THE SAFE DESIGN OF CHEMICAL PLANTS WITH NO NEED FOR PRESSURE RELIEF SYSTEMS

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This paper considers whether, in the face of growing environmental concern, it would be possible to design chemical plants to be so inherently safe that no pressure relief systems were necessary. It is found that, with current knowledge, it would be difficult to avoid pressure relief completely. There is, however, considerable scope for reducing the number of pressure relief systems on chemical plants by applying an inherent safety approach. Examples are given.

Pressure relief   Inherent safety

1. INTRODUCTION

Pressure relief systems are widely accepted as a means of protecting vessels and other equipment against the hazard of overpressurisation. They have the advantages that they are readily available, well accepted and, in most cases, well understood.

There are, however, problems with the use of pressure relief systems, highlighted by the accidents at Seveso and Bhopal. The disadvantages of the use of pressure relief systems include :-

a) A pressure relief system, even though it is self-acting, is an "active" means of protection, and therefore has a finite chance of not working when required.

b) An ongoing commitment to maintenance and inspection is necessary in order to ensure the integrity of the pressure relief system. This costs money.

c) In many cases, the material relieved is too hazardous to be vented direct to atmosphere. A suitable disposal system of sufficient reliability must therefore be provided. This adds to the cost of the system. In some cases, especially relief from reactors, there is a lack of understanding of how to design such disposal systems (1). It is difficult to design a relief system/disposal system combination to have high reliability (2).

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d) Relief systems sometimes operate spuriously. This may cause an emission to atmosphere, a demand on a downstream disposal system and/or an interruption to the process. In some cases of a demand on a disposal system, eg liquid relieving to a dump tank, the subsequent operation of the pressure relief system may be compromised until the procedure to empty the dump tank has been followed.

e) In some cases, no pressure relief system can be designed that would protect the vessel. Examples are reactor relief systems which would need to be too large to fit on the vessel, and fire relief of gas-filled vessels where the vessel would fail anyway due to over-temperature.

As environmental pressures increase, there is likely to be a need to design plants with minimal, or preferably no emissions to atmosphere. This is a considerable engineering challenge. This paper arose from asking the question whether it is possible to safely design plants with no need for pressure relief systems.

It is likely that a plant with no pressure relief systems is some way in the future. It is hoped, however, that the approach given here will also be useful in reducing the need for pressure relief systems, without necessarily going to the extreme of eliminating them all. It should also be useful in designing out the need for pressure relief systems in those cases where provision of pressure relief is either very expensive or impracticable.

2. INHERENTLY SAFE DESIGN

2.1 General

The intention here is to design the plant so that there are no potential causes of overpressure or underpressure (vacuum). In this context, overpressure is defined as any pressure in excess of that allowed by the equipment design code. If no relief is to be provided, the maximum pressure will usually be the equipment design pressure. Underpressure is defined as any pressure below the vacuum design pressure specified in the equipment design code.

Another way of saying this is that all equipment on the plant should be designed for total containment of the pressures.

The approach to design is to identify all potential causes of overpressure or underpressure, and to design them out wherever that is economic. The principles of inherently safe design (see for example Kletz, reference 3), can be used to help design out the overpressure or underpressure hazards. The equipment design pressure would then be made higher than the maximum pressure that could be generated by those causes of overpressure which it is not economic to design out.

2.2 Causes of overpressure or underpressure

A number of basic causes of overpressure and underpressure are given below. A systematic approach is necessary in order to identify all the potential causes of overpressure and underpressure. The next stage will be to take each potential cause, in turn, and to design them out. The identification exercise needs to be done early in the plant design because the process of designing out causes of overpressure or underpressure is likely to make substantial changes to the design.

The generic causes of overpressure are :-

a) Heat input. This will increase pressure by simply raising the gas temperature, by increasing the vapour pressure, and/or by causing gas to come out of solution. "Heat input" includes both external heating of the equipment contents, and mixing of hot and cold material within the equipment.

b) Flow from a high pressure source. (Specifically, a pressure higher than the equipment design pressure)

c) Chemical reaction within the equipment. This could generate heat and/or evolve gas.

d) Momentum effects, eg pressure surge or water hammer.

The generic causes of underpressure are :-

e) Cooling. This could condense vapour and/or lower the pressure by reducing the gas temperature.

f) Flow out of the vessel. This could be either by gravity, or to a source of sub-atmospheric pressure.

g) Chemical reaction. This could either remove a reactant gas/vapour, or lower the temperature.

For each cause of overpressure or underpressure, the equipment should be considered to be in the worst condition, whether that is totally isolated, or open to a high or low pressure source. Credible combinations of events should also be considered, eg chemical reaction initiated by heating.

2.3 Examples of designing out the need for pressure relief

2.3.1 Interface failure in heat exchangers

Tube failure in heat exchangers does occur occasionally. For pressure relief purposes, it may be necessary to assume a scenario of full-bore failure of one tube (4). Calculating the required relief rate for this case can often be subject to considerable uncertainty. For example, if tube failure would result in a high pressure gas or vapour entering a liquid, then the fluid to be relieved is likely to be a two-phase mixture. If the liquid is on the shell-side of the heat exchanger, then it may be reasonable to assume good mixing in the shell before relief; if the liquid is on the tube-side, then plug-flow may occur to some degree. Usually, the worst case between plug flow and complete mixing will need to be taken.

If the operating pressure of the gas-side is significantly higher than the liquid-side design pressure, then experience has shown that very large pressure relief systems are likely to be required. This usually provides an economic justification for designing out the need for pressure relief. This can be done by specifying the liquid-side design pressure to be as high as the gas-side design pressure. Sometimes the maximum gas pressure is known reliably to be less than the gas-side design pressure, in which case the liquid-side design pressure can be specified to be equal to the maximum gas-side pressure.

The above will eliminate the need for pressure relief unless mixing of the fluids from either side of the heat exchanger would lead to chemical reaction. One example of this would be water used to cool a concentrated sulphuric acid stream. In such cases, the best solution is likely to be to substitute the cooling medium with one which will not react. Air-cooled heat exchangers can sometimes be used for this purpose. However, the use of air-cooled exchangers in areas in which external fire is possible should be avoided, since the cooler would turn into a very efficient heater/vaporiser.

Another consideration for heat exchanger interface failure is whether it would be hazardous for the material on one side of the heat exchanger to contaminate that on the other. (This is equally a problem if pressure relief is to be used as a means of protection.) Examples might be :

a) flammable gas getting into the plant cooling water system and forming a flammable cloud at the cooling tower, or

b) contamination of the plant nitrogen system with an oxidising agent such as oxygen or chlorine.

In such cases, some sort of detection and shut-down system would need to be designed.

2.3.2 Process heating

If the need for pressure relief is to be avoided, then the total pressure of the materials being heated, at the heating medium temperature, must be less than the design pressure. The total pressure includes the vapour pressure and the partial pressure of any permanent gas. In calculating the partial pressure of permanent gas, account should be taken of the decrease in gas-space volume due to liquid thermal expansion. If a vessel is nearly liquid-full, then the effect of liquid expansion on gas pressure can be considerable.

Ways of designing out the need for pressure relief, therefore, will be :

a) to limit the heating medium temperature, eg by the use of hot water heating rather than steam heating,

b) to ensure that there is adequate gas space volume for the effects of liquid thermal expansion,

c) to increase the vessel design pressure,

d) substitute a solvent with a lower vapour pressure (but also think about whether the solvent could be present in an unusually low concentration).

e) in cases where it is necessary to allow equipment to become liquid-full, arrange for it not to be isolated. In some cases, it may be possible to rely on procedures or interlocks to do this. Otherwise pressure relief into a small total containment system may be the most economic option, since for the case of liquid thermal expansion, the total quantity to be relieved will be very small.

It can often be more economic to lower the heating medium temperature and/or raise the design pressure than to provide pressure relief. If heating could cause vaporisation at the relief pressure, then two-phase relief is likely (5), and the size of the pressure relief system would be likely to be large.

2.3.3 Chemical reactions

There are such a large variety of chemical reactions that the comments here will necessarily not be exhaustive.

The objective in preventing overpressure of a chemical reactor must be to ensure that the design pressure is greater than the maximum pressure that can be generated by any credible reaction. This high design pressure must also include all items of equipment such as reflux columns which may be attached to the reactor. For certain reactions, in which decomposition can occur at high temperature, it may also be desirable to limit the maximum temperature that can be achieved.

For any type of reaction, a systematic testing strategy such as those described in references 6 and 7 is essential to identify the hazards. Some reactions have little or no exotherm and no gas generation. Clearly such reactions are to be preferred over reaction routes involving large exotherms and permanent gas generation. It is unlikely to always be practicable to use only reactions with no exothermic or gas-generating activity. However, safety could perhaps be improved by carrying out a safety study on reactions, at the stage of developing the chemistry of a process, which sought to find processes which were easy to incorporate into inherently safe plants.

Some reactions give rise to a modest exotherm and no permanent gas generation. In such cases the reactor can usually be designed for the maximum pressure. It should be noted that in order to calculate the maximum temperature (and hence pressure), the exotherm should be added to the maximum process heating medium temperature (or the maximum ambient temperature for unheated processes).

Other reactions will give rise either to an exotherm high enough to result in a very high maximum pressure, and/or to generation of a permanent gas, which will also give rise to a very high maximum pressure in a closed system. The safest way of carrying out such reactions is in a continuous or semi-batch reactor so that the flowrate of the limiting reagent is controlled and so that there is no accumulation of the limiting reagent in the reactor (ie the limiting reagent essentially reacts immediately). In such cases, it can readily be arranged to stop the feed of the limiting reagent if the pressure were rising too high. Perhaps the most inherently safe way of doing this would be to pump the reagent via a flow restrictor and to arrange for the maximum head developed by the pump to be less than the design pressure. Instrumented protective systems are sometimes used to stop the flow and this is discussed further in section 3 below.

It is very difficult to make a reactor totally inherently safe, because operating procedures or automatic control must usually be used to control the charging of the reactor. Getting the order of charging wrong, or charging too much or too little can often give rise to a hazard. The objective must be to ensure that the design pressure cannot be exceeded whatever goes wrong.

In summary, for the purposes of achieving containment of the maximum pressure, the following should be attempted :

a) chose reactions with low exotherms and no permanent gas generation

b) Use continuous or semi-batch processes in preference to batch processes

c) Avoid accumulation of reactants

d) Arrange, reliably, to stop the feed of limiting reactant if the pressure rises too high

e) Choose low vapour pressure solvents, to limit the maximum pressure generated (note that this is the opposite to the strategy when protection is to be by pressure relief, when it is desirable to reach the set pressure at a low temperature and low corresponding reaction rate (8)).

2.4 Choice of Design Pressure

If pressure relief is not to be provided on an item of equipment, then the equipment design pressure must be chosen to exceed the maximum pressure that can be generated. The additional cost of raising the design pressure by modest amounts is usually not great, unless a particularly expensive material of construction has been chosen.

The requirement to avoid the need for pressure relief for the case of flow from a higher pressure source means that all plant items would need to have the same design pressure. This could be expensive if some parts of the process operate at significantly higher pressures than others.

In order to avoid the need for vacuum relief, all equipment would need to be designed for full vacuum. This usually involves no additional expense provided that the positive design pressure of the equipment is more than a few bar. Designing for full vacuum is often necessary anyway because the required relief rate for some events (such as vapour condensation when a cold liquid is fed to a vessel) are often both large and difficult to quantify.

3. INSTRUMENTED PROTECTIVE SYSTEMS

Examples of instrumented protective systems used in place of pressure relief systems include :-

a) Downstream of a pressure let-down valve. If the let-down valve fails open, then the instrumented system detects the increase in downstream pressure and closes a quick-acting valve to protect downstream equipment.

b) As explained in 2.3.3 above, a instrumented protective system could be used to stop the reactant feed to a reactor in the event of high reactor temperature or pressure.

It is currently relatively unusual to find instrumented protective systems used instead of pressure relief systems. An exception to this may be in the protection of chemical reactors, where the provision of pressure relief systems may be infeasible due to a combination of their required size, uncertainty in the data and methodology required for designing them, and the unacceptability of venting the reactor contents to atmosphere. Usually instrumented protective systems are used as a "first line of defence", reducing the frequency of demands on the pressure relief system that comprises the "last line of defence".

The design of a instrumented protective system to replace a pressure relief system would require a full understanding of all the potential causes of overpressure. Stopping the feed to a reactor in the event of high pressure will only protect against overpressure from that cause. The vessel could still be overpressurised by, for example, overfilling with solvent. (It should be noted that the design of an inherently safe system also has the requirement to consider every cause of overpressure.)

The design of the instrumented protective system would need to consider, for each potential cause of overpressure, what the frequency of demands on the system would be. It would also be necessary to have a criterion for the acceptable frequency of overpressure of the equipment. The instrumented protective system would then need to be designed to achieve the criterion. It would be very important to take account of the effects of common mode failure and to design the system to be testable. It seems clear that the specification of an instrumented protective system would be a job for a competent and experienced hazard and reliability specialist. A procedure for reviewing the adequacy of protective measures is proposed in reference 9.

The problem with instrumented protective systems is that they are active rather than passive systems. In order to achieve a reasonable likelihood that they will work when required, they have to be tested. The testing required is usually much more frequent than for pressure relief systems, typically between monthly and three-monthly. Whereas most plants have systems in place for the testing of pressure relief systems, special procedures have usually to be set up for the testing of instrumented protective systems. Until a system for the periodic testing of instrumented protective systems is in place, it may be optimistic to place too much reliance on them.

In summary, whilst instrumented protective systems can be useful in certain carefully controlled cases, the approach of inherently safe design is to be preferred.

4. PROBLEMS WITH DESIGNING OUT THE NEED FOR PRESSURE RELIEF

4.1 External fire

The provision of pressure relief for external fire is well-established. Nevertheless, pressure relief is not always capable of protecting a vessel from failure in a fire. BLEVEs can occur when the wall temperature above the liquid surface gets too hot, resulting in mechanical failure at some fraction of the design pressure.

The first consideration of an inherently safe approach must be to avoid having fires. Non-flammable materials should be substituted for flammable ones wherever possible. However, since many products are flammable, and many of them are valued for their flammable nature (eg fuels, reactive intermediates), it will never be possible to eliminate flammable materials from all chemical processes.

The second consideration should be to minimise the quantity of flammables available. If the quantity of flammable material that can leak can be severely limited, then there may be insufficient energy available in the fire to heat a vessel contents to the temperature at which its vapour pressure equals the design pressure. Another approach might be to layout plants so that any spillage would flow away from the equipment and into an area in which it could burn safely. Research would be needed to define the gradients needed for such drainage, and house-keeping practices to prevent blockage of the drainage channels would be important.

If it were not possible to limit the quantity of flammables that might leak, the next approach would be to stop the heat from getting into the equipment. This would entail the use of fire insulation, together with inspections to ensure that it was all in place. It might be possible to use a criterion of preventing the pressure reaching the design pressure before a time by which the fire brigade might reasonably have been expected to have extinguished the fire. This approach might be more reasonable for small fires than for large ones, especially when escalation of the fire would be likely.

Another approach could be to install equipment high enough up in a structure to avoid direct flame impingement in the event of a fire. Heating of the vessel would still occur to some extent, but at a much lower rate. Data would be needed on the heating rate to be expected under such conditions.

Care should be taken not to increase equipment design pressure too far in an attempt to extend the time before the design pressure was reached in a fire. It would be necessary to limit the maximum temperature to avoid decomposition reactions. Also care should be taken if the maximum temperature is to exceed the thermodynamic critical temperature, as under certain conditions the rate of pressure rise with temperature could then be very high. If the design pressure is increased and the vessel does fail, then more stored energy is available to be released and the result is a bigger explosion.

Whilst there are some ways in which the need for fire relief can sometimes be avoided, it is likely that to eliminate the need for fire relief altogether would require substantial changes to processes and plant layout. Considerable additional expense would be involved in locating equipment at high level.

4.2 Atmospheric Storage Tanks

Because of their low design pressure (typically of a few millibars), fixed roof atmospheric storage tanks require to "breathe" during filling, emptying and ambient temperature changes. This is a form of pressure relief.

For relatively small tanks, floating roof tanks could be considered, at greater expense and with the added problem of maintaining the seal. However, pressure containment, even in floating roof tanks, would probably be ruled out by the possibility of flow from a higher pressure source elsewhere on the plant. The only option would then be to increase the design pressure, which is likely to be very expensive.

The inherently safe approach would be to remove the requirement for bulk storage by achieving a "just in time" relationship between production and use. It seems unlikely that that approach will always work.

5. CONCLUSIONS

1. Despite their ubiquitous use, pressure relief systems have a number of disadvantages, listed in the introduction.

2. It would be difficult and expensive to design chemical plants so as not to need any pressure relief systems.

3. The main problem areas in eliminating pressure relief would be external fire, atmospheric storage tanks and certain chemical reactions. Research would be needed in those areas if it were desired to build a plant without pressure relief.

4. There is, however, considerable scope for reducing the number of pressure relief systems, and the frequency of demands on them, by the application of inherent safety principles. Examples are given in the text.

5. Instrumented protective systems can sometimes, under carefully controlled conditions, be used in place of pressure relief systems. However, they are an "active" rather than inherently safe form of protection, and procedures for their safe design and testing need to be in place. An inherently safe solution is to be preferred when practicable.

6. Hazard indentification, finding all the potential causes of overpressure and underpressure is an essential step in the design of inherently safe systems and instrumented protective systems.

7. To design a chemical plant with no need for pressure relief systems, substitution of hazardous chemicals, processes and chemical reaction routes with safe ones would form an important part of the design process. Inherent safety considerations need to be applied early in process development, before the chemical reaction route has been frozen.

8. A chemical plant with no need for pressure relief would be likely to have :-

   a) all items of equipment designed for the same, relatively high design pressure and for full vacuum;

   b) either no flammables on the plant, severely restricted quantities of flammables, or the plant engineered so as to eliminate the need for fire relief. Research would be needed in order to define how to do this;

   c) minimal storage capacity and a "just in time" policy. All storage tanks would have the same high design pressure as the rest of the plant.

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