Water hammer in valves - solutions to improve stability

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1. Introduction

Very strong pressure pulses or surges, also referred to as water hammer, often occur in fluid-conducting pipes. The stresses on the pipes, valves and apparatus can be so high that the equipment concerned is damaged – or in extreme cases actually bursts. Before effective measures can be taken to combat this problem, it is important to analyse exactly which kind of water hammer is involved and what causes it. Yet no matter how carefully a facility is planned and constructed, the risk of pressure surges cannot always be completely ruled out, particularly if the plant is modified or extended or the operating mode changes frequently. If the plant components are designed with sufficient stability, half the battle is won.

2. Causes of water hammer

Water hammer in pipes can have a variety of causes. A basic distinction is drawn between hydraulic water hammer and thermal water hammer.

2.1. Hydraulic water hammer and cavitational hammer

If a globe valve (e.g. a butterfly valve) is closed abruptly while liquid is flowing through a pipe, the fluid flow immediately comes to a standstill and the kinetic energy is converted to pressure energy, in other words a water hammer pulse is produced upstream of the valve. This pulse is propagated at sound velocity from the point of origin against the original flow direction and reflected at points of discontinuity (vessels, pipe ends, etc.). The shock waves generally travel back and forth several times; they gradually lose their intensity due to dissipation be-fore finally fading away.

The pressure increase downstream of a fast-acting valve can be approximated using the classic Joukowski equation [1]:

$$\Delta p = \rho \cdot a \cdot \Delta \mathrm{v} \qquad (1)$$

Δp	Pressure increase [Pa]
ρ	Fluid density [kg/m]
a	Sonic speed [m/s]
$\Delta \mathrm{v}$	Change in flow velocity [m/s]

The pressure surge reaches its maximum height when: $t_s \leq 2 \cdot \frac{l}{a}$ (2)

t_s	Closing time [s] of the valve
l	Length [m] of the pipe section in which shock waves can be propagated without being reflected

Downstream of the valve, the pressure decreases due to the inertia of the trans-ported liquid. If it drops below the steam pressure, the liquid evaporates locally and a "cavitation bubble" forms [2]. The subsequent condensation process is usually very abrupt. The magnitude of the pressure peak, which is also referred to as "cavitational hammer", varies according to the valve type and closing speed and can be much higher than the normal system pressure. Once again, the resulting shock waves may be replicated a number of times in the pipe be-fore they come to a standstill due to friction.

2.2. Thermal water hammer

If hot steam meets large accumulations of condensate because the piping sys-tem is insufficiently drained, sudden evaporation (or "flashing") occurs. The re-sulting changes in volume are a cause of water hammer – in many cases violent – with strong pressure surges that can easily exceed the operating pressure.

Water hammer also occurs in condensate systems if sub-cooled condensate is fed into a condensate pipe that is partially filled with flash steam. A vacuum is created locally as the flash steam condenses. Strong pressure surges are like-wise produced by the subsequent inflow of condensate at high velocity. In other words, there is always a risk of water hammer if condensate with different temperatures collects in a header.

3. Measures to prevent water hammer

The water hammer described here can usually be prevented by designing the facility optimally; the measures that are suitable for avoiding hydraulic water hammer are totally different from those implemented to counter thermal water hammer.

Since the intensity of hydraulic water hammer depends on the operating times of the globe valves, the starting and stopping times of the pumps and the flow velocity, water hammer pulses can be restricted – if not completely eliminated – by altering these parameters. Unlike water hammer pulses on the inlet side of the valve, the formation of a cavitation bubble can only be prevented by selecting a significantly higher closing time, which will probably be unacceptable in practice. If the parameters are fixed, water hammer can be damped – though not avoided – by installing bladder accumulators or air vessels and leveraging the compressibility of the gas volume in this apparatus. Other preventative measures are described in [2].

A good first step towards eliminating thermal water hammer in steam facilities is to ensure adequate drainage. A wise choice of steam trap, in combination with an optimal arrangement of the drain and condensate pipes, is crucial here [3]. The risk of water hammer is particularly great when a cold plant is started up because this is when there is most condensate.

The measures that are required to prevent water hammer in conjunction with flashing, mixing and transfer of the condensate drained from steam pipes are also described in detail in [3].

4. Influence of water hammer on valves

Since it is not always possible to exclude water hammer in a facility completely, the possible consequences for fittings – and especially valves – are described in the following. Taking the "FABA®-Plus" globe valve as an example, Figure 1 shows the areas affected by pulsating pressure loads, which are also explained below.

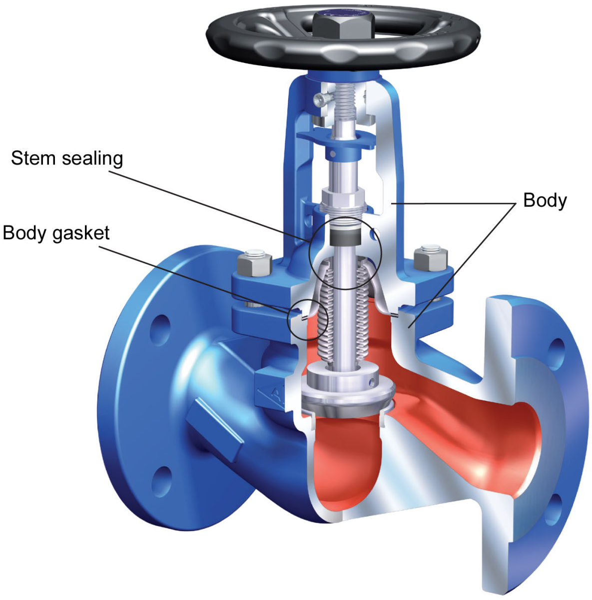

Fig. 1:
FABA®-Plus globe valve [4]

4.1. Body strength

The dimensions and design of the valve body are based on the "pressure" and "temperature" sizing parameters plus the safety margins laid down in the relevant regulations. As the water hammer values that occur in a plant can be far higher than the permissible values for the valves concerned, there is a risk that the body could break – at least with brittle materials that do not have a very high yield strength (e.g. cast iron). The use of these materials is restricted by several regulations for this reason [5, 6].

4.2. Body seals

The static sealing elements between the individual parts of the valve bodies are subjected to the same pressure and temperature loads as the body itself. If the maximum values for pressure and temperature stresses are exceeded here, the seals may develop leaks and fragments of them could even be "blown out".

4.3. Stem seals

Compared to the static body seals, the seals for the stem guide are additionally exposed to dynamic stresses caused by the movement of the stem, which can be axial, radial or a combination of the two. Manual valves tend to be only rarely operated while control valves are in action regularly, if not continuously. The gland packing (Figure 2) and the PTFE V-ring unit (Figure 3) are the two classic systems. If this kind of seal is already badly worn, water hammer can easily result in leakage; gland packings have the advantage here that they can be retightened.

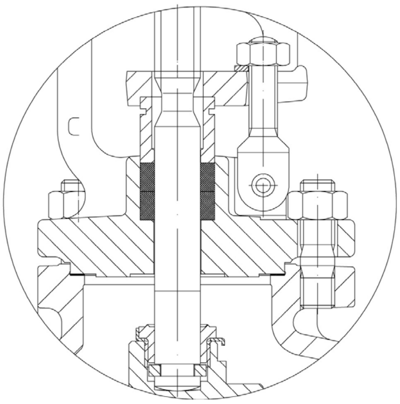

Fig. 2: Stuffing box packing

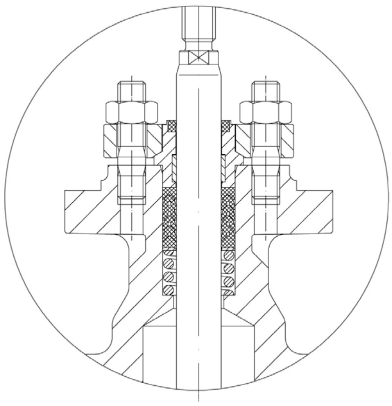

Fig. 3: V-ring unit stem seal

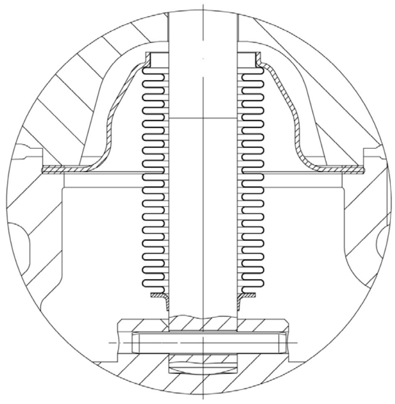

Fig. 4: Bellows stem seal

The stainless steel bellows seal shown in Figure 4 provides a permanently leak-proof and maintenance-free stem seal because wear is ruled out. The material most commonly used for the bellows seal is austenitic stainless steel, e.g. 1.4541 or 1.4571, with very thin walls to guarantee the necessary low rigidity. The resistance to water hammer is consequently limited because there is a risk of plastic deformation and possibly even cracks in the material.

5. Design measures

5.1. Design and choice of material

If water hammer cannot be completely prevented in the facility, a good starting point is to only use body materials that are sufficiently ductile. The design of the body parts also has a crucial influence on a valve's stability towards water hammer. This is explained in the following, taking the optimised bonnet of a globe valve as an example. Figure 5 illustrates the stress distribution when the finite element (FEM) calculation is applied to the "FABA®" valve. By optimising the design, it is possible to improve this distribution as shown in Figure 6. The bonnet was revised during the development of the "FABA®-Plus", resulting in a slight reduction in weight and approximately 60% better resistance; this has additionally been verified by means of tensile tests. The valve thus affords better protection against water hammer.

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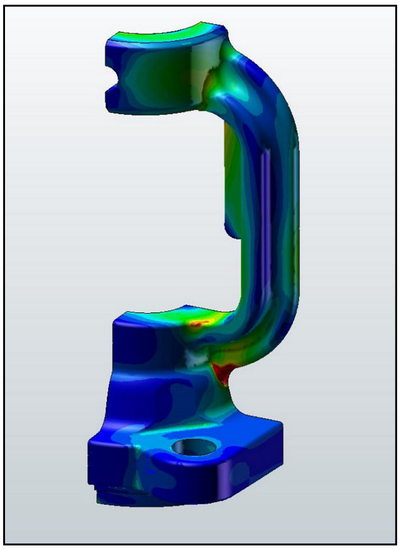
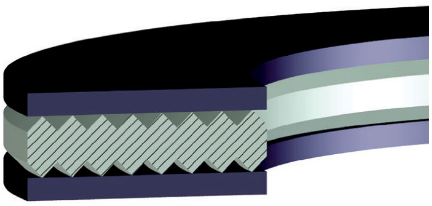


Fig. 5: Before optimisation

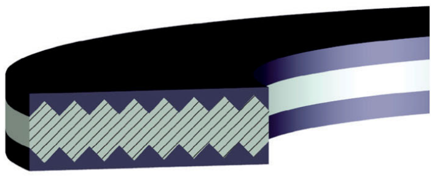
Fig. 6: After optimisation

5.2. Choice of seals and chambers

It is a good idea to choose a grooved design in order to prevent gaskets from being damaged, or in the worst case blown out, due to water hammer. These seals, which are shown in Figure 7, generally consist of a shaped metal carrier and a soft seal. Once the seal has been installed and preloaded, the soft material, e.g. graphite or PTFE, is pressed into the carrier profile to give additional anchorage.



Delivery condition



Assembly condition

Fig. 7: Grooved gasket

Chambered gaskets are another possible alternative. The "FABA®-Supra C" globe valve depicted in Figure 8 features a double-walled bellows seal between the top and bottom parts; the inner web shields the seal against the fluid. If water hammer occurs, it is prevented from even reaching the seal. The outer web provides support as well as extra protection against leakage. If the seal is faulty, no fluid jet can escape.

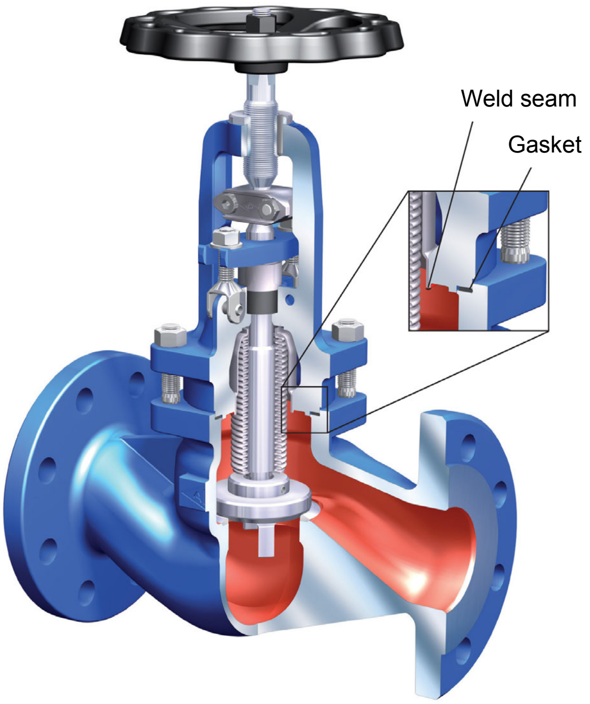


Fig. 8: FABA®-Supra C globe valve [4]

The movements of the bellows connectors due to water hammer have a considerable influence on the stability of the body seal. If these metal parts are clamped between gaskets, the latter could fail if a defined limit value is exceeded. The bellows connector of the "FABA®-Supra" (Figure 8) is welded directly to the top part of the body for this reason. At the same time, the number of seals is reduced to one.

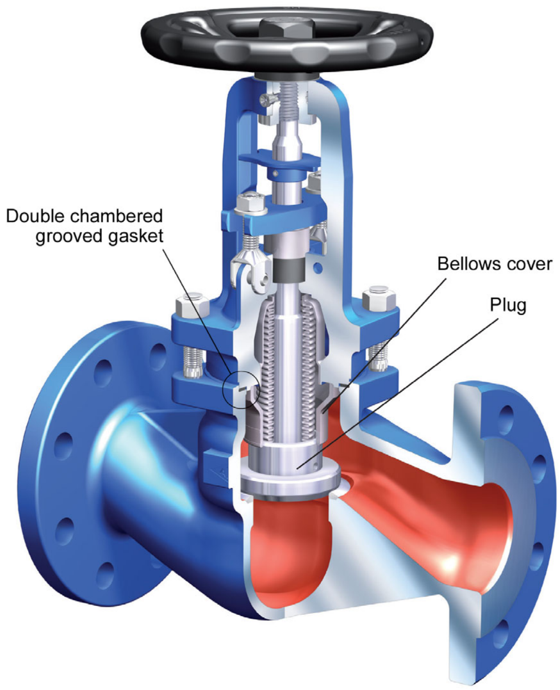


Fig. 9: FABA®-Supra i globe valve [4]

5.3. Bellows design

To prevent water hammer from damaging metal bellows, the bellows must be designed with sufficient compressive strength, including appropriate reserves. As a way to increase the nominal pressure, multi-walled designs should be preferred to single-walled bellows with thicker walls. The wall in contact with the fluid performs the sealing function while the other walls serve to support the bellows and give them a higher compressive strength. Since increasing the wall thickness or the number of walls simultaneously makes the bellows more rigid (higher spring rate), these measures are only limitedly suitable for preventing water hammer.

The resistance of bellows valves to water hammer can be further improved by shielding the bellows on the fluid side. The "FABA®-Supra i" shown in Figure 9 is a typical example of this type of design. The protective rim welded to the top part also acts as a plug guide. Pressure surges or water hammer never even reach the bellows and no plug vibration is excited by high flow velocities.

6. Practical trials

Extensive trials were carried out at the Fraunhofer UMSICHT Institute in Oberhausen [7] to determine the maximum loads as well as the effectiveness of the individual measures incorporated in the valve. Two bellows globe valves – "FABA®-Plus" and "FABA®-Supra" – were subjected to extreme stresses from water hammer.

6.1 Fraunhofer UMSICHT - Institute

The Fraunhofer UMSICHT Institute in Oberhausen owns an extensive testing facility on which hydraulic and cavitational water hammer can be produced under realistic conditions. The plant shown in Figure 10 takes the form of a closed piping system in which water is pumped by a centrifugal pump through a loop with a total length of 225 m and a nominal diameter DN 100 in stationary circulation. When a very fast-acting butterfly valve installed in the system is closed, the water column stops abruptly, resulting in water hammer at the inlet of the butterfly and cavitational hammer downstream of it. These pressure peaks are propagated through the system; the water hammer pulse is reflected and replicated several times with decreasing intensity. By varying the velocity of the liquid flow to be braked, it is possible to obtain defined pressure peaks, which in this arrangement have a maximum value of about 100 bar.

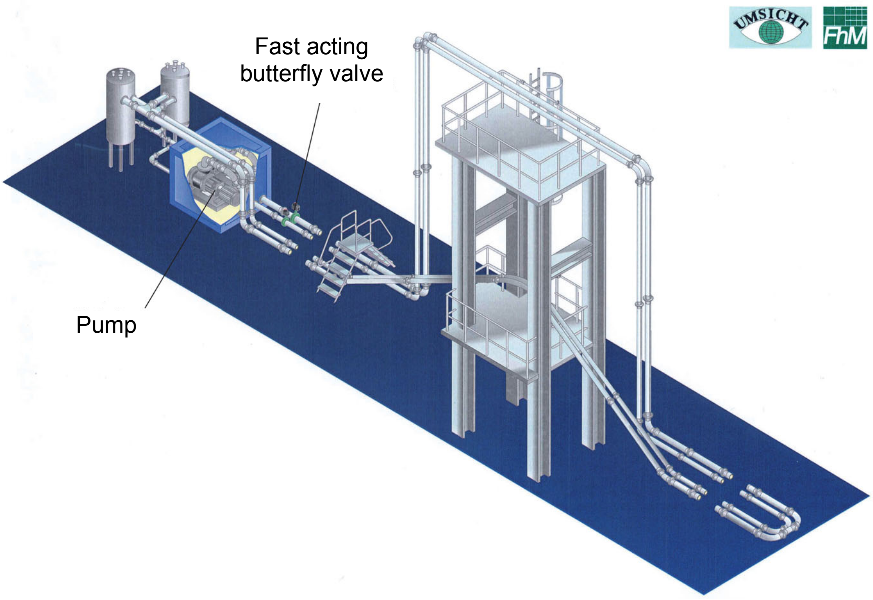


Fig. 10: The Fraunhofer UMSICHT Institute testing facility (Oberhausen) [7]

These maximum values can be doubled with the help of a small trick if the shock wave is directed into a branch line with a closed end (Figure 11). When it reaches the end of this line, the wave is reflected with twice its normal intensity. If the valve to be tested is installed there, the load on it from the pressure peak is approximately twice as high. Figure 12 shows clearly how it was possible to increase the pressure to a maximum of 200 bar.

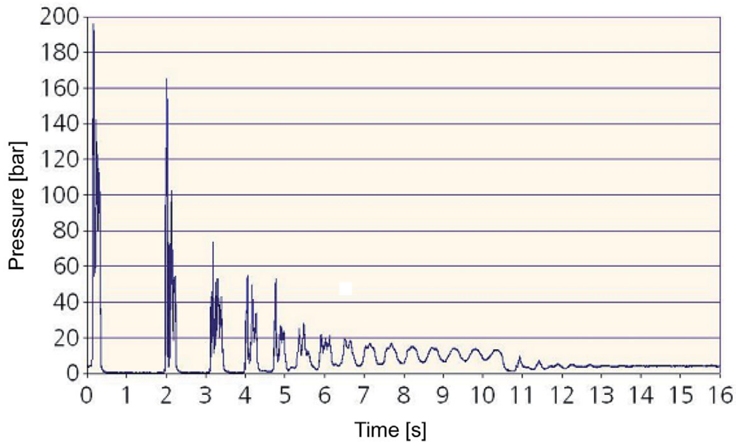


Fig. 12: Water hammer over time

Fig. 11:
Water hammer is doubled with a branch line [7]

6.2 Tests on the FABA®-Plus-Valve

The first tests were conducted on a standard "FABA®-Plus" valve (DN 80 / PN 40) as shown in Figure 1. In Figure 13, the valve is installed at the end of the pipe. The video provides a good visual and acoustic impression of the high loads. By successively increasing the water hammer, the Institute was able to determine the limit above which this standard 2-walled bellows is deformed. This valve is designed for a maximum pressure of 40 bar, yet there were still no negative values at 100 bar and no change to the bellows or the bonnet seal (Figure 14). The bonnet seal, which only has a single chamber with this valve, failed around 130 bar and the first deformation of the bellows was observed at about 150 bar.

Fig. 13: Test valve at the end of the branch line [7]

A single-walled test bellows (not a standard product!) was likewise tested in order to determine the reinforcing effect of the second, additional bellows wall. However, this bellows was already severely deformed at approximately 100 bar (Figure 15).

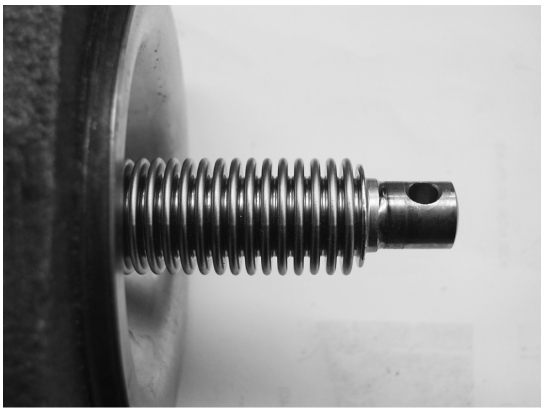


Fig. 14: Double-walled standard bellows of the FABA®-Plus

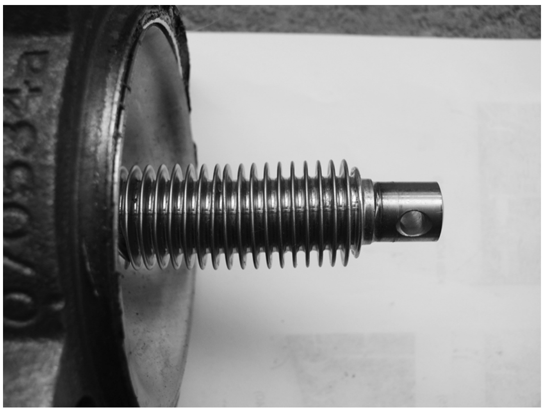


Fig. 15: Deformed, single-walled bellows

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6.3 Tests on the FABA®-Supra-Valve

The same tests were then carried out on the "FABA®-Supra" globe valve (DN 80 / PN 40), which is specially designed to withstand this kind of heavy load. The measures described in section 5 are systematically implemented in this valve, as can be seen in Figures 8 and 9. The material and the stress utilisation of the bonnet were similarly based on the high forces associated with water hammer and the geometry was optimised in line with the FEM calculation. The seal between the top and bottom parts has a grooved design; it is enclosed between the inner and outer webs, creating a double-walled bellows seal. The reinforced, double-walled, stainless steel bellows is welded directly to the top part by means of a sleeve. The second seal, which is essential with the "FABA®-Plus", can therefore be dispensed with and the elastic movements of the bellows due to water hammer are no longer transferred to the single seal. This weld is clearly visible in Figure 16 on the top part of the ARI-FABA®-Supra C.

Fig. 16:
Medium contacted bellows of the
FABA®-Supra-C

This design was subjected to 200 bar water hammer pulses in a series of tests without any deformation or leakage being detected (Figure 17).

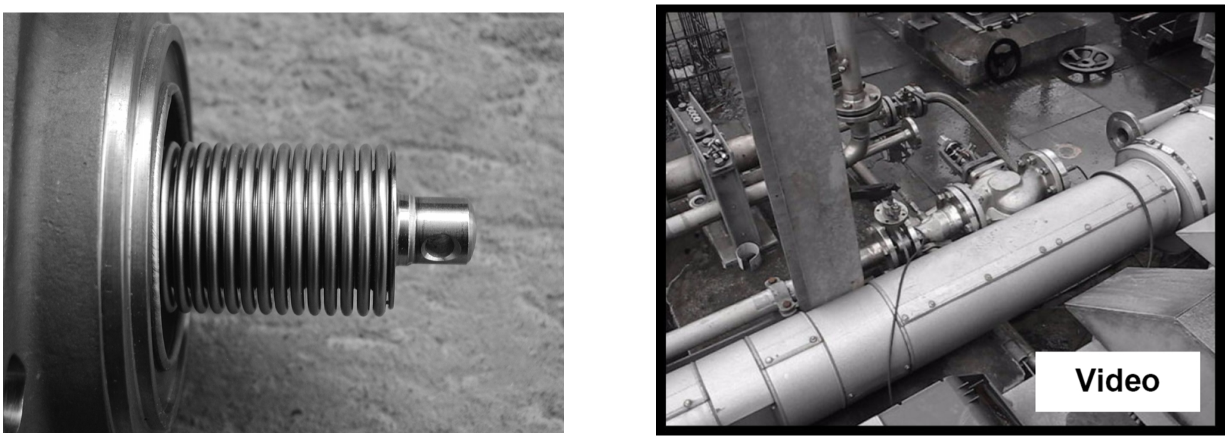

Fig. 17: Bellows of the FABA®-Supra-C PN 40 after 200 bar water hammer

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The additional shielding and integrated plug guide shown in Figure 18 further in-crease the resistance of this bellows valve, because water hammer no longer reaches the bellows.

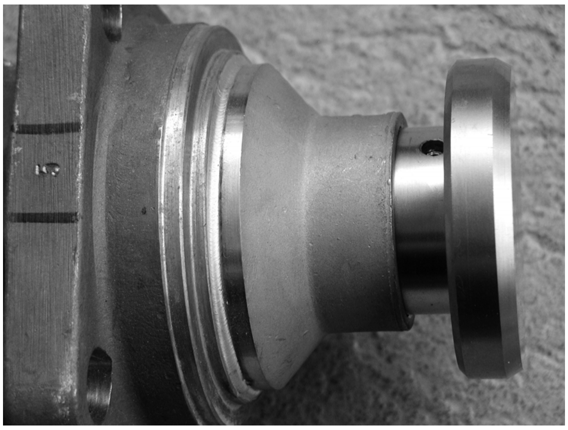

Bild 18: FABA®-Supra-i with shielded bellows

7. Summary

The water hammer that occurs in a facility's fluid-carrying pipes generally has a variety of causes that can never be completely ruled out. This article analyses the consequences for fittings, and especially valves, starting with the extremely diverse physical causes and continuing with the engineering options available for prevention. Several design measures are then described for making the valves more resistant to water hammer and improving their stability. The effectiveness of the design details outlined here is finally verified by referring to the extensive trials carried out at the Fraunhofer UMSICHT Institute in Oberhausen.

8. References

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