PRESSURE RELIEF AND TWO-PHASE FLOW

S. Selmer-Olsen

Det Norske Veritas (DNV), P.O. Box 300, N-1322 Hövik, Norway

Pressure relief systems have traditionally been sized assuming that vapour only will be vented. However, there is a growing awareness that this assumption leads to inadequate pressure relief in the likely event of gas/liquid mixture venting. Frequently used design recommendations like API 520 and 521 are not updated on these aspects, and the recommendations are by many regarded as obsolete and potentially leading to undersizing. The paper discusses available recommendations, also in light of own recent findings.

Keywords: overpressure, relief systems, two-phase flow, review

INTRODUCTION

Pressure relief systems, whether offshore or onshore, are of fundamental importance for the safe and reliable operation of a process plant. Such systems may serve operational control purposes, but most often they are last lines of defence in case of hazards leading to excessive overpressures in the plant. It has in recent years appeared that in many situations the venting fluids will be two-phase mixtures (gas/liquid) or flashing liquids. Current design methods consider the likelihood of other flows than single-phase gas (vapour) flow in a rather superficial way. If they consider such aspects, their recommendations seem to be obsolete and are possibly nonconservative.

There are disastrous consequences of inadequate pressure-relief, unfortunately given limited attention as the accidents requiring full relief capacity are rare. Huff (1988) discusses this in a perspective of 100 large losses over the past 30 years. About 25 % of the loss incidents involved inadequacies in the pressure-relief provisions. Either the relief flow capacity was inadequate or the system layout was not appropriate for safely venting and disposing of the effluent. The total loss from these incidents amounted to about $ 820.000.000 (January 1986 dollars) which averaged out to about $ 29.000.000 per incident. Huff (1988) does not quote the number of deaths or injuries. The remaining losses resulted from spills or releases that occurred while the pressure in the equipment was below design levels (maintenance errors, external mechanical damage, corrosion failures, etc.).

This article will in the following attempt to describe the status regarding design methods for pressure relief systems when two-phase flow ought to be considered. The discussion will focus more on offshore than on onshore systems. All viewpoints belong to the author and do not necessarily reflect those of DNV.

RELIEF SYSTEMS ONSHORE AND OFFSHORE

To avoid mechanical failure of vessels and piping systems there are constraints to the internal pressures, and these limits will depend on wall temperature. Most storage and process equipment in the process industry onshore, offshore and on ships are equipped with some kind of pressure-relief systems. Static overpressure will activate mechanical pressure relief devices (valves, disks, etc.). If installed, depressuring or blow-down devices may be activated manually or automatically in case of emergency situations (e.g. high temperatures from fires).

The design of relief and blowdown facilities normally takes place towards the end of the process plant design phase when the design data for auxiliary systems are available. The relief requirements are often determined by analysing for hazards associated with the design. This makes such safety systems suffer from constrained design flexibility. This is not eased by them being among the most difficult piping systems to design correctly. Without compromising with safety, there should be room for optimizing the size and complexity of depressuring systems by analysing process plant hazards also at early stages of the design process.

Recommended practices for design and operation of pressure-relieving and depressuring systems can be consulted in guides produced by API, ASME, ISO, DNV, etc. The API recommendations (RP 520, RP 521 and Std. 2000) are probably the most widely used. Various aspects of general relief system design are discussed in Fitt (1974), Kletz (1974), Pilz (1977), Scott (1980), Lees (1980) and Fisher (1991). Crawley and Scott (1984) and Morris (1988) specifically address offshore relief systems along with providing comparisons between onshore and offshore relief systems. These comparisons are recommended reading. Attention is especially drawn to the tight constraints of space and weight in offshore design which are normally not faced in onshore design.

Most systems containing both liquid and gas (vapour) have pressure-relief provisions located to a high point, e.g. the top of a vessel or a tank. This is based on the assumption that in this way vapour only will be relieved. Analyses of accidents and experiments the last 5-10 years have proven that generally for such systems two-phase relief must be considered. Fig. 1 from Fisher (1985, 1991) illustrates a simple experiment that was carried out to demonstrate such effects. In this example the liquid swelled and rose to the level of a top mounted emergency relief device. The depressurisation caused boiling in the bulk of the liquid making it swell from gas bubble holdup. The example demonstrates that viscosity and surface tension (foaming) influence the swelling tendency. We will later list other venting cases where two-phase ought to be considered. Fisher (1985) and Banerjee (1988) claim that designing relief devices for two-phase flow requires 2 to 10 times the vent area of single-phase gas or vapour (same limitations on overpressure) as well as a significantly larger size of the relief ducting. Moreover, completely different requirements have to be set to the treatment system for the relieved fluids in order to assure a safe operation. Consequently, existing relief systems might have to be backfitted to handle two-phase flows and the downstream equipment should also be given this capacity.

Some industrial reliefs do not require treatment (e.g. steam) and may be safely disposed to the atmosphere through cold vents and atmospheric vents. Sometimes venting of a nontreated relief will be acceptable provided there is safe distance to installations (intermittent small quantities, low hazard fumes, etc.). However, in general there are two broad categories for treating industrial reliefs of toxic or flammable fluids;

- containment in a large catch vessel with adequate cooling to assure quenching (and hopefully) condensation,
- or treatment by gas/liquid separation and either scrubbing or flaring of the vapour to ensure safe disposal of the waste gas. Scrubbing is used to remove hazardous components (often toxic) and flaring (combustion) is used to avoid flammable gas concentrations in the atmosphere.

The pressure relief device (pressure relief valve, rupture disk, etc.) is only representing a limited part of the costs associated with an emergency relief system and can to a certain extent be oversized (chattering and fluttering effects disregarded). However, the costs of downstream equipment, e.g. tailpipes, collecting manifolds (headers), scrubbers, separators, catch tanks, vent flares, etc. are substantial and must be of capacity to handle peak relief rates. It is worth noting that a factor of two uncertainty in predicting the relief flow rate, might result in an over-design of scrubbers or knockout drums by a factor of four (using traditional engineering safety margins). Consequently, there are incentives to keep the sizing of relief systems from being overly conservative. Without compromising with safety, these apply in particular:

- to reduce costs of systems of expensive geometries and materials (stainless steel),
- when there are weight and space limitations (e.g. offshore platforms), and,
- to reduce the subsequent quantity of material lost or released to the environment (e.g. due to restrictions on CO_2 emissions).

Does present technology enable reasonable relief sizing for two-phase flow ?

STATUS REGARDING TWO-PHASE PRESSURE RELIEF DESIGN

The complex two-phase relief problems on onshore chemical plants have been extensively studied the last 10 years, especially regarding chemical runaway, fire reliefs and flashing reliefs from e.g. pressure liquified gases, see e.g. Fauske et al (1980), Swift (1984), Mayinger (1981), Friedel and Purps (1984a,b), Fisher (1985, 1990), Huff (1982, 1988), Banerjee (1988) and IBC/HSE (1988). This work is in continuous progress, to a large extent in association with the American and European users groups of DIERS (Design Institute for Emergency Relief System), initiated by AIChE / CCPS (Center for Chemical Process Safety). There has been a significant technology transfer from the nuclear energy area to the chemical process industry.

Some personal viewpoints on the current situation regarding two-phase pressure relief design:

- There are no commonly accepted criteria for when designing for single-phase relief is sufficient and when two-phase relief must be considered. Some proposed criteria exist for special cases (e.g. in Morris, 1988; Sallet, 1990a; Fisher, 1991).
- There are no commonly accepted practice or guidelines for pressure-relieving and depressuring systems for two-phase flow. In general quantitative information on these aspects is of recent dates and yet not easily implemented through practical methods (user-friendly). Besides, a number of aspects are not fully understood or no practice has been proposed.
- At present the basis for design of pressure control and relief systems are very often the API codes. To the little extent that two-phase flashing relief is considered (mainly flashing), the work of DIERS seems to indicate that the API recommendations could

yield unsafe relief sizing (Leung and Nazario, 1989). There seems to be a growing awareness of this inadequacy and the need for updating these and other standards.

- The DIERS technology considers relief incidents in association with chemical runaway, fires and flashing liquids. The technology represents a considerable contribution in this complex area, but it is not complete and not commonly accepted.
- There is yet no single prediction method that is accepted to be generally applicable, for relating pressures and two-phase flow rates across a relief device, covering both choked and nonchoked flows.
- The classical HEM (Homogeneous thermal Equilibrium flow Model) seems to be more and more preferred by DIERS for sizing relief devices (valves, rupture discs, etc.) and relief pipework (Leung, 1992). This is said to be reasonably conservative. This might be so for the relief device (see later), but it is probably a nonconservative method (err on the wrong side) when used for the associated design of inlet ducting (chatter, flutter), outlet ducting or relief network (backpressure and velocity estimations) and downstream tanks (gas volumes).
- With a few exceptions (e.g. Friedel and Kissner, 1985), few of the published design methods for two-phase flow seem to have been verified against experimental data by independent users. Progress in "Round-robin exercises" in expert groups (e.g. ISO TC 185) and users groups (e.g. DIERS) might improve on this. Little data are available obtained on full scale industrial relief systems that could be used to verify the work of modellers. Large scale experiments are presented in Grolmes et al (1985) and Moodie et al (1988).
- There is a strong coupling between the thermohydraulic behaviour of a process system or vessel and the flow characteristics of a release device (Selmer-Olsen, 1991). This encourages a correct modelling of both problems when system dynamics as e.g. blowdown times are searched for. The modular approach used for design of single-phase gas release might not be directly applicable (see later).
- Some efforts have recently been given to new practical two-phase conceptual designs to accommodate two-phase relief in the chemical industry, e.g. Fauske (1988,1989,1990).
- Little has been published regarding design for two-phase flow in the complex relief systems found offshore. To date the best and most comprehensive discussions seem to be Crawley and Scott (1984) and Morris (1988a,1988b,1990a).

The above list emphasizes on what a practising engineer will feel to be missing. However, the fact that he is missing reliable recommendations hopefully makes him cautious. While awaiting better recommendations the most important thing is to be aware of the likelihood of two-phase relief and to not rely blindly on current recommended practices like the API. Comparing recommendations from different literature sources can be a good advice.

TWO-PHASE RELIEF SCENARIOS OFFSHORE

Crawley and Scott (1984) and Morris (1988) discuss characteristics of offshore relief systems. They emphasize the tight constraints on weight and space especially in relation to the complexity of the relief systems. For instance there are offshore platforms with more than 500 pressure relief valves. The reliefs from the pressure safety devices normally collect in relief headers with a possible segregation in high pressure, low pressure, sour and atmospheric vent headers. Sloping is required to avoid liquid accumulation and knockout drums are therefore

found located to the lower floors of the platform. The vented gas streams leaving the drums are routed to the flare. It is beyond the scope to discuss the offshore relief system in more detail, but a listing of possible two-phase relief scenarios offshore is appropriate.

First, it should be noted that runaway chemical reactions is not considered on offshore production platforms. This two-phase relief scenario which initially triggered the research of DIERS, is exclusive to the chemical industry and plants with exothermal chemical reactions or products that may undergo exothermal reactions after the ingress of a foreign reactant or catalyst (e.g. water). See Gustin (1989, 1990).

Fire is a major concern offshore. A possible onset of two-phase venting should be considered either through pressure safety devices or blowdown device. The reader is referred to works of Roberts et al (1983), Grolmes and Epstein (1985), Morris (1988), Moodie et al (1988), Wilday (1988), Epstein et al (1989) and Venart (1990).

Other relevant cases which should be examined for two-phase relief are (see also Morris, 1988):

- Mal-operation of valves
- Blocked outlets
- Gas breakthrough in liquid outlet of separators (cause pressure relief in receiver vessel)
- Heat exchanger tube failure (oil or gas coolers)
- Thermal expansion of liquid-filled vessels and pipes (check for flashing or boil-off)
- Depressuring of vessels generating level swell from bulk boiling
- Depressuring of pressure liquified gas bottles

Blocked outlets of production separators is a special two-phase case as provisions for reliefs of the maximum production rate (well-stream) will be required. The resulting relief devices are very large.

METHODS FOR TWO-PHASE FLOW DESIGN

The sizing of a pressure relief system often proceeds in 4 steps featuring a modular design procedure:

1) Assess the required maximum relief flow rate from evaluation of credible hazard scenarios.
2) Calculate the required minimum orifice area of the relief device, select the next larger relief device and prorate to actual maximum relief flow rate.
3) Size the inlet flow piping. Most codes limit the total pressure drop due to nonrecoverable losses to 3 % of the set pressure and recommend the device located as close as possible to the source of pressure as is practicable and oversizing of piping to be avoided. The prorated flow rate is used.
4) Size the outlet piping (discharge piping, laterals and relief manifolds). The back pressure, which may exist or may develop, should not reduce the relieving capacity of any relieving device that may operate simultaneously. Normally maximum back pressure should be 10 % of the set pressure for conventional safety relief valves and 30-50 % for balanced valves. The prorated flow rate is used, except for headers and manifolds where worst-case cumulative required flow rates are used. Consequently, the header or manifold sizing require assessing which devices might operate concurrently.

Besides API 520/521 (1990), ASME (1986), etc., some methods and discussions for step 2) can be found in Simpson et al (1979), Sallet (1984, 1990b), Sallet and Somers (1985), Friedel and Kissner (1985, 1987, 1988), Campbell and Medes (1985), Morris (1988, 1990a,b), Morley (1989a,b), Alimonti et al (1990), Curtelin (1991), Davis (1991), Simpson (1991). For the works of DIERS, Fauske and Associates Inc., etc. see Fisher (1991) and Leung (1992). Be aware that there is an error in the graphical evaluation of an integral in Morley giving too small relief areas. Replace:

$$\frac{1}{P+Q} \quad by \quad \frac{1}{\sqrt{P^2+Q^2}} \tag{1}$$

For step 3) see Cox and Weirick (1980), Zahorsky (1983) and Morris (1988).

For step 4) see Richter (1978), Friedel and Löhr (1982), Morris (1988, 1990a), Leung (1992). For computerised models see Nylund (1983, 1984), Middleton and Lloyd (1984), Bayliss (1987), Klein (1987), Evanger et al (1990), Skouloudis (1990), HTFS' "PIPE3" (National Engineering Laboratory, UK). The model of Klein (1987) does not assume homogeneous flow. The code "BLOW-DOWN" (Nylund, 1983, 1984) is a modular computer program for analysis of real hydrocarbon flow in vessel and pipework systems.

OBSTACLES TO COMMON MODULAR DESIGN PROCEDURES

The above procedure allows only a limited evaluation of how the whole relief system operates as a function of the interaction of each individual item. Most likely the procedure is sufficient for single-phase gas sizing, however, its justification is sometimes more doubtful with two-phase flow.

Liquid mixed with the gas or vapour might cause a relief network system malfunction since two-phase flow completely alters the operational characteristics by e.g.:

- back pressure requirements of safety relief device not respected due to increased pressure drop in header (consequences: nonchoked flow and/or reduced relief area from improper opening of PSV).
- choking in relief header instead of relief device, eventually oscillating location of the choking throat up and down the flow path (sometimes in header, sometimes in orifice/valve, a phenomenon sometimes described as the presence of multiple chokes).
- intermittency and plugging, especially with bad sloping or long and tortuous header pipework.
- prolonged blowdown times which can represent a hazard in e.g. fire emergency.
- blowback from header through relief device to lower pressure source inventory if improper matching of pressures and relief activation.
- liquid flashing or vapour condensation
- thermal and mechanical loads exceeding mechanical design of the relief system.
- effects of T-junctions on flow blockage, entrainment and phase mixing.
- what about systems designed for controlled blowdown operation (i.e. constant flow rate from header during depressuring sequence)? (see Paruit and Kimmel, 1979).

LIST OF POSSIBLE ASSUMPTIONS FOR PREDICTION MODELS

The flow patterns approaching a flow restriction can take many forms, and also allowing various kinds of assumptions regarding the most significant processes during the subsequent flow expansion. Table 1 gives a general listing.

The HEM (homogeneous thermal equilibrium model) assumptions may be justified in some cases and for some inlet pipe configurations, but not in all cases. Two-phase problems of the nature listed in the previous section might remain hidden. Bilicki and Kestin (1990) and Lemonnier et al (1991) discuss effects of accounting for the relaxation processes for thermal and mechanical nonequilibrium.

For an offshore relief system the relief device inlet flow conditions of major interest are probably:

- subcooled and saturated liquid (with possible flashing inside PSV or flow restriction)
- two-phase, multicomponent flow (negligible flashing)
- two-phase, multicomponent flashing flows with one or more non-flashing component(s)
- metastable vapour or high quality two-phase mixture with suppressed condensation

TABLE 1 Some possible assumptions for prediction models

LIQUID (single-phase	NO PHASE CHANGE (two-phase "frozen flow") (one component or more)		PHASE CHANGE (two-phase) (one component or more)		GAS/VAPOUR (single-phase)
Inert	Mechanical equilibrium (no slip - homogeneous velocities)		Thermal equilibrium (homogeneous temperatures)		Saturated vapour
Subcooled liquid	Adiabatic gas	Interfacial heat transfer	Velocity slip	No velocity slip	Vapour
Saturated liquid	Mechanical nonequilibrium (slip - inhomogeneous velocities)		Thermal nonequilibrium (inhomogeneous temperatures)		Superheated vapour (inert)

SOME SPECIFIC OBSERVATIONS FROM OWN WORKS

Depending on the upstream inlet length, the two-phase gas/liquid configuration entering a nozzle geometry will be more or less well defined. Traditionally this parameter has been considered of secondary importance for the choked mass flow rate and hence not accounted for at all in prediction models. Some experimental results also support this assumption. However, such works have in common that the upstream flow configuration was little modified as the flow passed the nozzle (quite homogeneously dispersed flow or completely separated and stratified phases).

Table 2 and Figure 2 show the characteristic dimensions of the nozzles used in the experiments of Selmer-Olsen (1991). The liquid was injected just upstream the converging part, either as a liquid film or as a central jet from a 8 mm pipe. Only the nozzle with a throat length of 100 mm showed a mass flow rate and exit flow characteristics which were independent of the method of liquid injection.

TABLE 2 The 3 converging-diverging nozzles studied by Selmer-Olsen (1991).

NOZZLE	5 mm	10 mm (long)	10 mm (short)
Area contraction ratio:	9.	21.2	21.2
Throat diameter (mm)	5.	10.	10.
Throat length (mm)	25.	100.	17.
Convergent half angle (°)	12.	30.	30.
Diffusor half angle (°)	3.	5.	5.

This mechanistic study of high quality ($X > 1.\ 10^{-2}$) air/water flow through convergent-divergent nozzles showed that (reference model is the homogeneous model of Tangren et al, 1949):

- Generally, the inlet phase configuration is a parameter of considerable importance for both the choked mass flow rates and the flow characteristics at the nozzle exit.
- However, as the length of the geometrical throat is increased, asymptotically the inlet configuration of gas/liquid ceases to have an influence.
- For short nozzles and low pressure (2 bar) a factor above two increase in the choked gas flow rate was observed compared to homogeneous flow models (HEM).
- As the throat length an inlet pressure were increased to 100 mm and 8 bar, respectively, the predictions of homogeneous models were approached, but never reached. Pressure drop from wall friction reduces the choked flow rate.
- Classical critical (choked) two-phase flow models in many cases fail in assessing the critical pressure and the location of the choking point. Flows assumed to be choked are in fact not choked. This can be handled by more sophisticated modelling accounting for the relaxation times of interfacial transfer of momentum, heat etc..

We may use the data of Selmer-Olsen (1991) to study how well in general various assumptions apply for relief system sizing. Assuming ideal gas behaviour and isothermal flow, the mass balance equations for a vessel like the one in Figure 1, allows us to set up (phase change only allowed for in vessel):

$$M_G + \frac{\rho_G}{\rho_L}M_L = \Gamma_G\left(1-\frac{\rho_G}{\rho_L}\right) - \frac{V_G\rho_G}{P}\frac{dP}{dt} \qquad (2)$$

where

M_G = venting mass flow rate of gas
M_L = venting mass flow rate of liquid
ρ_G = gas density
ρ_L = liquid density
Γ_G = mass vaporisation rate inside vessel
P = pressure in vessel
V_G = volume of gas in vessel
t = time

We see that the left-hand-side of equation 2 is an expression of how efficient the relief process will depressurize the vessel. We could call it the effective relief rate. The depressurisation rate will be a balance between the vapour production rate inside the vessel and the effective relief rate.

In Figure 3 we have presented the data of Selmer-Olsen (1991) as the ratio between the left-hand-side of equation 2 (the effective relief rate) and the relief rate based on isentropic single-phase choked gas relief (see any textbook), and this ratio is plotted as a function of the gas quality. No vaporisation is assumed in the vessel ($\Gamma_G = 0$).

The gas quality X is defined as:

$$X = \frac{M_G}{M_G + M_L} \qquad (3)$$

Figure 3 comprises all data of Selmer-Olsen (1991) for various nozzle geometries, inlet pressures and inlet gas/liquid configurations.

First of all we observe that two-phase venting requires significantly larger relief area to provide the same depressurisation effect as the obsolete assumption of single-phase gas relief, justification of statements of Fisher (1985) and Banerjee (1988).

Secondly, we observe some quite systematic trends. In Figure 4 we have assumed that the left-hand-side of equation 2 follows the relief rate predicted by a homogeneous flow, actually the version of HEM due to Tangren et al. (1949). This model gives isentropic single-phase gas flow for X=1. Moreover, the expression used for the y-axis tends towards infinity as X approaches zero (pure liquid flow). This is because the critical pressure ratio goes to zero. However, this effect is slow for pressures below 10 bar. Sallet and Somers (1985) assumed smooth transition to the Bernoulli equation (nonchoked liquid flow) for the lower quality end ($X = 0$). We notice that by superposing Figures 3 and 4 the model of Tangren et al (1949) gives a conservative decompression rate for all the data of Selmer-Olsen (1991) provided a discharge coefficient of 0.9 is used for both the liquid and the gas phases.

Thirdly, the fact that the experimental data indicate an effective relief rate higher than predicted by a homogeneous model seems to allow such a model to be used for selecting a required relief area, and gives some credit to the HEM assumptions adopted by DIERS for relief area sizing.

Fourth, Figures 3 and 4 indicate that also using a homogeneous model for the design of inlet and outlet pipework will err on the wrong side. More gas will pass the relief area of a safety device than predicted by a homogeneous model (see also Selmer-Olsen, 1991). This will result in higher flow velocities, pressure drop and risks of choking in the pipework as well as larger volumes of gas to be disposed, treated or flared. Consequently, a safe design of a relief system cannot be entirely based on the use of the HEM as suggested by DIERS (Leung, 1992). For the design of the complete relief system nonequilibrium effects must be accounted for.

The data discussed above are for steady and symmetric flows. Little information has been found in the literature concerning how intermittent or asymmetric two-phase flow patterns pass a nozzle. Morris (1988a) suggests that since two-phase flow has a tendency to be pulsatory in nature, this may be sufficient to excite the spring/mass system of a pressure relief valve causing chatter and flutter even for inlet pressure drops within the 3 % limit. Our own unpublished experiments with chokes support this assumption. When slug flow passed the flow restriction strong pressure waves were observed propagating in the countercurrent direction at a velocity much higher than the slug velocity. Their amplitudes could reach the range of 0.5-1. bar for inlet flow conditions of 10 bar mean pressure. Upon passing the choke these pressure surges did not damp out completely.

FUTURE WORK

The CEC (Commission of the European Communities) hosted a "Major Technological Hazards Colloquium" in Frankfurt am Main on December 17-18 1992. One of the four workshops reviewed research needs related to the so-called "source term". This somewhat exotic term originates from studies of hazards from accidental releases of chemicals (toxic, flammable, etc.) to the ambient surroundings. Specifically, the term covers the assessment of a credible release scenario, the release rate and the release characteristics. It encompasses releases through accidental loss of containment (tank breach, pipe rupture, etc.) and routed release through dedicated pressure-relieving and depressuring systems.

According to my notes the CEC colloquium concluded that research work is needed for:

- Modelling of pre-release conditions inside process inventory (e.g. to achieve improved nonsteady-state process control and the management of process plant transients).
- Early detection through appropriate instrumentation.
- Choked flow and discharged flow.
- Modelling of the transient inside the inventory.

- Design and operation of safety systems and devices (i.e. pressure relieving and depressuring systems and devices, especially with multiphase flow, comprising the treatment systems for the relieved fluids).

It was found that in general we must better understand the physics (in particular non-equilibrium phenomena) and the coupling of the whole chain of phenomena of a system, and there is a need for more data. There was a general consensus that still long term R&TD efforts will be required to improve environmental protection, safety and hazardous waste management.

Another trend ought also to be mentioned. The importance of reducing the environmental impact from industry caused by for instance flaring with CO_2 pollution gives incentives for alternative safety measures against pressure upsets. Recently the first high integrity pressure protection systems (HIPPS) was installed in the petroleum industry (Aarebrot and Svenes, 1992).

CONCLUSIONS

Various aspects of pressure relief with two-phase flow have been discussed. The complexity of the problem and the need for further research have been assessed. However, the practising engineer have to cope with two-phase relief **now**, both in designing new installation and reengineering old ones with inadequate pressure relief provisions. Various groups now work on providing new recommended practice (e.g. ISO TC 185, "Flashing liquids in safety devices"). In the mean time the most important recommendation is to be cautious. One should be aware of the likelihood of two-phase relief and not rely blindly on current recommended practices like the API. The advice is to do a good scenario evaluation regarding two-phase relief, evaluate the required relief area requirements and then compare the predictions from various design methods. A homogeneous equilibrium model approach seems appropriate for estimating the relief area, but will not be appropriate for designing the whole relief system unless nonequilibrium effects are accounted for. The modular design approach (4 steps) used for single-phase (gas) relief might not be directly applicable with two-phase relief. Finally, there seems to be room for optimising the design of relief systems by considering relief requirements at an earlier stage of the design process than what seems to be current practice.

REFERENCES

Aarebrot,E. and Svenes,S. (1992), "Increased level of safety by use of high integrity pressure protection systems in process plants (HIPPS)", Proc. 7th Int. Conf. on Loss Prevention and Safety Promotion in the Process Industries, Paper 66, Taormina (Sicily), Italy, 4-8 May.

Alimonti,C., Fritte,A. and Giot,M. (1990), "Critical two-phase flow: Models and data", European Two-Phase Flow Group Meeting, May 21-23 1990, EDF, Paris, France.

API (1990), API RP 520 Parts 1 and 2, "Sizing, Selection and Installation of Pressure-Relieving Devices in Refineries", Part I, 5th edition, July, The American Petroleum Institute, Washington DC, USA.

API (1990), API RP 521, "Guide for Pressure-Relieving and Depressuring Systems", 3rd edition, November, The American Petroleum Institute, Washington DC, USA.

API (1987), API Std. 2000, "Venting Atmospheric and Low-Pressure Storage Tanks (Nonrefigerated and Refrigerated)", 3rd edition, January 1982, reaffirmed December 1987, The American Petroleum Institute, Washington DC, USA.

ASME (1986), ASME Boiler and Pressure Vessel Code, The American Society of Mechanical Engineers, New York, USA.

Banerjee,S. (1988), "Multiphase Flow Aspects of Chemical Plant Safety", Chapter 18 in Notes from "Short Course on Modelling of Multiphase Systems for Industrial Applications", March 14-18 1988, Swiss Federal Institute of Technology (ETH), Zürich, Switzerland.

Bayliss,R.S. (1987), "Dynamic modelling of gas pipeline and processing plant network under relief valve discharge conditions", Proc. Int. Conf. on Vapor Cloud Modelling, Woodward,J. ed., November 2-4, Boston Marriott Cambridge, Massachusetts, AIChE, New York, pp. 274-292.

Bilicki,Z. and Kestin,J. (1990), "Physical aspects of the relaxation model in two-phase flow", Proc. Roy. Soc. London, Vol. 428-A, pp. 379-397.

Campbell,J.W. and Medes,J.S. (1985), "A comparative analysis of the flow of flashing liquids through pipe systems", IMechE Paper No. C19/85, Institution of Mechanical Engineers, Westminster, London, pp. 217-224.

Cox,O.J.Jr. and Weirick,M.L. (1980), "Sizing safety valve inlet lines", CEP, November, pp. 51-54.

Crawley,F.K. and Scott, D.S. (1984), "The design and operation of offshore relief systems", Proc. from The Protection of Exothermic Reactors and Pressurised Storage Vessels, Chester, April 25-27 1984, IChemE Symp. Series No. 85, IChemE, UK, pp. 291-314.

Curtelin,R. (1991), "Décompression d'un réservoir de propane liquéfié", Thèse de Doctorat de l'Ecole Centrale Paris, France.

Davis,M.R. (1991), "Compressible gas-liquid mixture flow at abrupt pipe enlargements", Experimental, Thermal and Fluid Science, Vol. 4, pp. 684-697, Elsevier.

DNV (1981), Det Norske Veritas Offshore Standards RP C106, "Recommended Practice: Emergency Support Systems", April 1981.

DNV (1987), Det Norske Veritas Offshore Standards RP C201, "Recommended Practice: Process Safety Systems", January 1987.

DNV (1987), Det Norske Veritas Offshore Standards RP C202, "Recommended Practice: Relief, Depressuring and Disposal System", March 1987.

Epstein,M., Fauske,H.K. and Hauser,G.M. (1989), "The onset of two-phase venting via entrainment in liquid-filled storage vessels exposed to fire", J. Loss Prev. Process Ind., Vol. 2, January, pp. 45-49.

Evanger,T., Fagertun,J.A., Hals,T.E. and Magnussen,B.F. (1990), "PIA : a computer program for simulation of blowdown of process equipment under hazardous conditions", Proc. Eurotherm Seminar no. 14 on Heat Transfer and Major Technological Hazards, (Bolle,L. ed.), May 15-17 1990, Louvain-la-Neuve, Belgium, pp. 19/1-10.

Fauske,H.K., Grolmes,M.A., Henry,R.E. and Theofanous,T.G. (1980), "Emergency pressure relief systems associated with flashing liquids", Swiss Chem., Vol. 2, Nr. 7/8, pp. 73-78.

Fauske,H.K. (1985), "Flashing flows or: Some practical guidelines for emergency releases", Plant/Operations Progress, Vol. 4, No. 3, July, pp. 132-134.

Fauske,H.K (1988), "The next step in accomodating major chemical accidents", Proc. of the Preventing Major Chemical and Related Process Accidents, England, May 10-12 1988, IChemE Symp. Series no. 110, pp. 185-193.

Fauske,H.K. (1989), "Preventing explosions during chemicals and materials storage", Plant/Operations Progress, Vol. 8, No. 4, October, pp. 181-184.

Fauske,H.K. (1990), "Practical containment concepts in connection with short duration high rate two-phase discharges", J.Loss Prev. Process Ind., Vol. 3, January, pp. 130-135.

Fauske,H.K., Grolmes,M.A., Henry,R.E. and Theofanous,T.G. (1980), "Emergency Pressure Relief Systems Associated with Flashing Liquids", Swiss Chem., Vol. 2, No. 7/8, pp. 73-78.

Fisher,H.G. (1985), "DIERS Research Program on Emergency Relief Systems", Chem. Engr. Progr. (CEP), August, pp. 33-36.

Fisher,H.G. (1991), "An overview of emergency relief system design practice", Plant/Operations Progress, Vol. 10, No. 1, January, pp. 1-12.

Fitt,J.S. (1974), "The process engineering of pressure relief and blowdown systems", Proc. of the 1st International symposium on Loss Prevention and Safety Promotion in the Process Industries, (Buschmann,S.H. ed.), May 28-30, The Hague, The Netherlands, pp. 317-324.

Friedel,L. and Löhr,G. (1982), The design of pressure-relief devices for gas-liquid reaction systems", International Chemical Engineering, Vol. 22, No. 4, October, pp. 619-630.

Friedel,L. and Purps,S. (1984a), "Modelle und Berechnungsverfahren für die plötzliche Druckentlastung von Gas/Dampf-Flüssigkeits-Reaktionssystemen", Chem.-Ing.-Tech., Vol. 56, No. 5, pp. 361-369.

Friedel,L. and Purps,S. (1984b), "Phase distribution in vessels during depressurisation", Int. J. Heat and Fluid Flow, Vol. 4, No. 5, December, pp. 229-234.

Friedel,L. and Kissner,H.-M. (1985), "Pressure loss in safety valves during two-phase gas/vapour flow", Proc. 2nd International Conference on Multiphase Flow, London, England, 19-21 June 1985, publ. BHRA, pp. 39-66.

Friedel,L. and Kissner,H-M. (1987), "Two-phase pressure loss model for safety valves", Proc. 3rd Int. Conf. on Multiphase Flow, May 18-20, The Hague, Netherlands, pp. 309-338 (Organised by BHRA, Bedford, UK).

Friedel,L. and Kissner,H-M. (1988), "Two-phase pressure drop in a rupture disc/safety valve unit", J.Loss Prev. Process Ind., Vol. 1, pp. 31-38.

Friedel,L. and Molter,E. (1989), "Depressurisation rates during emergency vessel top and bottom venting of two-phase systems", European Two-Phase Flow Group Meeting, Paris, May 29 - June 1.

Grolmes,M.A. and Epstein,M. (1985), "Vapor-liquid disengagement in atmospheric liquid storage vessels subjected to external heat source", Plant/Operations Progress, Vol. 4, No. 4, October, pp. 200-206.

Grolmes,M.A., Leung,J.C. and Fauske,H.K. (1985), "Large-scale experiments of emergency relief systems", CEP, Vol. 81, No. 8, pp. 57-62.

Gustin,J.L. (1989), "Vent sizing for runaway reactions using the DIERS Methodology. Data acquisition from closed Dewar experiments", Proc. 6th International Symposium on Loss Prevention and Safety Promotion in the Process Industries, June 19-22 1989, Oslo, Norway, Norwegian Society of Chartered Engineers (NIF), pp. 75/1-21.

Gustin,J.L. (1990), "Runaway reactions, their courses and the methods to establish safe process conditions (invited lecture)", Proc. Eurotherm Seminar no. 14 on Heat Transfer and Major Technological Hazards, (Bolle,L. ed.), May 15-17 1990, Louvain-la-Neuve, Belgium, pp. IL3/1-26.

Huff,J.E. (1982), "Emergency Venting Requirements", Plant/Operations Progress, Vol. 1, No. 4, pp. 211-229.

Huff,J.E. (1988), "Frontiers in pressure-relief system design", Chemical Engineering Progress, September, pp. 44-51.

IBC Technical Services Ltd and Health & Safety Executive (1988), Proceedings from the "1988 European Seminar on The Pressurised Storage of Flammable Liquids (Fire Problems and Fire Protection)", 24-26 October 1988, The Cafe Royal, London, UK.

IChemE (1987), Proceedings from the "Hazards from Pressure: Exothermic Reactions, Unstable Substances, Presure Relief and Accidental Discharge", June 16-18 1987, University of Manchester Institute for Science and Technology (UMIST), The Institution of Chemical Engineers Symposium Series No. 102, IChemE, Rugby, UK.

ISO (1991), "ISO 4126 Safety Valves", The International Organization for Standardization (TC 185).

ISO (1991), "ISO 6718 Bursting Discs and Bursting Disc Devices", The International Organization for Standardization (TC 185).

Klein,H.H. (1987), "A computer model for sizing two-phase emergency relief systems, validated against DIERS large scale test data", Proc. from the "Hazards from Pressure: Exothermic Reactions, Unstable Substances, Presure Relief and Accidental Discharge", June 16-18 1987, University of Manchester Institute for Science and Technology (UMIST), The Institution of Chemical Engineers Symposium Series No. 102, IChemE, Rugby, UK, pp. 143-155.

Kletz,T.A. (1974), "Over-pressure and other risks - some myths of the chemical industry", Proc. of the 1st International symposium on Loss Prevention and Safety Promotion in the Process Industries, (Buschmann,S.H. ed.), May 28-30, The Hague, The Netherlands, pp. 309-315.

Landis,R.L. (1982), "Solve flashing-fluid critical-flow problems", Chemical Engineering, March 8, pp. 79-82.

Lees,F.P. (1980), "Loss Prevention in the Process Industries", Vol. 1, chpts. 12 and 17, Butterworths.

Lemonnier,H., Selmer-Olsen,S., Aarvik,A. and Fjeld,M. (1991), "The effect of relaxed mechanical nonequilibrium on gas-liquid critical flow modeling", Proc. 27th ANS Nat. Heat Transfer Conf., Minneapolis, MN, USA, July 28-31.

Leung,J.C. (1990), "Two-phase flow discharge in nozzles and pipes - a unified approach", J.Loss Prev.Process Ind., Vol. 3, January, pp. 27-32.

Leung,J.C. (1990), "Similarity between flashing and nonflashing two-phase flows", AIChE Journal, Vol. 36, No. 5, May, pp. 797-800.

Leung,J.C. (1992), "Size safety relief valves for flashing liquids", Chemical Engineering Progress (CEP), February, pp. 70-75. (Correction in CEP, March 1992, p. 108.).

Leung,J.C. and Grolmes,M.A. (1987), "The discharge of two-phase flashing flow in a horizontal duct", AIChE Journal, Vol. 33, No. 3, March, pp. 524-527.

Leung,J.C. and Nazario,F.N. (1990), "Two-phase flashing flow methods and comparisons", J.Loss Prev. Process Ind., Vol. 3, April, pp. 253-260.

Leung,J.C. and Epstein,M. (1990), "A generalized correlation for two-phase nonflashing homogeneous choked flow", TASME J.Heat Transfer, May, Vol. 112, pp. 528-530.

Mayinger,F. (1981), "Stand der thermohydraulischen Kenntnisse bei Druckentlastungsvorgängen", Chem.-Ing.-Tech., Vol. 53, Nr. 6, pp. 424-432.

Middleton,A.A. and Lloyd,P.A. (1984), "Computer aided relief network design", Proc. from The Protection of Exothermic Reactors and Pressurised Storage Vessels, Chester, April 25-27 1984, IChemE Symp. Series No. 85, IChemE, UK, pp. 75-82.

Moodie,K., Cowley,L.T., Denny,R.B., Small,L.M. and Williams,I. (1988), "Fire engulfment tests on a 5 tonne LPG tank", J.of Hazardous Materials, Vol. 20, pp. 55-71.

Morley,P.G. (1989a), "Sizing pressure safety valves for gas duty", The Chemical Engineer, August, pp. 21-24.

Morley,P.G. (1989b), "Sizing pressure safety valves for flashing liquid duty", The Chemical Engineer, October, pp. 47-50.

Morris,S.D. (1988), "Offshore relief systems: Some guidelines in designing for two-phase flow", Report No. ETU - 027, Energy Technology Unit, Dept. of Mech. Engng., Heriot-Watt University, Edinburgh.

Morris,S.D. (1990a), "Flashing flow through relief lines, pipe breaks and cracks", J.Loss Prev. Process Ind., Vol. 3, January, pp. 17-26.

Morris,S.D. (1990b), "Discharge coefficients for choked gas-liquid flow through nozzles and orifices and applications to safety devices", J.Loss Prev. Process Ind., Vol. 3, July, pp. 303-310.

Nylund,J. (1983), "BLOW-DOWN - A computer program for dynamic analysis of hydrocarbon processes", Det Norske Veritas Report No. 83-1317.

Nylund,J. (1984), "Fire survival of process vessels containing gas", Proc. from The Protection of Exothermic Reactors and Pressurised Storage Vessels, Chester, April 25-27 1984, IChemE Symp. Series No. 85, IChemE, UK, pp. 137-148.

Paruit,B. and Kimmel,W. (1979), "Control blowdown to the flare", Hydrocarbon Processing, October, pp. 117-121.

Pilz,V. (1977), "Auslegung, Einsatz und Wirkungsweise von Blow-Down-Systemen als Sicherheitseinrichtung bei Chemieanlagen", Chem.-Ing.-Tech., Vol. 49, No. 11, pp. 873-883.

Richter,S.H. (1978), "Size relief systems for two-phase flow", Hydrocarbon Processing, July, pp. 145-152.

Roberts,A.F., Cutler,D.P. and Billinge,K. (1983), "Fire engulfment trials with LPG tanks with a range of fire protection methods", Proc. 4th Int. Symp on Loss Prev. and Safety Promotion in the Process Industries, Harrogate, UK, September 1983, IChemE Symp. Series No. 82, Vol. 3, pp. D1-D10.

Sallet,D.W. (1984), "Thermal Hydraulics of Valves for Nuclear Applications", Nuclear Science and Engineering, Vol. 88, pp. 220-244.

Sallet,D.W. and Somers,G.W. (1985), "Flow capacity and response of safety relief valves to saturated water flow", Plant/Operations Progress, Vol. 4, No. 4, October, pp. 207-216.

Sallet,D.W. (1990a), "On the prevention of two-phase fluid venting during safety valve action", J.Loss Prev. Process Ind., Vol. 3, January, pp. 53-58.

Sallet,D.W. (1990b), "Critical two-phase mass flow rates of liquified gases", J.Loss Prev. Process Ind., Vol. 3, January, pp. 38-42.

Scott,D.S. (1980), "Some seldom considered aspects of pressure relief systems", IChemE Conference on Explosions, Fire Hazards and Relief Venting in Chemical Plants, March 12 1980, University of Sheffield, UK.

Simpson,H.C., Rooney,D.H. and Grattan,E. (1979), "Two-phase pressure drops in valve and orifice restrictions", European Two-Phase Flow Group Meeting, June 5-8, Ispra, Italy.

Simpson,L.L. (1991), "Estimate two-phase flow in safety devices", Chemical Engineering, August, pp. 98-102.

Selmer-Olsen, S. (1991), "Etude théorique et expérimentale des écoulements diphasiques en tuyère convergente-divergente, Thèse de Doctorat de l'Institut National Polytechnique de Grenoble (INPG), France, (partly in English).

Skouloudis,A.N. (1990), "Fifteen benchmark exercises on vessel depressurisation with non-reacting fluids; hydrodynamic considerations", CEC/JRC Ispra Report EUR 12602 EN, Commisssion of the European Communities.

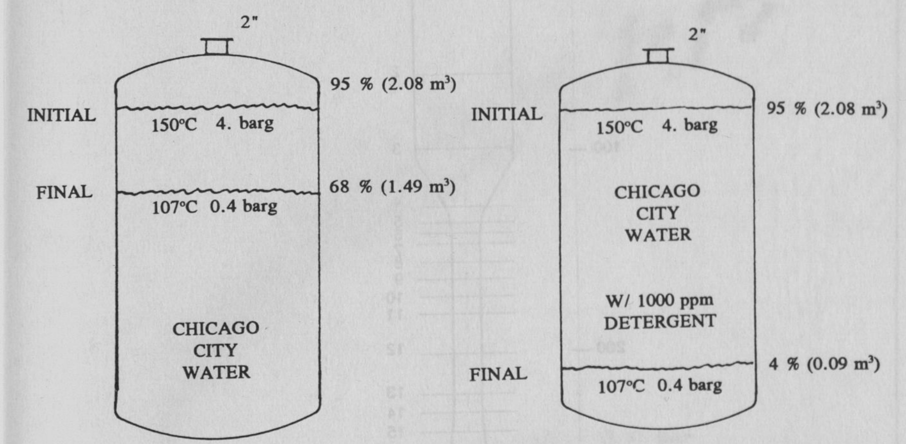
Swift,I. (1984), "Developments in emergency relief system design", The Chemical Engineer, August/September, pp. 30-33.

Tangren,R.F., Dodge,C.H. and Seifert,H.S. (1949), "Compressibility effects in two-phase flow", J. Applied Physics, Vol. 20, No. 7, pp. 637-645.

Venart,J.E.S. (1990), "In-vessel transient thermohydraulics", Proc. Eurotherm Seminar no. 14 on Heat Transfer and Major Technological Hazards, (Bolle,L. ed.), May 15-17 1990, Louvain-la-Neuve, Belgium, pp. IL1/1-12.

Wilday,A.J. (1988), "Pressure relief system sizing for external fire", Proceedings from the "1988 European Seminar on The Pressurised Storage of Flammable Liquids (Fire Problems and Fire Protection)", IBC Technical Services Ltd and Health & Safety Executive, 24-26 October 1988, The Cafe Royal, London, UK.

Zahorsky,J.R. (1983), "Degradation of pressure relief valve performance caused by inlet piping configuration", ASME Proceedings from Testing and Analysis of Safety/Relief Valve Performance, Pheonix, Arizona, The American Society of Mechanical Engineers, pp. 23-28.



Water blowdown example. **Foamy water blowdown example.**

Figure 1: Vessel blowdown example from Fisher (1985, 1991). Left pure tap water, right tap water with detergent causing foaming.

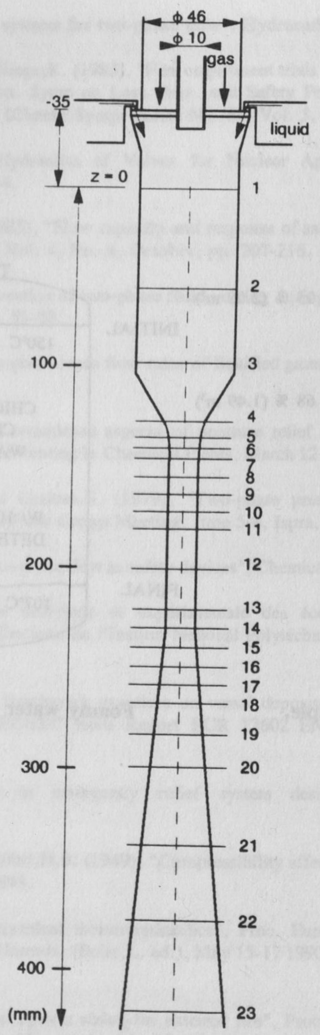


Figure 2: Sketch of the nozzle geometry used in the air/water experiments of Selmer-Olsen (1991). Liquid injected either as a wall film or as a central jet of diameter 8 mm.

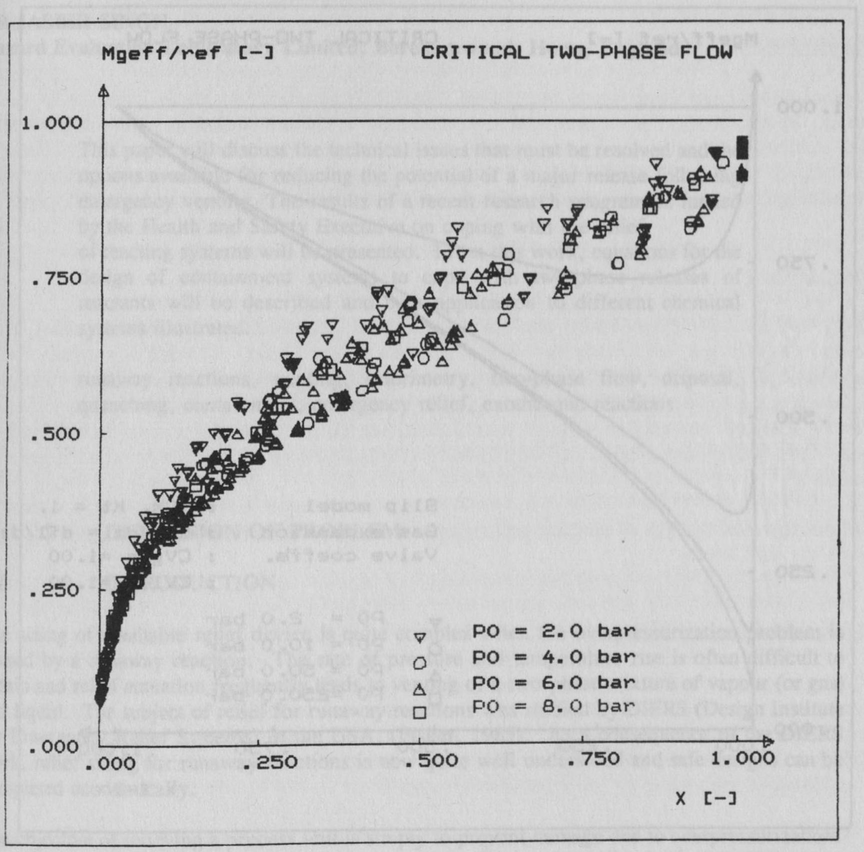


Figure 3: All datapoints of Selmer-Olsen (1991) plotted in the same graph; three different nozzles, four different pressures and two different gas/liquid injection modi. Gas quality on the x-axis and as y-axis the effective depressuring rate with two-phase flow over the depressuring rate assuming choked flow of gas (isentropic).

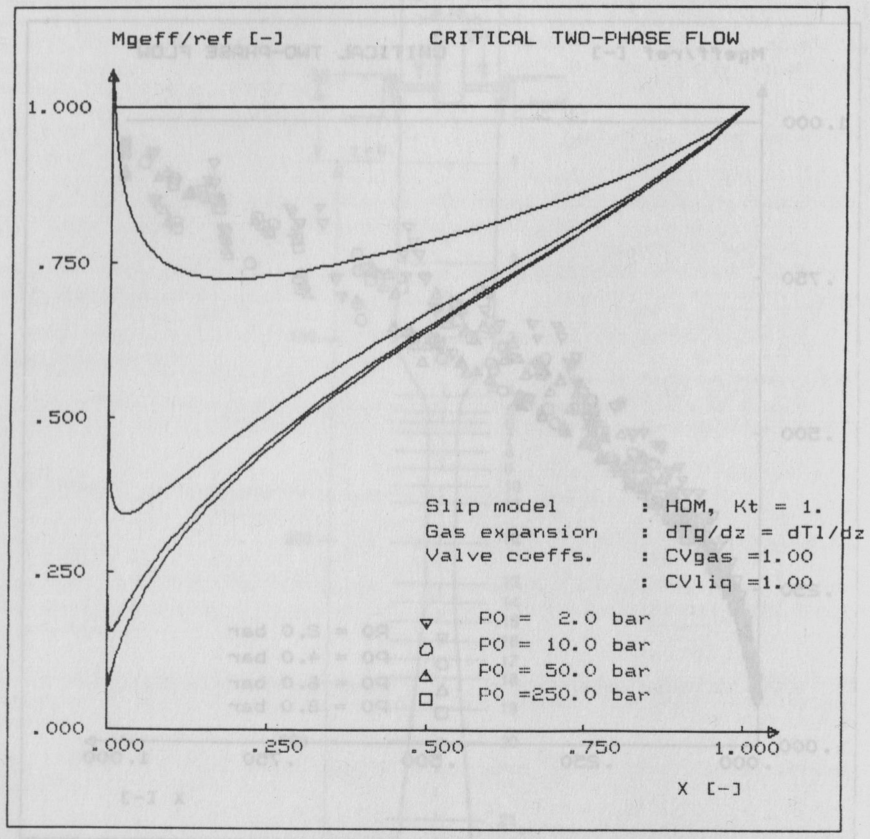


Figure 4: Effective depressuring rate assuming the homogeneous equilibrium model of Tangren et al (1949) over depressuring rate based on assumed choked flow of gas (isentropic). As x-axis the gas quality.

SAFE DISPOSAL OF REACTIVE CHEMICALS FOLLOWING EMERGENCY VENTING

DR JASBIR SINGH
Hazard Evaluation Laboratory Limited, Borehamwood, Herts, England

This paper will discuss the technical issues that must be resolved and the options available for reducing the potential of a major release following emergency venting. The results of a recent research programme funded by the Health and Safety Executive on coping with the relief of reacting systems will be presented. From this work, equations for the design of containment systems to cope with two-phase releases of reactants will be described and their application to different chemical systems illustrated.

runaway reactions, venting, calorimetry, two-phase flow, disposal, quenching, containment, emergency relief, exothermic reactions

1. DISCUSSION OF PROBLEM

1.1 INTRODUCTION

The sizing of a suitable relief device is quite complex when the overpressurization problem is caused by a runaway reaction. The rate of pressure and temperature rise is often difficult to obtain and relief actuation frequently leads to venting of a two-phase mixture of vapour (or gas) and liquid. The subject of relief for runaway reactions was studied by DIERS (Design Institute for Emergency Relief Systems) in the USA, (Fisher, 1985). As a consequence of the DIERS work, relief sizing for runaway reactions is now quite well understood and safe designs can be completed economically.

The objective of relieving a process unit is simply to prevent damage due to overpressurization. The disposal of the vented fluids is a separate matter and was not studied in the DIERS project. This paper will focus on design implications of venting into disposal tanks, either with a view to complete containment or followed by relief into a downstream unit (flare, absorber, incinerator etc). The use of small scale testing to provide the necessary information and the application of the information will be illustrated with examples.

1.2 RELIEF OF RUNAWAY REACTIONS - OVERVIEW

Almost invariably, the pressure rise in process equipment is due to the generation of vapour (or gas). For example, if fluid in a closed vessel undergoes exothermic reaction producing heat at a rate Q (W) then the rate of vapour generation M (kg/s) is given by (Q/λ) where λ (J/kg) is the latent heat of vaporisation.