# PRESSURE RELIEF VENTING SYSTEMS – EXAMPLES OF GOOD AND BAD PRACTICE[†]

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Pressure relief systems employed at chemical and petrochemical sites are a key safety measure. It is important that they are sized correctly so that they would function effectively if needed. The venting systems protect process vessels against various relief cases including fire and runaway chemical reactions. Through its role in providing technical support to Health and Safety Executive (HSE) inspectors, the Health and Safety Laboratory (HSL) is well placed to be aware of current industry practice and problems in pressure relief vent sizing. Although there is considerable guidance on good vent design, some misunderstandings and errors are still made, thus the key knowledge required and guidance sources needs to be reinforced. Examples of both good and bad practice are described. Bad practices include: runaway reactions cases not considered and vent lines and catch tanks made from unsuitable materials or not pressure resistant. Guidance on the design of venting systems are also discussed, including relevant API pressure relief codes, ISO standards on safety valves and bursting discs and HSE guidance on chemical reactor vent sizing.

## INTRODUCTION

Pressure relief is used to protect a process vessel or reactor from a pressure excursion. It is often the last line of defence when other systems such as fire prevention and process cooling have failed. There are various causes of overpressure, such as external fire and runaway reaction, which need to be considered. The design approach and calculation methods vary depending on the cause of the overpressure. Vent systems need to be sized for the worst case, which could be a fire relief case or a runaway reaction case. The venting system needs to be sized correctly otherwise it will fail to protect the process vessel or reactor with potentially serious consequences.

There is considerable guidance on the design of venting systems for both the fire and runaway cases. However some basic errors are still made by chemical plant operating companies. The key knowledge required and guidance sources thus needs to be reinforced. Through its role in providing technical support to Health and Safety Executive (HSE) inspectors, the Health and Safety Laboratory (HSL) is well placed to be aware of current industry practice and problems in pressure relief vent sizing. HSE is the enforcing authority and HSL is its in-house agency. Issues with process relief venting systems will be illustrated with examples of good and bad practice but without identifying the operating companies involved.

## RUNAWAY REACTION CASE – GENERAL APPROACH & GUIDANCE

Figure 1 shows the steps in design and sources of information for the runaway reaction case. Runaway reactions can occur when the rate of heat generation exceeds the rate of heat removal. Runaway reactions are discussed in two training packages produced by the IChemE and HSE. Identifying the potential for a runaway reaction and doing an initial reaction hazard assessment are key first steps. Barton & Rogers (1997) and HSG 143 (HSE 2000) deal with the reaction hazard assessment in considerable detail. These books describe design and safe operation of chemical reaction processes to avoid runaway. Nevertheless there will be worst-case scenarios where runaway reaction could occur.

During a runaway the reaction temperature will rise rapidly increasing the vapour pressure and/or permanent gas will be produced. The rapid increase in pressure, which would occur, shows the need for a pressure relief system. Two-phase flow often occurs in reactor venting because the vapour/gas is generated so rapidly in the liquid that it swells and flows out of the vent. This requires the vent size to be larger than would be needed for single-phase vapour/gas flow, as the vent has to carry higher density liquid as well as low-density vapour/gas. The vent sizing methods for runaway systems, which produce vapour and permanent gas, are different. They also both require calorimetric experiments to determine the rate of temperature rise or gas production rate. Two-phase flow needs also to be considered in the evaluation of the relief system capacity.

The American Institute of Chemical Engineers had a programme of work, DIERS (Design Institute for Emergency Relief Systems), which produced the vent sizing methods for runaway reactions. The DIERS project manual (Fisher et al. 1992) should be consulted as well as the HSE Workbook (Etchells 1998) on chemical reactor relief system design. ISO 4126 Part 10 deals with the sizing of safety valves for gas liquid two-phase flow. API 520-I (API 2008) now includes material on the vent capacity calculations for two phase flow.

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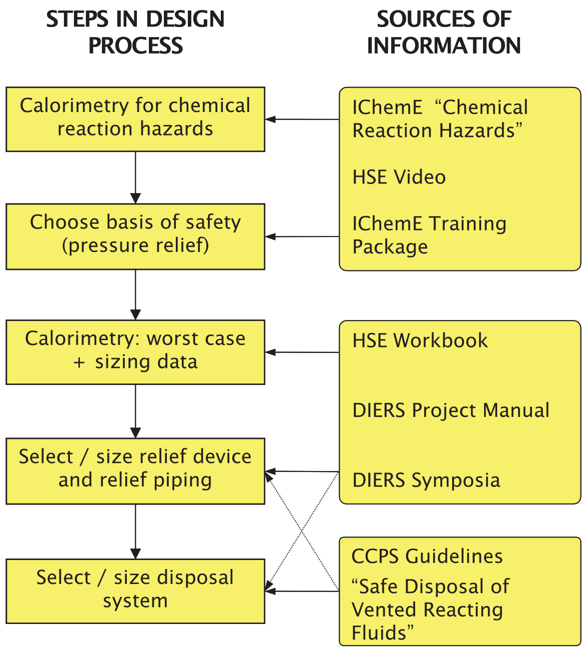

**Figure 1.** Runaway Reaction Case – Steps in design process and sources of information

## FIRE RELIEF CASE – GENERAL APPROACH & GUIDANCE

Figure 2 shows the steps in design and sources of information for the fire relief case. Vent sizing for the fire relief case is more straightforward. Firstly the wetted surface area of the vessel, as defined in API 521 (API 2007) is determined. Secondly the heat output produced by the fire is estimated using equations also given in API 521. Thirdly the required relief rate is calculated from the heat input from the fire and the latent heat of the fluid in the vessel. The system relief capacity must exceed the required relief rate. The relief capacity is calculated using methods given in API 520-I or ISO 4126. Single-phase vapour flow is generally assumed for fire relief cases. Thus the sections of API 520-I and ISO 4126 dealing with single-phase flow should be consulted. The CCPS Guidelines (CCPS 1998), Parry (1994) and Hellemans (2009) are useful references on pressure relief and relief cases including fire relief. API 520-II (API 2003) and ISO 4126 deal with the installation of pressure relieving devices.

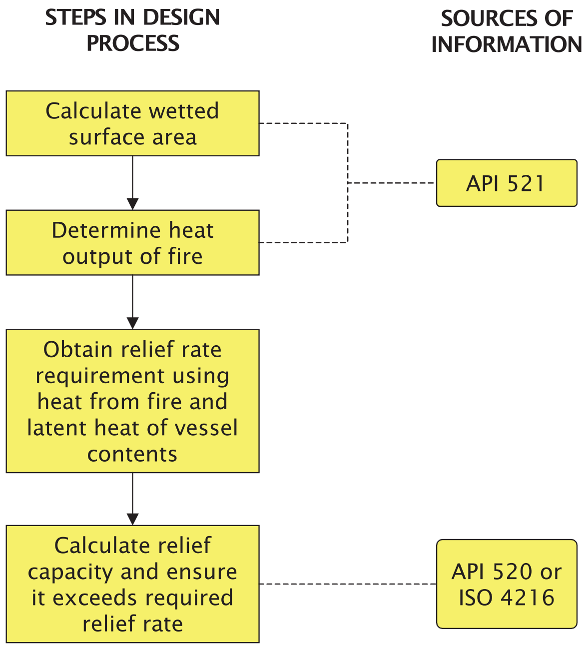

**Figure 2.** Fire Relief Case – Steps in design process and sources of information

## EXAMPLES OF GOOD AND BAD PRACTICE

### CALORIMETRY

A company calculated an adiabatic temperature rise from a heat of reaction measured isothermally. This is a valid approach. The company also tried to use isothermal data for vent sizing purposes. However, for runaway reaction vent sizing, adiabatic temperature rate data is required. Figure 3 shows an example of an adiabatic calorimeter, the DIERS bench scale apparatus, suitable for runaway reaction vent-sizing purposes. The physical properties of water were used rather than the resin mixture being produced. Since water and resin do not have same physical properties, it is best to use resin physical properties or do experiments with the correct reaction mixture.

A company tried to check the vent size for their polymerisation reactor without experimental adiabatic data. Adiabatic calorimetry experiments should be done on the polymerisation reaction. Annex 2 of the HSE "Workbook for chemical reactor relief system sizing" (Etchells 1998) discusses the experimental methods needed in chemical reactor vent sizing. The company used a reaction model they found on the internet, without any validation. Theoretical considerations could be used to develop a runaway reaction model. The model would need to cover the reaction, heat transfer and vapour pressure rise. Such models are available commercially such as the DIERS version of SuperChems. The model could be used to calculate the temperature rise rates and corresponding pressures needed for vent sizing under worst-case conditions. The model would also have to successfully simulate the adiabatic calorimetry tests.

Another company carried out a Dewar test, but the test was not performed under adiabatic conditions. Thus the experimental data used for vent sizing calculations was not the worst-case adiabatic data. Use of an adiabatic calorimeter, such as a Phi Tec, Vent Sizing Package (VSP) or adiabatic Dewar is recommended, which all measure adiabatic temperature and pressure. The first venting case was a vapour pressure system. The company's calculations ignored the effect of increasing vapour pressure with increasing temperature. An adiabatic calorimeter

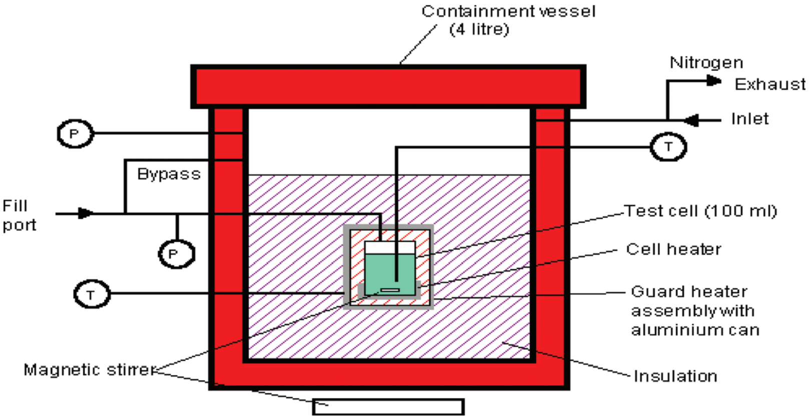

**Figure 3.** Adiabatic Calorimeter – DIERS bench-scale apparatus

providing pressure and temperature rate data will confirm the true maximum pressure. The company should use the HSE workbook (Etchells 1998) or similar guidance to help them. It describes the correct vent sizing methods (vapour pressure – chapter 6) and the possibility of two-phase flow (chapter 9) if required. The company's sizing calculations were based on vapour/gas flow and not on the more likely two-phase flow. Another venting case was a decomposition reaction producing a permanent gas (HSE workbook chapter 7). Open system adiabatic tests are recommended, for such gassy systems, to measure gas generation rates and two-phase flow could result. The company assumed vapour/gas flow which is not the worst case, see HSE workbook chapter 9.

## VENT SIZING

One company calculated the API 521 environmental factor F correctly provided that the thermal conductivity value was valid and the insulation still functioned. However there were some questions as to whether the insulation would function correctly due to the severity of the fire. The environmental factor F takes account of everything that reduces the heat input from the fire to the vessel. The company calculated F using US units. The current version of API 521 also allows F to be calculated using SI units, giving the same value of F. The company did a level swell calculation using the HSE workbook. The void fraction equation quoted for churn turbulent flow was used for bubbly flow as well. The correct workbook equation for bubbly flow should have been used instead. As the calculated void fractions were less than the void fraction at relief, vapour-only flow would result. The vent size used was larger than needed, which is not a bad thing in itself. However the flow rate out of the reactor will be greater because of the larger vent. Level swell could occur during depressurisation giving two-phase flow. The catch pot also needs to big enough to cope with any vented material.

For the same company, if the insulation failed then $F = 1$ should be used instead. If F should really be 1 then a much larger value of the heat input would be obtained. If however $F = 1$ then the heat input would be much larger and the level swell calculations would have to be done again. Two-phase flow would seem to be more likely in these circumstances. If $F = 1$ then the relief rate would increase and may again give two-phase flow. In this case the calculations would have to be done again using two-phase methods if appropriate.

Another company assumed that there could be no foreseeable reaction hazards scenario. Therefore the worst case was fire engulfment leading to vaporisation of vessel contents. The equation they used calculated the mass flow rate of vapour or gas, which the safety valve could pass. It did not consider the ability of the safety valve to pass two-phase flow, which may occur with reaction mixtures. It was claimed the vent sizing method assumed two-phase flow at constant pressure. In fact the equation used to calculate the vent area was one developed for vent sizing of a non-runaway two-phase cases (Wilday 1987), which did allow overpressure. API 521 does not permit credit to be taken for automatic sprinkler systems, which the company tried to do. Old versions of API 521 quoted by the company gave $F = 0.3$ for 1 inch of insulation. The current version of API 521 should be followed which would require F to be calculated based on the insulation thermal conductivity and thickness. Without any insulation, $F = 1$, the heat flux will be much larger causing the required vent diameter to increase.

A further company looked at the case of a reactor with an internal heat exchange coil. The company did not use the HSE workbook for chemical reactor relief system sizing. The production process involved multiple reaction stages so runaway reaction would have to be checked out for each stage. The relief conditions were not used in the calculation. The heating coil operated at 16 barg, the vessel design pressure was 3 barg. The flow from a high pressure to low pressure in the event of coil failure also needed to be considered. Two-phase flow was not considered properly. API 521 has a section 5.19.3 on tube failures in heat exchangers, which should be consulted. This is the same problem as tubes are at higher pressure than shell. The possibility of two-phase flow is also discussed in the API document.

An initial review of the data used by a company for vent sizing, identified that the references and data used, which had been obtained via an internet search, dated from the 1980s. Their methodology would not be suitable, as much work has been done on the subject since this time to establish methods to size reactor emergency relief vents more accurately and conservatively than was the generally established practice. The company were asked to provide additional information to demonstrate the suitability of the polymerisation reactor emergency relief systems. In particular they were asked to show that the vents are adequate to cope with potential two-phase relief streams for the rate of temperature rise that will occur at the set pressure on each reactor. The HSE Workbook (Etchells 1998) would guide the company in their vent sizing work. They should use Leung's method (Workbook chapter 6.3) to calculate the required relief rate (W). To calculate the two-phase capacity (G) they should use the Equilibrium Rate Model (ERM) initially (Workbook chapter 9.4.2) and later the Omega method (Workbook Annex 8) for greater accuracy.

## FIRE AND RUNWAY

One company identified the possibility of runaway as a result of cooling failure, as the reaction was a fast exothermic reaction with a potential for a high heat release. Solvent would be evaporated which would increase the vessel pressure and could lead to a potential uncontrolled release. The company noted that no reactant decomposition occurs at temperatures up to 110°C. The maximum temperature envisaged during relief for the fire case was 109°C. Thus runaway could occur whilst the vessel was venting to protect it from an external fire. There should be a greater margin between the normal reaction and the decomposition reaction. This could be achieved with a lower set pressure. There may also be scale effects associated with the onset of the decomposition reaction, which should be considered. The use of Layers of Protection Analysis (LOPA) for runaway reaction assessment should not be encouraged. Vents are designed to cope with the worst-case credible scenario, which has to be identified correctly irrespective of the scenario frequency.

One company calculated the heat input from a fire to a reaction vessel using API 2000. This standard is for low-pressure storage tanks. API 521 would be a better standard to use for the fire input to a pressure vessel. The API 2000 heat input formula varies depending on the wetted surface area, whilst API 521 always uses the wetted surface area to the power of 0.82. The vessel appears to be un-lagged. Having insulation would reduce the heat input from the fire and so the size of the vent required. Both the required relief rate and vent area were calculated assuming vapour flow through the vent. The possibility of two-phase flow was not considered which is possible for any reacting system.

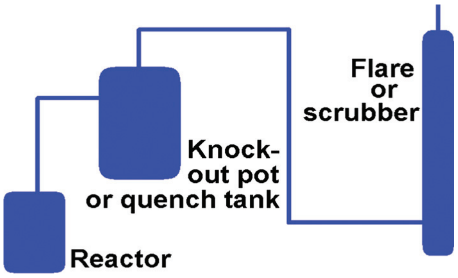

**Figure 4.** Total relief system

## VENT LINES

Figure 4 shows the total relief system for a single reactor. Figure 5 shows what very complex relief systems can look like on some plants.

A company were producing polymers in various reaction vessels. Their vent pipe work was not lagged so any vented material could solidify and block the pipe. Material could also collect at low points and "dog-legs" and solidify there. Some reaction vessels had bursting disc vent lines and pressure relief valves (PRVs) venting directly to atmosphere. In a runaway or fire relief situation the PRVs would operate as well as the bursting disc lines. This would cause material to be discharged to atmosphere, which could harm the plant operators. The PRV vent lines also need to have sufficient pressure rating otherwise a loss of containment will occur. The bursting disc vent line was made from 4" thin walled spiral wound galvanised steel ducting. The ducting pressure rating was possibly as low as 8 psig, which was inadequate.

Another company's vent sizing calculations did not take into account the pressure drop criteria associated with safety valve inlets and outlets given the convoluted nature of the relief pipe work. A vent line with 10 bends and a catch tank was of particular concern. The vent line will increase the pressure drop, could cause chattering and reduce the capacity of the vent. Vent line pressure drop needs to be taken into account in vent sizing. Chapter 9 of

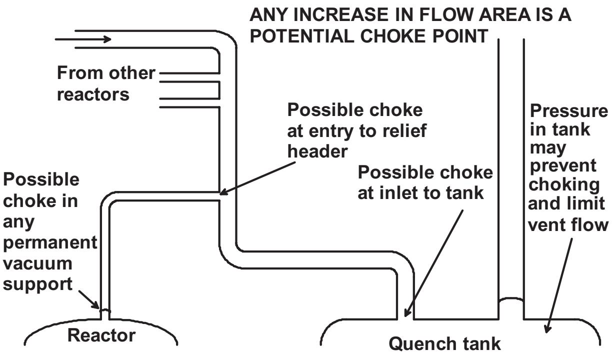

**Figure 5.** Very complex relief systems

the HSE workbook provides more information. Reaction forces likely during relief scenarios were not also taken into account in the installation as flexible hose was used in the relief pipe work.

On one company's site the relief systems for two vessels could not contain the two-phase flow that will be experienced under a fire engulfment scenario. In both cases a glass component of the system would fail with the primary hazard from this loss of containment being addition of fuel to the engulfing local fire. Vessel burst was not considered a credible scenario. Having a glass line burst in a relief scenario was not very satisfactory. Low-pressure items should be replaced so the vent line can be used properly. The entire header system was constructed from 200 mm NB pipe, which is assumed to be Schedule 40, and included both branches and the common section of the header. However the discharge from the knockout pot was 150 mm NB. This is not good practice; the knock out pot discharge should be at least as big as the incoming line so the vent flow is not impeded.

The same company had their vent lines tested every two years for any reduction in pipe diameter as part of their PSSR statutory testing. The company wanted to ensure that there is no diameter reduction due coating presumably from vented material. Unless the vents were used then no coating would be expected to occur. Also solids, viscous or polymeric materials could block vent line systems especially at safety valves, bends and tees. Some of the vent lines were being used for process purposes; having a dedicated emergency vent line would be recommended instead.

The same company calculated the vent header diameters by examining the flow areas of the incoming vents. If there were many inputs then the sum of the largest three vents was taken. This assumed that simultaneous venting would not occur. However common cause failures such as power failure or external fire could cause more vents to operate simultaneously. Also there could be a combination of their venting worst cases.

Later the company divided their plant into three fire zones to evaluate simultaneous relief cases. Three emergency vent header cases were outlined: Case A (all vessels in a fire zone relieve together and vessels do not have fire proof insulation), Case B (all vessels in fire zone relieve at same time and vessels have fire proof insulation) and Case C (Vessels relieve at different times and vessels have fire proof insulation). Pressure relief calculations were done for 21 vessels, two filter dryers, 15 receivers, the dump tank and emergency vent header. The results were given for the vessels – seven satisfied case A, five satisfied case B and eleven satisfied case C. All receivers were inadequately sized – sized for process relief not emergency relief. For the emergency headers – two fire zones were adequately sized for simultaneous releases and insulation; one fire zone was not adequately sized for simultaneous release and insulation. Thus the company still has some way to go in demonstrating a satisfactory relief system.

## CATCH TANKS

There were issues with catch tanks and the lack of them on a company's site. The company were required to ensure that the "dump tank" for two reactors' emergency relief vents was designed to provide adequate quenching and containment of the vent streams. They were also required to provide a safe means of disposal for the emergency vent stream from another reactor. Venting into a reactor bund was only acceptable if the process controls and safety-instrumented systems on the reactor were sufficiently reliable to make the likelihood of an emergency relief event sufficiently low. In other cases a suitable relief vent disposal system would need to be installed.

One company had various reactors and catch tanks. The reactors were grouped together, often sharing the same catch tank or "dump tank". The capacity of a dump tank needed to be checked. It should be able to cope with the contents of the two largest reaction vessels, which are connected to it. It was reasonable to assume that two reactors may vent at the same time due to failure of cooling water (runaway case) or a large pool fire beneath them (fire case). One dump tank had a sight-glass constructed from plastic hose and held by jubilee clips, this is not acceptable. Another dump tank was a 200 litre drum. As the pilot reactor connected to it had a 100 litre capacity, the drum capacity seems adequate. However the pressure rating of the drums was very low. The 200 litre drum receiver was also in an unsafe location.

On another company's site, a large number of vent lines were connected to the same dump tank. The following safety issues would arise: increased pressure drop, isolation issues, multiple use of the vent system and common mode failures. The company were asked to demonstrate that the design of the dump tank was correct and being operated to that design. A report provided by the company showed that the calculated pressure, during an emergency relief scenario, would not exceed the design pressure of the dump tank. However the company had not considered the possibility of more than one emergency relief scenario occurring at the same time.

## REACTOR INSULATION

A company claimed that the insulation material would stand temperatures of 1000°C. They were extrapolating well beyond the 400°C temperature quoted by the insulation supplier. The data provided by the insulation supplier gave thermal conductivity at various temperatures; but was not a performance test of the insulation. A certified performance test would show the ability of the insulation to withstand a particular fire (pool or jet) for a particular length of time.

## CONCLUSIONS

Adiabatic calorimetry data is required for runaway reaction vent sizing purposes.

Up to date vent sizing methodologies should be used – e.g. the latest version of API 521 and the HSE workbook.

Fire and runaway could occur at the same time. This worst case also needs to be considered.

Vent lines are part of the pressure envelope. They should be made of suitable material with sufficient pressure resistance. The vent line pressure drop reduces the vent capacity and so increases the required vent area.

Catch tanks should cope with the maximum discharges from vessels connected to them including any hold up due to level swell.

Insulation material properties can only be used within certain limits.

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