Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Loss Prevention in the Process Industries 16 (2003) 73–79
Journal of Loss Prevention in the process industries
www.elsevier.com/locate/jlp

Database-supported documentation and verification of pressure relief device design in chemical plants☆

O. Köper, F. Westphal *

Siemens Axiva GmbH & Co. KG, Process Safety, Industriepark Höchst C487, 65926 Frankfurt, Germany

Abstract

In this paper the results of a multi-year analysis of the pressure relief devices located in several plants in major chemical sites are summarized. The analysis consisted of a systematic evaluation of existing safety valves and rupture discs including the identification of the service conditions and design cases as well as the sizing calculations of the individual device and associated piping. Furthermore, from the total amount and the hazardous potential of the effluents the necessity of retention systems is evaluated to ensure a safe disposal.

Because the knowledge in the field of emergency pressure relief changed very rapidly in recent years, the design of some safety devices was not according to the state of the art. An essential part of the verification program was the recommendation of measures to find the most economical yet technically correct way to correct these deficiencies. Rather than by carrying out wholesale replacement of an incorrectly sized safety device or vent line, often a reduction of the mass flow rate to be discharged, for example, by an orifice in a supply line, is sufficient.

Results of the analysis were recorded on a novel database to capture the sizing information and maintain correct pressure relief device sizing into the future. The systematic databased approach has been used for the evaluation of about 4000 safety devices so far. The procedure has been proven to enable an experienced design engineer to carry out the analysis of a great number of pressure relief devices in a time-saving, reliable and reviewable way.

Keywords: Relief valve; Database safety audit; Design calculation

1. Introduction

The more stringent levels of environmental, plant and workplace safety required nowadays by official regulations and internal company standards make it increasingly necessary for plant managers to check and record, as completely as possible, the correct design of their apparatus, the risks involved by their processes and the protective measures and devices they employ.

Another motivation for the analysis is the demand from the general public to specify the amount and hazardous potential of the effluents from pressure relief devices. On the basis of the obtained data it can be evaluated, if a retention system is required and possibly the optimal retention system can be designed.

Plants used in the chemical and pharmaceutical industry make use of a great variety of pressurised vessels or apparatus fitted with pressure relief devices to protect against excessive overpressure. In the following, safety valves are discussed representative for other types of pressure relief devices. Nevertheless, the described method and also the database can be used for bursting discs or for vacuum protection devices (e.g. vent valves) as well. In a typical chemical plant sometimes there are about 400 safety valves in use. One problem—particularly with old plants—is that the design of these safety devices and the exact reasons for it have not been adequately documented. Another point is that the information on materials and operating conditions in the apparatus and the data for the respective safety valves are usually stored and managed in another place, thus making rapid verification and updating difficult.

For this reason the Process Safety Department of Sie-

* Corresponding author. Tel.: +49-69-3055777; fax: +49-69-30525609.

E-mail address: frank.westphal@siemens.com (F. Westphal).

☆ Dedicated to Prof. Dr.-Ing. Lutz Friedel on the occasion of his 60th birthday.

0950-4230/03/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
DOI: 10.1016/S0950-4230(02)00026-8

mens Axiva worked out a procedure permitting an overall state of the art analysis of all safety valve designs, at the same time making allowances for multiphase flow in the safety valves and pressure losses in the safety valve inlet pipes and downstream vent lines. It was also intended that this design should be comprehensively documented in a practice-relevant, easily updatable form together with all the necessary safety, apparatus and process data. A special safety valve database was developed for this purpose.

An introduction will be given here to the methods and procedures used by the authors for design analysis and documentation of about 4000 safety valves in the plants of various companies, together with an account of the results and general experience obtained.

2. Analytical procedure

The procedure used for analyzing and documenting the safety valve designs in a plant or factory is divided into five basic steps.

Step 1: Determining actual status and procuring information
Step 2: Identification and definition of design cases
Step 3: Calculation and sizing
Step 4: Evaluation and selection of corrective measures
Step 5: Documentation, elimination of deficiencies, updating

These steps, which may sometimes overlap, are accompanied and documented by appropriate inputs and additions to the information in the database. Each of these methodological steps will now be considered separately.

2.1. Step 1: Determining actual status and procuring information

To start with, all safety valves in a particular plant are systematically registered and entered in the database together with all data on the apparatus or components which they are intended to protect. For this purpose, already existing lists and other records are consulted and the P + I flowcharts evaluated in order as far as possible to reduce time-consuming visits to the plant. The necessary information and the usual sources are listed in Table 1.

One of the main problems is gathering data for older safety valve types which are no longer in service. Important items of information such as seat diameter or discharge factors were not always documented when they were first introduced. Here is one of the advantages of using a database—nowadays virtually every type of valve in use has been entered into the database and the one in question can be called up by the corresponding search functions, together with all the necessary data. This saves a lot of time-consuming enquiries, e.g. to the manufacturer.

For normal operation of the plant, usually most relevant information are available. But for deviation of the normal operation, this means for the higher temperature and pressure in the design case, it is often complicated to get physical property data, especially when dealing with multi-component systems. The toxicological and data about explosibility are necessary for the evaluation of the safe disposal of the discharged substances.

In contrast to new production plants, where the piping is frequently carried out by CAE-tools, in existing plants the vent lines are not documented all the time. Therefore an afterwards isometric drawing was necessary as a basis for the calculation of the pressure drop in the vent lines. Especially, retention systems have to be taken into account as a possible source of an additional backpressure.

A special case for information gathering, and later also for the calculations, is pressure build-up in a reactor resulting from chemical reactions. For this purpose it is important to study the available basic reaction data and kinetics and to supplement them where need be by new measurements using special calorimeters.

2.2. Step 2: Definition of design cases

As a general rule, before a safety valve can be checked or designed for a particular purpose, it is necessary to establish any deviations from normal operation which might lead to unallowable pressure build-up and hence to an opening of the valve. This is usually achieved by carrying out an analysis together with experts and plant personnel for the purpose of systematically identifying potential dangers and assessing the likelihood of them actually arising.

To enable this to be carried out in as short a time as possible, use is made of specially devised checklists with a set of carefully chosen questions, the answers to which allow possible pressure build-up mechanisms to be rapidly pinpointed and assigned to particular standardised safety valve design cases. This method also makes it possible to obtain a great deal of useful information during the course of discussions.

The standardised design cases draw basic distinctions between the following possible causes of pressure build-up in an apparatus:

- increase in the vapour pressure of the apparatus contents due to supply of extrinsic heat, e.g. from a fault in the heating system
- increase in the vapour pressure of the apparatus contents due to an exothermic chemical reaction (e.g. breakdown of the cooling system, catalyst overdosing)

Table 1
Necessary information and usual sources for the design of safety valves

Information type	Examples	Source of information
Process data	Materials, ingredients, operation, operating temperature, pressure and concentrations, feed rates, heating medium, level of liquid filling	Plant
Apparatus data	Vessel volume, max. allowable vessel pressure, effective heating surfaces, material, pressure head and volume flow rate of pumps, connected feed lines	Plant
Material data	Vapour pressures, densities, viscosities, specific heat capacities, latent heat, toxicological and explosibility classification (hazardous materials regulation), data of chemical reactions	Material databases, plant, measurements
Safety valve data	Manufacturer, type, opening characteristics, set pressure, seat diameter, discharge coefficients	Manufacturer, safety valve data base
Isometries of safety valve inlet/vent pipe	Pipe diameters and lengths, height differences, number of bends and tees, mountings and valves	Plant

- liquid entering the apparatus from a region with a higher pressure level (pump, supply network, overflow from another vessel, leakage in a heat exchanger, etc.), possibly also overfilling of the apparatus
- gas entering the apparatus from a region with a higher pressure level (fan, compressor, supply network, overflow from another vessel)
- gas produced by a chemical reaction
- thermal expansion of enclosed gaseous or liquid apparatus contents due to supply of extrinsic heat.

Definition of the design cases often reveals a variety of possible pressure build-up mechanisms, each of which might set the safety valve off and sometimes none of which can be identified a priori as the most critical case. Where this occurs it may prove necessary to carry out several calculations for a single safety valve to determine the most critical design cases either requiring the greatest relief cross-sections or resulting in the greatest pressure losses in the vent pipes, and to dimension the safety valve or the vent pipe for this particular case.

2.3. Step 3: Calculation and sizing

The procedure for the final safety valve sizing can be divided into the following calculation steps:

- determination of the required mass flow rate to be discharged via the safety valve
- determination of the mass flow rate which can be discharged via the safety valve actually installed, or dimensioning of the necessary relief cross-section area
- calculation of the pressure losses in the safety valve inlet pipe and the vent pipe (backpressure on the safety valve)
- calculation of the maximum flow forces liable to occur at the safety valve and in the vent pipe
- determination of the totally discharged masses through the safety valve (for the evaluation of safe disposal).

The method selected for calculation will depend largely on the design case and on the type of flow at the relief device (gas, liquid or two-phase flow). The calculations will be carried out with commercial or specially designed processing programs.

The decision tree below will help to show the principles on which the selection of the calculation methods is based (Fig. 1).

In the case of pressure increase due to a chemical reaction, the method selected will be that developed by DIERS (Design Institute for Emergency Relief Systems, Fischer et al. (1992)) for determining the volume of flow to be discharged and the necessary relief cross-section, starting out from the specific kinetic data for the reaction. More complex cases may sometimes require calculations with dynamic simulation programs such as SAFIRE (System Analysis for Integrated Relief Systems).

The DIERS method will also be used for designing safety valves in cases where, for example, high filler loadings, high viscosities or foaming media make a two-phase flow likely in the safety valve. In this case the necessary relief cross-sections will have to be considerably larger than in the desired case of gas/vapour flow. To be able to decide under what circumstances a two-phase flow can be safely assumed or when it will be permissible to use a valve suitable only for gas/vapour flow, it will generally be necessary to have good knowledge of the material system and the operating conditions. Decision criteria are set out by Friedel, Wehmeier and Westphal (1994).

The procedure for designing safety valves and the necessary discharge pipes for conducting gas/vapour/liquid mixtures in accordance with the DIERS method referred to above is described in detail by Schmidt and Westphal (1997).

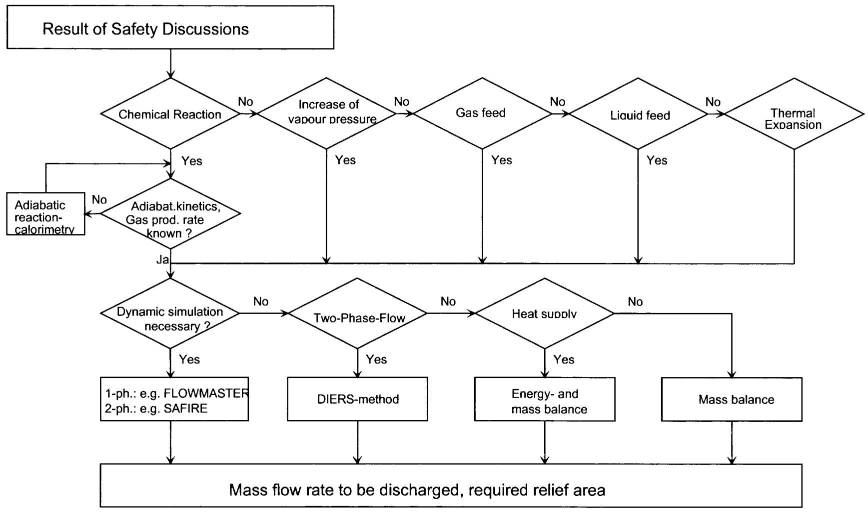

Fig. 1. Decision tree for identification of the calculation method of the mass flow rate to be discharged.

In all other design situations, i.e. where there is reason to assume that only single-phase gas/vapour or liquid flows will need to be discharged through the safety valve, the mass flow rates can be determined by energy or mass balances (vapour pressure increase, thermal expansion) or by methods of fluid mechanical calculation (gas or liquid input). Dimensioning of the appropriate relief cross-section for single-phase gas/vapour and liquid flows is carried out in accordance with the German technical regulations with reference to AD-Merkblatt A2 (2000), which is essentially identical to API RP 520 (1993).

One point frequently overlooked in the past when designing safety valves was the need to ensure that the maximum allowable limit values were observed for pressure losses in the safety valve inlet pipe and the backpressure on the safety valve in the situation in which it was to be installed. According to AD-Merkblatt A2, the pressure loss in the inlet pipe should not exceed 3% of the set pressure. The maximum allowable backpressure downstream from the safety valve given by safety valve is given by manufacturers and should be not greater than 10–15% of the set pressure for most types of valves. When the backpressure is compensated by a bellow, this value may even be as much as 35 to 50%.

Complete functioning of the safety valves can be guaranteed only if these limit values are observed; if not, one possibility is that the valve may “chatter” and then cease to function or even be destroyed. When safety valve designs are inspected, special importance will be attached to checking and ensuring the observation of these limit values.

Pressure losses in the pipes are calculated with the aid of commercial programs like FLOWMASTER® or specially designed processing programs, e.g. by Friedel and Schmidt (1993), which also allow for multiple critical flow conditions which frequently arise during release through safety valves.

2.4. Step 4: Evaluation and selection of corrective measures

Once the design cases have been defined and the design calculations have been carried out, it will be possible to analyze and evaluate the design both of the safety valve and of the safety valve inlet pipe and vent line.

Table 2 below summarizes the results obtained from an investigation of approximately 4000 safety valves. In general, deficiencies were revealed in 17% of the investigated cases, and these defects varied considerably depending on the design case in question.

As might be expected, in the relatively few cases (3%) where chemical reactions might be the cause of excessive pressure build-ups, deficiencies were present in only 6% of all chemical reaction cases investigated. This can be accounted for mainly by the fact that reactors in which exothermic chemical reactions or gas-producing reactions take place have, as a rule, been carefully analyzed and provided with the necessary safety measures.

Again, in the relatively many cases where pressure build-ups come about by thermal expansion of a enclosed liquid, the number of deficiencies will usually be very small. The reason for this is that the DN 25/25 proportional safety valves normally used are as a rule greatly over-dimensioned, and the pressure losses in the inlet pipes and vent pipes are generally negligible.

In the design cases “energy input” and “liquid input”, the deficiencies are distributed evenly over the three analyzed faults. As was feared even before the test action was initiated, many vent pipes in the past were under-dimensioned. A frequent error here is that the inlet pipe to the safety valve and the vent pipe downstream of the

Table 2
Results of the investigation of about 4000 safety valves

Cause for pressure rise	Percentage of total number	Percentage of deficiencies per design case	Diagnosed deficiencies		
			Safety valve relief diameter is not sufficient	Pressure loss in the inlet pipe >3%	Back pressure in the vent line >15%
chemical reaction	3%	6%	33%	50%	17%
external heating	16%	36%	41%	31%	38%
gas feed	18%	46%	82%	16%	18%
liquid feed	19%	22%	70%	18%	17%
thermal expansion	44%	2%	81%	–	23%
total	100%	17%	60%	18%	22%

safety valve are only as wide as the nominal inlet and outlet width of the valve.

The most frequent deficiencies were located in the design case "gas input". It is noticeable here that in 46% of the analyzed faults not even the diameter of the safety valves was sufficiently dimensioned. In most cases the diameter of the connected gas supply lines was too large, with the result that unallowed pressure build-ups were only too likely to occur if the control valve failed.

In Table 3 the percentile distribution of the measures recommended for eliminating the various deficiencies are depicted.

If "safety valve diameter insufficient" has been diagnosed, in 47% of all cases a larger safety valve will have to be fitted. In 53% of the cases, however, it will be sufficient to limit the energy or material input into the apparatus. For this purpose the heat is often throttled by installing orifices in the steam feed pipes to limit the volume flow rate or by fitting orifices in the gas supply pipes (Fig. 2).

In the event of excessive pressure loss in the inlet pipe or excessive backpressure downstream from the safety valve, the first obvious solution is to enlarge the nominal width of the pipe. Although this is often a relatively complicated procedure, it does in fact prove indispensable in one third of all cases in the inlet pipe and in a quarter of all cases in the vent pipe.

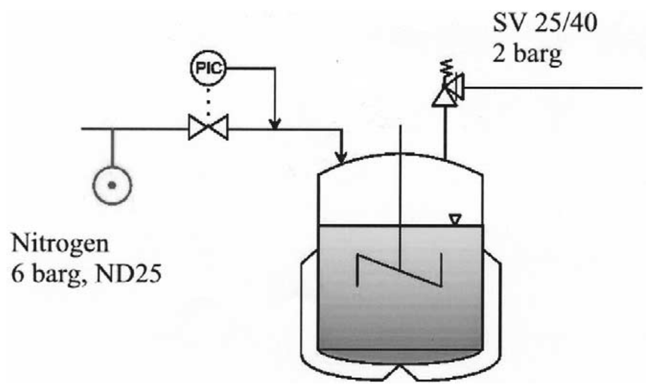

Fig. 2. Reduction of the mass flow rate to be discharged by an orifice as a simple correction measure.

However, it is often possible to reduce pressure losses at more a favorable cost by modifying the safety valve. One way is to limit the mass flow rate passing through a full-lift safety valve by fitting a vibration damper or by limiting the lift to match the mass flow rate, at the same time reducing the pressure losses in the piping. In some cases it is enough to install smaller safety valves which fit to the existing vent pipe better.

Table 3
Solutions recommended for correction of diagnosed deficiencies

Diagnosis/Deficiency	Solution	
Safety valve	Larger safety valve	47%
Diameter insufficient	Reduced feed volume flow rates	53%
Inlet pipe	Greater diameter	35%
Pressure loss >3%	Smaller safety valve	2%
	Vibration damper or limitation of lift	63%
Vent pipe	Greater diameter	22%
Back pressure >15%	Smaller safety valve	1%
	Vibration damper or limitation of lift	38%
	Bellow	39%

Another means of ensuring stable valve operation in the event of excessive backpressure in the vent pipe is to install metal bellows which partly compensate the backpressure. Depending on manufacturer and type, it is possible in this way to raise the maximum allowable backpressure up to 35 to 50% of the set pressure of the safety valve.

In practice especially in multipurpose plants there are space problems because of the connection of numerous supply pipes. Frequently the safety valve is installed with other armatures like manometers. Due to T-joints and bends the inlet pressure loss exceeds the maximum allowable value of 3% quite often. But in a lot of cases this can be easily corrected by a simple change of the inlet pipe (Fig. 3)

Usually there are several alternative methods for correcting a particular deficiency. The most suitable or the most economical must be chosen on a case-by-case basis.

Technical guidelines (e.g. Pressure Equipment Directive 97/23/EC, prEN 13445-6 Unfired Pressure Vessels and in Germany TRB 600) claim the safe disposal of chemical substances in the case of a pressure relief. If treatment or retention is necessary, mainly depends on the amount and hazard characteristics of the possible discharge substances. The German guideline TAA-GS-06 "Rückhaltung von gefährlichen Stoffen aus Druckentlastungseinrichtungen" (Retention of hazardous materials from pressure relief devices) recommends quantity threshold in relation to the contained substances as guide numbers (Table 4).

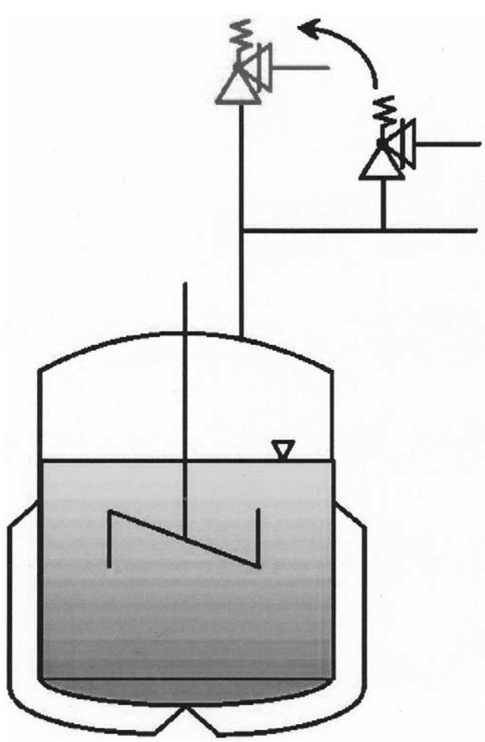

Fig. 3. Simple change of the inlet pipe if the inlet pressure loss exceeds 3%.

Furthermore it can be proofed by an individual case examination, regarding plant specific discharge conditions, that the concentration of the substances in case of a release is below a legally established limit (e.g. ERPG 2) at certain emission points. According to the German TAA guideline normally a retention system is required if this is not the case.

All relevant information like toxicity, mass flow rate and total mass discharge are already known. On the basis of these data an optimal retention system can be designed.

2.5. Step 5: Documentation, elimination of deficiencies, updating

All important data on safety valves, apparatus, design principles and design cases are entered and stored—together with the calculated mass flow rates to be discharged, the results of the analyses and the envisaged measures—in a specially developed database, where they can be retrieved in compressed form as lists and datasheets. This permits rapid access to information, servicing measures and data maintenance.

An important element of the database is the documentation of all design cases—including those which on closer analysis turn out to be of less critical importance. It is also possible to record several design cases for each safety valve, thus allowing for adequate discharging of different amounts or different materials.

The database also permits full follow-up of correcting measures taken at the plant. Inlet back of the measures implemented serves in turn to update the database.

As an interesting extra benefit, the database offers a simple method of drawing up an emission register for the discharged masses released from the safety valves. The substance combinations necessary for this purpose are documented together with the mass flow rates discharged and can be evaluated by the criteria described in Step 4.

Table 4
Quantity threshold according to German TAA-Guideline

Hazard warning (acc. to German "Gefahrstoffverordnung")	Quantity threshold [kg]
Highly toxic (T+)	200
Caustic (C), Irritant (Xi)	750
Toxic (T), Harmful to health (Xn), Environmentally hazardous (N)	2000
Carcinogenic Substances	
–listed (§15a (1))	0
–Category 1	20
–Category 2	200

3. Conclusion

So far the database has been used by the authors for the design and review of about 4000 pressure relief devices. Now, the investigated plants have a complete documentation of all pressure relief devices to prove the adequate design to the authorities. Furthermore the detailed analyses of the design cases resulted sometimes in the conclusion that a pressure relief devices is not necessary and can be dismantled, which leads to a reduction of maintenance costs.

Since the substances and their quantities released from the pressure relief devices are documented, the database offers an assessment of emissions from pressure relief devices in the whole plant. Based on this data, it can be evaluated if a retention system is necessary and furthermore this information helps to design a new retention system. In some cases it came out as the result of the analysis, that the amount and the hazardous potential of the effluents from the safety valve can not be discharged to the atmosphere and the additional effort to build closed retention systems would be too large. In these cases pressure relief via safety valves is not suitable and other safety measures have to be chosen, like safety related measurement control and regulation devices.

About 17% of the examined safety valves had defects. A clearly worse quota is reported from the USA, where on the basis of the legal regulations (OSHA 1910.119) nowadays, also to a large extent, audits on the examination of safety valves are carried out. According to a statistical evaluation by Berwanger, Kreder and Wai-Shan (2000), here, 40% of approximately 15 000 examined safety valves are insufficient.

The number of deficient designed safety valve is not surprising. Some deficiencies were due to changes in the methods used to size safety valves using current knowledge such as the DIERS technology, some were caused by changes in process related service conditions, some due to errors in maintenance, and some due to piping changes upstream or downstream of the valve. The state of the art changes rapidly thanks to computer-based calculation methods. For instance the issue of pressure loss in the inlet line of the safety valve is still under investigation, among others at the Technical University of Hamburg-Harburg by Cremers (2000).

Without a systematic approach using modern tools, large numbers of safety valves could not be managed in the past. Nowadays this methodology enables an experienced design engineer to carry out the analysis of a great number of safety valves in a time-saving, reliable and reviewable way.

References

AD-Merkblatt A2 (2000). *Sicherheitseinrichtungen gegen Drucküberschreitung—Sicherheitsventile*. Berlin: Beuth-Verlag.

API RP 520 (1993). Sizing, selection and installation of pressure relieving systems in refineries.

Berwanger, P., Kreder, A., & Wai-Shan, L. (2000). Analysis identifies deficiencies in existing pressure relief systems. *Process Safety Progress*, *19*(3), 166–172.

Cremers, J. (2000). Auslegungsmethode zur Vermeidung von Schwingungen bei federbelasteten Vollhub-Sicherheitsventilen mit Zu- und Abblaseleitung. Dissertation Technical University Hamburg-Harburg.

Fisher, H.G. et al. (1992). Emergency relief system design using DIERS technology. The Design Institute for Emergency Relief Systems, Project Manual.

Friedel, L., & Schmidt, J. (1993). Design of long safety valve vent line systems for gas relief. *J. Loss Prev. Proc. Ind.*, *6*(5), 293–301.

Friedel, L., Wehmeier, G., & Westphal, F. (1994). Pressure relief system design for vapour or two-phase flow? *Trans. IChemE*, *72*((Part B)), 142–148.

Schmidt, J., & Westphal, F. (1997). Praxisbezogenes Vorgehen bei der Auslegung von Sicherheitsventilen und deren Abblaseleitungen für die Durchströmung mit Gas/Dampf-Flüssigkeitsgemischen. *Chem.-Ing.-Techn*, *69*(6), 776–792.