

Overpressure allowance for transient pressures = 115% of working pressure.

Other pipes

Over pressure allowance is 100% of working pressure.

Pipe linings

Pipe linings are required for protection against corrosion. Pipelining effect frictional characteristics thus affecting head vs discharge relationship. Pipe linings have bearing on the allowable pressures so it is very important to study them.

Strength of the lining such as cement mortar decides allowable pressures in the pipeline.

Types of linings

Bitumen, coal tar enamel, coal tar epoxy, cement mortar, paints, polyethylene.

Bitumen: mixture of 80% bitumen and 20% dry lime.

Bitumen lining deteriorates with age result in loss of lining in raw water pipelines and appears like tuberculated.

Coal tar enamel: This lining is not used in potable water mains. It is used in pipes to supply water to agricultural fields.

Coal tar epoxy lining: coal tar epoxy lining is not used in potable water lines. It is lighter and may be used in pipes where weight is a consideration.

Cement mortar: Cement mortar is a standard lining for Ductile Iron steel pipes and Cast Iron pipes. This is the best lining material, however it is a brittle material which can fail catastrophically.

Maximum pipe deflection should be $\leq$ 2%.

Paints: paint is used onto steel or onto existing cement mortar lining. Paint is used to inhibit corrosion of cement mortar lining in a low pH value environment.

Polyethylene lining: Polyethylene lining is used for steel pipes to prevent corrosion in sewer pipes in aggressive environment.

Plastic pipes:

Plastic pipes do not need any painting or lining.

Plastic pipes divided into (1) Thermo setting plastics, (2) Thermo plastics and (3) Glass fibre reinforced thermosetting resins.

Thermo setting plastics:

Thermo setting plastics have greater stiffness.

Eg. Glass Reinforced Plastic (GRP), Fibre Reinforced Plastic (FRP), Reinforced Plastic Matrix (RPM)

Thermo setting plastics are poor in chemical resistance, advantage of thermo setting plastics is failure is not catastrophic. The test pressures in these pipes is upto 64 barg.

Thermoplastics:

Thermoplastics are PVC (polyvinyl chloride), polyethelene (PE). PVC pipes were developed by Germans whereas PE pipes were developed in UK.

It is well known that working pressures of PVC pipes are low.

Types of PVC pipes and their working pressures

type	Working pressure, bar g
Class B	6
Class C	9
Class D	12
Class E	15

PE (polyethylene) pipes:

PE pipes are divided into (1) LDPE, low density PE pipe, (2) Medium density PE, MDPE and (3) HDPE, high density PE pipes.

Types of PE pipes and their densities

LDPE	$0.91 < \rho < 0.925$
MDPE	$0.925 < \rho < 0.940$
HDPE	$0.940 < \rho < 0.965$

LDPE used in small bore water pipes. MDPE and HDPE water main and effluent main duties. HDPE is used for transport of slurries.

Types of HDPE pipes and their working pressures

Type	Working pressures, bar g
1	2.5
2	3.2
3	4.0
4	6.0
5	10.0

Another classification of HDPE pipes based on diameter to wall thickness (SDR ratio) is given below.

Type	SDR11	SDR17
	Working pressure (barg)	Working pressure (barg)
PE80	12.5	8.0
PE100	16	10

Failure modes of pipes:

Two pipes of failure modes are available, there are (1) collapse, and (2) brittle failure.

Brittle failure: Brittle fracture is a phenomenon in which ca long, fast brittle crack runs along the pipeline in a characteristically wavy manner.

Brittle fracture depends on hoops stress, in general < 0.5% is safe and brittle fracture do not develop. Brittle fracture in PVC pipes follows slow growth of a crack. Brittle fracture is also caused by change in mechanical properties.

Maximum pressures and allowable amplitude of surge in plastic pipes

Thermo plastic pipes generally have no over pressure allowance, i.e., working pressure = teat pressure. Thermo plastic pipes cannot take transient pressures. Their life expectancy is decreased if there is a transient event. For PVC pipes and PE pipes, over pressure allowance is 50% of workshop pressures.

Minimum pressures

Thin walled pipes, pipes have small deformation modulus are susceptible to collapse due to buckling. Fatigue damage may cause ovalization of a flexible pipe. Ovalization increase with time, finally causes collapse of pipe by reducing the pipe stiffness. During low pressures, gas cavities are formed, collapse of gas cavities may result in excessive pressures. Evolution of certain gases attack the lining such as bitumen lined steel pipes. Codes of practice recommended to maintain positive pressure in pipelines used for transporting potable water. A minimum pressure head of +2 m water head to be maintained all the time. For deeply buried pipes, minimum pressure head is more than +2 m water head.

When analysis is important

(1) Sub atmospheric pressures could be avoided in the pipeline.

(2) During pipe commissioning, transient pressure can be tested and appropriate protective measures must be implemented.

(3) ASCE (1975) published two stage checklist. Particular attention should be paid to behavior of booster pumps, air valve operation, and fast acting valves.

Pipe friction:

Friction term derived from steady flow measurements and assumed to be applicable under transient flow conditions. To find friction factor in a pipeline or tunnel, it is ideal to measure on site head loss in the field but which is not possible in many instances. Therefore selection of appropriate friction coefficient should be on the side of caution.

Especially steady flow in pumping mains, during pump selection roughness coefficient is chosen towards upper limit of the range of likely variables. This ensures that the pump selected is able to develop the necessary head. However, in unsteady flows, where velocity changes directly affect pressure transients, pressure transient may be more severe, if the velocity change is greater which implies that roughness factor should be selected at the lower end of likely values.

Generally it is correct to study surge pressures using alternative friction coefficients as a trial and error method.

$$h_L = \frac{fLV^2}{2gD} \ (Darcy\ equation)$$

$$f = \left(\frac{k}{D}, R_e\right)$$

$R_e < 2100$ Laminar for which $f = \frac{64}{R_e}$

Friction factor for transition and fully developed turbulent flow Colebrook White equation (implicit formulation) is the best.

$$\frac{1}{\sqrt{f}} = -2log10\left(\frac{2.51}{R_e\sqrt{f}} + \frac{k}{3.71D}\right)$$

More convenient formula approximating Colebrook equation is Haaland equation (1985),

$$\frac{1}{\sqrt{f}} = -1.8log10\left(\left(\frac{(k/D)}{3.7}\right)^{1.11} + \frac{6.9}{R_e}\right)$$

where k = equivalent uniform sand grain roughness height. Values of k for different pipe materials and conditions can be found in fluid mechanics books and pipe supplier manuals. While determining k value corrosion and sliming must be taken care of.

Corrosion:

Metal pipes for example steel pipes and Cast Iron (CI) pipes are expected to corrode.

Colebrook & White (1939) undertaken studies to quality increase in 'k' for older asphalted Cast Iron (CI) pipes. The rate of increase in roughness height (Δk) with time is obtained from

$2\log_{10}(12\Delta k) = 3.8 - \text{pH}$

Where Δk = ${}^{ft}/_{year}$ for cast iron pipe

The present value of k

k = k_0 + $\Delta k.t$

k_0 = new pipe roughness height

Δk = rate of increase in roughness height with time (${}^{ft}/_{year}$)

t= age of the pipe in years

Sliming

Sewage and waste water mains are liable to sliming roughness of sliming pipes is a function of velocity

k = $\alpha V^{(-2.34)}$

Where α=0.054 (lower bound)

= 0.446(mean)

= 3.660 (upper bound)

From above equation $V \rightarrow \infty$ then $k \rightarrow 0$

V = 1.0 m/s   0.15< k <0.6

V = 1.5m/s   0.06< k <0.3

V =2.0 m/s   0.03< k ≤0.15

Unsteady Friction

Steady state friction factor gives satisfactory results for computing first peak of unsteady pressure. The computed pressure oscillation show very slow dissipation (rate of dissipation) as compared to the laboratory and field tests on actual pipes. The computed results are not reliable for multiple operations such as starting the pumps following a power failure, load acceptance on turbines following load rejection and sequential starting or stopping of turbo machinery etc. several methods have been proposed to account for the unsteady friction effects in unsteady flow computations. Unsteady friction modeling is three types: (1) Quasi 2D model, (2) Convolution Integral method, and (3) Instantaneous acceleration based (IAB) methods.

Quasi 2D Models

In Quasi-2D method, continuity & momentum equations in cylindrical coordinates are solved. Flow is assumed to be Axisymmetric. Shear stress τ for laminar flow is evaluated by newton's law. For turbulent flow, a simple stress model is assumed in viscous sub layer based on newton's law, in the turbulent region or the Prandtl mixing length hypothesis. These methods are computationally intensive and have been used primarily for simple piping systems.

Convolutional Integral Methods

These methods are suitable for only 1-D models which use past histories of local accelerations and waiting functions. These methods are time consuming and require large computational memory. For laminar unsteady flows, an exact solution is available to compute unsteady friction. Recently this method has been extended to smooth and rough turbulent flows.

Instantaneous accelerated based (IAB) methods

Momentum equation

$$\frac{\partial H}{\partial x} + \frac{1}{g}\frac{\partial V}{\partial t} + J_S + J_u = 0$$

J_S = steady friction term, J_u = unsteady friction term

This method assumes that the damping is attributable to local & convective accelerations

$$J_S = \frac{f_{V|V|}}{2gD}$$

$$J_u = \frac{k}{g}\left[\frac{\partial V}{\partial t} + sign(V)\ a\ \left|\frac{\partial V}{\partial x}\right|\right]$$

(Single coefficient method)

Two coefficient model

$$J_u = \frac{1}{g}\left[k_{ut}\frac{\partial V}{\partial t} + k_{ux} sign(V)\ a\ \left|\frac{\partial V}{\partial x}\right|\right]$$

Method of characteristics

$$\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0$$

$$\frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + \frac{fQ|Q|}{2DA} = 0$$

Rewrite the governing equations as following

$L_1 = \frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + RQ|Q| = 0$

$L_2 = a^2\frac{\partial Q}{\partial x} + gA\frac{\partial H}{\partial t}=0$

Where R = $\frac{F}{2DA}$

Let us write linear combination of equations (1) & (2)

L= L_1+ λL_2 = 0

$(\frac{\partial Q}{\partial t} + \lambda a^2\frac{\partial Q}{\partial x}) + \lambda gA(\frac{\partial H}{\partial t} + \frac{1}{\lambda}\frac{\partial H}{\partial x}) + RQ|Q|= 0$ ……………(3)

H & Q are functions of space & time

Let us write total derivatives

$\frac{dQ}{dt} = \frac{\partial Q}{\partial t} + \frac{\partial Q}{\partial x}\frac{dx}{dt}$ ….(4)

$\frac{dH}{dt} = \frac{\partial H}{\partial x} + \frac{\partial H}{\partial x}\frac{dx}{dt}$ ……(5)

Eq.(3) can be written as

$\frac{dQ}{dt} + \lambda gA\frac{dH}{dt} + RQ|Q| = 0$ ……..(6)

$\frac{dx}{dt} = \lambda a^2$ $\quad\frac{dx}{dt} = \frac{1}{\lambda}$, $\quad\lambda = \pm\frac{1}{a}$ ………………..(7)

$\frac{dQ}{dt} + \frac{gA}{a}\frac{dH}{dt} + RQ|Q|= 0$……..(8), $\quad\frac{dx}{dt} = a$……………..(9)

$\frac{dQ}{dt} - \frac{gA}{a}\frac{dH}{dt} + RQ|Q|= 0$……..(10), $\quad\frac{dx}{dt} = -a$……………..(11)

It may be noted that Eq. (8) is valid if Eq. (9) is satisfied and Eq. (10) is valid if Eq. (11) is satisfied.

$$a_m = \sqrt{\frac{1}{\left[\rho_l\left(1-\frac{\alpha_0 P_0}{P}\right)+\rho\alpha_0 g_0\right]\left(\frac{\alpha_0 P_0}{P^2}+\frac{1}{K_l}+\frac{D_c}{E_c e}\right)}}$$

Mathematical model of cavity collapse

A mathematical model based on the MOC was developed upstream boundary condition was a centrifugal pump. The d/s boundary condition is a constant head reservoir.

The effect of the entrained air in the pipeline is assumed to be concentrated at discrete air cavities.

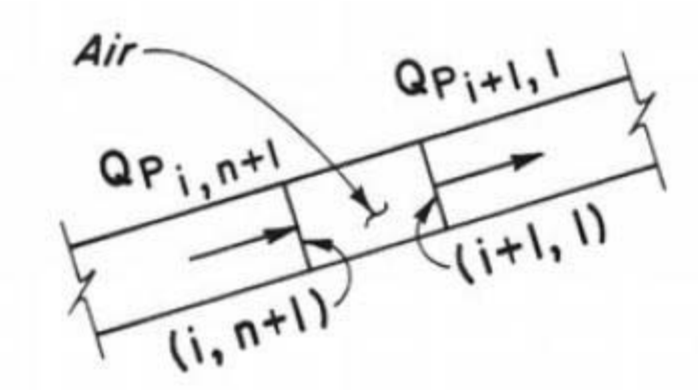

Fig. 5.3 Cavity model

The volume of the air cavity

$$\forall_i = \alpha A_i L_i$$

α is void fraction

A_i=cross sectional area of pipe

L_i= Length of pipe

The expansion and contraction of the air pocket is assumed to follow the polytropic equation for a perfect gas

$$H_{P_{i,n+1}} \forall_{P_i}{}^{m} = C \quad (1)$$

$\forall_{P_i}$=volume of the air pocket at the end of time step

$H_{P_{i,n+1}}$=water head above the datum at section $(i, n+1)$ at the end of time step (absolute pressure)

C = a constant determined from the initial steady state condition for the air pocket.

The exponent m = 1.0 for isothermal process m = 1.4 for adiabatic process

The continuity equation at the cavity may be written as

$$\forall_{P_i} = \forall_i + 0.5\Delta t\left[\left(Q_{P_{i+1,1}} + Q_{i+1,1}\right) - \left(Q_{P_{i,n+1}} + Q_{i,n+1}\right)\right] \quad (2)$$

In which Δt = size of the time step

$\forall_i$ and $\forall_{P_i}$ volumes of the air cavity at the beginning and end of the time step; $Q_{i,n+1}, Q_{P_{i,n+1}}$ are the flowrates a the upstream end of the air cavity at the beginning and at the end of time step and $Q_{i+1,1}$ and $Q_{P_{i+1,1}}$ are the flowrates at the downstream end of the air cavity at the beginning and end of the time step.

Volumes of the variables at the beginning of the time step are known and at the end of the time step are unknown.

$$Q_{P_{i,n+1}} = C_P - C_{a_i} H_{P_{i,n+1}} \quad (3)$$

$$Q_{P_{i+1,1}} = C_n + C_{a_i} H_{P_{i+1,1}} \quad (4)$$

If the head losses at the junction are neglected, then

$$H_{P_{i+1,1}} = H_{P_{i,n+1}} \quad (5)$$

Five unknowns ($\forall_{P_i}, Q_{P_{i,n+1}}, Q_{P_{i+1,1}}, H_{P_{i,n+1}}, H_{P_{i+1,1}}$) are determined from Eqs. (1) to (5) by an iterative technique.

Design considerations

A pipeline may be designed to withstand pressures generated b re-joining separated columns such a design however may be uneconomical. Therefore various control devices or appurtenances to prevent cavitation and column separation are considered to obtain an overall economic design. The following devices are employed to prevent column separation.

a) Air chambers,
b) surge tanks,
c) fly wheels,
d) air inlet valves, and
e) Pressure relief valves and pressure regulating valve.

1. Air chambers and surge tanks are usually costly.
2. Increasing motor inertia by means of a fly wheel.
3. By providing a pressure relief valve or a pressure regulating valve, the pressure rise following column separation may be reduced by letting the columns re-join under controlled conditions.

4. Air inlet valves are provided to prevent sub atmospheric pressures in the pipeline. However, admitted air has to be removed from the line prior to refilling

The selection of the surge control devices are mainly based on the (1) the cost and ease of maintenance and flexibility of operation.

Transient control

A piping system may be designed with a liberal factor of safety to withstand possible maximum and minimum pressures. Such a design is however uneconomical. Therefore a factor of safety is chosen depending upon the risks and the probability of occurrence of a particular operating condition during the life of the project, i.e., the higher the probability of occurrence, the higher is the factor of safety.

Based on the frequency of occurrence, operating condition may be classified as normal, emergency or exceptional.

Normal operating conditions

All operations that are likely to occur several times during the life of a system are termed as normal.

1. Manual/Automated starting or shutting down of pumps if there are multiple pumps all are shut downed simultaneously
2. Check valve slam

A FOS of 3 based on the ultimate bursting strength of the member and FOS=3 against collapse are recommended for the transient pressures caused by the normal operations.

Emergency

The emergency operating conditions in pumping systems are those in which one of the transient control devices malfunctions. These conditions include

(1) One of the surge suppressors, surge tanks, or relief valves is inoperative
(2) Closure of the check valve is delayed during the power failure and slams at the time of maximum reverse flow.
(3) Air inlet valves are inoperative

Since the probability of occurrence of these conditions is rather small, a FOS=2 based on the ultimate bursting or collapsing strength as recommended.

Exceptional

Exceptional conditions are those in which the protective equipment fails to function in the most unfavourable manner such as loss of all air in the air chamber, very sudden abnormal opening or closing of a valve or a gate and pump shaft failure. Because, the probability of occurrence of any of the conditions is extremely remote, a FOS of 1.25 based on the ultimate bursting or collapsing strength may be used.

Maximum pressure rise, i.e., maximum transient state pressure – steady state pressure, should be limited to 10% rated head of the pump, however it must be reduced to less than 5%

To eliminate or to reduce undesirable transients such as high or low transient pressures, column separation and excessive pump or turbine over speed control devices such as surge tanks, air chambers, and valves are utilized. Control devices are usually costly and there is no single device that suitable for universal applications on all systems or to handle all operating conditions. Therefore to design a piping system a number of alternatives with and without control devices are considered. The alternative that gives an overall economical system, an acceptable system response and desired flexibility of operation is selected. Here, various devices commonly used to eliminate undesirable transients are presented.

Surge Tank

A surge tank is an open chamber or a tank connected to the pipeline for transient control. This tank reflects the pressure waves and supplies or stores excess water resulting from the operation of turbines pumps or control valves.

Rapid transients in a pipe system having a surge tank may be analysed by using the method of characteristics. However, slow transients, e.g., oscillations of the water level in a surge tank following a load change on a turbine may be analysed as a lumped system.

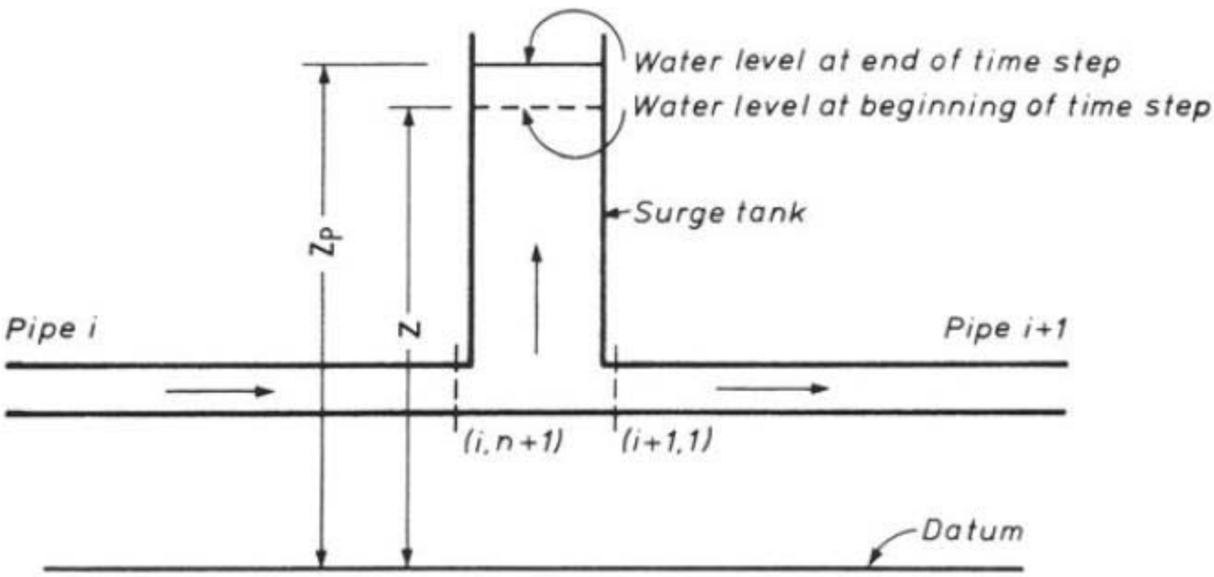

Fig. 5.4 Free body diagram of a surge tank

The head loss at the junction of the tank and the pipe is small and neglected.

PCE: $$Q_{P_{i,n+1}} = C_P - C_{a_i} H_{P_{i,n+1}}$$

NCE: $$Q_{P_{i+1,1}} = C_n + C_{a_{i+1}} H_{P_{i+1,1}}$$

CE: $$Q_{P_{i,n+1}} = Q_{P_{i+1,1}} + Q_{PS}$$

Where Q_{PS} = flow into the tank at the end of the time step (flow into the tank is considered positive), Q_P and H_P are discharge and head at the end of time step, respectively.

Energy Equation (EE): $H_{P_{i,n+1}} = H_{P_{i+1,1}} = Z_P$

Surge tank water level:

Let Z and Z_P be the heights of the liquid surface in the tank above the datum at the beginning and at the end of the time step. Note that Δt is small.

$$Z_P = Z + \frac{1}{2}\frac{\Delta t}{A_s}(Q_{PS} + Q_S)$$

Where A_s = horizontal cross sectional area of the tank, Q_S= flow into the tank at the beginning of the time step.

Solving above equations for $H_{P_{i,n+1}}$

$$H_{P_{i,n+1}} = \frac{C_P - C_n + Q_S + \left(\frac{2A_s Z}{\Delta t}\right)}{C_{a_i} + C_{a_{i+1}} + \left(\frac{2A_s}{\Delta t}\right)}$$

It was assumed that the length of the stand pipe between the pipeline and tank is short and therefore may be neglected.

Air Chamber

An air chamber is a vessel with compressed air at its top and water in its lower part. To restrict the inflow into or outflow from the chamber, an orifice is provided between the chamber and the pipeline. The orifice creates more head loss for inflow into the chamber than for a corresponding outflow from the chamber. Such an orifice is called as differential orifice. To prevent column separation, the outflow from the chamber should be energy loss efficient, while the inflow may be restricted to reduce the size of the chamber. The ratio of head loss between inflow and outflow is 2.5. Since the volume of air may be reduced due to leakage or due to solvation in the water after period of operation, an air compressor is provided to keep the volume of the air within the limits.

To prevent reverse flow a check valve is provided between the pump and the air chamber. Upon power failure, the pressure in the pipeline drops and water outflows from the air vessel into the pipeline.

When the flow in the pipe reverses, the check valve closes instantaneously, and water flows into the chamber. Because of the inflow or outflow from the chamber, the air in the chamber contracts or expands and the pressure rise and drop in the pipeline are reduced due to energy dissipation.

As compared to a surge tank, air chamber has the following advantages.

1. The volume of an air vessel required for keeping the maximum and minimum pressures within the prescribed limits is smaller.
2. An air chamber can be installed with its axis parallel to the ground. This reduces foundation costs and reduced wind and earth quake loads.
3. An air chamber can be located near the pump due to its reduced weight and smaller volume. This reduced maximum and minimum transient pressures.

4. To prevent freezing in cold countries, it costs less to heat an air chamber than a surge tank because of smaller size.

Disadvantage of an air chamber is that requirement of an air compressor and supporting equipment.

The method of characteristics is used for the transient analysis of an air vessel.

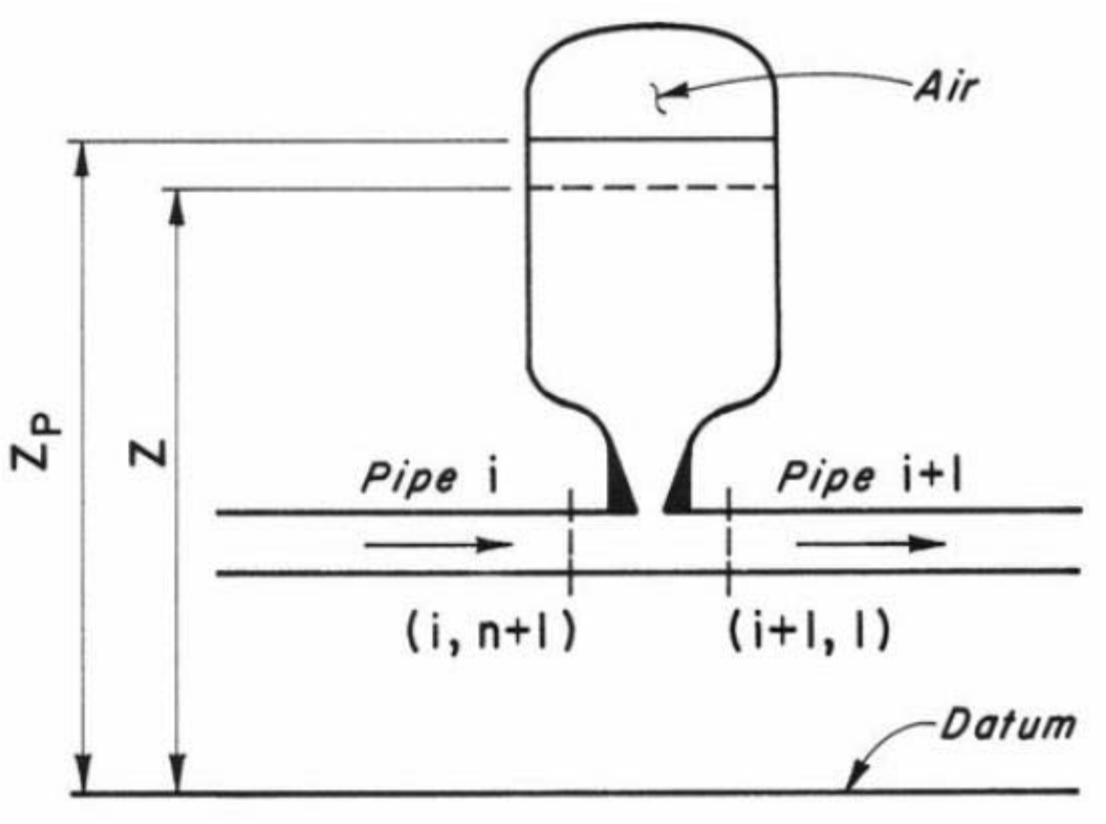

Fig. 5.5 Free body diagram of an air vessel

PCE: $$Q_{P_{i,n+1}} = C_P - C_{a_i} H_{P_{i,n+1}}$$

NCE: $$Q_{P_{i+1,1}} = C_n + C_{a_{i+1}} H_{P_{i+1,1}}$$

CE: $$Q_{P_{i,n+1}} = Q_{P_{i+1,1}} + Q_{p_o}$$

Where Q_{p_o} = flow into the air vessel at the end of the time step (flow into the tank is considered positive), $Q_P$and $H_P$are discharge and head at the end of time step, respectively.

Energy Equation (EE): $H_{P_{i,n+1}} = H_{P_{i+1,1}} = Z_P$

Another equation is required which gives relation between inflow into the tank and change of pressure in the air vessel.

$$H_{P}{}_{air}^{*} \forall_{P}{}_{air}^{m} = C$$

$H_{P}{}_{air}^{*}$ and $\forall_{P_{air}}$ are pressure head and volume of the enclosed air at the end of the time step, respectively.

$$C = H_{P}{}_{0air}^{*} \forall_{P}{}_{0air}^{m}$$

Here '0' refers to the steady state condition.

m = 1.0 for isothermal condition

m = 1.4 adiabatic expansion or contraction.

m = 1.2 is recommended

The headloss for the flow through the orifice may be expressed as

$$h_{p_o} = C_o Q_{p_o} \left| Q_{p_o} \right|$$

C_o is coefficient of orifice losses

h_{p_o} headloss through orifice for a flow of Q_{p_o}

$H_{P}{}_{air}^{*} = H_{P_{i,n+1}} + H_b - Z_P - h_{p_o}$

H_b=barometric pressure head

$$\forall_{P_{air}} = \forall_{air} - A_s(Z_P - Z)$$

$$Z_P = Z + 0.5\left(Q_O + Q_{p_o}\right)\frac{\Delta t}{A_s}$$

A_s = cross-sectional area of air vessel

Z and Z_P are the height of the water surface in the vessel above the datum at the beginning and at the end of the time step.

Finally there are nine equations and nine variables. These nine equations are reduced to two equations.

$$Q_{p_o} = (C_P - C_n) - (C_{a_i} + C_{a_{i+1}})H_{P_{i,n+1}}$$

$$\forall_{P_{air}} = \forall_{air} - A_s(Z_P - Z)$$

$$\left(H_{P_{i,n+1}} + H_b - Z_P - C_o Q_{p_o}\left|Q_{p_o}\right|\right)\left[\forall_{P_{air}}\right]^m = C$$

Valves

Here different types of valves and their boundary conditions for transient analysis is carried out by the method of characteristics is presented.

Transients are controlled by the following valve operations.

1. The valve opens and closes to reduce the rate of net change in the pipeline flow velocity.
2. If the pressure exceeds a set limit, the valve opens for rapid outflow which causes the pressure to drop thus reducing the maximum pressure.
3. The valve opens to admit air into the pipeline thus preventing the pressure from dropping to the sub atmospheric pressure.

Valves commonly used for transient control are

1. Safety valves
2. Pressure relief valves
3. Pressure regulating valve
4. Air inlet valve
5. Check valve

Safety valve:

Safety valve is a spring or weighted loaded valve which opens as soon as the pressure inside the pipeline exceeds the pressure limit set on the valve and closes abruptly when the pressure drops below the specified limit. A safety valve is either fully open condition or fully closed condition, no intermediate condition.

Pressure relief valve (surge suppressor)

Pressure relief valve is similar to that of a safety valve except that its opening is proportional to the amount by which the pressure in the pipeline at the valve exceeds the specified limit. The valve proportionately closes when the pipeline pressure drops and is fully closed when