Selection and Sizing of Orifice Area of Pressure Relief Valve

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Abstract -The function of a pressure relief valve is to protect pressure vessels, piping systems, and other equipment from pressures exceeding their design pressure by more than a fixed predetermined amount. The permissible amount of overpressure is covered by various codes and is a function of the type of equipment and the conditions causing the overpressure. It is not the purpose of a pressure relief valve to control or regulate the pressure in the vessel or system that the valve protects, and it does not take the place of a control or regulating valve. The aim of safety systems in processing plants is to prevent damage to equipment, avoid injury to personnel and to eliminate any risks of compromising the welfare of the community at large and the environment. Proper sizing, selection, manufacture, assembly, test, installation, and maintenance of a pressure relief valve are critical to obtaining maximum protection.

Keywords: Pressure relief valve, proper sizing, orifice area, blowdown .

I. INTRODUCTION

A pressure relief valve must be capable of operating at all times, especially during a period of power failure; therefore, the sole source of power for the pressure relief valve is the process fluid. The pressure relief valve must open at a predetermined set pressure, flow a rated capacity at a specified overpressure, and close when the system pressure has returned to a safe level. Pressure relief valves must be designed with materials compatible with many process fluids from simple air and water to the most corrosive media[1]. They must also be designed to operate in a consistently smooth manner on a variety of fluids and fluid phases. These design parameters lead to the wide array of pressure relief valve products available in the market today.

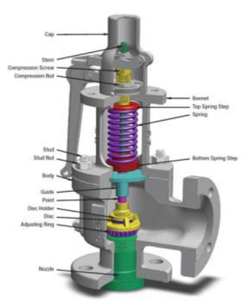

Figure 1. Cross Sectional Views of PRV

The standard design safety relief valve is spring loaded with an adjusting ring for obtaining the proper blowdown and is available with many optional accessories and design features. Refer to Figure 1 for cross-sectional views of typical valve. The bellows and balanced bellows design isolate the process fluid from the bonnet, the spring, the stem, and the stem bushing with a bellows element. Jacketed valve bodies are available for applications requiring steam or heat transfer mediums to maintain viscosity or prevent freezing. Pilot-operated valves are available with the set pressure and blowdown control located in a separate control pilot. This type of valve uses the line pressure through the control pilot to the piston in the main relief valve and thereby maintains a high degree of tightness, especially as the set pressure is being approached. Another feature of the pilot-operated valve is that it will permit a blowdown as low as 2 %. The disadvantage of this type of valve is its vulnerability to contamination from foreign matter in the fluid stream.

1.1 Equation nomenclature -

All symbols used in this paper are defined as follows:
A = Valve effective orifice area, in^2.
C = Flow constant determined by the ratio of specific heats.
G = Specific gravity referred to water = 1.0 at 70°F
K = Coefficient of discharge obtainable from valve manufacture.
Kb = Correction factor due to back pressure.
Kn = Correction factor for saturated steam at set pressures > 1,500 psia, see Equation 6
Kp = Correction factor for relieving capacity vs. lift for relief valves in liquid service, see Equations 1 & 2
Ksh = Correction factor due to the degree of superheat in steam (Ksh = 1.0 for saturated steam)
Kv = Correction factor for viscosity, see Equations 8 & 9 (use Kv =1.0 for all but highly viscous liquids)
Kw = Correction factor due to back pressure for use with balanced bellows valves
M = Molecular weight, see Table 2 for values of some common gases
P_1 = Upstream pressure, psia (set pressure + overpressure + atmospheric pressure)
!P = Differential pressure (set pressure, psig ! back pressure, psig)
Q = Flow, gpm
T = Inlet vapor temperature, °R
R_{NE} = Reynolds numbers,
W = Flow, lb/hr
Z = Compressibility factor (use Z = 1 for ideal gas)
μ= Liquid dynamic (absolute) viscosity, centipoise

II.SIZING AND SELECTION

Pressure relief valves must be selected by those who have complete knowledge of the pressure relieving requirements of the system to be protected and the environmental conditions particular to that installation. Too often pressure relief valve sizes are determined by merely matching the size of an existing available vessel nozzle, or the size of an existing pipe line connection [2]. Correct and comprehensive pressure relief valve sizing is a complex multi-step process that should follow the following stepwise approach:

1. Each piece of equipment in a process should be evaluated for potential overpressure scenarios.
2. An appropriate design basis must be established for each vessel. Choosing a design basis requires assessing alternative scenarios to find the credible worst case scenario.
3. The design basis is then used to calculate the required pressure relief valve size. If possible, the sizing calculations should use the most current methodologies incorporating such considerations as two phase flow and reaction heat sources.

This paper addresses pressure relief valves as individual components. Therefore, detailed design aspects pertaining to ancillary piping systems are not covered. These are clearly noted in the course. These design issues can be addressed by piping analysis using standard accepted engineering principles; these are not within the scope of this paper. Where relief device inlet and outlet piping are subject to important guidance by the ASME Code [2], it is so noted.

In order to properly select and size a pressure relief valve, the following information should be ascertained for each vessel or group of vessels which may be isolated by control or other valves. The data required to perform pressure relief valve sizing calculations is quite extensive. First, the equipment dimensions and physical properties must be assembled. Modelling heat flow across the equipment surface requires knowledge of the vessel material's heat capacity, thermal conductivity, and density (if vessel mass is determined indirectly from vessel dimensions and wall thickness). The vessel geometry – vertical or horizontal cylinder, spherical, etc. – is a necessary parameter for calculating the wetted surface area, where the vessel contents contact vessel walls. Second, the properties of the vessel contents must be quantified. This includes density, heat capacity, viscosity, and thermal conductivity. Values of each parameter are required for both liquid and vapour phases. Boiling points vapour pressure, and thermal expansion coefficient values also are required[3]. Ideally, the properties will be expressed as functions of temperature, pressure, and compositions of the fluid.

2.1 .Determination of the Worst-Case Controlling Scenario -

As process plants become larger and are operated closer to safety limits, a systematic approach to safety becomes a necessity. The most difficult aspect of the design and sizing of pressure relief valves are ascertaining the controlling cause of overpressure. This is sometimes referred to as the worst case scenario. Overpressure in equipment may result from a number of causes or combination of causes. Each cause must be investigated for its magnitude and for the probability if its occurrence with other events. The objective might be to document why the particular design basis is the correct choice[5].
The question that will always remain: which scenario is the credible worst case? Among the techniques available to solve this problem is fault-tree analysis. A fault tree is a graphical representation of the logical connections between basic events (such as a pipe rupture or the failure of a pump or valve) and resulting events (such as an explosion, the liberation of toxic chemicals, or over-pressurization in a process tank). A complete treatment of fault-tree theory and analysis is beyond the scope of this course.
The usual causes of overpressure and ways of translating their effects into pressure relief valve requirements are given in the following list. In most cases, the controlling overpressure will be that resulting from external fire.

- Heat from external fire
- Equipment failure
- Failure of Condenser system
- Failure of Cooling Medium
- Failure of Control system
- Chemical reactions
- Entrance of Volatile Fluid
- Closed Outlets
- Thermal Expansion of Liquids
- Operating error

Pressure relief valves must have sufficient capacity when fully opened to limit the maximum pressure within the vessel to 110% of the maximum allowable working pressure (MAWP). This incremental pressure increase is called the pressure accumulation. However, if the overpressure is caused by fire of other external heat, the accumulation must not exceed 21% of the MAWP.

2.2 Determination of Set Point Pressure -

Process equipment should be designed for pressures sufficiently higher than the actual working pressure to allow for pressure fluctuations and normal operating pressure peaks. In order that process equipment is not damaged or ruptured by pressures in excess of the design pressure, pressure relief valves are installed to protect the equipment. The design pressure of a pressure vessel is the value obtained after adding a margin to the most severe pressure expected during the normal operation at a coincident temperature.
Depending on the situation, this margin might typically be the maximum of 25 psig or 10%. The set point of a pressure relief valve is typically determined by the MAWP[6]. The set point of the relief device should be set at or below this point. When the pressure relief valve to be used has a set pressure below 30 psig, the ASME Code specifies a maximum allowable overpressure of 3 psi.
Pressure relief valves must start to open at or below the maximum allowable working pressure of the equipment. When multiple pressure relief valves are used in parallel, one valve should be set at or below the MAWP and the remaining valve(s) may be set up to 5% over the MAWP. When sizing for multiple valve applications, the total required relief area is calculated on an overpressure of 16% or 4 psi, whichever is greater? Much confusion often prevails because there are so many possible pressure values that simultaneously exist for a given process and pressure relief valve application. It may help to view these values graphically. Look at the diagram in Figure 2 below. The pressures are arranged in ascending value from bottom to top:

BURST PRESSURE

OVERPRESSURE VALUE (PSI)

DESIGN PRESSURE

ACCUMULATION

MAX. ALLOWABLE WORKING PRESSURE**

SET PRESSURE*

OPERATING MARGIN

NORMAL WORKING PRESSURE

* The SET PRESSURE is not allowed by Code to exceed the MAWP.

** Depending on the application, this pressure value can simultaneously be the SET PRESSURE and/or DESIGN PRESSURE

Figure 2 – Hierarchy Of Pressure Values

2.3 Back Pressure Considerations

Back pressure in the downstream piping affects the standard type of pressure relief valve. Variable built-up back pressure should not be permitted to exceed 10% of the valve set pressure. This variable back-pressure exerts its force on the topside of the disc holder over an area approximately equal to the seat area. This force plus the force of the valve spring, when greater that the kinetic force of the discharge flow will cause the valve to close. The valve then pops open as the static pressure increases, only to close again. As this cycle is repeated, severe chattering may result, with consequent damage to the valve. Static pressure in the relief valve discharge line must be taken into consideration when determining the set pressure. If a constant static back-pressure is greater than atmospheric, the set pressure of the pressure relief valve should be equal to the process theoretical set pressure minus the static pressure in the discharge piping.
Conventional pressure relief valves are used when the back pressure is less than 10%. When it is known that the superimposed back pressure will be constant, a conventional valve may be used. If the back pressure percentage is between10 to 40, a balanced bellow safety valve is used. Pilot operated pressure relief valves are normally used when the back pressure is more than 40% of the set pressure or the operating pressure is close to the pressure relief valve set pressure. If back pressure on valves in gas and vapour service exceeds the critical pressure (generally taken as 55% of accumulated inlet pressure, absolute), the flow correction factor Kb must be applied. If the back pressure is less than critical pressure, no correction factor is generally required.

2.4 Overpressure Considerations

Back pressure correction factors should not be confused with the correction factor Kp that accounts for the variation in relieving capacity of relief valves in liquid service that occurs with the change in the amount of overpressure or accumulation. Typical values of Kp range from 0.3 for an overpressure of 0%, 1.0 for 25%, and up to 1.1 for an overpressure of 50%. A regression analysis on a typical manufacturer's performance data produced the following correlation equations for Kp:

For % overpressure < 25,

K p = − 0.0014 (% overpressure) 2 + 0.073 (% overpressure) + 0.016 (1)

For 25 " % overpressure < 50,

K p = 0.00335 (% overpressure) + 0.918 (2)

III.DETERMINATION OF EFFCTIVE ORIFICE AREA

Once the pressure and rate of relief have been established for a particular vessel or pipeline, the required size of the pressure relief valve orifice, or the effective area, can be determined. Sizing formulae in this course can be used to calculate the required effective area of a pressure relief valve that will flow the required volume of system fluid at anticipated relieving conditions. The appropriate valve size and style may then be selected having an actual discharge area equal to or greater that the calculated required effective area. The industry has standardized on valve orifice sizes and has identified them with letters from D through T having areas of 0.110 in^2 through 26.0 in^2 respectively. The standard nozzle orifice designations and their corresponding discharge areas are given in Table 1.

Table 1 – Standard Nozzle Orifice Data

NOZZLE ORIFICE AREAS	
Size Designation	**Orifice Area, in^2**
D	0.110
E	0.196
F	0.307
G	0.503
H	0.785
J	1.280
K	1.840
L	2.850
M	3.600
N	4.340
P	6.380
Q	11.050
R	16.000
T	26.000

There are a number of alternative methods to arrive at the proper size. If the process fluid application is steam, air, or water and the pressure relief valve discharges to atmosphere, manufacturer's literature can be consulted. These publications contain capacity tables for the manufacturer's various valves for the fluids just mentioned at listed set pressures plus several overpressure values. Given the large quantity of tables usually presented, caution must be exercised to use the proper table. With careful consideration, the tables' usefulness can be expanded by making the proper adjustments via correction factors for specific heat ratio, temperature, molecular weight, specific gravity, inlet and outlet piping frictional pressure losses, and fluid viscosity.

Most major pressure relief valve manufacturers also offer sizing software. While not an endorsement, two such products are Size Master Mark IV by Farris Engineering and Crosby – Size marketed by The Crosby Valve

Company[8]. Pressure relief valve sizing software is unlimited in its capability to accept wide variability in fluid properties and is therefore extremely versatile. When standard tables are not applicable or software is not available, the Engineer is relegated to manual calculation to determine size. The required orifice size (effective area) may be calculated with the following formulae.

Vapour or gas,

$$A = \frac{W\sqrt{TZ}}{CK\,P_1\,K_b\,\sqrt{M}} \tag{3}$$

Steam,

$$A = \frac{W}{51.5K\,P_1\,K_n K_{sh}} \tag{4}$$

Liquids,

$$A = \frac{Q\sqrt{G}}{27.2\,K_P\,K_v K_w \sqrt{\Delta P}} \tag{5}$$

Manufacturer's customized versions of Equation 5 should be used when available. These typically modify the equation presented to reflect actual coefficients of discharge (Kd) based on required ASME capacity certification testing. In some cases, the variable Kp may be absent. The gas and vapour formula presented is based on perfect gas laws. Many real gases and vapours, however, deviate from a perfect gas. The compressibility factor Z is used to compensate for the deviations of real gases from the ideal gas. In the event the compressibility factor for a gas or vapour cannot be determined, a conservative value of Z = 1 is commonly used. Values of Z based on temperature and pressure considerations are available in the open literature.

The standard equations listed above may not fully take into consideration the effect of back pressure on the valve capacity. The capacity of pressure relief valves of conventional design will be markedly reduced if the back pressure is greater than 10% of the set pressure. For example, a back pressure of 15% of the set pressure may reduce the capacity as much as 40%. The capacities of bellows valves with balanced discs are not affected by back pressure until it reaches 40 to 50% of the set pressure. Equation 4 is based on the empirical Napier formula for steam flow. Correction factors are included to account for the effects of superheat, back pressure and subcritical flow. An additional correction factor Kn is required by ASME when relieving pressure (P1) is above 1,500 psia:

$$Kn = \frac{0.1906P_1 - 1000}{0.2292P_1 - 1061} \tag{6}$$

3.1 Inlet and Outlet Piping Considerations -

While the detailed design or stress analysis of the inlet and outlet piping of pressure relief valves is not within the scope of this course, some important considerations are worth mentioning:

Satisfactory operation of a pressure relief valve requires that it be mounted vertically, preferably on a nozzle at the top of a vessel or on a tee connection on top of a pipeline. The minimum inlet piping size should be equal in size to the pressure relief valve; the length should be minimized to reduce pressure drop and bending moments resulting from the reaction thrust developed from the discharging fluid. A rule of thumb is to design the inlet piping such that the total pressure drop in the inlet piping does not exceed 3% of the valve set pressure. When a single pressure relief valve is installed to protect several vessels, the connecting piping between these vessels should be adequate in size to keep the pressure drop within these limits.

The type of discharge piping selected will depend largely on the hazardous nature of the service and on the value of the material that might be lost through a discharge event. For air or non-hazardous gas service, the discharge piping is normally directed vertically and extended such that it does not present a safety concern. Discharge elbows fitted with drain lines are normally used on steam and vapour services. The vapour discharge from these elbows is directed into a larger diameter riser pipe that is independently supported. The discharge piping should be extended vertically downward to a suitable drain for non-hazardous liquid service. A closed discharge piping system is required for hazardous services, or for services involving expensive chemicals. Collection systems for these categories of fluids may consist of a considerable quantity of piping with numerous pressure relief valves discharging into a common manifold. The pressure drop through this type of piping system must be calculated accurately, taking into consideration the fact that simultaneous discharge events may occur.
The classical methods for pressure drop determination can be employed for both inlet and outlet piping arrangements. Values for the density, velocity, and viscosity of the discharging fluid should be based on the average pressure and temperature of the respective pipe component. The formation of hydrates, polymerization, and fluid solidification in pressure relief valve piping might be an additional concern.
A rule of thumb is to design the discharge piping such that the total pressure drop in the outlet piping does not exceed 10% of the valve set pressure. Supports for pressure relief valve piping should be designed to minimize the transference of pipe loads to the valve body. Allowance shall be made for piping expansion in cases of high temperature service; valve displacement due to thermal expansion may cause valve leakage or faulty operation. The internal pressure, dead loads, thermal expansions, reaction thrust, resulting dynamic forces, and resulting bending stresses due to discharging fluid will be exerted on the pressure relief valve inlet and outlet bends and elbows.

Additional considerations are:

1. Design discharge piping with clean-outs to preclude internal obstructions.
2. Test the piping hydrostatically to 150% of the maximum anticipated pressure of the discharge system.
3. Provide covers or caps to prevent the intrusion and accumulation of rain or the entrance of birds or rodents.
4. Design piping to be self-draining.

3.2 Viscous Fluid Considerations -

The procedure to follow to correct for a viscous fluid, i.e. a fluid whose viscosity is greater than 150 centipoise (cP) is to:

1. Determine a preliminary required pressure relief valve orifice size (effective area) discounting any effects for viscosity. This is done by using the standard liquid sizing formula and setting the viscosity correction factor Kv = 1.0. Select the standard orifice size letter designation that has an actual area equal to or greater than this effective area.
2. Use the actual area of the viscous trial size orifice to calculate a Reynolds number (RNE) using the following formula:

$$R_{NE} = \frac{2800\, G\, Q}{A\, \mu} \qquad (7)$$

3. Use the Reynolds number calculated in Step 2 to calculate a viscosity correction factor Kv from the following equations:

For $R_{NE} < 200$,

$$Kv = 0.27 \ln R_{NE} - 0.65 \qquad (8)$$

For $200 \leq R_{NE} < 10{,}000$,

$$Kv = -\,0.00777\,(\ln R_{NE})^{2} + 0165 \ln R_{NE} + 0.128 \qquad (9)$$

4. Determine a corrected required effective area of the pressure relief valve orifice using the standard liquid sizing formula and the value of Kv determined in Step 3.
5. Compare the corrected effective area determined in Step 4 with the chosen actual orifice area in Step 1. If the corrected effective area is less than the actual trial area assumed in Step 1, then the initial viscous trial size assumed in Step 1 is acceptable. Repeat this iterative process until an acceptable size is found.

IV. CONCLUSION

The adequacy of any safety relief system is subject to certain conditions that are the principle basis for the design. Determination of correct required relieving capacity is often times the most obtuse step in the design process. For this reason, knowledge of sophisticated failure probability and evaluation techniques such as fault-tree analysis are important in making correct decisions regarding process upset severity. While the tired and true methods for pressure relief valve sizing are probably adequate, and generally produce conservative results, increased knowledge in the field of two phase hydraulics, highlighted by test work and information published by groups such as AIChE's DIERS, should be considered in any design of a pressure relief system [4].

Pressure relief valves should be designed to passively protect against a predetermined set of "worst case" conditions and should be installed to react to these conditions regardless of daily operation activities. For each piece of equipment requiring overpressure protection, a credible worst-case scenario should be defined. For a given vessel, several plausible scenarios may exist – from external fire to various operating contingencies, such as overfill or vessel swells conditions. System overpressure is assumed to be caused by the controlling scenario. Most controlling scenarios are loaded with conservative assumptions that are never achieved in actual operating conditions. It is the controlling scenario relieving rate that dictates the pressure relief valve size. If sized correctly, the pressure relief valve should have enough discharge capacity to prevent the pressure in the pressure vessel rising 10% above its maximum allowable working pressure.

In addition to liquids, the scope of this paper has been limited to all vapour flow. It is applicable when it is known that only vapour will be present or when the liquid portion is assumed to completely flash. Where mixed flow is present, and the total mass quantity (flow rate) is known, an all vapour model should yield conservative results.

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