Operational Behaviour of Safety Valves with Constant Superimposed Backpressure

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When selecting spring loaded safety valves, an accurate knowledge and consideration of the specific operating conditions are vital to ensure that these devices work reliably. As optimal resource use becomes an increasingly relevant criterion, plant owners focus particular attention on components that can be depended on absolutely – even at their physical limits.
In the design of a safety valve, the existence of a backpressure must be considered in addition to the usual parameters for dimensioning. In this present report, the function of a safety valve is intended to be shown when a constant superimposed backpressure is present in the discharge and thus acts against the direction of opening of the safety valve.

Introduction

A spring loaded safety valve is a valve which allows a defined amount of fluid to be discharged automatically – unaided by any form of energy other than the medium itself – in order to prevent a predetermined safe pressure from being exceeded. It is designed in such a way that it closes as soon as normal conditions are restored, so that no more fluid exits. [2, p. 4] As the final protective device in the technical system, it plays a special role and must be depended on to work absolutely reliably.

Careful design and sizing by the systems engineer as well as expert execution of the entire installation are essential for proper functioning. As far as the safety valve itself is concerned, it is important that the spring(s) and disc (closure component) can perform their work (lift) undisturbed. If this is not the case, in other words if the required lift is restricted, impeded or blocked, delayed actuation, flutter and reduced performance could be the outcome – in short, operation outside the limits allowed by the regulations. The safety and reliability of the installation as a whole would be jeopardised.

All safety valves approved under European or American regulations are subject to strict standards and component monitoring procedures. The safety valves manufactured by ARI-Armaturen are approved, for example, to DIN EN ISO 4126 [5] and ASME VIII Div. 1 [7].

Background

Based on the following equation [11, p. G28]

$$p = \frac{F}{A} \tag{1}$$

the balance of forces of a spring loaded safety valve can be expressed simply as

$$F_{pressure} < F_{springforce} \qquad \text{Safety valve closed} \tag{2}$$

$$F_{pressure} > F_{springforce} \qquad \text{Safety valve open} \tag{3}$$

In other words, the valve opens if the pressure (and hence the force underneath the disc) in the pressure vessel is greater than the force which presses the disc against the seat (nozzle). A basic distinction is made here between two different types of actuation, namely sudden (rapid opening) and almost continuous (but not necessarily linear opening). [2, p. 4]

Whereas the operational behaviour of spring loaded safety valves with a built-up backpressure has already been the object of a detailed study in [1], this paper examines their operational behaviour with a preset, constant superimposed backpressure and a cold differential test pressure (CDTP) setting.

Figure 1

Plant planners and owners are particularly interested in answers to the following two questions:

a) How does the existence of a constant superimposed backpressure influence the design of a spring loaded safety valve?

b) What effect does a constant superimposed backpressure have on the safety valve's functionality (opening pressure difference, closing pressure difference), performance and leakproofness and to what extent does a cold differential test pressure setting influence the valve's functional characteristic?

In the context of safety valves, we differentiate between built-up backpressure and superimposed backpressure. Amongst other things, the existence of backpressure is conditional on the use of a metal bellow.

Built-up backpressure

Excess pressure in the outlet pipe of the safety valve which is built up during the blow-off phase (opening) and is therefore variable.

Superimposed backpressure

Excess pressure which is already present in the outlet pipe of the safety valve before the blow-off phase begins. It can be either constant or variable.

Equations (2) and (3) change as follows in the presence of superimposed backpressure (refer also to Figure 2):

Figure 2

$$F_{pressure} < F_{springforce} + F_{BPsuperimposed} \qquad \text{Safety valve closed} \qquad (4)$$

$$F_{pressure} > F_{springforce} + F_{BPsuperimposed} \qquad \text{Safety valve open} \qquad (5)$$

If the safety valve is closed, the superimposed backpressure thus also acts on the seat against the pressure in the vessel in the closing direction.

$$F_{setpressure} = F_{springpreload} + F_{BPsuperimposed} \qquad (6)$$

This additional force must be taken into account when setting the compression spring, which requires correspondingly less preload. [6, p. 17] The safety valve will otherwise be actuated at too high a pressure, namely at the sum of equation (6).

CDTP setting

The procedure described in section background is the norm when sizing and setting American safety valves to API/ASME [6, p. 25]; it is referred to as the "CDTP setting".

$$CDTP = F_{springpreload} - F_{BPsuperimposed} \tag{7}$$

According to the European regulatory framework provided by DIN EN ISO 4126 [2, p. 5], the CDTP may include a correction for backpressure and temperature. Yet how does this procedure influence the operational behaviour of the safety valve? Extensive measurements to determine this have been carried out on an air dynamometer at Albert Richter ARI-Armaturen GmbH & Co. KG (refer to section results).

Note: The set pressure correction which is necessary if the temperature during the setting significantly exceeds room temperature when the safety valve is in service is also based on the CDTP, but is not described in this report.

Backpressure compensation with a built-in metal bellows

The backpressure can be compensated by installing a metal bellows (refer to Figure 3). The optimal effect is achieved if the mean bellows diameter corresponds as closely as possible to the mean seat diameter of the safety valve. A bellows is always required if the superimposed backpressure $F_{BPsuperimposed}$ is variable because a variable backpressure will otherwise cause the set pressure to change constantly.

Figure 3

Parameters

The operational behaviour must be assessed using the parameters described in the recognised standards [2, 3]. The backpressure ratio, which determines whether critical or subcritical operating conditions apply, is crucial here.

$$Back\ pressure\ ratio\ [\%] = \frac{Back\ pressure\ abs.}{Set\ pressure\ abs.} = \frac{p_b}{p_0} \tag{8}$$

$$\frac{p_b}{p_0} \leq \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \qquad \text{Critical flow} \tag{9}$$

$$\frac{p_b}{p_0} > \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \qquad \text{Subcritical flow} \tag{10}$$

Assuming that the isentropic exponent k is constant, the term

$$\left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \tag{11}$$

describes the transition point from critical to subcritical operation. Critical operation means that if the pressure behind the valve seat drops further, the mass flow no longer increases. [3, p. 7] Under subcritical flow conditions, therefore, the term

$$q_m = 0.2883 * C * \sqrt{\frac{p_0}{v_0}} \tag{12}$$

must be multiplied by the correction factor K_b in order to calculate the theoretical mass flow.

$$q_m = 0.2883 * C * K_b * \sqrt{\frac{p_0}{v_0}} \tag{13}$$

According to [3, pp. 8 and 23], K_b can be either calculated or read off, it has a direct influence on the determination of the coefficient of discharge K_d (or K_{dr}). [3, p. 7ff]

$$K_d = \frac{\sum_1^n\left(\frac{q'm}{qm}\right)}{n} \tag{14}$$

$$K_{dr} \leq 0.9 * K_d \tag{15}$$

Figure 4

Under subcritical flow conditions, therefore, the term

$$\dot{Q}_m = 0.2883 * A * K_{dr} * C * \sqrt{\frac{p_0}{v_0}} \tag{16}$$

must be multiplied by the correction factor K_b in order to calculate the mass flow. The narrowest cross-section A of the safety valve which is derived from this

$$A = \frac{\dot{Q}_m}{0,2883 * C * K_{dr} * \sqrt{\frac{p_0}{v_0}}} \tag{17}$$

must accordingly be extended with the factor K_b in the denominator if subcritical flow occurs.

$$A = \frac{\dot{Q}_m}{0,2883 * C * K_{dr} * K_b * \sqrt{\frac{p_0}{v_0}}} \tag{18}$$

The Albert Richter ARI-Armaturen GmbH & Co. KG dynamometer

Figure 5 and 6

The air dynamometer at Albert Richter ARI-Armaturen GmbH & Co. KG has the following specifications:

- Compressed air reservoir: 6 [m³]; 100 [bar]
- Static pressure vessel: 1.5 [m³]; [100 bar]
- Available standard air volume: Approx. 600 [Nm³]
- Max. transient standard volume flow: Approx. 100,000 [Nm³/h]
- Backpressure vessel: 4 [m³]; 10.5 [bar]

The following values were recorded automatically for the measurements presented in section results:

- Pressure p_0 (set pressure) [bar-g]
- Backpressure p_b [bar-g]
- Lift [mm]

The following values were read off afterwards manually from the measurement plot:

- Closing pressure p_s [bar-g]
- Closing pressure difference [%]
- Opening pressure p_c [bar-g]
- Opening pressure difference [%]

- Lift (actual) [mm]

Measurements

Safety valves used

1) Safety valve to DIN EN ISO 4126, 901 series (full lift), PN 16
   DN 25/40, d_0=22.5 mm, nominal lift: 5.2 mm

2) Safety valve to DIN EN ISO 4126, 901 series (full lift), PN 16
   DN 32/50, d_0=29.0 mm, nominal lift: 6.7 mm

3) Safety valve to ASME Section VIII, 970 series, ANSI 150 x 150,
   1" x 2", nominal lift: 3.0 mm

4) Safety valve to ASME Section VIII, 970 series, ANSI 150 x 150,
   1.5" x 3", nominal lift: 6.6 mm

Measurement parameters

Each of the four safety valves was set to the following set pressures:

Set pressure [bar-g]	3	5	9	12		

A constant pressure was then preset in the outlet pipe. This pressure was increased to the following percentages before each measurement:

Constant superimposed backpressure [%]	0	10	20	30	50	70

Equation (6) now yields the following total set pressures for 5 [bar-g], for example:

Total set pressure [bar-g]	5.0	5.5	6.0	6.5	7.5	8.5

Procedure

It creates the following sequence was determined:

The safety valve has been adjusted to the stated pressure (Definition: Initial Audible). Then the constant backpressure was increased and accounted for as a percentage of each explains the measured values. To reduce the time for rebuild on an adjustment of the valve (clamping bolt) and thus the CDTP correction has been omitted. Additionally, it was kept almost nearly constant through the use of an automatic control valve in the discharge line of the backpressure to the set value. The influence of built-up backpressure was negligible (see Fig. 6).

Figure 7

The results are accordingly plotted in section results based on equation (6) and the set pressure should correspond to the sum of $F_{springforce}$ + $F_{BPsuperimposed}$ as described in section measurement parameters.

Three measurements were performed for each setting; the mean value in each case was taken as a basis for the diagrams in section results.

Results

An excerpt from the measurements with safety valve 1 is reproduced below as an example.

Constant superimposed backpressure without metal bellows

Figure 8

Figure 9

Constant superimposed backpressure with metal bellows

Figur 10

Figur 11

Summary

The results of the measurements presented in part at the valve 1 of the BR901 DN 25/40, with a start set pressure of 5 [bar-g] can recognize the following:

The safety valve responds within the allowed limits, thus despite the presence of constant superimposed backpressure and a setting according to (6) correctly, the general function characteristic of the response is not adversely affected. Despite the constant superimposed backpressure, the valve reaches its full stroke.

In the version without metal bellows, the opening pressure difference increases linearly to the backpressure ratio (Fig. 9), but is within the specified range, with metal bellows it is almost constant despite increasing backpressure ratio (Fig. 11).

A constant backpressure and the resulting adjustment according to (7) affects the working behavior of the safety valve in particular to the effect that the blowdown changed (it decreases linearly to the backpressure ratio (Fig. 11)). This means there is a risk that the safety valve with increasing backpressure ratio or a higher opening pressure after the response is no longer reliably closes and has a permanent, "creeping" leakage.

In the design and sizing of safety valves with constant backpressure of the concrete application and the operating conditions are therefore always taken into account. For this purpose, the respective manufacturer should be contacted in particular to take into account the operating limits and changing operating parameters in the selection and interpretation.

Meanings of symbols

p	Pressure	[bar]
p_0	Set pressure	[bar]
F	Force	[N]
A	Area	[mm^2]
$F_{pressure}$	Force due to pressure in the pressure vessel	[N]
$F_{springforce}$	Force due to the compression spring	[N]
$F_{BPsuperimposed}$	Force due to pressure in the vessel	[N]
CDTP	Cold differential test pressure	[bar]
v_0	Specific volume at blow-off pressure and temperature	[m^3/kg]
κ	Isentropic exponent	[-]
C	Function of the isentropic exponent	[-]
q_m	Theoretical discharge mass flow	[kg/(h·mm^2)]
q'_m	Actual discharge mass flow	[kg/(h·mm^2)]
K_d	Coefficient of discharge	[-]
K_{dr}	Reduced coefficient of discharge	[-]

List of sources

[1]   E. Stork; Backpressure Safety Valves
       Technische Überwachung; Bd. 47 (2006) No. 7/8 July/August; Springer VDI Verlag
[2]   DIN EN ISO 4126-1 : 12.2013
[3]   DIN EN ISO 4126-7 : 12.2013
[4]   AD 2000 Specification, Revised Version, 07.2013
[5]   VdTÜV Component Test Sheet, Safety Valve 663, 12.2014
[6]   API 520 PT1 Sizing and Selection, 07.2014
[7]   http://www.nationalboard.org
[8]   Tabellenbuch für Metalltechnik; 12. Auflage; Verlag Handwerk und Technik – Hamburg, 2007

List of figures

All figures   Albert Richter ARI-Armaturen GmbH & Co. KG
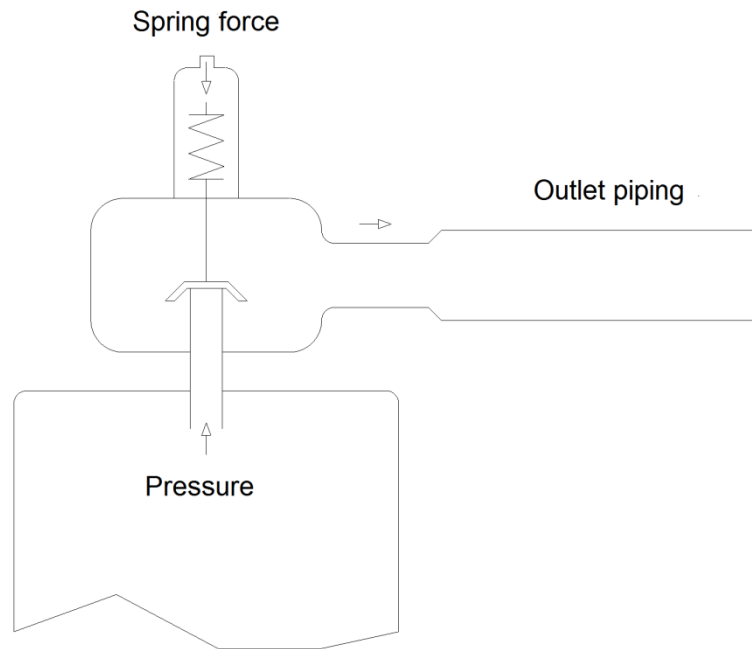
Figures

Spring force

Outlet piping

Pressure

Fig. 1: Safety valve (closed) with pressure vessel and outlet piping

Spring force

Outlet piping

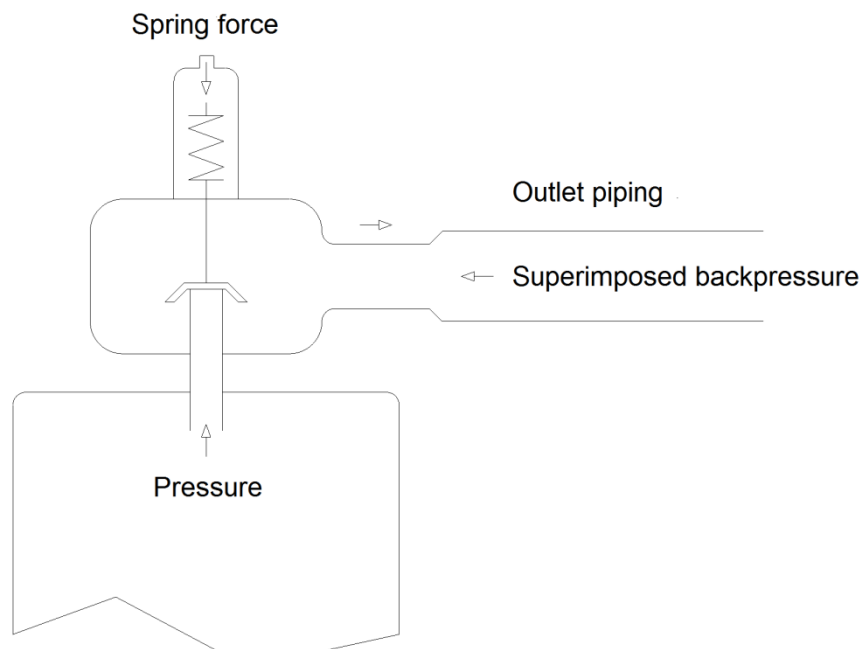Superimposed backpressure

Pressure

Fig. 2: Safety valve (closed) without metal bellows, with pressure vessel and superimposed backpressure in the outlet piping
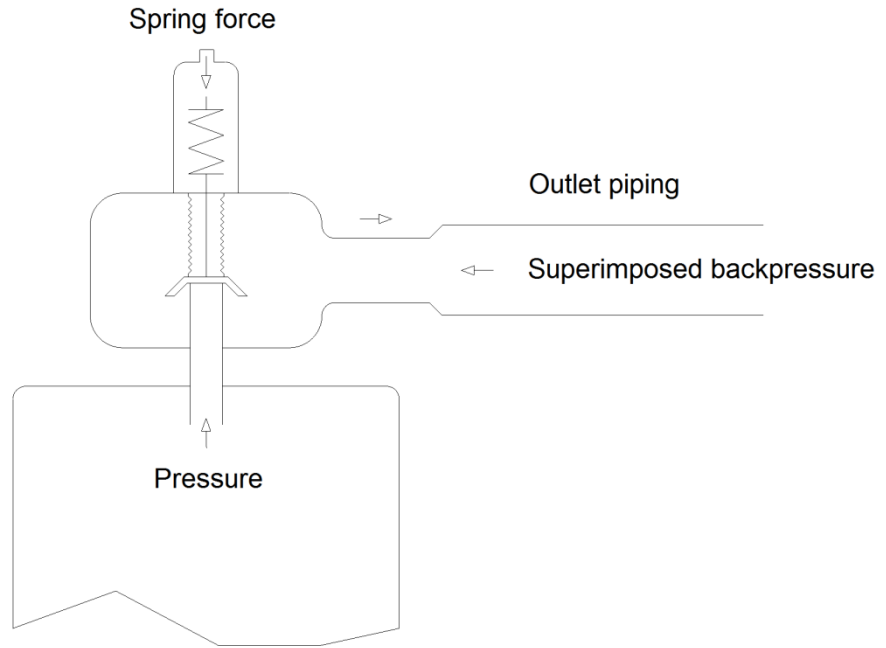
Fig. 3: Safety valve (closed) with metal bellows, pressure vessel and superimposed backpressure in the outlet pipe
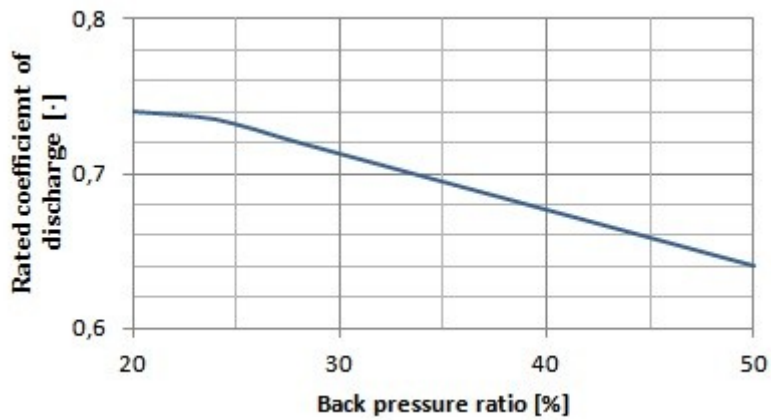

Fig. 4: Excerpt from the component test sheet VdTÜV SV663 – DN 25/40 – h/d0 = 0.23

Fig. 5 and 6: Air dynamometer at Albert Richter ARI-Armaturen GmbH & Co. KG
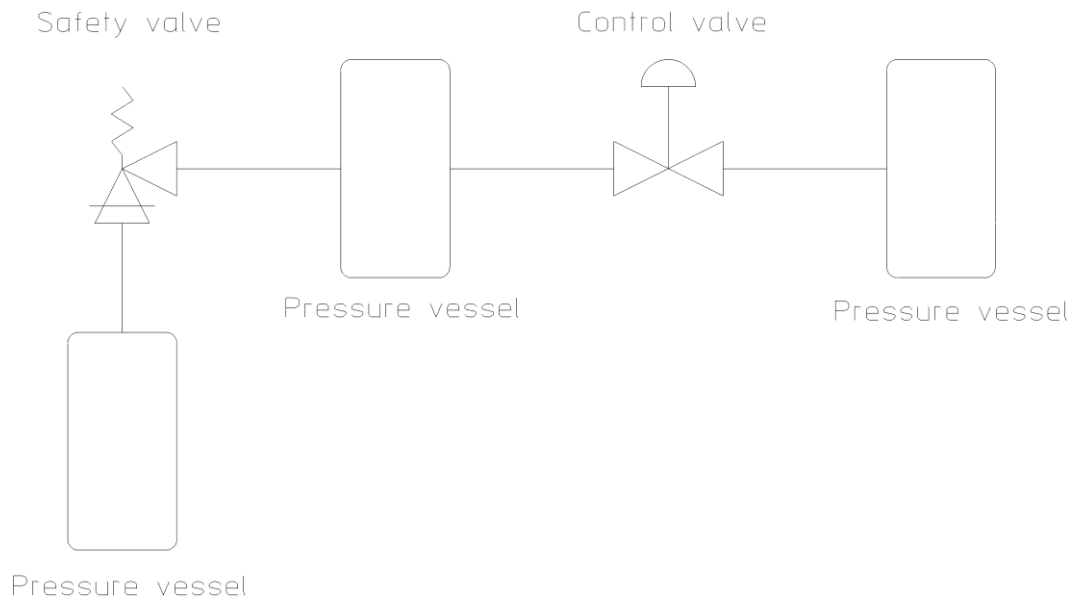
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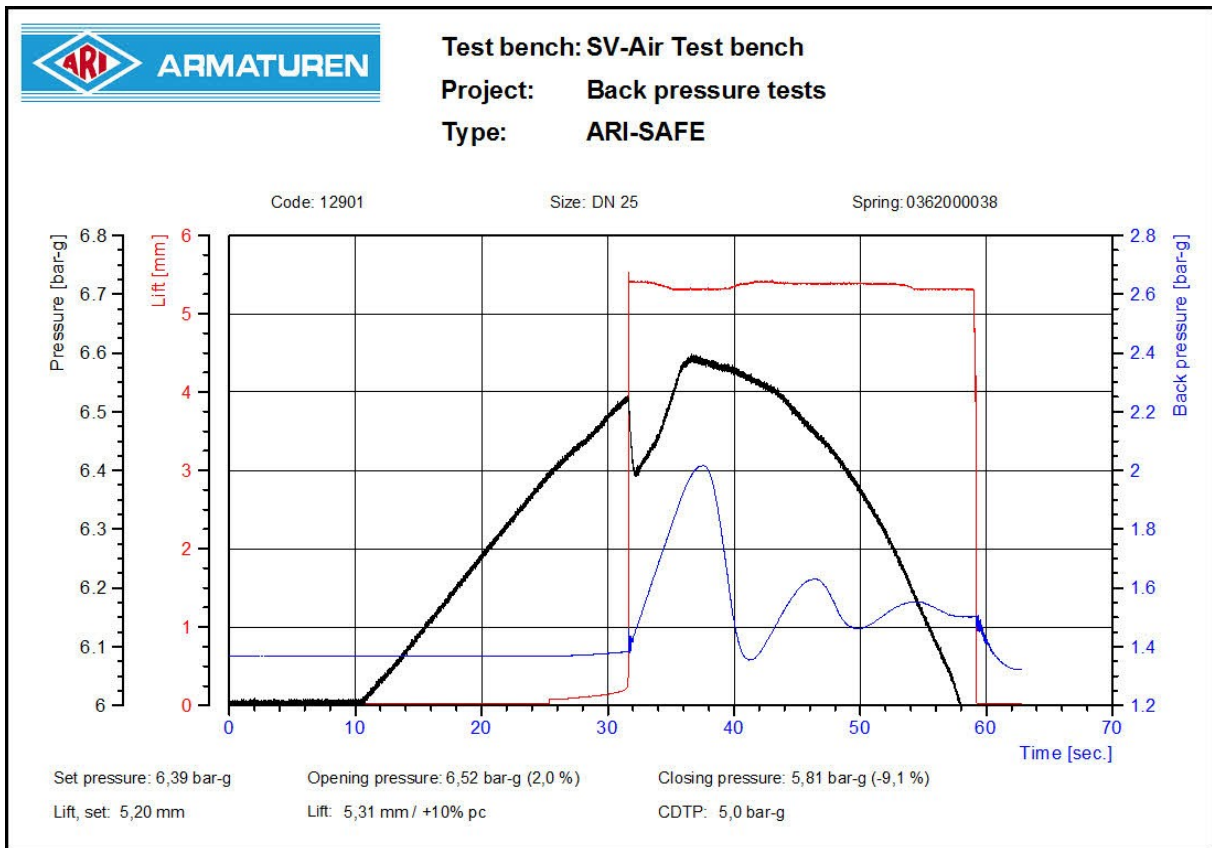
Fig. 8: Measurement plot for BR901 – DN 25/40 – CDTP: 5 bar-g – superimposed backpressure: 30[%]
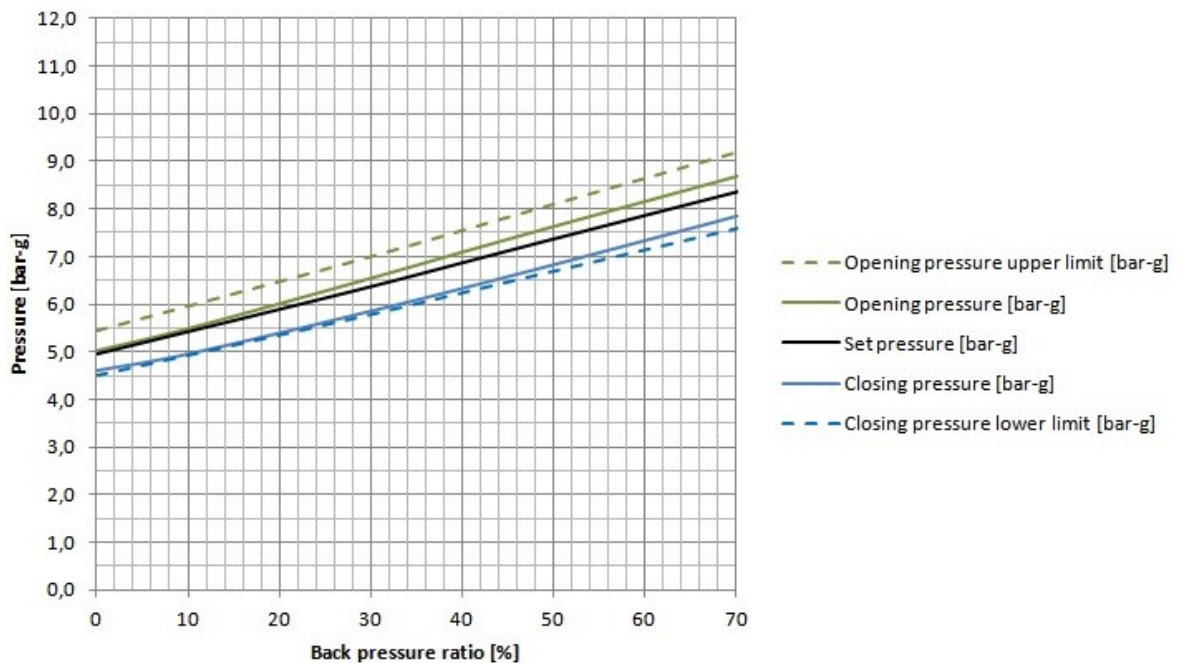

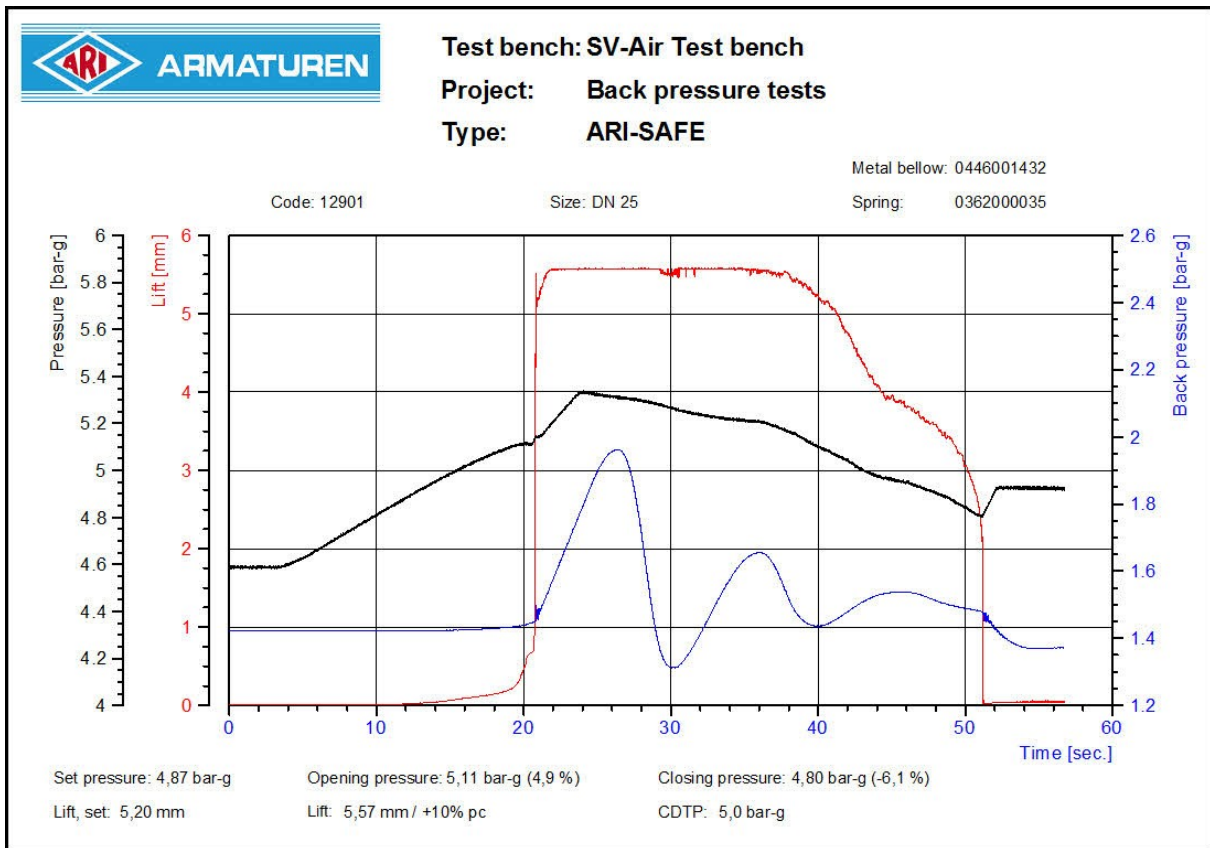Fig. 9: Results for BR901 – DN 25/40 – initial set pressure 5 bar-g – without metal bellows

Fig. 10: Measurement plot for BR901 with metal bellows – DN 25/40 – CDTP: 5 [bar-g] – superimposed backpressure: 30[%]
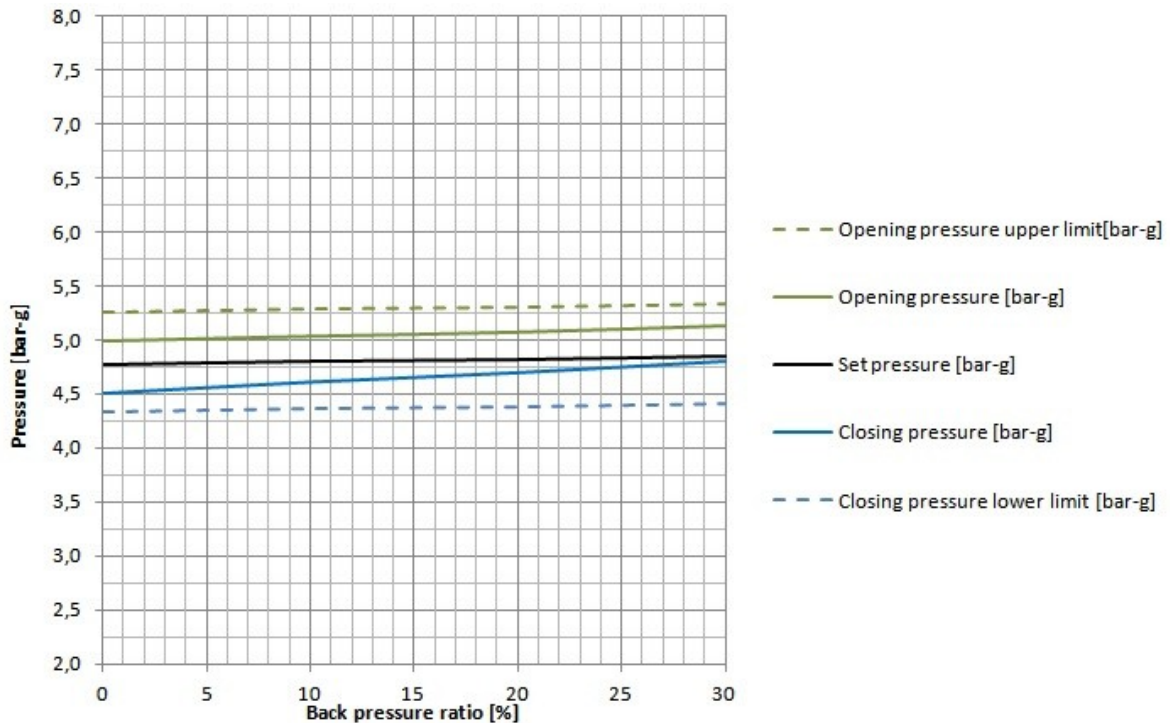

Fig. 11: Results for BR901 – DN 25/40 – initial set pressure 5 [bar-g] – with metal bellows