UNIT 15 WATER HAMMER AND SURGE TANKS

Structure

15.1 INTRODUCTION

In this unit we will be discussing a class of unsteady flows. As you know, the flow is classified as unsteady or steady depending on whether the flow characteristics such as discharge, velocity, pressure etc. at a point change with time or not. The analysis of unsteady flows is rather complicated except that some unsteady flow problems can be solved without much difficulty under simplifying assumptions. Water hammer and surge tanks are two such situations, wherein the flow unsteadiness involves slow periodic or cyclic fluctuations, and it is these Periodic Flows which we propose to discuss.

Objectives

After studying this unit, you should be able to

* understand the phenomenon of water hammer,
* compute the rise in pressure due to water hammer, and
* understand the necessity and working of a surge tank.

15.2 WATER HAMMER

Water hammer is a phenomenon encountered in a pipe line, when the velocity of the flowing liquid is suddenly reduced by closing a valve. Such a closure results in sudden and large rise in pressure due to the change in inertia of the fluid and a hammering sound is produced. In many cases this continues with regular periodicity unless the periodic motion is damped out. This phenomenon can cause problem like bursting of pipe lines - specially if they are long and is very important in case of penstocks which carry water from a storage to a power house.

To get a clear concept of the phenomenon of water hammer, let us consider a long pipeline with a valve at the downstream end. The pipeline is discharging some fluid and the valve is suddenly closed.

Phase I

When the valve is open, the hydraulic gradient line for the flow is given by CD, when the valve is closed instantaneously the lamina of fluid in contact with the valve is brought to rest and it will be compressed by the rest of the fluid flowing against it causing a rise in pressure p. At the same time, the walls of the pipe surrounding this lamina will be stretched by the excess pressure produced. In other words the kinetic energy of the fluid is converted into the strain energy of water and pipe. This process continues upstream and a pressure wave travels in the upstream direction (from B to A) at a speed equal to the velocity of sound C. When the pressure wave reaches the end A, all the fluid in the pipe is at rest and the whole pipe is at an excess pressure with a hydraulic gradient shown by line EF. This condition occurs at time $T = L/C$.

Phase II

The increased pressure p in the pipe causes the fluid to flow from A to the reservoir, thus relieving the excess pressure. A wave of pressure unloading travels back from A to B with a velocity C, and all the strain energy gets converted into kinetic energy.

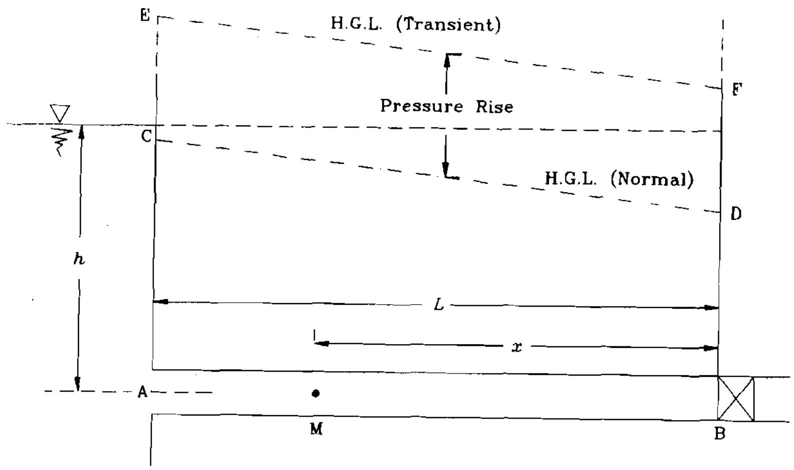

Figure 15.1 : Definition Sketch

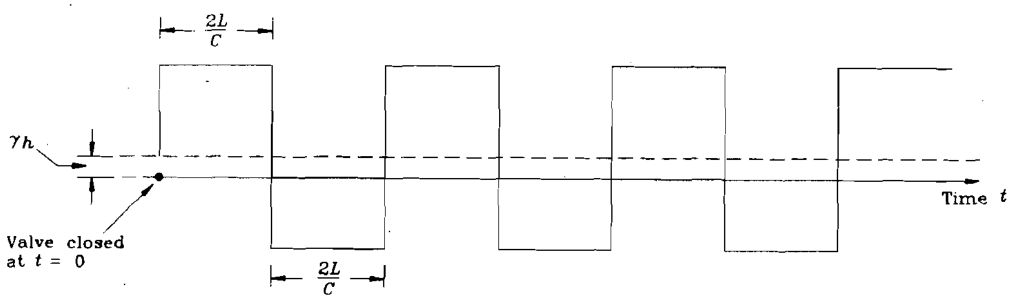

Figure 15.2 : Pressure Variation at B

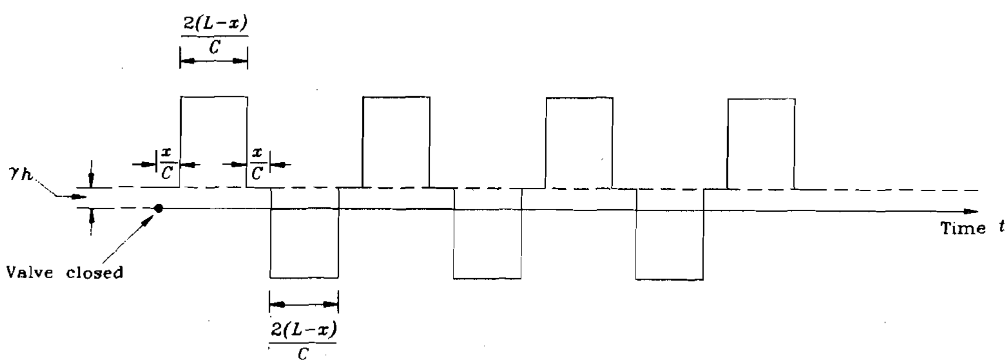

Figure 15.3 : Pressure Variation at M

15.2.1 Expression for Rise in Pressure

[A] Slow Closure

If the valve is closed slowly, such that the time of closure is several times larger than $\frac{2L}{C}$, the maximum pressure rise will be less than that in case of a rapid closure. This is so because the wave of pressure unloading will reach the valve before its complete closure and will thus prevent any further rise in pressure.

We can get an expression for the rise in pressure in such a case making use of the momentum equation.

Thus if the initial velocity of flow in the pipe is V_0 and the time of closure of the valve is $t_c \left(t_c \geq \frac{2L}{C} \right)$, the rate of retardation of flow will be $\frac{V_0}{t_c}$.

The mass of water in the pipe will be ρAL where ρ is the mass density of water and A the area of cross-section of the pipe.

If the pressure rise due to closure of the valve is Δp, then the force will be ΔpA.

Equating the force to the product of the mass and deceleration we get

$$\Delta pA = \rho AL \frac{V_0}{t_c}$$

or $$\Delta p = \frac{\rho L V_0}{t_c} \qquad (15.1)$$

[B] Rapid Closure

If the time of closure of the valve is less than $\frac{2L}{C}$, it is termed as a rapid closure. In fact if the valve is closed instantaneously i.e., $t_c = 0$. Equation (15.1) will give an infinite pressure rise. Practically however, the pressure rise is finite and this is at time $T = \frac{2L}{C}$, this wave reaches B and the pipe is at normal pressure with the fluid flowing back into the reservoir.

Phase III

The reverse velocity from pipe to the reservoir has to be stopped and therefore the pressure at B drops down to $-p$, thereby sending a wave of rarefaction from B to A with velocity C. This wave reaches A at time $T = \frac{3L}{C}$ when all the liquid in the pipe is stationary and at a negative pressure p.

Phase IV

The liquid now flows back into the pipe again and at time $T = \frac{4L}{C}$, the whole liquid in the pipe is moving towards B with the original velocity and at normal pressure.

The cycle of events now repeats. The variation of pressure with time at representative points B and M is shown in Figures 15.2 and 15.3.

The pipe friction and damping are not considered in the above discussion. Due to these two effects, the amplitude of this pressure wave will go on diminishing. So because in the case of an instantaneous closure, the compressibility effects became important.

We can obtain the expression for pressure rise in rapid closure as follows :

Let,

the initial velocity of flow in the pipe	$= V_0$
diameter of the pipe	$= D$
thickness of pipe walls	$= t$
bulk modulus of elasticity of the fluid	$= E_f$
modulus of elasticity for the pipe material	$= E_m$
and specific weight of the fluid	$= \gamma$

Then,

volume of fluid in the pipe	$= \frac{\pi}{4} D^2 L$
original kinetic energy of the fluid	$= \frac{\gamma}{g} \frac{\pi}{4} D^2 L \frac{V_0^2}{2}$

As already mentioned, this kinetic energy is stored as the strain energy in the fluid and the pipe when the valve is closed.

Strain Energy of the fluid $= \frac{1}{2} \Delta p \times$ change in volume.

and Strain energy of the pipe $= \frac{f^2}{2E} \times$ volume .

Where f is the hoop stress in the pipe and $f = \frac{\Delta p\, D}{2t}$

To fluid the change in volume of the pipe, we recall the definition of the Bulk modulus of elasticity K.

$$E_f = \frac{\Delta p}{\left(\frac{\text{change in volume}}{\text{original volume}}\right)}$$

or Change in volume $= \frac{\Delta p}{E_f} \times$ Original volume

$$= \frac{\Delta p}{E_f} \frac{\pi}{4} D^2 L$$

$\therefore$ Strain energy of fluid $= \frac{1}{2} \Delta p \frac{\Delta p}{E_f} \frac{\pi}{4} D^2 L$

and Strain energy of pipe $= \frac{f^2}{2E_m} \pi D L t = \frac{\Delta p^2 D^2}{4 t^2} \frac{1}{2E_m} \pi D L t$

Equating the original kinetic energy and the strain energies, we get

$$\frac{\gamma}{g} \frac{\pi}{4} D^2 L \frac{V_o^2}{2} = \frac{1}{2} \Delta p \frac{\Delta p}{E_f} \frac{\pi}{4} D^2 L + \frac{\Delta p^2 D^2}{4 t^2} \frac{1}{2 E_m} \pi D L t$$

or

$$\frac{\gamma}{g} V_0^2 = \Delta p^2 \left[\frac{1}{E_f} + \frac{D}{t E_m}\right]$$

or

$$\Delta p = V_0 \sqrt{\frac{\gamma}{g\,[\,1/E_f + D/(tE_m)\,]}} \qquad (15.2)$$

Further, we know that the velocity of propagation of a wave (C) is given by

$$C = \sqrt{\frac{K}{\rho}}$$

Where K is the overall volume modulus of elasticity of the fluid.

When the pipe is rigid, i.e. $E_m \to \infty$, $K = E_f$, While if E_m is finite K is given by

$$\frac{1}{K} = \frac{1}{E_f} + \frac{D}{t E_m}$$

Thus the expression for pressure rise equation (15.2) can also be written as

$$\Delta p = \rho C V_o \qquad (15.3)$$

Where

$$C = \sqrt{\frac{K}{\rho}}$$

and

$$K = \frac{E_f}{1 + \frac{D}{t} \frac{E_f}{E_m}}$$

In case the closure time t_c is slightly greater than $\frac{2L}{C}$, we can assume that the pressure rise is reduced in proportion to $\frac{2L}{C} \frac{1}{t_c}$, yielding

$$\frac{\Delta p}{\Delta p_{max}} = \frac{2L}{C} \frac{1}{t_c} \qquad (15.4)$$

Where Δp_{max} is the pressure rise given by equation (15.3)

Example 15.1 :

A 20 cm dia pipe carries water at a velocity of 3.0 m/s. Find the rise in pressure if a valve at the end of the pipe is suddenly closed. Treat the pipe to be rigid and take $E_{water} = 2.08 \times 10^9 \text{ N/m}^2$.

Solution :

$$V_o = 3.0 \text{ m/s}$$

$$E_{water} = 2.08 \times 10^9 \text{ N/m}^2$$

Density of water $\rho_w = 998 \text{ kg/m}^3$

$$\therefore \quad C = \sqrt{\frac{E}{\rho}} = \sqrt{\frac{2.08 \times 10^9}{998}} = 1443.66 \text{ m/s}$$

$\therefore$ Rise in pressure $\Delta p = \rho\, C\, V_o$

$$= 998 \times 1443.66 \times 3$$

$$= 4322332 \text{ N/m}^2$$

$$= 4322.33 \text{ kN/m}^2$$

Example 15.2 :

A 100 cm diameter 50 km long steel pipe with a thickness of 10 mm carries water at a rate of 2.0 m^3/s. What will be the increase in pressure if a valve at the downstream end of the pipe is closed in (a) 3 seconds (b) 11 seconds.

Take E for steel and water as 2.08×10^{11} N/m^2 and 2.08×10^9 N/m^2 respectively.

What will be the pressure rise in (a) above if the pipe is treated as being rigid.

Solution :

Here $E_f = 2.08 \times 10^9 \text{ N/m}^2$ and $E_m = 2.08 \times 10^{11} \text{ N/m}^2$

$D = 1 \text{ m}, \quad t = 10 \times 10^{-3} \text{ m}$

$$\therefore \quad K = \frac{E_f}{1 + \frac{D}{t}\frac{E_f}{E_m}} = \frac{2.08 \times 10^9}{1 + \frac{1}{10^{-2}}\frac{2.08 \times 10^9}{2.08 \times 10^{11}}}$$

$$= 1.04 \times 10^9 \text{ N/m}^2$$

$$\therefore \quad C = \sqrt{\frac{K}{\rho}} = \sqrt{\frac{1.04 \times 10^9}{998}} = 1020.82 \text{ m/s}$$

$\therefore$ Time required for pressure wave to travel from the valve to the inlet and back

$$= \frac{2L}{C} = \frac{2 \times 5000}{1020} = 9.8 \text{ seconds}$$

(a) Since closing time $t_c = 3$ secs. is smaller than $\frac{2L}{C}$ (9.85)

$$\Delta p = \rho\, C\, V_o$$

$$V_o = \frac{Q}{\frac{\pi}{4} D^2} = \frac{2.0 \times 4}{\pi\, 1^2} = 2.546 \text{ m/s}$$

$$\therefore \quad \Delta p = 998 \times 1020.82 \times 2.546$$

$$= 2594298 \text{ N/m}^2$$

$$= 2594.30 \text{ kN/m}^2$$

(b) If closing time is 11seconds, it is slightly more than 9.85 and hence

$$\frac{\Delta p}{\Delta p_{max}} = \frac{2L}{C}\frac{1}{t_c}$$

$$\Delta p_{max} = 2594.30 \text{ kN/m}^2, \quad \frac{2L}{C} = 9.8 \text{ sec}, \quad t_c = 11 \text{ sec}.$$

$$\Delta p = 2594.30 \times \frac{9.8}{11} = 2311.29 \text{ kN/m}^2$$

If the pipe is treated as rigid

$$C = \sqrt{\frac{E_f}{\rho}} = \sqrt{\frac{2.08 \times 10^9}{998}} = 1443.66 \text{ m/s}$$

$$\therefore \quad \Delta p = \rho\, c\, V_o = 998 \times 1443.66 \times 2.55 = 3673.97 \text{ kN/m}^2$$

Thus we see that the pressure rise is overpredicted if the elasticity of the pipe is neglected.

SAQ 1

When will the rise in pressure due to water hammer be more - if the pipe is rigid or if the pipe is elastic - other conditions remaining the same?

SAQ 2

If the time of closure of a valve is greater than $\frac{2L}{C}$, will the pressure rise be more or less than the corresponding value for an instantaneous closure.

15.3 RAPID ACCELERATION OF FLOW

Let us consider the pipe AB connected to a reservoir as shown in Figure 15.1. It is apparent that if friction is neglected, the velocity V_o through the pipe is given by

$$V_o = \sqrt{2gh}$$

Let us, however, consider a slightly different situation i.e., having a valve at B which is closed to start with. If this valve is opened suddenly, the velocity of flow in the pipe does not attain a value V_o instantaneously but increases gradually. It can be shown than assuming the fluid to be incompressible and neglecting friction, the time T taken for the velocity to attain a value V can be given by

$$T = \frac{L}{\sqrt{2gh}} \ln \left[\frac{1 + \frac{V}{U_o}}{1 - \frac{V}{U_o}} \right] \tag{15.5}$$

Two facts are apparent from the above equation viz. that the time required to attain V equal to V_o is infinity, though V may become almost equal to V_o in a relatively short time and that the time required for V to become nearly equal to V_o will be more for a longer pipe.

If on the other hand, we take the compressibility of flow into account, it can be shown that when the valve at B is opened suddenly, the velocity in the pipe increases in steps of magnitude $V_1 = g\frac{h}{C}$ where C is the velocity of propagation of a wave as defined earlier. Each such increase takes place at a time interval of $\frac{2L}{C}$ and the total number of time steps required for the flow to establish completely will be $\frac{V_0}{V_1}$.

15.4 SURGE TANKS

Surge tanks are large diameter vertical open tanks provided just upstream of hydro-electric power plants.

Before talking about surge tanks, let us try to discuss the problems we may face in hydroelectric power plants. As you know, in such plants turbines convert the potential energy of water into mechanical energy. The water stored in reservoir upstream of dams is carried to the power plant by means of large diameter pipes called penstocks. These penstocks generally are quite long - at times, a few kilometer in length. Depending on the power demand, the discharge through the turbines may have to be increased or decreased. A turbine may have to be shut down sometimes or started as the demand increases. Whenever a turbine is shut down, the closure of the valve at the turbine end is going to result in water hammer and hence increased pressures throughout the penstock. The penstock must therefore, be designed to withstand these increased pressures and in case of long penstocks, this may prove very costly. Likewise, whenever a turbine is started the time required for the flow to establish will be considerable in case of long penstocks. It is desirable, therefore, to reduce the length of pipe in which the effects of water hammer pressures or flow establishment are felt. This purpose is achieved by providing surge tanks.

The working of a surge tank can be understood with reference to Figure 15.4. A surge tank is a tank connected to the penstock quite close to the powerhouse.

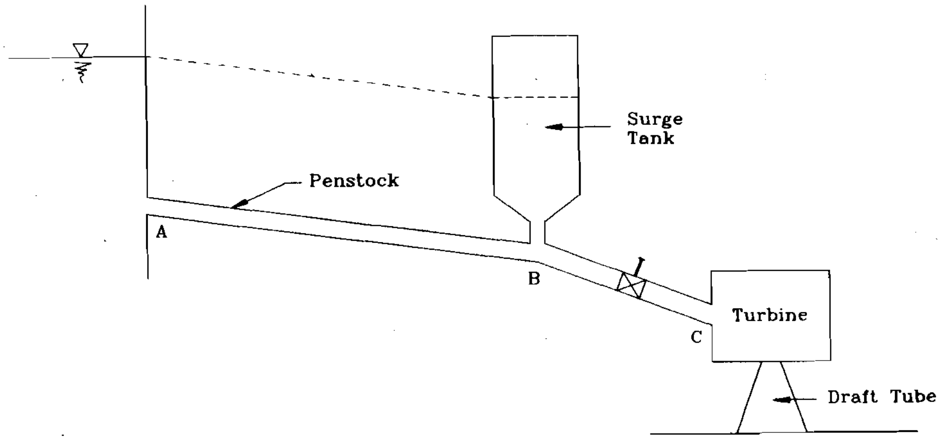

Figure 15.4 : Schematic Diagram of Surge Tank

Let us consider a situation, when due to load rejection, the valve at the turbine is closed suddenly. The water hammer pressure wave travels upstream from C. However, at B this causes a rise in water level of the tank and relieves the penstock upstream from B of the water hammer pressures. Thus only the length BC has to be designed to withstand water hammer.

In case the valve at the penstock is opened suddenly, the surge tank supplies additional flow, till the water in the whole pipe is accelerated.

The surge tank thus acts as a balancing reservoir and helps in both load rejection and increased demand. There are various types of surge tanks viz. simple, restricted orifice, differential etc. Also, the stability of surge tanks is an important criterion for their design. This, however, is beyond the scope of the present course and hence not discussed further.

15.5 SUMMARY

This Unit is primarily devoted to a discussion of Water Hammer - a phenomenon which occurs when a valve at the downstream end of a pipeline carrying a liquid is suddenly closed. This causes a rise of pressure in the pipe which is influenced both by the time of closure of the valve, as well as, the elasticity of the pipe. Expressions for this pressure rise have been obtained. A sudden opening of a valve at the downstream end of a long pipeline gives rise to the problem of establishment of the flow, which has also been discussed briefly. Finally the utility of surge tanks for both the aforesaid situations has been indicated.

15.6 KEY WORDS

Minor Loss : Hydraulic loss in pipe lines on account of different forms and fittings in pipe line and other than those due to friction.

Equivalent Pipe : A hypothetical pipe line of uniform diameter resulting in the same head loss as in the actual pipe line.

Pipe Network : Pipes of different length and diameters connected in different ways.

15.7 ANSWERS TO SAQs

SAQ 1

Pressure rise will be more for a rigid pipe (Ref. Example 15.2)

SAQ 2

The pressure rise will be less, if the time of closure is more than $\frac{2L}{C}$

(Ref. Example 15.2)