## Fluid Mechanics - Course 123

## WATER HAMMER

---

We have considered steady state flow where the fluid is considered incompressible and have examined the effects of directional changes in flow. An everyday event that is worthy of examination is the unsteady flow phenomenon produced by change in flow rate. It is quite possible that the increases in pressure caused by water hammer are sufficient to fracture pipework and for this reason alone, the study of the mechanism involved is of considerable practical importance.

If the flow rate changes occur rapidly, the elastic forces become significant. As a result of the elasticity of the fluid and also the lack of perfect rigidity of the boundary walls, changes in pressure do not take place instantaneously throughout the fluid, but are propagated by pressure waves. A change of velocity at a particular point in a fluid always gives rise to a change of pressure and an important instance of such pressure changes is the phenomenon known as 'Water Hammer' in pipe lines. The terminology is perhaps a little unfortunate because not only water but any fluid - liquid or gas - may be involved.

It is a common experience that when a faucet is turned off very quickly, a heavy knocking sound may be heard and the entire pipe vibrates. These effects follow from the rise in pressure brought about by the rapid deceleration of the water in the pipe when the tap is turned off. A similar phenomenon may occur with a pump due to the slamming shut of a non-return valve when the pump is shut down.

To see why it is necessary to account for the elasticity of the fluid we may first consider the simple case of a fluid, originally flowing with a certain velocity in a pipe, being brought to rest by the closing of a valve at the downstream end of the pipe. If the fluid was entirely incompressible and the walls of the pipe were perfectly rigid, then all the particles in the entire column of fluid would have to decelerate together. From Newton's Second Law, $F = mA$, the more rapid the deceleration the greater would be the corresponding force and with an instantaneous closure of the valve all the fluid would be stopped instantaneously and the force would be infinite. However, even a liquid is to some extent compressible and so its constituent particles do not decelerate uniformly. An instantaneous closure of the valve would not bring the entire column of fluid to a halt instantaneously, only those particles of fluid in contact with the valve would be stopped at once and others would come to rest later. Although an instantaneous closure of a valve is not possible in a practice, an extremely rapid closure may be made and the concept of instantaneous valve closure is valuable as an introduction to the study of the actual event.

When a faucet is suddenly closed, the knocking sound produced may be heard not only at the faucet but also - and often just as strongly - elsewhere in the house. It is evident that the disturbance, caused by the sudden closing of the faucet, must travel along the pipe to other parts of the system. Consider the instantaneous closing of a valve in a pipeline. Just before the closure, the pipe is full of fluid moving with a certain velocity. If the valve is suddenly closed, the fluid immediately next to the valve is stopped whilst the fluid farther upstream continues to move as though nothing had happened. Consequently, the fluid next to the valve is compressed slightly; its pressure is increased and the pipe (no longer assumed rigid) expands slightly as a result of the increased pressure. The next element of fluid finding an increased pressure in front of it, too comes to rest and is compressed, expanding the pipe slightly.

Each of the fluid column elements thus stops the following element, until all the fluid in the pipe has been brought to rest. At this point in time the pressure wave has travelled to the upstream end of the pipe and the whole of the pipe is at an elevated pressure.

Similarly, on the downstream side of the valve the pressure is reduced and a wave of lower pressure moves downstream which also reduces velocity. If the closure is rapid enough and the steady state pressure low enough, cavitation may be produced downstream from the valve.

At the point in time when the upstream flow has stopped, all the fluid is at the elevated pressure, all the momentum has been lost and all the kinetic energy has been converted into elastic energy by compressing the fluid and stretching the pipe wall. This presents an unbalanced situation at the upstream end of the pipe because the source pressure has not changed and the pressure difference is such as to cause the fluid to flow in the reverse direction, commencing with the upstream end of the pipe. This reverse flow returns the pressure to the normal valve before closure, the pipe wall returns to normal and the fluid has reverse flow at the same rate as existed in the normal direction. At the instant when the normal pressure wave returns to the valve, the whole system has returned to its normal pressure and the fluid velocity is - its original value - in the reverse direction.

Since the valve is closed, no fluid is available to maintain flow at the valve and a low pressure develops such that the fluid is brought to rest. This low pressure wave travels upstream and brings the fluid to rest causing it to expand because of the lower pressure and allowing the pipe wall to contract. If the static pressure in the pipe is not sufficiently high the liquid may vapourize and continue to move in the reverse direction over a longer period of time.

At the instant the low pressure wave arrives at the upstream end, the fluid is all at rest but at the low pressure, which is less than the pressure prior to closure. This again leaves an unbalanced condition at the upstream end of the line and fluid flows into the pipe acquiring the original velocity and returning the pipe and fluid to normal conditions as the wave progresses downstream.

The speed of the pressure wave in the fluid is equal to the speed of sound in the fluid, which in turn depends upon the Bulk Modulus of the fluid and the Modulus of Elasticity of the pipe material in relation to the wall thickness.

It therefore follows that the time taken for the pressure wave to travel the length of the pipe, L is L/a secs where a = speed of sound.

Thus, a complete cycle takes 4 L/a secs. The action of fluid friction and imperfect elasticity of fluid and pipe wall is to damp out the vibration and eventually cause the fluid to come permanently to rest. Closure of a valve in less than 2 L/a secs is termed 'rapid closure'; 'slow closure' refers to closure times in excess of 2 L/a secs. The speed of sound in the fluid for a non rigid pipe is given by the following expression:

$$'a' = \left[ \frac{E_B}{\ell \left( 1 + \frac{E_B \times d}{E \times t} \right)} \right]^{\frac{1}{2}}$$

Where $E_B$ = Bulk modulus of the fluid.
$E$ = Modulus of elasticity for pipe material.
$\ell$ = Density of fluid.
$d$ = Inner pipe diameter.
$t$ = Pipe wall thickness.
(All in consistent units)

<u>Change in Pressure</u> = density x velocity of sound x change of velocity

$$= \underline{\underline{\ell \times a \times dV}}$$

Example

Water @ 30°C is flowing along a 16" SCH 40 line @ 0.5 $m^3/s$. A control valve shuts in 1.8 secs, the line is 1500 m long.

(E for pipe = $200 \times 10^9$ Pa)

Calculate

(a) The speed of sound in the fluid.

(b) Whether the closure is 'rapid' or 'slow'.

(c) The maximum pressure rise.

(d) The increase in the circumferential pipe stress.

(a) Speed of sound in the fluid = a = $\left[\dfrac{E_B}{\ell\left(1 + \dfrac{E_B \times d}{E \times t}\right)}\right]^{\frac{1}{2}}$

For water @ 30°C from table

$= 995.7 \text{ kg/m}^3, \; E_B(k) = 223 \times 10^7 \text{ Pa}$

16" SCH 40 $\quad d = 15"$

$t = 0.5"$

$$\text{Thus } a = \left[\frac{223 \times 10^7}{995.7\left(1 + \dfrac{223 \times 10^7 \times 15}{200 \times 10^9 \times 0.5}\right)}\right]^{0.5}$$

$$= \left[\frac{223 \times 10^7}{995.7(1 + 0.3345)}\right]^{\frac{1}{2}}$$

$$= (1.678 \times 10^6)^{\frac{1}{2}} = \underline{\underline{1295.47}} \text{ m/s}$$

(b) Rapid closure $t < \dfrac{2L}{a}$

$$= \frac{2 \times 1500}{1295.47} = 2.32 \text{ secs}$$

Thus the closure of 1.8 secs is a 'rapid' one.

(c) $\Delta P = \ell \times a \times dV$

$$Q_V = A \times V \quad \therefore \quad V = \frac{0.5}{1140 \times 10^{-4}} = \underline{\underline{4.39\ m/s}}$$

$$\Delta P = 995.7 \times 1295.47 \times 4.39$$

$$= \underline{\underline{5.66\ MPa}}$$

(d) Thin walled cylinder circumferential stress

$$= \frac{P \times radius}{thickness\ of\ wall} = 2 \times longitudinal\ stress$$

$$= \frac{5.66 \times 10^6 \times 15}{0.5 \times 2}$$

$$= \underline{\underline{84.9\ MPa}}$$

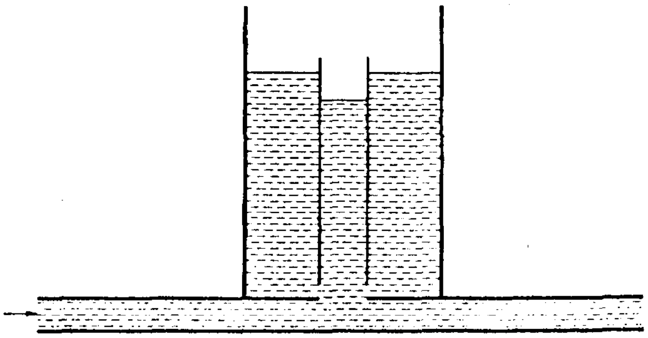
Many of the problems associated with water hammer may be circumvented by the use of a surge tank. In hydro electric plants, for example, the turbines must frequently be supplied with water via a long pipeline or a tunnel cut through rock. If the power output is suddenly changed and the flow rate changes, the consequent acceleration or deceleration may give rise to water hammer.

The pipeline still has to be capable of withstanding water hammer when surge tanks are used but the pressures are lower.

Surge tanks may be classed as simple, orifice or differential. The simple surge tank has an unrestricted opening into it and must be large enough not to overflow or not to be emptied, allowing air to enter the pipeline. It should also be of a size that will not fluctuate in resonance with the system. The period of oscillation of a simple surge tank is relatively long.

The orifice surge tank has an orifice between the pipeline and tank and therefore allows a more rapid pressure change than the simple surge tank. The losses through the orifice aid in dissipating the excess available energy which results from a valve closure.

The differential surge tank is, in effect, a combination of an orifice surge tank and a simple surge tank of small cross-sectional area. In the case of rapid valve opening a limited amount of liquid is directly available from the central riser and flow from the large tank supplements this flow. For sudden valve closures the central riser may be designed so that it overflows into the outside tank.



Differential surge tank.

Surge tanks operating under air pressure are utilized in certain circumstances, eg, after a reciprocating pump. They are generally uneconomical for large pipelines.

Another means of controlling surge and water hammer is to supply a quick opening bye pass valve that opens when the control valve closes. The quick opening valve has a controlled slow closure at such a rate that excessive pressure is not developed in the line. The bye pass valve washes liquid, however, and does not provide relief from surge due to opening of the control valve or starting of a pump.

## ASSIGNMENT

1. Discuss how the sonic velocity and pressure change are affected when considering a compressible fluid such as steam.

2. A line carries water at a pressure of 3 MPa(g) and at 60°C. A control valve in the 800 m long line, which is 10" SCH 40 shuts in 0.8 secs. The flow rate is 0.5 $m^3/s$. The maximum tensile force in the line is not to exceed 300 MPa. Calculate the longitudinal and circumferential stresses and determine if over stressing has occurred.

3. The Bruce bulk steam line is 1500 m long, 66" O.D. 65" I.D. The flow rate is 700 kg/s, $V_g = 140.72 \times 10^{-3}$ $m^3/kg$.

($E_{STEEL} = 200 \times 10^9$ Pa, $E_B = 1.56$ MPa)

Determine the maximum time for fast closure.

Determine the maximum stress in the pipe under fast closure if normal operating pressure is 1.415 MPa(a).

J. Irwin-Childs