Check Valve contra Water Hammer

When fluid in motion is abruptly stopped, high-pressure shock waves are generated in a pipeline. This unsteady state phenomenon, caused by the sudden change between kinetic energy and pressure energy is often referred to as water hammer or hydraulic transient. The induced pressure can amount to six times the system’s operating pressure destroying pipe walls, flanges, valves and fittings. When no relief devices are provided, the shock wave will travel back and forth until friction dissipates the excessive pressure in the pipeline.

According to the theories derived by Joukowski and Allievi, the water hammer head $\Delta H$ is calculated from the formula:

$$\Delta H = \frac{c \cdot v_0}{g}$$

where:
- $c$ = wave celerity or speed of the transient wave,
- $v_0$ = fluid velocity immediately before it was stopped,
- $g$ = gravitation constant (9.806 m/s$^2$)

The speed of the transient wave $c$ depends on the density and elasticity of the flowing liquid as well as the pipeline characteristics (diameter, wall thickness and material elasticity).

In case of water flowing in a steel pipeline we may use the following simplified formula: $\Delta H(m/WC) \equiv 110 \cdot v_0$.

The most common causes of water hammer are:
- sudden closing or opening of valves,
- pump start-up,
- pump shut-down due to switching-off or power failure

Starting or stopping the pump can cause water hammer provided no flow decelerating devices are used.

In everyday practice, the case of generating water hammer by sudden closing or opening of valves rarely takes places (sudden closing means in time usually less than 2 seconds). Most of the shut-off valves found in the water systems today are gate valves and/or butterfly valves. The design of the closing system of these valves, i.e. the threaded stem of the gate valve and the gearbox of the butterfly valve, make it impossible to close them quickly. This could happen in case of butterfly valves equipped with a hand lever, however, usually the maintenance staff is fully aware of the danger such action could create.

When referring to quick-closing valves in our systems, we usually think of solenoid valves and control valves. Indeed, these valves can close very quickly and depending on the system configuration create a considerable water hammer. Therefore, the effect of application of these valves in a given installation should be carefully studied beforehand.
Pump start-up also stops fluid in motion. The dynamically propelled by the pump fluid is abruptly stopped when it contacts the inert and static fluid in the pipeline creating a shock wave. In order to avoid this phenomenon, the pump should always be started with the downstream isolation valve completely closed. Once the pump is on, by the gradual opening of the valve we can control the acceleration of the fluid in the system and thus avoid the water hammer.

The water hammer generated when the pump is shut-off is most dangerous and difficult to control, especially when the pump suddenly stops due to power failure. When a pump stops, the fluid in a pipeline continues to flow with diminishing velocity until its kinetic energy is expended to overcome the head losses and the pipeline gradient. Simultaneously, the pressure at the pump outlet is decreasing and in the end it drops below the system’s static pressure. Next, due to the differential pressure in the pipeline, the water column is reversed in the direction of the check valve with a growing reverse velocity \( v_r \). The closed check valve generates the water hammer when it abruptly stops the returning mass of fluid. As the returning flow slams into the pump's check valve, its kinetic energy is converted into high-pressure surges. According to the earlier mentioned Joukowski’s theory, the value of the water hammer head \( \Delta H \) directly corresponds to the reverse velocity \( v_r \) measured in front of the check valve before the flow is stopped. Actually, the velocity of the return flow is very difficult to assess. Generally, it depends on the system configuration and particularly on the design of the check valve installed downstream of the pump.

When the pump is stopped, the system will always force the flow to return through the check valve. How fast this happens is a measure of the deceleration rate of the particular system. The deceleration of the system depends on piping configuration (its gradient, pipeline outlet, other downstream pressure sources). Regardless of the initial velocity of the flow (before the pump shut-off), the reverse velocity \( v_r \) is dependent only upon the deceleration of flow and the closing time of the check valve. As long as the deceleration rate shows the potential of the system to develop the reverse velocity, the check valve decides to what eventual value the reverse velocity grows. Recapitulating, the quicker the check valve closes the smaller the reverse velocity is developed.

Dynamic flow testing of check valves conducted by Delft Laboratories in the Netherlands and independently at Utah Water Research Laboratory brought the following conclusions:

- Reverse velocities and pressure surges are greater for valves with a larger mass of valve components.
- Reverse velocities are greater for valves with larger strokes or longer travel of the components to close.
- Reverse velocities are less for valves that are spring assisted to close.
- Reverse velocities will be greater for valves with increased friction in the valve shafts, guides, and other components.
The above conclusions are justified because of the increased time necessary to overcome the inertia of the valve internal parts and the distance they must travel.

The figure below is a comparison plot of the tests of three different check valves tested at different initial velocities (i.e. velocities before the pump shutdown). We can see that the relationship between reverse velocity and flow deceleration is independent of initial velocity.

Reverse velocity - f/s

Flow deceleration - f/s²

The comparison plot also proves, that the center-guided and spring-assisted check valves by closing quickly allow for considerably smaller return velocity (and thus water hammer) than the traditional simple swing check valves.

It may seem confusing to find quick-closing check valves generating smaller water hammer when compared to the first case presented in this paper – the sudden closing of a valve. Both cases are different. During the long closure of a gate valve we actually reduce the initial speed of the water column traveling in the pipeline. In case of the check valve, its quick closing limits the accelerating speed of the returning fluid. However, in both cases the velocity of the fluid slamming into the closed valve is decisive for the magnitude of the resulting water hammer.