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Experimental investigation of check valve behaviour during the pump trip

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Abstract. The paper is focused on the description of an experimental investigation of a nozzle check valve. Attention is paid to the behaviour during transitions when the flow is decelerating. Flow reversal is often accompanied with the check valve slam, because the check valve closes with a delay after the flow changes its direction. The maximal back flow velocity determines the maximal pressure peak when the check valve closes, so this velocity was found for different flow decelerations.

1. Introduction

The check valve is supposed to prevent flow reversal in a system. Typically, check valves are placed in the discharge pipe immediately behind the pump, but they can be placed anywhere, where only one directional flow is desired. Basic demands on check valves are: low resistance in the positive flow direction and infinite resistance in the negative flow direction (no leakage).

There are many different designs of check valves with different properties, but all of them try to fulfill the two basic demands written above. Several examples of design are: ball check valve, swing check valve, tilted disc check valve, dual disc check valve, nozzle check valve, etc. It is not an easy task to choose the best check valve for a specific system and, according to [1], many criteria should be taken into account: The initial cost, the maintenance cost, the head loss, the flowing fluid, the flow characteristic and others including the non-slam characteristic, which describes the potential of the check valve to slam. When the flow decelerates, e.g. due to pump stop, the check valve is supposed to shut precisely at the moment when the flow velocity reaches zero, so that no reverse flow appears. However, the check valve closes with a shorter or a longer delay, when some reversal flow velocity has already developed. Sudden closure immediately stops the water column and causes water hammer. Check valve slam can damage the check valve and cause problems anywhere in the hydraulic system.

One can see that the selection of the most suitable check valve is not an easy task and requires a deep knowledge of the entire system and it is not possible to find a specific design appropriate for all systems.

Regarding safety and reliability, the non-slam characteristic of the check valve is crucial. There are many cases when the piping was damaged by the check valve slam [2], [3] and [4].

Generally, there are two ways to prevent problems with check valve slam. The first way is to secure fast closing, when the flow reverses. According to [5], who cites [6], fast closing requires: low inertia of the disc and low friction, the travel of the disc should be short or the motion should be assisted with springs. Similarly, the role of a spring could be fulfilled by a counterweight, which also helps with closing.

The other way is to slow down closing. In this case, a high reverse flow can evolve and closing has to be slow enough to avoid the water hammer effect and the vortex structures creation [7]. The time period of closing depends on the system and it can be even several minutes. Slow closing is often secured by oil dashpots. Devices slowing down closing have to be robust enough to withstand the hydraulic forces acting on the check valve disc. Authors of this article have already seen systems where dashpots were completely destroyed.

Obviously, the behavior of the check valve during flow reversal is important and the non-slam characteristic gives an indication of the suitability of the specific check valve for the system. This characteristic shows maximal reverse velocity which develops in the system before closing of the check valve. It is, however, necessary to obtain the deceleration value of the system, for example by computation using a special software allowing simulation of the unsteady flow in pipelines.

2. Experiments

MSA, the Czech producer of check valves, is widening their product line and needs to know the dynamic characteristics of the check valves. For the first test, we got a nozzle check valve of an old design to obtain data which will serve for comparison. The first step was building an experimental circuit which allows flow reversal. The circuit scheme is shown in figure 1.

A suction tank (volume 10 m^3) feeds a pump with water, which is pumped through a discharge pipe DN100 into a small tank (volume 2.5 m^3). The water can flow back to the suction tank through a return pipe. The small tank can be pressurized with the compressor and depressurized with an air valve. The check valve is installed in the straight part of the discharge pipe, which has a length of 6 m. The scheme of the check valve is shown in figure 2. The body of the check valve is equipped with a window, so that it is possible to observe the position of the disc. This is the only possibility, because the check valve is compact and no moving parts are outside of the body.

The pump speed is controlled with a dynamometer which also measures torque and speed of the pump. The steady flow rate is measured with an electromagnetic flowmeter (Q in figure 1) and pressure is measured with six pressure sensors – BD sensors DMP 331 (three pieces are mounted on the pipe wall in front of the check valve and thee sensors are behind the check valve).

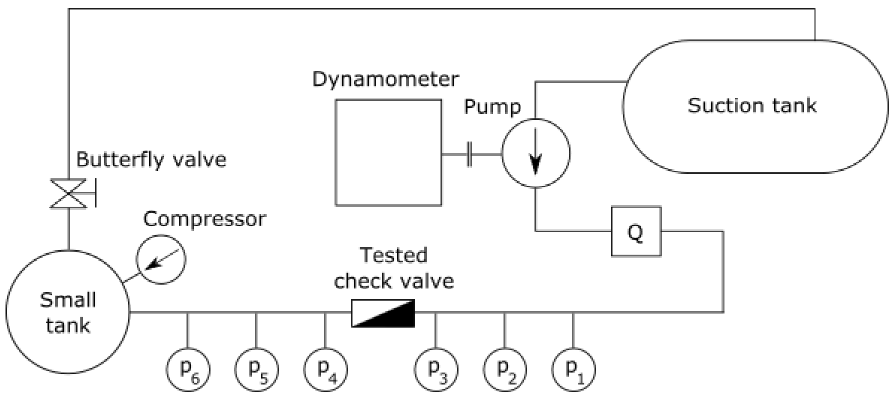

Figure 1. Test circuit.

The steady characteristic of the check valve can be determined using data from the flowmeter and nearest pressure sensors (p_3 and p_4 in figure 1) while the small tank is full of water. The butterfly valve must be open to allow water to circulate in the system.

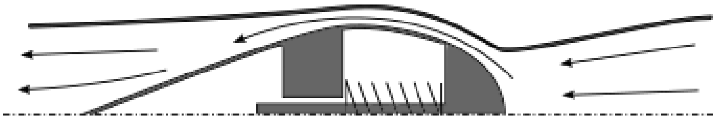

Figure 2. Nozzle check valve.

When dynamic characteristic is measured, the butterfly valve is closed and only 20% of the small tank is filled with water. The experiment starts when the pump runs with steady speed. The flow rate reaches its maximal value and starts going down due to increasing pressure in the small tank (the air in the tank is compressed). Then, the pump is braked so the deceleration becomes more intense. The flow changes its orientation and the check valve closes with a slam.

2.1. Static characteristic

For evaluation of the static characteristic, data from pressure sensors p_3 and p_4 (pressure loss) were used together with data from the flowmeter. Flow coefficient was computed according to equation (1) and the result is shown in figure 3.

$$K_v = 10Q\left(\frac{\rho}{\Delta p}\right)^{1/2} \tag{1}$$

The flow coefficient is changing with the flow rate. The higher flow rate the higher force acts on the spring and the check valve is more open. The stiffness of the spring is 2550 N/m. It was measured in the absence of water. The positon of the disc was determined from pictures taken with a camera during the experiment. The mean position for given flow rate was taken as the disc was not steady but slowly oscillating around the mean position. This is a prevention from getting stuck due to rust or limescale and reduces the risk that the disc does not close when the flow rate goes to zero. Maximal valve opening is 50 mm.

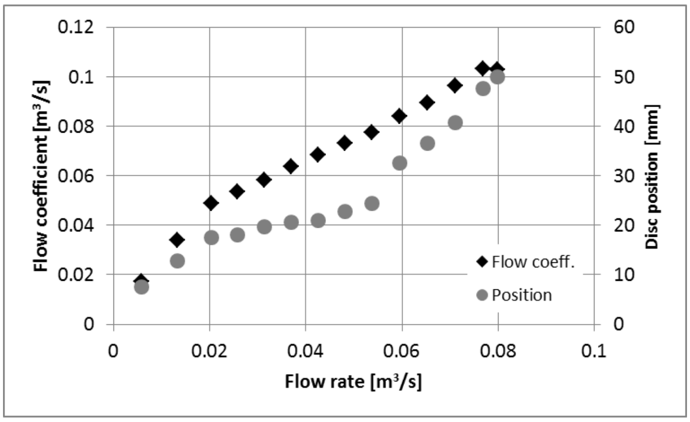

Figure 3. Static characteristic of tested nozzle check valve.

2.2. Dynamic characteristic

Dynamic characteristic shows a relationship between fluid deceleration and maximal reverse flow velocity through the check valve. As the electromagnetic flowmeter is not suitable for the measurement of unsteady flow, Gibson (the so-called time-pressure) method was used to obtain flow rate data, see equation (2).

$$Q(t+\Delta t) = Q(t) - \frac{\Delta t S}{L\rho}\left[\Delta p(t) + RQ(t)|Q(t)|\right] \tag{2}$$

Δp, in equation (2), can be substituted with the pressures in front of the check valve p_1 and p_3 or behind the check valve p_4 and p_6. The results correspond to each other since there is no column separation. Figure 4 shows the evaluated flow rate according to equation (2).

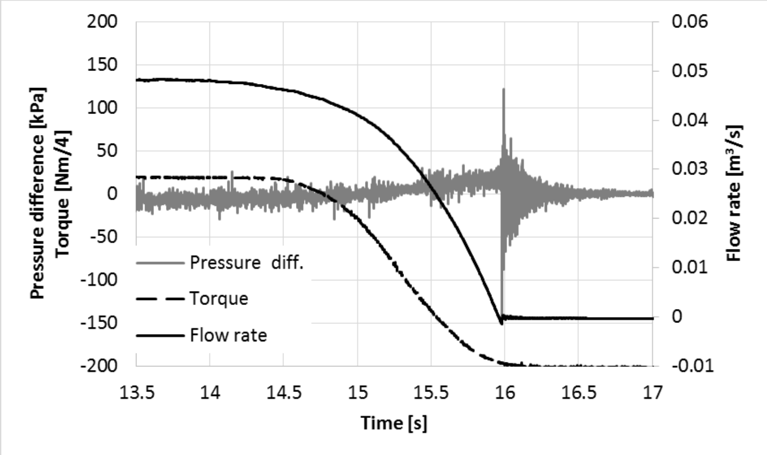

Figure 4. Flow rate change during pump braking.

Figures show pressure difference in front of the check valve. The pump started being braked when the flow rate was 48 l/s in this case. The maximal reverse flow rate was found 1.4 l/s, then the disc hit the seat and caused water hammer.

The limitation of the dynamometer is 800 Nm in either direction. This value defines maximal deceleration that can be reached in this system. In this case, the limit was reached after the check valve shut.

There is a question how to define the flow deceleration dv/dt. [5] uses the time period when the flow rate reaches zero from steady state without any further comments and value of steady flow velocity is used for velocity difference dv. [8] defines the time period from the moment when the downstream pressure starts increasing to the moment when this pressure reaches its maximal value. Velocity difference is the sum of the steady flow velocity and the maximal reverse velocity.

We determined expression dv/dt from the time when the torque at dynamometer is zero until the time when the reverse flow rate reaches maximal value. From figure 4: dt=15.98-14.77 and dv=(0.0448+0.0014)/S. Complete results are plotted in figure 5 and compared with results by [5].

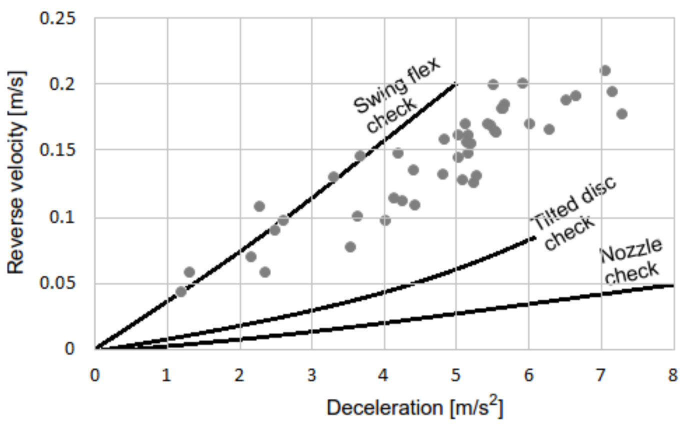

Figure 5. Dynamic characteristic of measured nozzle check valve (spots) and results by [5] (solid lines).

3. Summary and discussion

Static and dynamic characteristics of a nozzle check valve were measured. The check valve was mounted into the test circuit and, at first, the static characteristic was determined. Beside the flow coefficient, the disc position was observed with the camera. For dynamic characteristic determination, the flow deceleration was induced with the dynamometer which braked the pump. Maximal deceleration rate was 7.3m/s^2. The obtained results were compared with results presented in [5].

Unlike the static characteristic, the dynamic characteristic measurement is not treated in the standards. Different authors use different approach to the measurement as well as to the evaluation. Definition of deceleration rate dv/dt is crucial in this case. We decided to use two clearly identifiable points: the moment when the torque of the dynamometer is zero (pump starts braking) and the moment when the reverse flow rate is maximal (disc is hitting the seat). This can be one of the reasons why results by [5] vary noticeably (figure 5). Other reasons can include different construction of the check valve, different mass of moving parts or different spring stiffness, so the comparison is rather informative.

The measured points are scattered because they were obtained from different initial flow rates, so the disc opening varied and closing time depends on the current opening.

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Table 1. Nomenclature.

Symbol	Unit	Meaning	Symbol	Unit	Meaning
K_v	m^3/s	flow coefficient	S	m^2	pipe cross-section
L	m	length	t	s	time
p	Pa	pressure	Δp	Pa	pressure difference
Q	m^3/s	flow rate	Δt	s	time difference
R	kg/m^7	resistance	ρ	kg/m^3	density

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