Challenges in designing API safety relief valves

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The development of a new series of API safety relief valves is only possible following extensive investigation into fluid flows. This paper describes how a new method of “Flowforce - Characteristic - Measurement” facilitated extensive review of the quality of the shape of all parts in the flowing area and enabled parts to be optimised. Further, a world-class test facility enabled verification of the required characteristics for a larger range of pressures and sizes than needed for an ASME certification. In addition to these measurements, special flow calculations provided information about local fluid dynamics. Components in the flow area could therefore be optimised with high accuracy. This has resulted in a new series of API safety relief valves with ASME and TÜV certification, providing significant advantages for end users.

The so-called “API safety valve” is the most widespread type of safety valve and is found world-wide. API stands for “American Petroleum Institute” and it points to the fact that this safety valve standardisation originates in the petrochemical industry, although in the meantime it has been adopted by many other industrial branches. The standard API 526 [1] defines the design characteristics of safety valves such that the safety valves of different manufacturers are interchangeable. The planning engineer can already define the safety valves in the planning phase independent of the manufacturer and can include them bindingly into his system. In order to permit this, API 526 defines the following design characteristics:

- the blow-off capacity for gases/steams which are assigned to the safety valves according to the seat letter symbol (from D to T)
- the connecting dimensions (side lengths) depending on the inlet and outlet flanges of the given nominal diameters (e.g. 4 x 6 inches or 100 x 150 mm) and the required pressure rating (e.g. ANSI 300 x 150)
- the maximum set pressure referring to the nominal pressure rating of the inlet flange depending on the selected material and the maximum operating temperature.

The observance of this standard is not checked or confirmed by any approval but is only documented by the manufacturer-indication “designed acc. API 526”.

The manufacturer’s approval

The most commonly required approval for manufacturing the API safety valve is the approval according to ASME (American Society of Mechanical Engineers). The approval according to ASME Section VIII [2] is valid for pressure vessels and every safety valve is then marked with the so-called “UV-Stamp” (UV = Unfired Vessel).

This approval confirms the manufacturer’s qualification with regard to the quality requirements according to ASME VIII.

The product approval or product certification

The function and the flow quantity of the safety valve series are proved with air, saturated steam and water in accordance with the requirements of ASME VIII in the course of a product approval. These tests are carried out on behalf of ASME by the National Board (NB) in Columbus, Ohio, in the USA. The results are published for every safety valve in the so-called “Red Book” with the title “Pressure Relief Device Certifications”. This document gives information which safety valves are certified with which pressure range and for which flow quantities, e.g. according to the requirements of ASME VIII or of the size of the current nozzle diameter do and the allowed discharge coefficient Kd, respectively. There are only very few manufacturers world-wide who cover the performance range of the API 526 with their safety valve program, have the approval according to ASME VIII and are certified in accordance with the National Board and may identify every API safety valve with the UV Stamp and the indication NB on the nameplate.

After the Bopp & Reuther API 526 safety valve series Si 81/83/84 (Figure 1) was approved in this manner in 1995 the same series was also TÜV type test approved with the type test approval mark BKZ 1006 [3]. This TÜV-approval also permits utilisation of this safety valve according to the API Standard in systems where a TÜV approval is required.

Object of the development

In order to be able to obtain the above mentioned approvals quickly and reliably and to achieve high product safety and reliability, specific objectives were defined for the development of these safety valves and the modern methods of simultaneous engineering were utilised systematically.

In case of selection of the construction with one blow down ring these safety valves are classified according to ASME VIII with the
following functional requirements (percentages refer to the set overpressure):

Gases/steams: open +10 % (min 0.2 bar) close -5 % during approval test (min 0.2 bar) -7 % during series fabrication

Liquids: open +10 % (min 0.2 bar) close no requirement

For the TÜV Approval there is no classification as to design with or without blow down ring. The function requirements to be fulfilled according to regulation AD-A2 [4] are the following:

Gases/steams: open +10 % (min 0.1 bar) close 10 % (min 0.3 bar)

Liquids: open +10 % (min 0.1 bar) close -20 % (min 0.6 bar)

One specification during the development of these safety valves was an optimised, uniform inlet nozzle giving optimal flowforce diagrams for gases/steams as well as for liquids, so that with suitable springs all function requirements for gases, steams and liquids can be fulfilled. Hence this series of safety valves is also suitable for two-phase flow even if there is no regulation as yet which defines the procedure and in particular the design as to flow capacity in such cases.

Furthermore, the valve disk shall always be in its stable position at the lift stop in case of full opening. This minimum lift was determined such that, for example, during all tests including set pressure 1 bar (subcritical pressure ratio) the certified discharge factor could be \( kd = 0.85 \pm 5\% \) for gases/steams.

The seat diameters in the actually used nozzle were then defined such that the discharge capacity specified according to API 526 for gases/steams was obtained, i.e. the following equation is fulfilled:

\[
A_{API} \times 0.975 = A_{ats} \times 0.944 \times 0.9 = A_{ats} \times 0.85
\]

In this equation \( A_{API} \) equals the seat area defined in API 526 for a seat letter symbol and 0.975 the corresponding theoretical flow coefficient with which the selection of the safety valve of this standard has to be made in accordance with API 520 Part I Appendix C.

For liquids the requirements should be fulfilled with the same valve program, i.e. without modification of the nozzle at the disc for ASME and TÜV Approval. This means that the closing pressure difference must always be smaller than 20% and the blow off capacity is then relatively high. It is not defined according to API 526.

To anticipate the result:

In fact the following discharge coefficients were certified during the NB certifications:

Gases/steams: 
Liquids: 

\[ K_d = 0.86 = 0.955 \times 0.9 \]
\[ K_d = 0.675 = 0.75 \times 0.9 \]

Thereby, the discharge capacity required for gases/steams according to API is safely obtained with a reserve of 1%. For liquids the same valves show very great discharge capacities at 10% increase in pressure. Thereby, as the test record of the NB tests proved, the closing pressure differences for liquids were always within 20%. Although this requirement was not given, it
was fulfilled as well anticipating the requirements of the subsequent TÜV Approval.

**Fulfilment of the development**

The function opening and closing of a spring-loaded safety valve follows from the interaction of flowforce and spring force. In the certification tests the result of the correct combination flowforce/spring force is only checked with individual test valves, the size and set pressure of which are also limited by the capacity of the test laboratory. As to the approval of the whole series according to API 526 it is the manufacturer’s responsibility how to guarantee safe function even for valves of great size and/or in the case of high pressure.

Starting from this situation Bopp & Reuther has built one of the most modern test facilities of its kind as the solution to this responsible task (Figure 2). The installation permits tests with air and water and is characterised by its wide pressure range – up to 320 bar - as well as by the high flow capacity – up to 200 t/h for air and up to 500 m³/h for water.

The test valves for steam were checked at this test facility in the same way as for air. The subsequent verification during the tests in America with saturated steam confirmed our measuring results with regard to flow and function, i.e. steam is also covered as compressible medium. This large-scale test facility has been described with all its possibilities in [5].

Before looking for a suitable spring in order to solve the task of opening and closing within given limits there is the task of developing a flow geometry which is able to furnish optimal flowforce gradients.

For this purpose the method of “flowforce-characteristic-measurement” [6] was developed. This method permits the evaluation of the quality of the flowforce performance gradients over a large pressure range (Figure 3). Local discontinuities which usually remain undiscovered during individual function tests (if a test is not accidentally carried out within the hazardous pressure range) are immediately discovered with this method.

Together with the “flowforce-characteristic-measurement” the flow behaviour of the safety valve is detected with a nozzle installed in front of the test specimen.

Before coordinations of flowforce and spring force are evaluated from the flowforce characteristic for desired function values opening/closing (Figure 4) the following conditions have to be met: (i) the individual form of a flowforce-characteristic, determined by continuity and linearity of the force gradients, has to give a positive characterisation of the functional behaviour to be expected with suitable springs and (ii) the flow coefficient has to be high enough and constant enough under the required pressure conditions from 1 bar onwards in order to meet the ±5% requirement.

A further evaluation results in the searched “Spring law” of a safety valve with the parameter closing pressure difference (Figure 5).

Only then were “real” functional tests carried out to confirm the actual spring adjusting ranges for the safety valve depending on the medium (gases/steams or liquids, respectively) and for the design with/without bellow. Typical results of functional measurements with spring-loaded safety valves are shown in Figures 6 & 7.

This optimisation process was carried out for a uniform flow geometry for gases/steams and liquids. Hereby, the parameter “position of the

![Performance Measurement with Air](image1)

![Performance Measurement with Air](image2)

Fig.6: Result of a functional measurement with air / DN 80 x 100 30 bar

Fig.7: Result of a functional measurement with air / DN 80 x 100 30 bar
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Valve/H17075/H17076

World

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The blow down ring was not utilised. In other words, the blow down ring is not important for the basic development of the optimised part in the flowing area because it is always maintained in deep position. Actually, the manufacturing costs for the blow down ring could be saved but because of the ASME VIII classification "with blow down ring" this is impossible. The advantage for the user, however, is that in the plant no optimisation will become necessary for positioning the blow down ring.

An essential role in this optimisation process was played by numerical calculations of the flow field in the safety valve with a CFD program system according to the Finite Volume Method. The calculations were carried out for three-dimensional compressible and non-compressible flow. The procedure was carefully checked by means of flow shapes known from the literature. Finally, these calculations were confirmed very well by comparison with experiments with compressible supersonic flow at a plane valve model [7].

The calculation results of the spatial flow in the safety valve can be given in sections as Mach number distribution (Figure 8) or as pressure distribution (Figure 9). Figure 8 shows a detail of the compressible supersonic flow between the valve seat and the shape of the disk and lifting bell. In the narrowest flow cross-section between the seat and the disk there is the strongly curved "sound line" with the Mach number Ma = 1. It is followed by a distinctive ultrasonics area with Mach numbers up to Ma = 3.3. When arriving at the lifting bell the flow deviation leads to a sloped compression wave behind which the Mach number falls to approximately Ma = 1.7. At the outer lifting bell edge a "ring-shaped" Prandtl-Meyer-Expansion occurs with a new acceleration to ultrasonics with Ma = 2.2. Such flow shapes have strong influence on the pressure distribution at the disk and the lifting bell (Figure 9) and, thus, on the resulting flow force. The integration of the pressure distribution at the disk and the lifting bell according to Figure 9 result in the flow force acting at the spindle which could always be compared to the measurements on the test facility. It was thus possible to determine effects of geometrical variants for the desired optimisation process and to make statements as to reasons for certain measured results (NB: because of the better resolution the colour scale from red to blue indicates the pressure from 5 bar to 0.2 bar. In the area of acceleration between the seat and the disk the isobars 10, 15, 20, 25 and 30 were entered into the red colour range!)

In addition to the calculations of stability according to ASME and AD/TRD, which were required for the approvals, finite element calculations were also carried out. In this connection Figure 10 shows the cross linkage of an API safety valve body. Regular stress distributions could be realised so that higher stresses are only present at the flanges in the area of the force introduction through the connecting screws. The situation at the flanges, however, is prescribed by the standards.

Special design

Thanks to the good flow characteristics it has been possible to derive from this series a special safety valve (figure 11) which permits a proportional performance and a stable opening for 100 bar hot water 265°C. This safety valve size 2” x 3” was the solution for the problem that the 1994 loss of coolant incident at Pickering NPP [8] could happen due to a standard safety valve which shattered and caused the breakdown of a pipe. In the meantime the existing standard safety valves for this application were replaced by this Special Design Safety Valve in about 30 NNP in the primary loop worldwide! Extensive tests at Bopp & Reuther and in the Wyle Laboratorium in Alabama, USA, under installation conditions in the plant and under operating conditions with evaporating hot steam showed that this special design...
performs very well under all test conditions providing stable and reliable operation.

Figure 12 shows the proportional opening of the valve within the pressure increase of only 10% over the set overpressure of 100.6 bar. It becomes quite evident how the valve follows the pressure increase during the lift course. If the system pressure falls to 106 bar after having reached 107 bar the valve lift remains constant and only increases when the pressure continues to increase.

This high functional stability is also the result of the effect of the installed vibration damper. During the tests with hot water in Alabama a partial evaporation, the so-called “Flashing” additionally occurred during the release.

Conclusion

The design of a safety valve which meets all the needs of end users is a complex affair and should not be underestimated. However, as this paper shows, the development of a new method of ‘Flowforce – Characteristic – Measurement’ plus investment in a test facility has enabled Bopp & Reuther to optimise a new line of safety valves. The essential characteristics of the new design are:

- conformity with all specifications of API 526
- approvals according to ASME with NB-Certification and approval by TÜV
- optimised equal flow geometry for gases/steams and liquids without adjusting the blow down ring
- therefore destined for 2-phase - flows
- high-positioned full nozzle pipe so that after the deviation at the lifting bell the flow has the body volume at its disposal for undisturbed discharge flow
- full opening (pop action) to the lift stop, i. e. stable final position
- the bellow is outside the main flow
- the bellow is balanced with the seat cross section under consideration of the production tolerances and therefore compensates the back pressure, i. e. consideration of the plant back pressure is not necessary during valve adjustment
- for lapping the disk can be easily dismounted from the lifting bell
- the springs are subject to high special quality requirements.

Literature:


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