



**PDHonline Course M112 (3 PDH)**

---

# **Selection and Sizing of Pressure Relief Valves**

*Instructor: Randall W. Whitesides, PE*

**2020**

**PDH Online | PDH Center**

5272 Meadow Estates Drive  
Fairfax, VA 22030-6658  
Phone: 703-988-0088  
[www.PDHonline.com](http://www.PDHonline.com)

An Approved Continuing Education Provider

# SELECTION AND SIZING OF PRESSURE RELIEF VALVES

Randall W. Whitesides, P.E.

## GENERAL/SCOPE/INTRODUCTION

### Introduction

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.

Note: For ease of learning, the student is encouraged to print the glossary and refer to the definitions of **words** or **phrases** as they first appear while studying the course material.

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.

### Types, Design, and Construction

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. 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.

## STANDARD DESIGN

## BALANCED-BELLOWS DESIGN

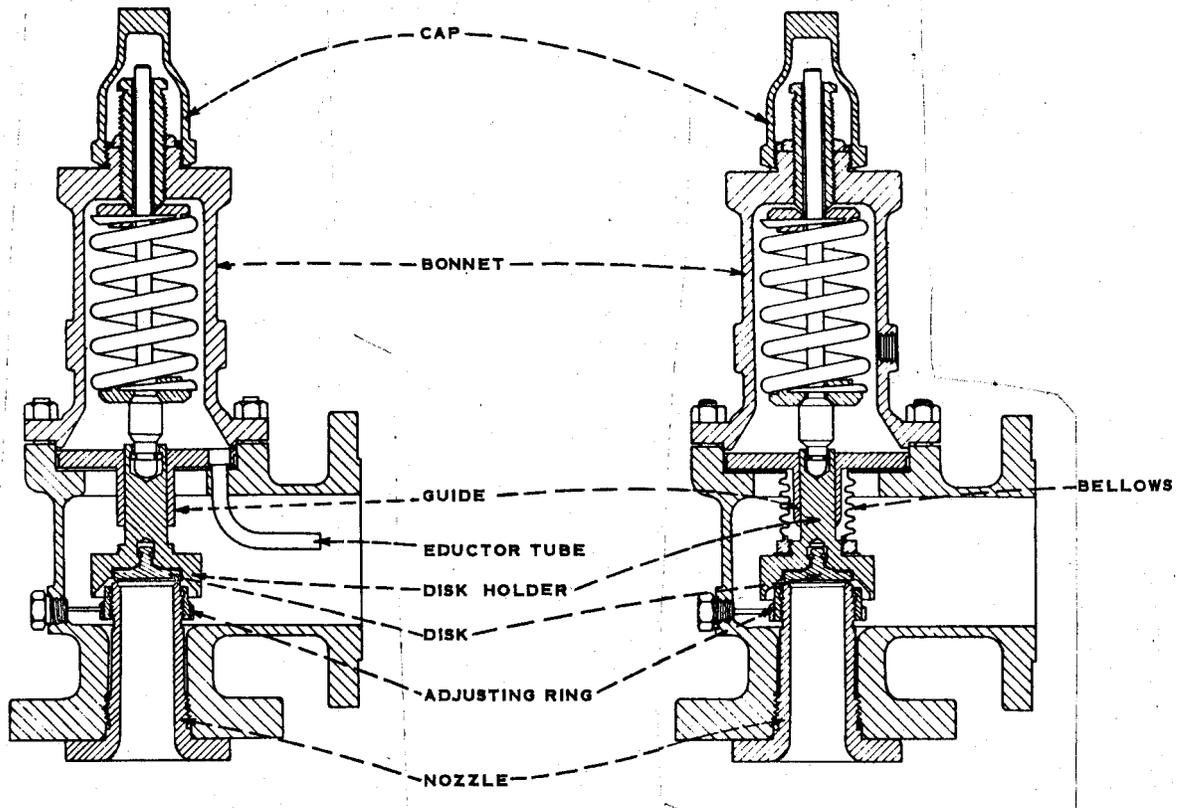


FIGURE 1 - TWO TYPES OF RELIEF VALVES

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 valves. 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.

## CODES AND STANDARDS

### Introduction

Since pressure relief valves are safety devices, there are many Codes and Standards in place to control their design and application. The purpose of this section of the course is to familiarize the student with and provide a brief introduction to some of the Codes and Standards which govern the design and use of pressure relief valves. While this course scope is limited to ASME Section VIII, Division 1, the other Sections of the Code that have specific pressure relief valve requirements are listed below. The portions of the Code that are within the scope of this course are indicated in red:

List of Code Sections Pertaining to Pressure Relief Valves

|                           |   |
|---------------------------|---|
| Section I                 | Power Boilers   |
| Section III, Division 1   | Nuclear Power Plant Components                                  |
| Section IV                | Heating Boilers   |
| Section VI                | Recommended Rules for the Care and Operation of Heating Boilers |
| Section VII               | Recommended Rules for the Care of Power Boilers                 |
| Section VIII, Division 1  | Pressure Vessels  |
| Appendix 11               | Capacity Conversions for Safety Valves                          |
| Appendix M                | Installation and Operation                                      |
| Section VIII, Division 2  | Pressure Vessels - Alternative Rules                            |
| B31.3, Chapter II, Part 3 | Power Piping - Safety and Relief Valves                         |
| B31.3, Chapter II, Part 6 | Power Piping - Pressure Relief Piping                           |

ASME specifically states in Section VIII, Division 1, paragraph UG-125 (a) “All pressure vessels within the scope of this division, irrespective of size or pressure, shall be provided with pressure relief devices in accordance with the requirements of UG-125 through UG-137.”

Reference is made to the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1. The information in this course is NOT to be used for the application of overpressure protection to power boilers and nuclear power plant components that are addressed in the Code in Section I and Section III respectively. The student should understand that the standards listed here are not all inclusive and that there exists specific standards for the storage of chlorine, ammonia, compressed gas cylinders, and the operation of refrigeration units, among probable others.

A Brief History of the ASME Code

Many states began to enact rules and regulations regarding the construction of steam boilers and pressure vessels following several catastrophic accidents that occurred at the turn of the twentieth century that resulted in large loss of life. By 1911 it was apparent to manufacturers and users of boilers and pressure vessels that the lack of uniformity in these regulations between states made it difficult to construct vessels for interstate commerce. A group of these interested parties appealed to the Council of the American Society of Mechanical Engineers to assist in the formulation of standard specifications for steam boilers and pressure vessels. (The American Society of Mechanical Engineers was organized in 1880 as an educational and technical society of Mechanical Engineers). After years of development and public comment the first edition of the code, *ASME Rules of Construction of Stationary Boilers and for Allowable Working Pressures*, was published in 1914 and formally adopted in the spring of 1915. From this simple beginning the code has now evolved into the present eleven section document, with multiple subdivisions, parts, subsections, and mandatory and non-mandatory appendices.

The ASME Code Symbol Stamp and the letters “UV” on a pressure relief valve indicate that the valve has been manufactured in accordance with a controlled quality assurance program, and that the relieving capacity has been certified by a designated agency, such as the National Board of Boiler and Pressure Vessel Inspectors.



### Adoption of the ASME Code by the States

As of this writing, all states of the United States, with the exception of South Carolina, have adopted the ASME Code as jurisdictional law. The student should consult with local regulatory authorities, *e.g.* state agencies, to determine any specialized jurisdictional requirements for pressure relief valves that may be applicable.

### EQUATION NOMENCLATURE

Unless otherwise noted, all symbols used in this course are defined as follows:

$A$  = Valve effective orifice area, in<sup>2</sup>.

$C$  = Flow constant determined by the ratio of specific heats, see Table 2 (use  $C = 315$  if  $k$  is unknown)

$G$  = Specific gravity referred to water = 1.0 at 70°F

$K$  = Coefficient of discharge obtainable from valve manufacture ( $K = 0.975$  for many nozzle-type valves)

$K_b$  = Correction factor due to back pressure. This is valve specific; refer to manufacturer's literature.

$K_n$  = Correction factor for saturated steam at set pressures > 1,500 psia, see Equation 6

$K_p$  = Correction factor for relieving capacity vs. lift for relief valves in liquid service, see Equations 1 & 2

$K_{sh}$  = Correction factor due to the degree of superheat in steam ( $K_{sh} = 1.0$  for saturated steam)

$K_v$  = Correction factor for viscosity, see Equations 8 & 9 (use  $K_v = 1.0$  for all but highly viscous liquids)

$K_w$  = Correction factor due to back pressure for use with balanced bellows valves

$M$  = Molecular weight, see Table 2 for values of some common gases

$P_I$  = Upstream pressure, psia (set pressure + overpressure + atmospheric pressure)

$\Delta P$  = 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)

$\mu$  = Liquid dynamic (absolute) viscosity, centipoise

## SIZING AND SELECTION

### Introduction

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.

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 course 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 course. Where relief device inlet and outlet piping are subject to important guidance by the ASME Code, 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. Modeling 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 vapor phases. Boiling points, vapor pressure, and thermal expansion coefficient values also are required. Ideally, the properties will be expressed as functions of temperature, pressure, and compositions of the fluid.

### 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 is 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 of its occurrence with other events. The objective might be to document why the particular design basis is the correct choice. 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.

1. Heat from external fire
2. Equipment failure
3. Failure of Condenser system
4. Failure of Cooling Medium
5. Failure of Control system
6. Chemical reactions
7. Entrance of Volatile Fluid
8. Closed Outlets
9. Thermal Expansion of Liquids
10. 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 or other external heat, the accumulation must not exceed 21% of the MAWP.

Section VIII does not outline a detailed method to determine required relieving capacity in the case of external fire. Appendix M-14 of the Code recommends that the methods outlined in Reference 3 be employed. The student is directed to Reference 7 for an excellent treatment, including examples, of the methodology of API Recommended Practice 520 (Reference 3).

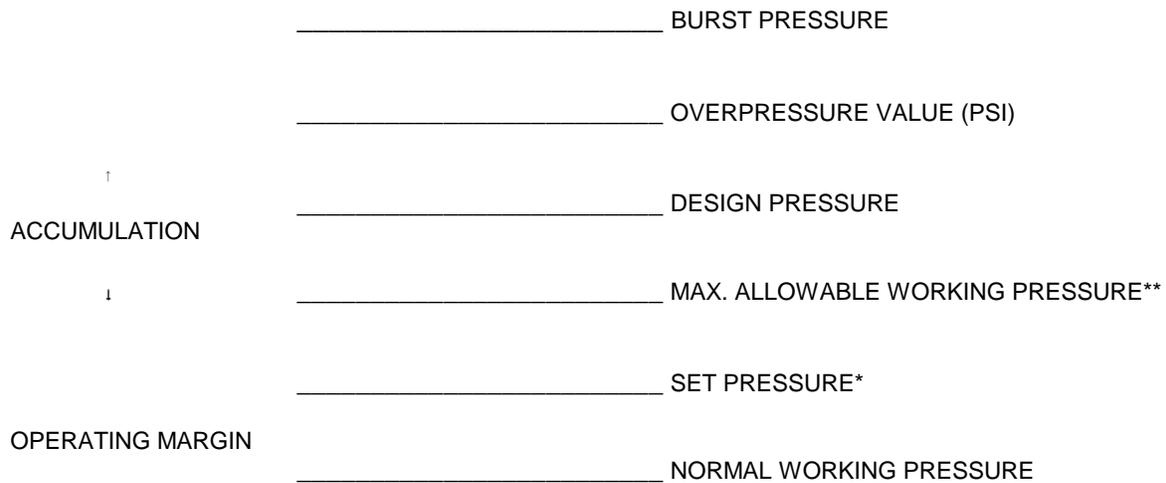
#### Determination of Set Point Pressure

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. 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:



\* 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**

*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 than 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 between 10 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 vapor service exceeds the critical pressure (generally taken as 55% of accumulated inlet pressure, absolute), the flow correction factor  $K_b$  must be applied. If the back pressure is less than critical pressure, no correction factor is generally required.

#### Overpressure Considerations

Back pressure correction factors should not be confused with the correction factor  $K_p$  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  $K_p$  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  $K_p$ :

For % overpressure < 25,

$$K_p = -0.0014(\% \text{ overpressure})^2 + 0.073(\% \text{ overpressure}) + 0.016 \quad (1)$$

For  $25 \leq \% \text{ overpressure} < 50$ ,

$$K_p = 0.00335(\% \text{ overpressure}) + 0.918 \quad (2)$$

#### Determination of Effective 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 than 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<sup>2</sup> through 26.0 in<sup>2</sup> respectively. The standard nozzle orifice designations and their corresponding **discharge areas** are given in Table 1.

| NOZZLE ORIFICE AREAS |                               |
|----------------------|-------------------------------|
| Size Designation     | Orifice Area, in <sup>2</sup> |
| 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                        |

**TABLE 1 – STANDARD NOZZLE ORIFICE DATA**

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. This extrapolation of the standard tables is not recommended by this writer.

**EXAMPLE 1** (Steam Application)

Given:

Fluid: Saturated steam  
 Required Capacity: 40,000 lb/hr  
 Set Pressure: 140 psig  
 Overpressure: 10% (or 14 psig)  
 Back Pressure: Atmospheric  
 Inlet relieving Temperature: Saturation temperature  
 Molecular Weight: 18

Find: XYZ Valve Company's standard orifice for this application.

Solution: Refer to Figure 3 and find that a "P" orifice is required, which will have a capacity of 53,820 lb/hr.

**THE XYZ VALVE COMPANY**

**Approved: API-ASME and ASME  
Pressure Vessel Codes**

**Certified: National Board of Boiler  
and Pressure Vessel Inspectors**

Capacity in Pounds per Hour of Saturated Steam at Set Pressure Plus 10% Overpressure

| Set Press (psig) | ORIFICE DESIGNATION |      |        |        |       |        |       |        |        |        |        |        |        |        |
|------------------|---------------------|------|--------|--------|-------|--------|-------|--------|--------|--------|--------|--------|--------|--------|
|                  | D                   | E    | F      | G      | H     | J      | K     | L      | M      | N      | P      | Q      | R      | T      |
| 10               | 141                 | 252  | 395    | 646    | 1009  | 165    | 10    | 3666   | 4626   | 5577   | 8198   | 14200  | 20550  | 33410  |
| 20               | 202                 | 360  | 563    | 923    | 1440  | 2362   | 3373  | 5235   | 6606   | 7964   | 11710  | 20280  | 29350  | 47710  |
| 30               | 262                 | 467  | 732    | 1200   | 1872  | 3069   | 4384  | 6804   | 8586   | 10350  | 15220  | 26350  | 38200  | 62010  |
| 40               | 323                 | 575  | 901    | 1476   | 2304  | 3777   | 5395  | 8374   | 10570  | 12740  | 18730  | 32430  | 47000  | 76310  |
| 50               | 383                 | 683  | 1070   | 1753   | 2736  | 4485   | 6405  | 9943   | 12550  | 15120  | 22230  | 38510  | 55800  | 90610  |
| 60               | 444                 | 791  | 1939   | 9030   | 3167  | 5193   | 7416  | 11510  | 14530  | 17510  | 25740  | 44590  | 64550  | 104900 |
| 70               | 504                 | 899  | 1408   | 2306   | 3599  | 5901   | 8427  | 13080  | 16510  | 19900  | 29250  | 50660  | 73400  | 119200 |
| 80               | 565                 | 1005 | 1576   | 2583   | 4031  | 6609   | 9438  | 14650  | 18490  | 22290  | 32760  | 56740  | 82100  | 133500 |
| 90               | 625                 | 1115 | 1745   | 2860   | 4463  | 7317   | 10450 | 16220  | 20470  | 24670  | 36270  | 69890  | 90900  | 147800 |
| 100              | 686                 | 1220 | 1914   | 3136   | 4894  | 8024   | 11460 | 17790  | 22450  | 27060  | 39780  | 68900  | 99700  | 162110 |
| 120              | 807                 | 1440 | 2252   | 2690   | 5758  | 9440   | 13480 | 20930  | 26410  | 318300 | 46800  | 81050  | 117000 | 190710 |
| 140              | 998                 | 1655 | 2590   | 4943   | 6621  | 10860  | 15550 | 24070  | 30370  | 36610  | 53290  | 93210  | 135000 |        |
| 160              | 1050                | 1870 | 2927   | 4796   | 7485  | 12270  | 17530 | 27200  | 34330  | 41380  | 60830  | 105400 | 152500 |        |
| 180              | 1170                | 2085 | 3265   | 5349   | 8348  | 136900 | 19550 | 30340  | 38290  | 46160  | 67850  | 117500 | 170000 |        |
| 200              | 1290                | 2300 | 36030  | 5903   | 9212  | 15100  | 21570 | 33480  | 42250  | 50930  | 74870  | 129700 | 188000 |        |
| 220              | 1410                | 2515 | 3940   | 6456   | 10080 | 16520  | 23590 | 36620  | 46210  | 55700  | 81890  | 141800 | 205500 |        |
| 240              | 1535                | 2730 | 4278   | 7009   | 10940 | 17930  | 25610 | 39760  | 50170  | 60480  | 88910  | 154000 | 223000 |        |
| 260              | 1655                | 2945 | 4616   | 7563   | 11800 | 19350  | 27630 | 49890  | 54130  | 65250  | 95920  | 166100 | 240500 |        |
| 280              | 1775                | 3160 | 4953   | 8116   | 12670 | 20770  | 29660 | 46030  | 58090  | 70030  | 102900 | 178300 | 258000 |        |
| 300              | 1895                | 3380 | 5291   | 8669   | 13530 | 22180  | 31680 | 49170  | 62050  | 74800  | 110000 | 190400 | 276000 |        |
| 320              | 2015                | 3595 | 5629   | 9223   | 14390 | 23600  | 33700 | 52310  | 66010  | 79570  | 117000 | 202600 |        |        |
| 340              | 2140                | 3810 | 5967   | 9776   | 15260 | 25010  | 35720 | 55450  | 69970  | 84350  | 124000 | 214800 |        |        |
| 360              | 2260                | 4025 | 6304   | 10330  | 16120 | 26430  | 37740 | 58590  | 73930  | 89120  | 131000 | 226900 |        |        |
| 380              | 2380                | 4240 | 6642   | 10880  | 16980 | 27840  | 39770 | 61720  | 77890  | 93900  | 138000 | 239100 |        |        |
| 400              | 2500                | 4455 | 6980   | 1440   | 17850 | 29260  | 41790 | 64860  | 81850  | 98670  | 145100 | 251200 |        |        |
| 420              | 2620                | 4670 | 7317   | 11990  | 18710 | 30680  | 43810 | 68000  | 85810  | 103400 | 152100 | 263400 |        |        |
| 440              | 2745                | 4885 | 7655   | 12400  | 19570 | 32090  | 45830 | 71140  | 89770  | 108200 | 159100 | 275500 |        |        |
| 460              | 2865                | 5105 | 7993   | 13100  | 20440 | 33510  | 47850 | 74280  | 93730  | 113000 | 166100 | 287700 |        |        |
| 480              | 2985                | 5320 | 8330   | 13650  | 21300 | 34920  | 49870 | 77420  | 97690  | 117800 | 173100 | 299800 |        |        |
| 500              | 3105                | 5535 | 8668   | 14200  | 22160 | 36340  | 51900 | 80550  | 101600 | 122500 | 180100 | 312000 |        |        |
| 550              | 3410                | 6075 | 9512   | 15590  | 24390 | 39880  | 56950 | 88400  | 111500 | 134500 | 197700 | 343400 |        |        |
| 600              | 3710                | 6610 | 103600 | 169700 | 26480 | 43490  | 62000 | 96250  | 121400 | 146400 | 215200 | 372800 |        |        |
| 650              | 4015                | 7150 | 11200  | 18350  | 28640 | 46960  | 67060 | 104100 | 131300 | 158300 | 232800 |        |        |        |
| 700              | 4315                | 7690 | 12050  | 19740  | 30800 | 50500  | 72110 | 111900 | 141200 | 170300 | 250300 |        |        |        |
| 750              | 4620                | 8230 | 128900 | 21120  | 32960 | 54030  | 77170 | 119800 | 151100 | 182200 | 267900 |        |        |        |

**FIGURE 3 - HYPOTHETICAL TYPICAL CAPACITY TABLE**

Most major pressure relief valve manufacturers also offer sizing software. While not an endorsement, two such products are *SizeMaster Mark IV* by Farris Engineering and *Crosby-Size* marketed by The Crosby Valve Company. 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 formulas:

Vapor or gases,

$$A = \frac{W \sqrt{TZ}}{CKP_1 K_b \sqrt{M}} \quad (3)$$

Steam,

$$A = \frac{W}{51.5 P_1 K K_n K_{sh}} \quad (4)$$

Liquids,

$$A = \frac{Q \sqrt{G}}{27.2 K_p K_w K_v \sqrt{\Delta P}} \quad (5)$$

Manufacturer's customized versions of Equation 5 should be used when available. These typically modify the equation presented to reflect actual coefficients of discharge ( $K_d$ ) based on required ASME capacity certification testing. In some cases, the variable  $K_p$  may be absent. The gas and vapor formula presented is based on perfect gas laws. Many real gases and vapors, 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 vapor 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  $K_n$  is required by ASME when relieving pressure ( $P_1$ ) is above 1,500 psia:

$$K_n = \frac{0.1906 P_1 - 1000}{0.2292 P_1 - 1061} \quad (6)$$

**EXAMPLE 2** (Manual calculation verification of Example 1)

Given: Same conditions and fluid properties as Example 1

Find: The correct size standard orifice to meet the given requirements.

Solution:

(1) Because the steam is saturated and the set pressure < 1,500 psia,  $K_{sh} = 1.0$  and  $K_n = 1.0$

(2) Calculate an orifice effective area using Equation 4:

$$A = \frac{W}{51.5 P_1 K K_n K_{sh}} = \frac{40000}{(51.5)(140 + 14 + 14.7)(0.975)(1)(1)} = 4.72 \text{ in}^2$$

(3) From Table 1 find the smallest standard orifice designation that has an area equal to or greater than A.

(4) Select a “P” orifice with an actual area equal to 6.38 in<sup>2</sup>.

**EXAMPLE 3** (Gas/Vapor Application)(see Table 2 on the next page)

Given:

|                              |   |
|------------------------------|---|
| Fluid:                       | Saturated ammonia vapor   |
| Required Capacity:           | 15,000 lb/hr  |
| Set Pressure:                | 325 psig (constant back pressure of 15 psig deducted)           |
| Overpressure:                | 10%   |
| Back Pressure:               | 15 psig (constant)  |
| Inlet relieving Temperature: | NH <sub>3</sub> saturation temperature @ P <sub>1</sub> (138°F) |
| Molecular Weight:            | 17  |

Find: The correct size standard orifice to meet the given requirements.

Solution:

(1) Determine from Table 2 that NH<sub>3</sub> has a nozzle constant of  $C = 347$ .

(2) Because the back pressure is < 40% of set pressure, assume  $K_b = 1.0$

(3) Assume that NH<sub>3</sub> is an ideal gas, ∴  $Z = 1.0$

(4) Calculate an orifice effective area using Equation 3:

$$A = \frac{W\sqrt{TZ}}{CKP_1 K_b \sqrt{M}} = \frac{15000\sqrt{(138+ 460)(1)}}{(347)(0.975)(325 + 32.5 + 14.7)(1)\sqrt{17}} = 0.707 \text{ in}^2$$

(5) From Table 1 find the smallest standard orifice designation that is equal to or greater than A.

(6) Select an “H” orifice with an actual area equal to 0.785 in<sup>2</sup>.

| Gas or Vapor          | Molecular Weight M | Ratio of Specific Heats k (14.7 psia) | Coefficient C' | Specific Gravity | Critical Pressure psia | Critical Temp. (°R) (°F+460) |
|-----------------------|--------------------|---------------------------------------|----------------|------------------|------------------------|------------------------------|
| Acetylene             | 26.04              | 1.25                                  | 342            | 0.899            | 890                    | 555                          |
| Air                   | 28.97              | 1.40                                  | 356            | 1.000            | 547                    | 240                          |
| Ammonia               | 17.03              | 1.30                                  | 347            | 0.588            | 1638                   | 730                          |
| Argon                 | 39.94              | 1.66                                  | 377            | 1.379            | 706                    | 272                          |
| Benzene               | 78.11              | 1.12                                  | 329            | 2.696            | 700                    | 1011                         |
| N-Butane              | 58.12              | 1.18                                  | 335            | 2.006            | 551                    | 766                          |
| Iso-Butane            | 58.12              | 1.19                                  | 336            | 2.006            | 529                    | 735                          |
| Carbon Dioxide        | 44.01              | 1.29                                  | 346            | 1.519            | 1072                   | 548                          |
| Carbon Disulphide     | 76.13              | 1.21                                  | 338            | 2.628            | 1147                   | 994                          |
| Carbon Monoxide       | 28.01              | 1.40                                  | 356            | 0.967            | 507                    | 240                          |
| Chlorine              | 70.90              | 1.35                                  | 352            | 2.447            | 1118                   | 751                          |
| Cyclohexane           | 84.16              | 1.08                                  | 325            | 2.905            | 591                    | 997                          |
| Ethane                | 30.07              | 1.19                                  | 336            | 1.038            | 708                    | 550                          |
| Ethyl Alcohol         | 46.07              | 1.13                                  | 330            | 1.590            | 926                    | 925                          |
| Ethyl Chloride        | 64.52              | 1.19                                  | 336            | 2.227            | 766                    | 829                          |
| Ethylene              | 28.03              | 1.24                                  | 341            | 0.968            | 731                    | 509                          |
| Freon 11              | 137.37             | 1.14                                  | 331            | 4.742            | 654                    | 848                          |
| Freon 12              | 120.92             | 1.14                                  | 331            | 4.174            | 612                    | 694                          |
| Freon 22              | 86.48              | 1.18                                  | 335            | 2.985            | 737                    | 665                          |
| Freon 114             | 170.93             | 1.09                                  | 326            | 5.900            | 495                    | 754                          |
| Helium                | 4.02               | 1.66                                  | 377            | 0.139            | 33                     | 10                           |
| N-Heptane             | 100.20             | 1.05                                  | 321            | 3.459            | 397                    | 973                          |
| Hexane                | 86.17              | 1.06                                  | 322            | 2.974            | 437                    | 914                          |
| Hydrochloric Acid     | 36.47              | 1.41                                  | 357            | 1.259            | 1198                   | 584                          |
| Hydrogen              | 2.02               | 1.41                                  | 357            | 0.070            | 188                    | 60                           |
| Hydrogen Chloride     | 36.47              | 1.41                                  | 357            | 1.259            | 1205                   | 585                          |
| Hydrogen Sulphide     | 34.08              | 1.32                                  | 349            | 1.176            | 1306                   | 672                          |
| Methane               | 16.04              | 1.31                                  | 348            | 0.554            | 673                    | 344                          |
| Methyl Alcohol        | 32.04              | 1.20                                  | 337            | 1.106            | 1154                   | 924                          |
| Methyl Butane         | 72.15              | 1.08                                  | 325            | 2.491            | 490                    | 829                          |
| Methyl Chloride       | 50.49              | 1.20                                  | 337            | 1.743            | 968                    | 749                          |
| Natural Gas (Typical) | 19.00              | 1.27                                  | 344            | 0.656            | 671                    | 375                          |
| Nitric Oxide          | 30.00              | 1.40                                  | 356            | 1.036            | 956                    | 323                          |
| Nitrogen              | 28.02              | 1.40                                  | 356            | 0.967            | 493                    | 227                          |
| Nitrous Oxide         | 44.02              | 1.31                                  | 348            | 1.520            | 1054                   | 557                          |
| N-Octane              | 114.22             | 1.05                                  | 321            | 3.943            | 362                    | 1025                         |
| Oxygen                | 32.00              | 1.40                                  | 356            | 1.105            | 737                    | 279                          |
| N-Pentane             | 72.15              | 1.08                                  | 325            | 2.491            | 490                    | 846                          |
| Iso-Pentane           | 72.15              | 1.08                                  | 325            | 2.491            | 490                    | 829                          |
| Propane               | 44.09              | 1.13                                  | 330            | 1.522            | 617                    | 666                          |
| Sulfur Dioxide        | 64.04              | 1.27                                  | 344            | 2.211            | 1141                   | 775                          |
| Toluene               | 92.13              | 1.09                                  | 326            | 3.180            | 611                    | 1069                         |

TABLE 2 - TYPICAL PROPERTIES OF GASES

### 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 vapor services. The vapor 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.

### 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  $K_v = 1.0$ . 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 ( $R_{NE}$ ) using the following formula:

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

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

For  $R_{NE} < 200$ ,

$$K_v = 0.27 \ln R_{NE} - 0.65 \quad (8)$$

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

$$K_v = -0.00777 (\ln R_{NE})^2 + 0.165 \ln R_{NE} + 0.128 \quad (9)$$

4. Determine a corrected required effective area of the pressure relief valve orifice using the standard liquid sizing formula and the value of  $K_v$  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.

#### **EXAMPLE 4** (Viscous Liquid Application)

##### Given:

|                              |                |
|------------------------------|----------------|
| Fluid:                       | No. 6 Fuel Oil |
| Required Capacity:           | 1,200 gal/min  |
| Set Pressure:                | 150 psig       |
| Overpressure:                | 10%            |
| Back Pressure:               | Atmospheric    |
| Inlet relieving Temperature: | 60°F           |
| Dynamic Viscosity:           | 850 cP         |
| Specific Gravity:            | 0.993          |

Find: The correct size standard orifice to meet the given requirements.

##### Solution:

- (1) Since the overpressure is  $< 25\%$ , determine the correction factor  $K_p$  from Equation 1:

$$K_p = -0.0014(\% \text{ overpressure})^2 + 0.073(\% \text{ overpressure}) + 0.016$$

$$= -0.0014(10)^2 + 0.073(10) + 0.016 = 0.61$$

(2) Select a orifice trial size by setting  $K_v = 1.0$  and using Equation 5. Since the back pressure = 0, then  $K_w = 1.0$ :

$$A = \frac{Q\sqrt{G}}{27.2 K_p K_w K_v \sqrt{\Delta P}} = \frac{1,200\sqrt{0.993}}{(27.2)(0.61)(1.0)(1.0)\sqrt{150-0}} = 5.89 \text{ in}^2$$

(3) From Table 1 it can be seen that an orifice size designation “P” with an actual area of 6.38 in<sup>2</sup> must be used.

(4) Using the “P” orifice area, calculate the Reynolds number using Equation 7:

$$R_{NE} = \frac{2800 G Q}{\mu A} = \frac{(2800)(0.993)(1200)}{(850)(6.38)} = 615$$

(5) Since  $R_{NE} > 200$ , use Equation 9 and compute a viscosity correction factor  $K_v$ :

$$K_v = -0.00777(\ln R_{NE})^2 + 0.165 \ln R_{NE} + 0.128$$

$$= (-0.00777)(6.422)^2 + (0.165)(6.422) + 0.128 = 0.87$$

(6) Compute a corrected orifice effective area based on the now known value of  $K_v$ :

$$A = \frac{Q\sqrt{G}}{27.2 K_p K_w K_v \sqrt{\Delta P}} = \frac{1,200\sqrt{0.993}}{(27.2)(0.61)(1.0)(0.87)\sqrt{150-0}} = 6.76 \text{ in}^2$$

(7) Since the corrected orifice effective area (6.76 in<sup>2</sup>) is greater than the selected trial orifice area (6.38 in<sup>2</sup>), the “P” orifice is unacceptable. Select the next larger size orifice (Q) with an area of 11.05 in<sup>2</sup> for this viscous application.

### Two-Phase Flow Considerations

In recent years, methodologies originally used to determine pressure relief valve orifice areas have come under increasing scrutiny. Research into current design codes and practices for pressure relief valves has shown that the commonly applied calculation methods may underestimate relief capacity. Newer more theoretically sound models are now being developed. Because flashing-liquid (two-phase) flow is so commonplace in the chemical process industries, this subject is at the forefront of the developmental effort.

The flow occurring in a pressure relief valve is complex. In order to select an appropriate model a number of factors such as flow patterns, phase distribution, flow conditions and fluid properties must be considered with respect to the nature of the fluid. There are a wide variety of theoretical models which apply to two-phase flow. Each model has limitations and while a particular model may work well under certain conditions, it may not be applicable in others. In some special processes, it has even been determined that some two-phase flow is actually three phase, *i.e.* solid, liquid, and gas flow.

Because two phase flow generally has a decreased flow capacity compared to single phase flow, greater relief orifice area often is required for two-phase flow. Sizing technology that is no longer considered adequate or appropriate can be problematic. Oversizing can be as detrimental as undersizing. Oversizing a pressure relief valve with two-phase flow can have dangerous consequences. Excessive fluid flashing on the downstream side of an oversized pressure relief valve can cause the back pressure buildup to the point that the relief device function is impaired. The result could be a catastrophic vessel failure.

Recent research conducted by AIChE's Design Institute for Emergency Relief Systems (DIERS) has indicated that the API method of sizing pressure relief valves for two-phase flow leads to undersized valves in comparison with homogenous equilibrium models (HEM) under certain conditions. The HEM treats the flashing two phase flow mixture much like a classical compressible gas while undergoing an adiabatic expansion with thermodynamic equilibrium in both phases. The HEM yields conservative estimates of the flow capacity in a pressure relief valve.

### **SUMMARY**

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.

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 swell 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 course has been limited to all vapor flow. It is applicable when it is known that only vapor 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 vapor model should yield conservative results. It may be prudent to be conservative given the uncertainty of two-phase prediction models.

### **ADDITIONAL RESOURCES**

The student should read/review Reference 2 paragraphs UG-125 through UG-137 when designing

pressure relief systems and selecting and sizing pressure relief valves.

The American Society of Mechanical Engineers  
United Engineering Center  
345 East 47<sup>th</sup> Street  
New York, NY 10017  
www.asme.org

American Petroleum Institute  
2101 L Street Northwest  
Washington, DC 20037  
www.api.org

## GLOSSARY

This section contains common and standard definitions related to pressure relief valves. It is in accordance with generally accepted terminology.

***accumulation*** – a pressure increase over the maximum allowable working pressure (MAWP) of the equipment being protected, during discharge through the pressure relief valve, usually expressed as a percentage of MAWP. Compare with ***overpressure***.

***actual discharge area*** – the net area of a selected orifice which dictates the pressure relief valve relieving capacity.

***back pressure*** – the static pressure existing at the outlet of a pressure relief valve due to pressure in the discharge system.

***balanced safety relief valve*** – a pressure relief valve which incorporates means of minimizing the effect of back pressure on the operational characteristics (opening pressure, closing pressure, and relieving capacity).

***blowdown*** – the difference between actual lifting pressure of a pressure relief valve and actual reseating pressure expressed as a percentage of set pressure.

***blowdown pressure*** – the value of decreasing inlet static pressure at which no further discharge is detected at the outlet of a pressure relief valve after the valve has been subjected to a pressure equal to or above the lifting pressure.

***built-up back pressure*** – pressure existing at the outlet of a pressure relief valve caused by the flow through that particular valve into a discharge system.

***chatter*** – abnormal rapid reciprocating motion of the movable parts of a pressure relief valve in which the disc contacts the seat.

***closing pressure*** – the value of decreasing inlet static pressure at which the valve disc reestablishes contact with the seat or at which lift become zero.

***coefficient of discharge*** – the ratio of the measured relieving capacity to the theoretical relieving capacity.

***constant back pressure*** – a superimposed back pressure which is constant with time.

***conventional safety relief valve*** – a pressure relief valve which has its spring housing vented to the

discharge side of the valve. The operational characteristics (opening pressure, closing pressure, and relieving capacity) are directly affected by changes in the back pressure on the valve.

***design pressure*** – the value selected for the design of equipment for the most severe condition of coincident pressure and temperature expected in normal operation, with provision for a suitable margin above these operating conditions to allow for operation of the pressure relief valve. The design pressure usually becomes the maximum allowable working pressure.

***discharge area*** – see *actual discharge area*.

***effective discharge area*** – a nominal or computed area of flow through a pressure relief valve, contrasted to actual discharge area. For use in recognized flow formulas to determine the required capacity of a pressure relief valve.

***flow capacity*** – see *rated relieving capacity*.

***flow-rating pressure*** – the inlet static pressure at which the relieving capacity of a pressure relief valve is measured.

***inlet size*** – the nominal pipe size of the inlet of a pressure relief valve, unless otherwise designated.

***lift*** – the actual travel of the disc away from the closed position when a valve is relieving.

***maximum allowable working pressure*** – (1) the pressure determined by employing the allowable stress values of the materials used in the construction of the equipment. It is the least value of allowable pressure value found for any component part of a piece of equipment for a given temperature. The equipment may not be operated above this pressure and consequently, it is the highest pressure at which the primary pressure relief valve is set to open. (2) the maximum gage pressure permissible at the top of a pressure vessel in its normal operating position at the designated coincident temperature specified for that pressure.

***nozzle constant, nozzle coefficient*** - a variable in the standard gas and vapor sizing formula which is dependent on the specific heat ratio of the fluid. See equation 6, Figure 2, or Table 8.

***operating pressure*** – the service pressure to which a piece of equipment is usually subjected.

***orifice area*** – see *actual discharge area*.

***outlet size*** – the nominal pipe size of the outlet of a pressure relief valve, unless otherwise designated.

***overpressure*** – a pressure increase over the set pressure of a pressure relief valve, usually expressed a percentage of set pressure. Compare with ***accumulation***.

***pilot-operated pressure relief valve*** – a pressure relief valve in which the major relieving device is combined with and is controlled by a self-actuated pressure relief valve.

***pressure relief valve*** – a generic term for a re-closing spring loaded pressure relief device which is designed to open to relieve excess pressure until normal conditions have been restored.

**rated relieving capacity** – that portion of the measured relieving capacity permitted by the applicable code of regulation to be used as a basis for the application of a pressure relief valve.

**relief valve** – a pressure relief valve actuated by inlet static pressure and having a gradual lift generally proportional to the increase in pressure over opening pressure. It is primarily used for liquid service.

**relieving pressure** – set pressure plus overpressure.

**safety valve** – a pressure relief valve actuated by inlet static pressure and characterized by rapid opening or pop action. It is normally used for steam and air service.

**safety relief valve** – a pressure relief valve characterized by rapid opening or pop action, or by opening in proportion to the increase in pressure over the opening pressure, depending on the application. It may be used in either liquid or compressible fluid applications based on configuration.

**set pressure** – the value of increasing inlet static pressure at which a pressure relief valve begins to open.

**superimposed back pressure** – the static pressure existing at the outlet of a pressure relief valve at the time the valve is required to operate. It is the result of pressure in the discharge system from other sources.

## **REFERENCES**

1. Department of Labor, Occupational Safety and Health Administration, *Process Safety Management of Highly Hazardous Chemicals*, 29 CFR 1910.119, February 24, 1992.
2. American Society of Mechanical Engineers, *ASME Boiler and Pressure Vessel Code*, Section VIII, *Pressure Vessels*, Division 1, ASME, New York, 2001 plus addenda.
3. American Petroleum Institute, *API Recommended Practice 520, Sizing, Selection, and Installation of Pressure-Relieving Devices in Refineries*, Part I, *Sizing and Selection*, API, Washington D.C., 2000.
4. Fisher, H.G., *et al.*, *Emergency Relief System Design Using DIERS Technology*, AIChE's Design Institute for Emergency Relief Systems, DIERS, AIChE, New York, 1992.
5. Quoc-Khanh, Tran and Reynolds, Melissa, *Sizing of Relief Valves for Two-Phase Flow in the Bayer Process*, Kaiser Engineers PTY Limited, Perth, Western Australia, 2002.
6. Hauptmanns, Ulrich and Yllera, Javier, *Fault-tree Evaluation by Monte Carlo Simulation*, Chemical Engineering magazine, January 10, 1983.
7. Crosby® Engineering Handbook Technical Publication No. TP-V300, *Pressure Relief Valve Engineering Handbook*, Crosby Valve Company, Somewhere, somedate.
8. The Crane Company Technical Paper No. 410, *Flow of Fluids through Valves, Fittings, and Pipe*, 25<sup>th</sup> printing, 1991.

9. Blackwell, Wayne W., *Calculating Two-phase Pressure Drop*, Chemical Engineering magazine, September 7, 1981, pp. 121-125.