Fluid Mechanics - Course 223

WATERHAMMER

We have looked at steady state flow situations where the fluid is considered to be incompressible. We have examined the effect of a jet of liquid and the effects of directional change in flow on the containment system.

One important aspect, which is a common everyday event that is worthy of examination, is the result of changing the steady state conditions by altering the flowrate.

The flowrate is altered every time a control valve is opened or closed. These events produce an acceleration or retardation of the flow. As we have already seen from the force momentum equation, if there is an acceleration, then energy levels change and forces are created.

If the changes in flow are gradual, then we may analyse the problem in a simple state by considering the liquid to be incompressible and the containment to be rigid.

In practice, as in most other situations, life is never as simple as we would sometimes wish it! If the flow is altered rapidly, then we must recognise that the liquid is compressible and that the containment is elastic, ie, if a force is applied, the material will elastically deform and return to its original configuration when the force is removed.

Before we consider the full implications of rapid closure let's examine what happens to the system initially. When a valve is rapidly closed in a pipeline during flow, the flow through the valve is reduced. This increases the pressure on the upstream side of the valve, because the KE is converted into pressure energy, and this causes a high pressure pulse to be sent up-stream. The effect of this pressure pulse is to decrease the velocity of flow.

At the same time, on the downstream side of the valve the pressure is reduced, because pressure energy is being converted into KE to try and maintain flow, and a wave of low pressure travels downstream, which also reduces the velocity. If the closure is rapid enough and the static pressure low enough, cavitation may occur downstream from the valve. When the vapour pocket collapses, a high pressure wave downstream will be produced.

The process is reversed and repeated and an understanding of the mechanism and the parameters upon which it depends is important. We will look again at the effect produced by rapidly reducing the flow by closing the valve. At the instant of valve closure, when time = 0 seconds, the fluid nearest the valve is compressed and brought to rest and the pipe wall is stretched. As soon as the first layer is compressed, the process is repeated for the next layer. The liquid upstream from the valve continues to move downstream with undiminished speed, until successive layers have been compressed back to the end of the system. Thus, to summarise, a high pressure wave moves upstream bringing the liquid to rest as it passes, compressing it and expanding the pipe. When the wave reaches the upstream end of the pipe, all the liquid is at the higher pressure, all the momentum has been lost and all the KE has been converted into elastic energy, ie, energy used in expanding the pipework and compressing the liquid.

The time taken for the wave to reach the end of the system is dependent upon the speed of sound in the liquid and the length of pipe. Thus the time taken for the wave to reach the source is given by:

$$t = \frac{\text{Length of Pipe}}{\text{Speed of Sound}}$$

You can see that the velocity of the shock wave is independent of initial velocity, flowrate, pipe diameter or pressure of the fluid. It is, however, a function of the temperature.

When the high pressure wave arrives at the upstream end of the line, there is, at that instant, an unbalanced condition because the supply pressure remains unchanged. The liquid now starts to flow backwards, beginning at the upstream end. The flow returns the pressure at the valve to normal before closure, the pipe wall returns to normal and the liquid has a velocity equal to its original value but in a backward or reverse direction. Again this occurs at the speed of sound in the liquid. Thus the time when the wave returns to the closed valve =

$$\frac{2 \times \text{Length of Pipe}}{\text{Speed of Sound in the Liquid}}$$

At the instant when the wave arrives at the closed valve, all the pressures are back to normal but the whole of the flow is in the reverse direction at the magnitude of the original velocity.

Since there is no further liquid available to maintain flow at the valve, a low pressure develops and the liquid is brought to rest. The low pressure wave travels upstream, again at the speed of sound, bringing the liquid to rest; causes it to expand and allows the pipe walls to contract.

This is the third time that the wave has traversed the length of the pipe and thus the time from closure to this point =

$$\frac{3 \times \text{Length}}{\text{Speed of Sound in the Liquid}}$$

Now the situation is reversed, the fluid has all come to rest but is all at a lower pressure than existed before closure. Again an unbalanced condition arises at the supply point and liquid flows into the system. The whole liquid acquires velocity of the same magnitude and the same direction as before closure. When the wave reaches the closed valve the total path travelled is four lengths of the pipework and the time taken is thus:

$$\frac{4 \text{ Lengths}}{\text{Speed of Sound in the Liquid}}$$

This whole process is repeated every -

$$\frac{4L}{a}$$

secs. 'a' = speed of sound in the liquid. The whole process is repeated until fluid friction, elasticity of the fluid and pipe dampen out the vibration and the system comes to rest.

This is the basic concept of waterhammer. The rate at which closure occurs is of paramount importance. If the valve closes instantaneously a 'rapid closure' is postulated and the whole of the system is subjected to the high pressure. If the valve closes at a medium rate then the pressure rise is not so great and the damping effect is greater, such that only the local area upstream from the valve is affected. If there is a gradual closure rate then the pressure rise is relatively low and limited to the immediate area of the valve.

A common, everyday event may be used to illustrate the mechanism of waterhammer. Consider a locomotive pulling a number of rail cars, the locomotive and rail cars are in equilibrium relative to each other and are all travelling at the same speed. Suddenly, the emergency brakes operate and the locomotive comes to a rest. The rail cars behind the locomotive continue to travel forward until all the couplings have been compressed and the caboose has come to rest. At this point in time all the kinetic energy has been converted into stored energy within the couplings.

With no kinetic energy, there is an energy imbalance and the stored energy in the couplings starts to push the rail cars in the reverse direction. The locomotive remains stationary throughout this operation. At the point when all the stored energy has been released, all the rail cars are moving in the reverse direction. The couplings are now the only constraint. Thus the car nearest the locomotive stops travelling in the reverse direction first and finally the caboose.

There is again an imbalance due to the decelerating force applied by the couplings and the rail cars start to move in the direction of the applied force, ie, towards the locomotive, starting with the first rail car and ending with the caboose. Thus all the cars are once again moving forwards and possess kinetic energy. This is the same point in the cycle that we considered initially. The exercise continues until the KE has been used in doing work in moving the cars and compressing the couplings. This analogy is closely the same situation which occurs with the body of fluid in waterhammer.

For interest, rapid closure is defined as the time less than -

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

'a' = speed of sound in a liquid = $\sqrt{K/\rho}$

Where K = Bulk modulus for the fluid
ρ = density

Example

Consider water in a line 100m long and at 55°C.

What is the closure rate at which the whole of the system would be subjected to high pressure shock wave?

$$\text{Time} = \frac{2L}{a} \qquad a = \sqrt{K/\rho}$$

$$K = 23.1 \times 10^7 \text{ N/m}^2$$

$$\rho = 985.7 \text{ Kg/m}^3$$

$$\text{Thus } a = \sqrt{\frac{2.31 \times 10^7}{985.7}} = \underline{1.53 \times 10^3 \text{ m/s}}$$

$$\text{Time} = \frac{2L}{a} = \frac{2 \times 100}{1.53 \times 10^3}$$

$$= \underline{0.13 \text{ secs}}$$

We have seen that pressure which is generated is directly a function of the rate at which the valve is closed. How can we reduce waterhammer? Initially, this may be achieved by reducing closure rates. This is fine, unless time is essential, as in a hydraulic turbine when an overspeed situation could result in damage if the electrical load was removed and the water flow maintained. In this situation there is no option but to close the control valve as quickly as possible.

How is the waterhammer accommodated? We have already seen that the waterhammer is damped by fluid and pipework effects. Additional features may be added to reduce the effect of waterhammer.

Surge tanks may be installed close to the source of the shock to control the pressure changes resulting from rapid changes in flow.

In a pumping situation, where there is a long discharge line, it is possible that the negative surge can cause the water column to separate. If the water column separates, extremely high pressure may be generated when the column reforms. The installation of an air chamber on the discharge side of the pump ensures that the discharge pressure is maintained as the pump runs down, before the check valve closes, thereby reducing velocity changes. The reverse flow, in the discharge line, is cushioned by the air in the chamber.

ASSIGNMENT

1. Describe 'waterhammer' in your own words.

2. What is the speed of the pressure wave in a waterhammer situation?

3. What is the velocity of flow in the reverse flow situation?

4. How can waterhammer be avoided?

5. How may the effects of waterhammer be reduced? Detail four plant situations.

6. Where would you expect to find waterhammer? Describe how the flow is reduced.

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