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European Program on Evaluation of Safety Valve Stability

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Safety valve instability can lead to incidents with serious danger to human health and the environment. Plant downtime as a result of damage to property causes loss of revenue. To avoid such incidents the approval of safety valves and the construction of inlet and outlet lines are determined by national standards. However, recent findings from a comprehensive test program with API valves disproved the current sizing criteria according to standards like API 520 Part II. Due to these findings new sizing criteria are to be developed. The question that arises is whether these new sizing criteria also have to be applied as is to the installations in Europe. In fact, European safety valves are generally different in geometry and design. Therefore, the European Program on Evaluation of Safety Valve Stability (EuroValve) was started to investigate the stability of safety valves experimentally and to determine appropriate stability criteria especially for European safety valve designs. The focus will be on evaluating and quantifying the influencing parameters on the safety valve stability regarding to the individual valve design and the process and test conditions respectively in a great depth. For the development of these "EuroValve sizing criteria" the physical phenomena causing valve instability must be understood. There is a large number of related parameters which influence valve stability. The present paper outlines a number of these parameters regarding valve design, piping and testing procedures. Different kind of current test rigs are discussed and requirements for practically orientated test conditions are defined. Further, the differences between European and API valves are analyzed regarding valve stability. Finally the key data of the EuroValve program are presented.

1. Introduction

In the chemical, pharmaceutical and petrochemical industries, reactors are protected against overpressure by safety relief devices such as pressure relief valves. In recent years a discussion evolved about design criteria for valve stability. Current design standards worldwide are based on the fact that the root cause for instability is too large pressure drop in inlet and outlet vent line systems. From experience it is known that the criteria are applicable for the majority of the current sizing conditions, but in some of the installations valve instability may not be ruled out. In order to establish appropriate general design guidance, the Petroleum Environmental Research Forum (PERF) initiated a large research program in the US in 1999, which was extended by a second program in 2013. Two years later, the European chemical and petrochemical industries also initiated a research program – EuroValve – with a focus on European safety valve designs.

2. Safety valve instability

Safety valve instability which occurs in the form of fluttering or chattering during an emergency relief event poses a serious risk to the plant and the environment. Fluttering and chattering is to be understood as high frequency (typically > 10 Hz) uncontrolled, chaotic opening and closing of a safety valve in operation. In theory fluttering describes oscillations of the valve disc that does not result in the disc contacting the seat. However, chattering describes the more violent type when the valve disc is repeatedly impacting with the seat. In practice, fluttering often develops into chattering. Chattering causes intense vibration in the entire relief system consisting of inlet line, safety valve and outlet line. The inlet and outlet lines may crack thereby releasing explosive and toxic substances to the environment in an uncontrolled manner. Vibrations also may cause mechanical damage to the safety valve. An incident at a petrochemical plant in Cologne, Germany on 05.06.2011, is just one example of property damage and environmental pollution caused by safety valve

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instability – resulting in costs of about 500,000 Euro (Umweltbundesamt, 2014). Furthermore experiments have shown that the discharge mass flow rate in an instable valve is up to 50 % lower than the design mass flow rate of a stable open valve. Local temperature rise due to friction may jam the spindle in the guide. These facts put the safety of the entire technical plant at risk (Schmidt, 2011) (Paul, 2015).

3. RAGAGEPs and state of knowledge

In international standards like ISO 4126-9 and API 520 Part II safety valve instability is described as a problem caused primarily by the pressure change in inlet and outlet line of the safety valve. Therefore, in these standards the maximum allowable pressure loss in the inlet line and the maximum allowable back pressure is limited to 3 % and 10 % respectively. But these are just Recognized and Generally Accepted Good Engineering Practices (RAGAGEPs), which still have not been verified scientifically. In the US a number of safety valve installations do not comply with the 3 % rule. This is based on previous API standards with the argument that in case of a 7 % or higher blowdown the valve could not close. However, the Occupational Safety & Health Administration (OSHA) did not accept this argumentation and started levying fines against companies violating the 3 % rule (Smith et al., 2011). Hence, in recent years PERF started a research program with the aim of establishing a new stability criterion for rating safety valve installations. The original intention was to show that inlet pressure losses even up to 5 % do not cause valve instability. Though, the PERF research program’s experimental results did not confirm this presumption. Even the 3 % rule is not conservative and needs to be adapted or replaced. For example, the experimental results presented by Hős et al. (2014) proved unstable behavior for an 2J3 API valve with straight inlet piping of 1.22 m. Compared to the 3 % rule or even a 5 % rule the maximum allowable pipe length is 1.62 m and 2.96 m respectively – calculated according to “AD 2000-Merkblatt A2”.

First findings of the PERF program were already included in the current API 520 Part II standard, which was released in March 2015. In this standard, in a comprehensive chapter about pressure relief valve stability five potential causes of valve instability are discussed, additionally to the 3 % rule: excessive built-up back pressure, retrograde condensation, improper valve selection, oversizing of the valve and acoustic interaction. Even though the 3 % rule is still part of this standard it is clear that it needs to be replaced or at least amended – as the following quotation from the API 520 Part II reveals: “Limited testing has shown that in many cases PRVs did not chatter when inlet losses exceeded 3 % of set pressure while in some tests PRVs chatters when inlet pressure loss were less then 3 %.”

The question that arises Europe-wide is whether the findings from PERF have to be applied as is to the installations in Europe. In fact, European safety valves are generally different in geometry and design. For instance area ratios, nozzle and disc designs are different. Secondly, test rigs and testing procedures, which should be close to real operating conditions, are not standardized and may affect the results of regarding valve stability.

4. Type tests for design certification of safety valves

Safety valves in Europe are approved by type tests subject to e.g. the standard VdTÜV-Merkblatt Sicherheitsventile 100. However, this examination only states that the approval standards like AD 2000-Merkblatt A2 or DIN EN ISO 4126-1 have been applied correctly. The type tests do not evaluate the performance of a safety valve under typical operating conditions. In industrial plants vent lines comprise of complex inlet and outlet lines including tees, bends, expanders and other fittings. In addition, the protected equipment like vessels, reactors and pipes vary in size depending on the particular plant. Also process conditions like the reaction speed and the associated rate of pressure rise differ from process to process. Although these parameters effect the valve’s functional characteristics significantly, it is not examined in safety valve type testing. In Europe, the administrative bodies which are charged with regular pressure equipment inspections usually perform the type tests at a facility which is provided by the manufacturer. The test facility and the performance tests are not specified in detail to ensure reproducible results independent of the test facility. Hence, the valve is certified on the same test rig where it was developed and optimized.

The tests are usually done with new safety valves, installed directly on top of a vessel, usually without an inlet and outlet line with discharge to atmosphere. Test procedures are not standardized. There is neither a regulation for the rate of pressure rise nor for the required fluid capacity upstream in the buffer vessel. Further the geometry of the stub pipe for the experimental setup is not standardized. Well-rounded as well as sharp edged inlets are permissible. But the inlet geometry and shape of the stub pipe is suspected of being crucial for the valve stability because of its influence on flow acoustic resonance phenomena and the formation of vortices. However, even the use of reducers between the pressure vessel flanges and the safety valve is allowed. This was acceptable as these kinds of type tests do not focus on examination of the safety valve stability. Another disability of the current test facilities is the limitation for the maximum test pressure. As a consequence safety valves with high set pressures can't be tested. Further, the facilities are restricted by the buffer volume of the test rig. Therefore, the maximum valve size which can be tested is also limited. For the case that the capacity of a test facility is inadequate, as an exception models with a flow diameter of at least 40 mm are currently acceptable in accordance with the standards. This is based on steady state scaling of the flow, although there is no proof that scaled models behave the same way as the original valve regarding to valve stability.

As a consequence, there is a debate between manufacturers on whether steady state conditions or dynamic measurements are more suitable for those tests. The standard stipulates steady state conditions but dynamic measurements seem to be more practice-oriented.

Today's type tests conducted under laboratory conditions do not cover the necessary aspects of the functionality and reliability of a safety valve in practice. It is just a proof of a product without inlet and outlet line. An adaption of the test methods to real operating conditions is necessary. Besides the valve specific parameters the influence of the experimental setup on safety valve stability must be investigated. Different relief scenarios have to be tested and evaluated.

5. Experimental tests for evaluation of safety valve stability criteria

The standards define an allowable pressure loss between vessel and valve outlet as less than 3 % of the difference between set pressure and superimposed back pressure at the maximum mass flow rate. This is called the 3 % rule. According to this rule the diameter of the inlet pipe is the most relevant parameter affecting the maximum allowable length of a straight inlet pipe. In industry several tests were made like Schmidt (2011) to investigate the effect of pressure inlet losses on the functionality of the safety valve. In these tests inappropriate test setups were used where the pressure loss is caused by a restriction like an orifice plate or a control valve between the pressure reservoir and the safety valve. Bommes (1984) has shown that these kind of simplified experimental setups are not suitable to evaluate safety valve stability. His experiments have shown safety valves in stable operation at pressure inlet losses up to 20 % when the pressure loss is caused artificially at a local point, while in a second setup with real inlet pipes and a linear pressure loss of only 4 % the same valve becomes already unstable. In conclusion he considered that self-excited oscillations of the valve can only occur if the pressure reservoir and the safety valve interacts with a time delay. Concluding from the results of Bommes: inlet pressure losses are not the only and probably not the most important cause for valve chattering, and previous experiments with simplified experimental setups are unsuitable to investigate valve instability. It emphasizes the importance of experimental setups and testing procedures to be comparable to installations and process conditions in real plants. It also explains the contradictory results of previous research programs presented in table 1.

There are other approaches for sizing criteria than the 3 % rule – e.g. the pressure surge rule of Cremers (2000). This rule is based on the Joukowski equation to describe the rapid pressure drop on the upstream side of the valve disc caused by the rapid opening of the valve. This rule includes valve specific parameters like the valve opening time and the blowdown. However, in practice this data are unknown because these parameters vary significantly within a particular safety valve type and size or even within a production batch. For example, Singh and Shak (1982) have shown a deviation of about 2 % of the blowdown as a result of a typical manufacturing tolerance on the spring stiffness constant of about 5 %. 2 % difference in blowdown lead to a completely different functional characteristic of the valve, considering the maximum blowdown of an API valve of about 7 %. Figure 1 displays recent experimental results for an 2J3 API valve in gas service with straight inlet piping compared to

Table 1: Selection of contradictory experimental results about the influence of inlet piping on safety valve stability

Author	Valve / Medium	Conclusion
ERPI (1982)	3 API valves / water	3 % rule is not always conservative for large sized valves
Bommes (1984)	DN 25/40 / water	test setups with local pressure losses are not representative
Kastor (1986)	API DN 25/50 / air	3 % rule is overly conservative
Stremme (1993)	DN 50/80 / water	pressure surge rule – improper replacement for the 3 % rule
Schmidt (2011)	DN 25/40 / nitrogen	3 % rule is conservative
Cremers (2000)	DN 25/40 / gases	pressure surge rule as suitable replacement for the 3 % rule
Izuchi (2010)	API 1E2, 1.5F2 / gas	inlet piping: 1 m to 5 m (unstable); 0 m and > 10 m (stable)
Smith et al. (2011)	550 API valves	some valves in practice operate stable while 3 % rule is violated
Hős et al. (2014)	3 API valves / gas	3 % rule is not conservative

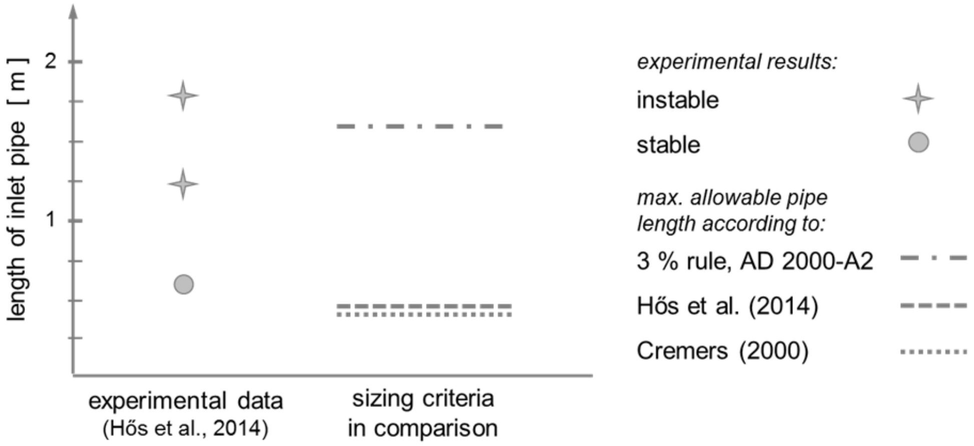

Figure 1: Experimental results for an API 2J3 valve in gas service with straight inlet piping compared to the calculated maximum allowable pipe length according to three different sizing criteria.

the calculated maximum allowable inlet pipe length according to three different sizing criteria. According to the 3 % rule a straight inlet pipe up to 1.6 m would be allowed while the other criteria restrict the maximum allowable length to about 0.5 m. The experiments prove the 3 % rule as not conservative because chattering already appeared by tests with an inlet pipe length of 1.22 m. The alternative rules are much more conservative in dimensioning of the pipe length. The third sizing criteria in figure 1 by Hős et al. (2014) is a mathematical model assuming that the physical phenomenon of instability can be mathematically described as a Hopf bifurcation involving the fundamental, quarter-wave pipe mode. Hős et al. provide several models which require many valve specific parameters – more than the pressure surge rule of Cremers. The advantage of these alternative models is the physical basis of the semi-empirical functions considering valve specific parameters. However, in practice most of these parameters are unknown.

6. Valve specific parameter regarding safety valve stability

In the context of the PERF program Darby and Aldeeb (2014) outlined several parameter which are taken into account by their mathematical model to describe the dynamic response of pressure relief valves in vapor or gas service: set pressure, blowdown, mass of moving parts, spring constant, damping factor, closed disk contact diameter, open disk effective diameter, full open discharge coefficient, partly open discharge coefficient, fluid deflection angle from horizon and initial and maximum lift. Darby's model is solely validated by experimental results for API valves. Tests with European valves may reveal additional influence parameter because API and European valves show some significant differences regarding the design concepts. Regarding this figure 2 displays API valves from two different European manufacturers together with their vale designs for the European market. The figure outlines manufacturer-specific differences and fundamental design differences between API and European valves. They mainly differ in the size of the valve components relative to the individual narrowest flow diameter d_1 of the valve. Due to the screwed-full-nozzle the narrowest flow diameter of API valves is always smaller. Therefore, the proportions of API safety valves are much larger than those of typical European valves. Thus the volume of the housing is different. This influences the rate at which the built-up back pressure increases in the housing and also counteracts with the disc thereby affecting the valve opening characteristics. The dimensions and the form of the nozzle influences the flow conditions, the momentum of the flow and the resonance. Sharp edges may induce vortex shedding which in turn may affect stability. Further, the inlet between the two designs differs as the API design has a rounded inlet at the API nozzle pipe, while the valve in Europe has a sharp-edged inlet. Another difference arises from the fact that the valve lift may be restricted or the valve disc may flow in the stream without a restriction as typical for API valves. To adjust the valve characteristics, in particular the blowdown, API valves are equipped with an additionally nozzle-ring. The mounting height between nozzle and outlet flange or rather the h_1 to h_2 influences the fluid dynamics and the vortices in the housing. Beyond this, the form of the housing influences the fluid dynamics in the housing. Experimental results of tests with API valves may not be transferred to European valves. It needs to be emphasized that latest research programs on safety valve stability focused on API valves. Hence, comparative measurements with European valves are essential for the development of a generally valid design rule.

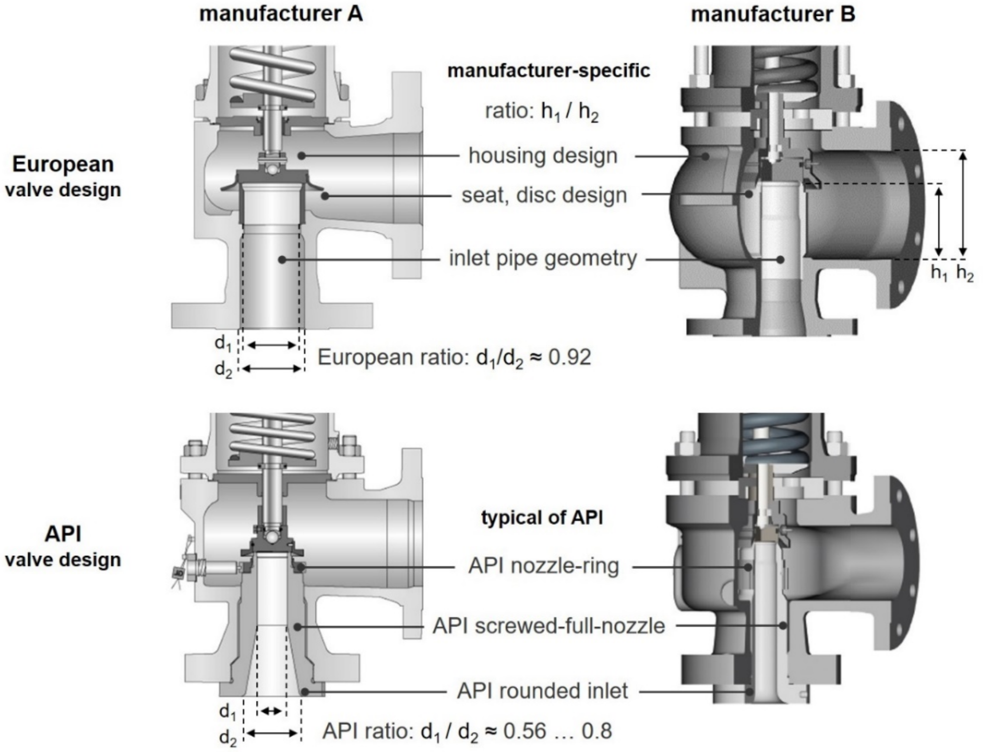

Figure 2: Safety valve designs of two European manufacturers A (LESER, 2013) and B (Bopp & Reuther, 2011). Comparison between typical European and API designs (upper and lower), and comparison between different manufacturer-specific designs (left and right).

7. EuroValve program

The chemical, petrochemical and pharmaceutical industry in Europe jointly started the EuroValve program at the Center of Safety Excellence (CSE institute, Germany) in 2015. The main focus is the investigation of safety valves built according to European standards thereby taking into consideration real installation conditions and procedures. The requirements for the experiments are based on data from the European industry: 90 % of all safety valves in use have a seat diameter of 40 mm and below and 70 % have a set pressure less than 40 bar. Thus the first phase of the EuroValve measurement program is focusing on:

- safety valves DN 25x40 and DN 50x80, targeting the effects of valve size
- set pressure range of 0.5 barg to 20 barg
- examination of special forms like dampers and bellows
- tests with inlet piping: different lengths and fittings like bends, tees, reducers, etc
- tests with outlet lines
- evaluation of the impact of test procedures regarding pressure rise rate and buffer vessel volume
- study of measures to counter or minimize risk of flattering, e.g. plant specific pulsation dampeners.

Preliminary tests have already taken place together with IMI Bopp & Reuther in Mannheim, analogous to the tests in PERF (Hős et al., 2014). For a detailed evaluation of this test result further experiments are required. To perform the safety valve tests for the EuroValve project a large test facility will be established at the CSE institute. In the final stage of the installation tests with gas, water and two-phase mixtures will be conducted. The test facility will consist of three sections: one with a design pressure of 160 bar and a buffer volume of 67 m^3, a second high pressure section of up to 650 bar design pressure and a vessel volume of 6 m^3 and a third super high pressure section of up to 3400 bar and 0.6 m^3 vessel volume. It allows for testing of relief devices at industrial scale as well as for very high set pressures.

8. Conclusion

Type tests for design certification of safety valves are unsuitable to evaluate the valve stability. They are performed without inlet and outlet piping. Currently inlet lines are sized according to the 3 % rule. The findings of the recent PERF experiments have shown that this is not a conservative sizing method to ensure a stable valve operation. A new sizing rule is expected to be more conservative. The comparison between the calculated inlet pipe length according to the 3 % rule and alternative sizing methods like the Cremers model and the Hős model results in a restriction of the pipe length of less than a third. The findings of PERF are based on tests with API valves. Because of the design difference in the construction of European and API safety valves these results may not be applied to European valve designs. Due to the complexity of physics including valve fluttering or chattering further investigations and as a result general stability criteria are strongly needed. Therefore, the European industry started the EuroValve program at the Center of Safety Excellence, Germany (CSE institute) with a focus on European safety valve designs. Former industry-driven measurement programs used simplified test setups which were not suitable for the evaluation of valve chattering. Future test setups need to be reproduced in facsimile regarding inlet and outlet piping. Process conditions and testing procedures respectively must be considered. Parameters like rate of pressure rise and the volume of the buffer vessel are therefore not negligible. Scaling effects between different valve sizes and phenomena for different set pressures have to be investigated. The future test facility at the CSE institute provides the required equipment for such a wide range of tests.

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