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Practical Experiences with the Assessment of Safety Valve Design in Chemical Plants

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Over the last few decades most of the chemical companies have started a complete re-assessment of their pressure relief devices. The main reason for these sometimes extensive projects is to meet the state of the art, aiming for a comprehensive documentation as claimed in technical guidelines. Consilab has been involved in re-assessing pressure vessel safety in many chemical plants throughout the past 5 years. One of the major objects was the calculative inspection of rupture discs and safety valves as well as their inlet lines and vent lines. A database supported documentation of assumptions, results and, if necessary, measures was customized to provide the operating companies with reliable and comprehensive information about their state of safety. Interesting facts on how the awareness of safety in chemical plants changed over the decades could be derived from the comparison of the results of the last 5 years to statistics from the 1990s, published by Köper and Westphal (2001).
The latest statistics can help to answer questions such as which errors in the design of pressure relief devices are most likely to occur in a typical chemical plant and which are the most decisive. These answers should provide measures for safer chemical production sites in all areas.

1. Motivation for re-assessments of pressure relief devices in existing chemical plants

When a new plant is to be built, the decision to safeguard pressurized equipment with mechanical pressure relief devices is part of the basic safety concept. Then, the design of the safety valve is part of the detail engineering phase. The calculative design of pressure relief devices as well as their inlet lines and vent lines is state of the art and clearly and distinctly implemented in the guidelines, e.g. ISO 4126 parts 1-10 or ISO 23251. Hence, authorities insist on a comprehensive documentation for these devices before approval.
That there is still need for action in older plants is often detected by coincidence, e.g. when audits of insurance companies reveal lacks in documentation. In some cases, the documentation of safety valve design seems to consist of some instrument list for periodical inspection, only. If the design cases are neither documented nor known, the proof of reliable design of the pressure relief device does not exist. In other cases, a plant is to be extended or the number of emission points is to be reduced but the obligatory questions by the authorities cannot be answered because of a lack in documentation. In a few cases, the lack of documentation is only noticed after a safety valve was activated and chemicals had been discharged into the environment.
Since more and more companies tend to do re-assessments of their complete stock of pressure relief devices nowadays, the awareness for safety seems to have grown. The targets are to find out if safety had been inattentively disregarded at some point in the past, the chance to change and to prove pressure vessel safety in all areas.

2. Comparison of statistical data

The existing data base with sizing results of approximately 1500 safety valves over the last 5 years suggests itself to be compared to the published data from the 1990s. So the results from the data base had to be brought into the same form as the published.
Tables 1 and 2 show the results of the recent investigation whereat the numbers in brackets were directly derived from the publication of Köper and Westphal (2001).

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Table 1: Results of the investigations: Ratio of design cases and types of deficiencies

Design Case	Ratio of SV per design case	Ratio of SV with design failure	Type of Deficiency		
			SV size too low	Inlet pressure loss	Back pressure in vent line
Chemical Reaction	5 % (3 %)	1 % (6 %)	0.5 % (2 %)	0.1 % (3 %)	0.4 % (1 %)
Excessive heating	18 % (16 %)	15 % (36 %)	3 % (15 %)	7 % (12 %)	5 % (14 %)
Gas feed	25 % (19 %)	36 % (46%)	5 % (38 %)	20 % (7 %)	11 % (8 %)
Liquid Feed	12 % (19 %)	10 % (22 %)	1 % (15 %)	2 % (4 %)	7 % (4 %)
Thermal Expansion	40 % (44 %)	3 % (2 %)	0 % (1 %)	1 % (0 %)	2 % (1 %)
Total	100 %	14 % (17 %)	2 % (10 %)	6 % (3 %)	6 % (4 %)

The actual result from table 1 is that in recent years about 14 % of all checked safety valves had a design failure. This is slightly less than 15 years before. While in the 1990s 10 % had a relief area which was too small, it were only 2 % in the years 2010 to 2015. But the results of the calculations for the inlet lines and vent lines unfortunately rose from 3 % and 4 % to 6 % for both. Remarkably the re-assessed safety valves for the design case of gas feed still have the most design failures.

It can also be derived, that thermal expansion with a ratio of 40 % is the most surveyed design case although the ratio dropped a little since the 1990s. The ratio of liquid feed dropped from 19 % to only 12 % while the ratio of the other design cases slightly rose. In the 1990s only 3 % of the safety valves were designed for the most complex case of a chemical reaction while it is 5 % nowadays. Design cases as vapour pressure rise because of excessive heating, gas feed or liquid feed were almost equally spread slightly below 20 % each in the past. Nowadays liquid feed was taken into consideration less than half as often as gas feed. The most remarkable fact according to the design cases is, that almost half of the safety valves that had been re-assessed for the design case of gas feed in the 1990s had design failures. Mostly the safety valve had been too small. In the recent investigation gas feed was still the design case with the most design failures but it is most noticeable, that the issues appear with the piping system and not much with the size of the safety valve.

In table 2 the required measures to resolve the deficiencies are related to the different types of deficiencies. While in the 1990s 60 % of the total deficiencies consisted of a too small relief area, 15 years later this ratio dropped down to 14 %. Even today still more than half of these issues can be resolved by a larger safety valve and the other half by restriction of feed.

43 % of the valves have too high pressure losses in their inlet line and another 43 % of the valves have too high back pressure. Both of these ratios had been around 20 % in the 1990s. In the past, 63 % of the valves with too high pressure losses in their inlet line could be cured by either a lift restriction or a vibration damper, for 35 % an inlet line with a larger diameter had to be installed and for only 2 % a smaller safety valve was required to meet all tolerable limits. In the recent investigation only 29 % of the inlet line issues could be cured by either a lift restriction or a vibration damper. For the majority of 59 % an inlet line with a larger diameter had to be installed and for 14 % a smaller safety valve was required to meet the tolerable limits.

While in the 1990s the majority of measures to too high back pressures in the vent line were almost equally split between bellow with 39 % and a lift restriction or a vibration damper in 38 % of the cases, nowadays a bellow has to be applied in 54 % of the cases. While in the past only 1 % of the problems with too high back pressures could be solved by the application of a smaller safety valve, this recommendation rose up to 23 %. The ratio of the cases where a larger diameter of the vent line was required dropped from 22 % to 15 %.

The most considerable difference between the two re-assessments of the safety valve design is that the emphasis of deficiencies has clearly shifted from too small relief areas to too high pressure losses in the pipe lines.

The most important result of the comparison of the two statistics is the most surprising, too. The ratio of failures in pressure relief design has not dropped as remarkably as expected. Reducing the ratio of safety valves with design failures from 17 % to 14 % within 15 years is not satisfying at all. It must be analyzed where the most decisive failures can occur and how they can be prevented.

Table 2: Results of the investigations: Ratio of deficiencies and required measures

Deficiency	Ratio	Required Measures	Ratio
Safety valve not sufficiently sized	14 % (60 %)	Larger safety valve	60 % (53 %)
		Restriction of feed	40 % (47 %)
Pressure loss in inlet line > 3%	43 % (18 %)	Larger Diameter	57% (35 %)
		Smaller safety valve size	14% (2 %)
		Restriction of lift/ Vibration damper	29 % (63 %)
Back pressure in vent line too high	43 % (22 %)	Larger Diameter	15 % (22 %)
		Smaller safety valve size	23 % (1 %)
		Restriction of lift/ Vibration damper	8 % (38 %)
		bellow	54 % (39 %)

3. Tracing down the design errors

3.1 Seven steps to a properly sized pressure relief device

At consilab the sizing of a safety valve usually consists of seven steps, as shown in figure 1. In each step, from the identification of the design case to the documentation of the results, far-reaching mistakes can be made that have to be certainly prevented. Thus, it is very useful to maintain the step-by-step approach while designing pressure relief systems.

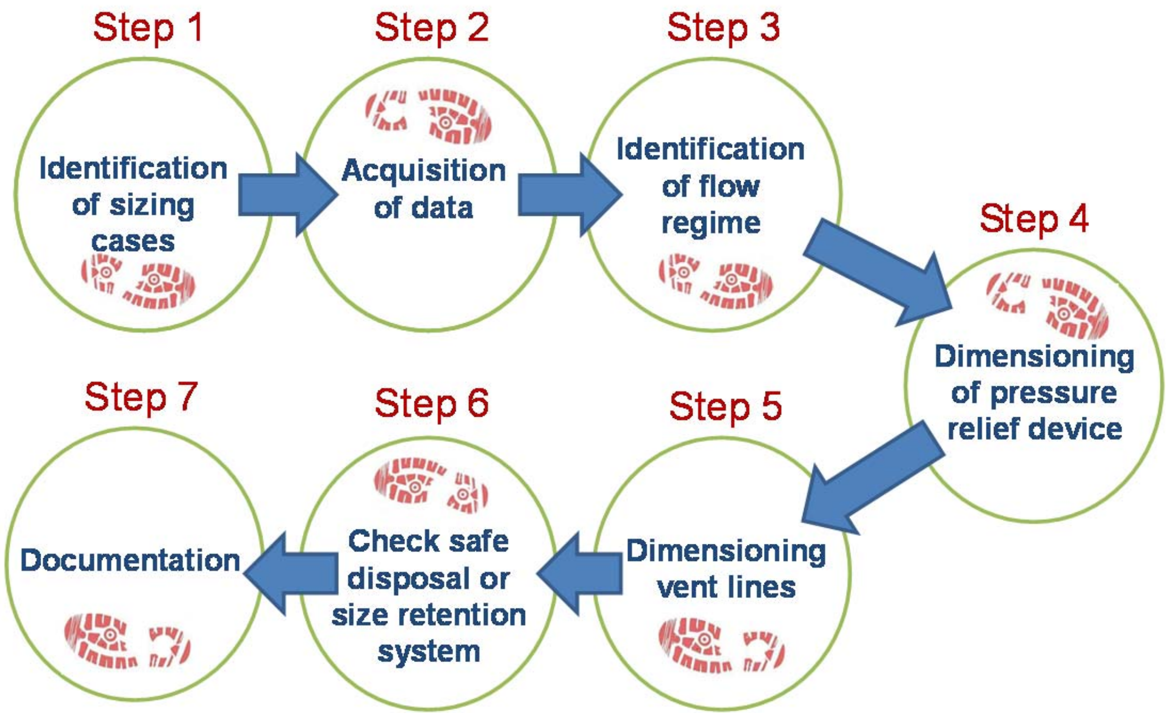

Figure 1: Seven steps to a properly sized pressure relief device

3.2 Step 1: Common errors at the identification of the design case

The result of a relief area design for safety valves is determined primarily by the design case, less than by calculation methods. So the most important part is, not to overlook a critical design case. Usually design cases should be defined in a safety analysis or risk assessment meeting. Since the quality of the results of those meetings is substantially dependent on the team line-up, the team should consist of members who know the process from different points of view, like chemists, process engineers, safety specialists, piping experts and even plant operators.

Whatever systematic safety analysis is preferred, the basic question is: how can an inadmissible pressure increase arise in the system to be protected.

The design cases can be divided into three categories, mechanical, thermal and chemical causes. Mechanical causes, as liquid feed via pump or gas feed from a net, such are sometimes overlooked because only the reduced pressure of a controller is taken into account instead of the maximum pressure at controller failure, or,

because the PID only shows the normal pump delivery rate and pump delivery head instead of the maximum values. Different pressures also have to be taken into account, if a ball valve in a connecting line of two vessels can be abruptly opened while one of them is under pressure.
In case of thermal causes, it can happen that the normal heating temperature is taken into account but not the maximum heater temperature at controller failure or that the vapor pressures of solvents, especially in case of CIP (cleaning in place) media, are underestimated.
Chemical causes can be dangerously underestimated by chemists who know by experience that there is no – or at least almost no – exothermal appearance in the test tube. Since the volume area ratio in a big vessel is so much higher as in a test tube, there can always be surprises as a fast temperature rise. Very often there is just a lack of proper data. Especially this topic is extensively described in several publications, e.g. in the German TRAS 410.

3.3 Step 2: Common errors at the acquisition of data

Reliable technical data as well as the temperature dependent physical properties of the single solvents are usually at hand for the calculation. Mostly vapor pressure rise of a single component solvent can be established as a conservative case. In some cases, the vapor pressure rise of a multi component solution is worse. Thus identifying physical properties is much more challenging. In some cases, binary interaction parameters (BIP) are available from databases and seem to be the key for good property data. If not, the calculations will be carried out with an idealized system. The influence of idealized system properties and BIP generated properties on the relief area of a safety valve compared to the influence of measured data was investigated by S. Dreisch (2014). Figure 2 shows the calculated relief diameter of a safety valve over the mass fraction of the mixture for an acetone/ chlorobenzene mixture. It clearly indicates that the results with the idealized properties are unsafe. The results from the calculations with the BIP properties are conservative but lead to oversized safety valves over a wide range.

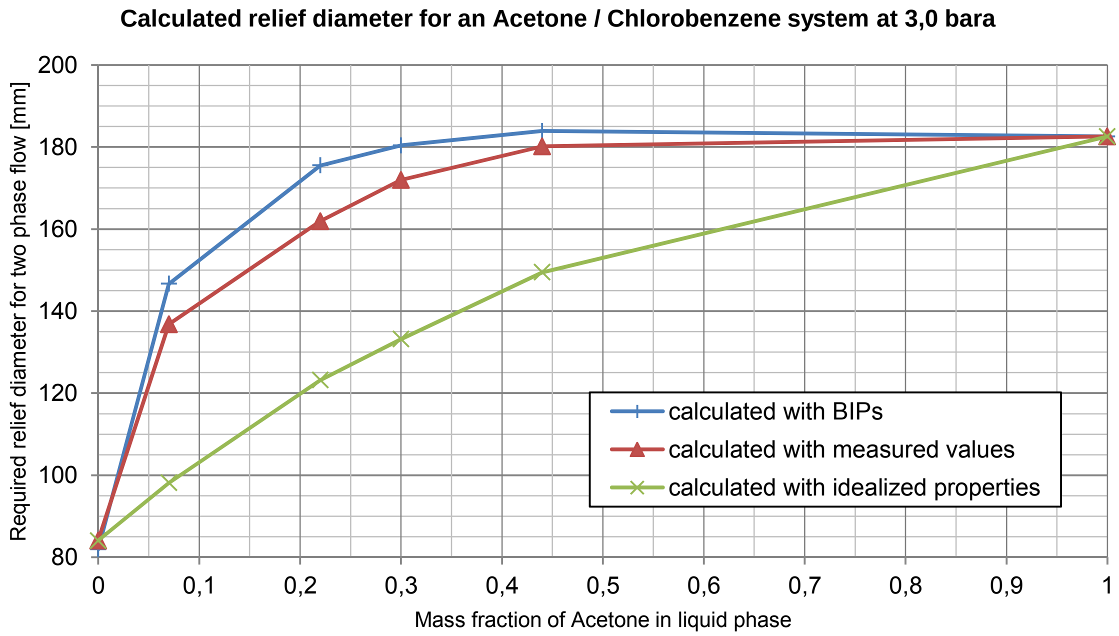

Figure 2: Influence of idealized physical properties of multi component systems on the size of a safety valve

The influence of improper data on the size of relief areas for the case of exothermal runaway reactions was clearly evaluated by M. Christ (2009). The results are summarized as recommendations in table 5.

Table 3: Influence of improper input data on the size of relief areas

Input parameter	Influence on max. deviation	Recommendation for conservative results
Set pressure	high	better estimate too low
Difference to max. allowable over pressure		better estimate too low
Temperature at set pressure		better estimate too high
Max. temperature difference		better estimate too low
Temperature rise rate at max. pressure		better estimate too high
Molar mass		better estimate too low
Mass of reactants	medium	better estimate too high
Temperature rise rate at set pressure		better estimate too high
Compressibility factor Z		better estimate too high
Flow coefficient		better estimate too low
Liquid specific heat		better estimate too high
Liquid density (without respect to fill level)	low	better estimate too high

3.4 Step 3: Common errors at the definition of flow regime

Although there have been hundreds of publications on two phase flow through pressure relief devices and there has been activity from DIERS starting about 1980 plus the ISO 4126 part 10 has been valid since 2010, there is still a huge lack of awareness. Very often the complexity of the calculation seems to be the reason that the level swell phenomenon or the foam formation are often ignored. Meanwhile many simulation programs which include two-phase flow calculations, like ASPEN PLUS©, ChemCad-Safetynet© or Superchems©, are available, so that this “poor excuse” should be not allowed any more.

3.5 Step 4: Common errors at the sizing calculation

Especially for the design case of a chemical runaway reaction, there are numerous methods recommended for vent sizing calculations. Christ and Westphal (2009) compared the results of sizing methods to actual data from relief tests. The DIERS recommended methods and the method recommended in ISO 4126-10 arise as reasonable tools for a sizing calculation. While the FIA-Nomogram resulted in up to 200 % over dimensioned relief diameters, others, like Fauske’s “quick” and “simple” methods, which are partially surprisingly good, in some cases resulted in under dimensioned relief diameters.

In summary, the quality of the sizing results mainly depends on the sizing method retrieved by experience, the technical data retrieved from the PID or the plant engineers, the reaction data retrieved from reaction calorimetry tests and the physical properties retrieved from data bases.

3.6 Step 5: Common errors at the sizing of the inlet line and vent line

Looking at the inlet lines of safety valves, compliance with the 3 % rule, which is still part of some standards, is sometimes a challenge. In older plants, it is usual that several feed lines are combined via several T-pieces and led into one socket of the vessel to be protected. As a safety valve is not needed for the usual process, it is very common to install it at the very end of such a construction. If the diameter of the pipe construction is not markedly larger than the diameter of the valve inlet, pressure losses of up to 20% can occur. The best solution for this kind of problem is to find an available socket for the safety valve alone.

Issues with vent lines often appear if the retention system has not been considered, or, if collecting vent lines for several safety valve vent lines have recently be installed and the collecting system is just too long. Very often, the collecting system leads to the roof top. However, if liquids have to be vented, the hydrostatic pressure in the vent line can prevent the safety valve from opening at the right pressure. In many cases, catch tanks are installed to collect the liquids but the vent line of the catch tank is just too small to vent the gases.

3.7 Step 6: Common errors at the installation of retention systems

The discharge of hazardous materials has to be prevented. Depending on the boundary conditions and the properties, there are several possibilities for retention systems, as shown in figure 3. The design of this kind of systems is described very well in the literature, e.g. Guidelines for Pressure Relief and Effluent Handling Systems, CCPS-Book (1998). Nevertheless, especially knock-out drums are often undersized in older plants, so that, in case of a foaming fluid system, larger amounts of liquids are discharged into the environment.

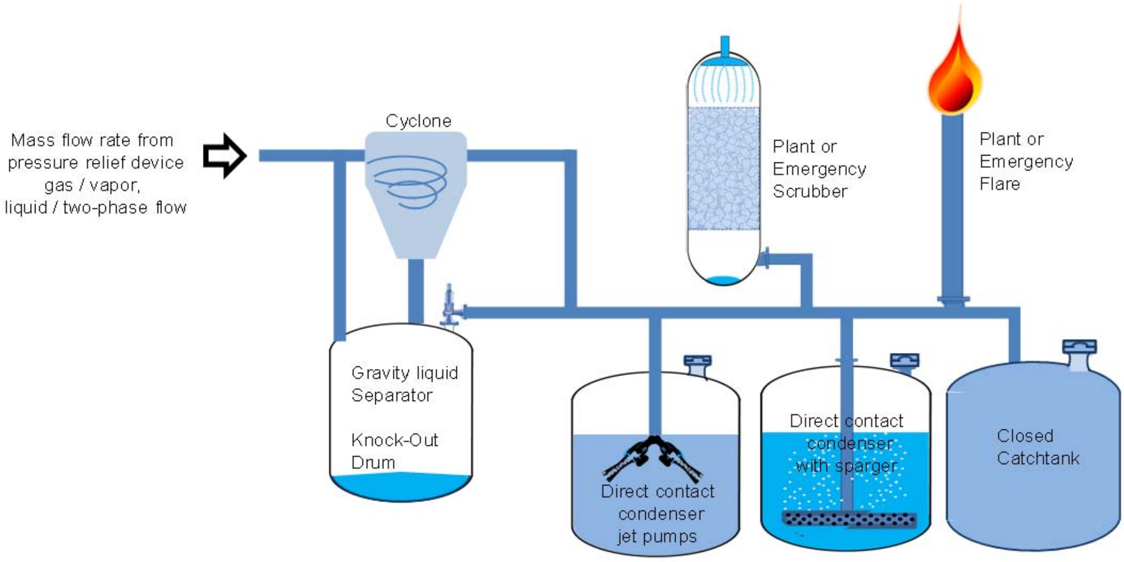

Figure 3: Alternative components for retention systems

3.8 Step 7: Documentation

The documentation of the safety valve design must be reliable and comprehensive. The complete information should be at one place. The data used for the calculation as well as the result should be documented for every considered design case, plus there should be a list of all considered design cases and a list of the maximum discharge flows as basis of an emission cadastre. There should also be one page with the complete information about the safety valve, for purchase. In the end, there should be signatures of all persons responsible.

4. Conclusion

The reliability of safety valves is substantially dependent on the sizing of the safety valve and its installation in the plant. To keep track of the changes in a production site over time is essential for pressure vessel safety since any exchange may require a complete re-assessment of the pressure relief system.

The awareness has changed to the better, when results from the 1990s are compared to recent investigations. Most of the later issues arise from the installation of better venting systems or retention systems. It is a step into the right direction but by far not satisfying yet.

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