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Abstract: This study covers the critical concerns related to the sizing, selection, installation, maintenance, and testing of pressure safety valves (PSVs). The aim is to ensure the safety of pressurized systems, hydrostatic transmission systems, and hydraulic plants, including process plants, thermal power plants, and nuclear reactor systems. PSVs are devices that ensure the safety and reliability of pressurized vessels, lines, and systems during overpressure events. The task of selecting which PSV features are of greatest value for a specific purpose is complex—especially in the design of a high-pressure experimental thermal-hydraulic facility for hydrostatic and transient testing of the reactor system—when the systems are in the design and development phases and require qualification and demonstration to prove that they have reached a given level of technological readiness. The present study highlights the required steps for users to follow the associated rules, guidelines, and recommendations. As a part of this research, case studies are presented to help readers better understand the applicable strategy and standards. A discussion and a review of PSV performance degradation and failure are summarized to provide a better understanding of varied process applications and conditions, including fluid flow dynamics, boundary-layer formation and pressure drops, gas bubble formation and collapse, geometric configurations, inlet/outlet piping, abrupt pressure fluctuations, and acoustic resonance. Moreover, this study discusses the servicing and testing of PSVs in a multiphase pressurized system. Overall, it provides a basic overview of how PSVs ensure the safety of pressurized systems, supported by case studies and industrial practices.

Keywords: pressurized system; pressure vessel; pressure relief valve; safety

1. Introduction

A pressure safety valve (PSV) or pressure relief valve (PRV) protects a pressurized system or vessel during an overpressure scenario [1]. The term 'overpressure event' refers to any condition that causes the pressure of a vessel or system to exceed its specified design pressure or maximum allowable working pressure (MAWP) [2–4]. Several codes and standards are written to control the design and application of PSVs and PRVs [5–9]. In order to maximize reliability, PSV/PRV designs should be as simple as possible [10]. In the event of an overpressure situation, the valve must open at a predetermined pressure, allow flow at a rated capacity, and then close when the system pressure has returned to an acceptable level [11,12]. Various process fluids—including air, water, and other potential corrosive media—must be compatible with PSVs/PRVs [13] A consistent, smooth, and stable operation is also required for various fluids and fluid phases [14]. Differences exist in the operating principles behind PRVs and PSVs as follows:

- (a) PRVs gradually open as the fluid pressure further exceeds the setpoint pressure whereas PSVs pop open once the setpoint pressure value is reached.
- (b) During operation, PRVs remain partially open, whereas PSVs cycle between being fully open and fully closed.



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). (c) Last, PRVs are installed to prevent unnecessary opening of PSVs during pressure transients.

Overpressure protection begins with determining the setting pressure, back pressure, allowable overpressure, and relieving capacity [15]. It is possible to determine operating pressures and allowable overpressures based on the operating pressures of the system. Calculating the required relieving capacity, dynamic behavior, model development, measurements, and instability mechanisms is a challenging task [16,17]. The PSV/PRV must relieve sufficient fluid to keep the system within a desired pressure range. It is important to evaluate all causes of overpressure [1,18] (that might occur in the system due to the failure of a pump, control system, or stop valve; a fire; or an uncontrolled chemical reaction. The maximum capacity required is determined based on the worst case combination of these factors [2–4].

This study discusses the critical issues in sizing and selecting PSVs/PRVs for typical process safety applications. It also covers how valves compensate for overpressure load disturbances and maintain the safety of the equipment and the system. An overview of valve sizing, selection, manufacturing, testing, installation, and maintenance is presented for thermal-hydraulic system-level experimentations for pressurized systems (e.g., pressurized water reactor) and applications. Appropriate sizing and selection of PSVs/PRVs enhances the safety of pressurized systems, which scope matches the process safety and environmental protection (PSEP) for process plants, oil refining plants, power generation plants, and other related industrial applications. The applicability of this study covers various topics, including risk assessment, technical safety, modeling, reaction hazards, and inherent safety [19,20]. The accurate sizing and selection of PSVs are pivotal for designing a thermal-hydraulic experimental facility to ensure the safety of systems, components, and environments. For example, developing a nuclear reactor system requires integrated and separate effect testing facilities to investigate system performances and obtain experimental data for the transient behaviors of the reactor. Pressurized water reactor operating pressures are about 15-16 megapascals (MPa), requiring several PSVs to provide system safety due to overpressure conditions to prevent system failure (i.e., leaks/breaks [21–23]). Generally, the thermal-hydraulic experimental facilities for water-cooled reactors are designed for two-phase flow to mimic reactor system loss-of-coolant accident scenarios [24]. Experimental two-phase (i.e., steam-water mixture) pressurized flow and break flow increase system pressure oscillation, cause vibration, and degrade their performance [25]. In addition, lessons learned from the control and combined valve studies are supportive [12] of the need to appropriately size and select PSVs. The success of the experimental program depends on successful operation and testing of the facility in which adequate overpressure protection devices (i.e., PSVs or PRVs) are essential.

This study contributes to PSEP by providing guidelines and recommendations for PSV sizing, selection, installation, maintenance, and testing, which is essential for preventing accidents, equipment damage, and environmental harm. By understanding the causes of overpressure events and selecting appropriate PSVs, engineers and researchers can minimize the risk of accidents and environmental harm in thermal power plants, nuclear reactor systems, and process plants.

The main sections of the work are as follows: Section 1 introduces the importance and scope of this study; Section 2 highlights industrial aspects and selected accident case studies, terminologies, factors, and operational principles; Section 3 discusses sizing valves/orifices and selecting valve types; and Section 4 presents the findings and conclusions.

2. Aspects Related to Industrial Processes and Case Studies

Overpressure protection studies relate to technical safety and loss prevention in industrial processes [26]. These studies emphasize the importance of PSVs in high-pressure thermal–hydraulic systems and connect to various core topic areas of PSEP [27]. This includes risk assessment, technical safety, modeling, reaction hazards, and inherent safety. Overall, these studies are a suitable contribution to the field, addressing crucial aspects of thermal–hydraulic experimental facility development and safety system demonstration [28,29].

2.1. PSV in High-Pressure Thermal–Hydraulic Experiments

Dynamic performance is vital for a PRV's function, with transient simulation being a key method for its study. Notable work has been conducted by various research groups. An exemplary PSV performance testing setup for thermal–hydraulic systems is presented in Figure 1. It is similar to one used by Yang et al. [30] as per the ASME PTC 25 standards. The components for the experimental system are marked as the supercritical boiler (1), steam separator (2), on-off valve (3), storage vessel (4), on-off valve (5), pressure measuring system (6), isolating valve (7), lift testing device (8), measured PRV (9), silencer (10), quick exhausting valve (11), testing vessel (12), and control valves (13–17). Saturated steam from a supercritical boiler is stored in a high-pressure vessel, and the PSV is attached to a test vessel. Such test facilities are designed for specific purposes for testing and performance qualification. For example, the test facility described by Yang et al. [30] considered an increase in pressure in both vessels of up to 90% of the PRV's expected set pressure then a further increase until the PRV activated. PRV lift, test vessel pressure, and relevant PRV features require test data under prototypic conditions to evaluate performance and qualification of the PRVs/PSVs, thus ensuring safety of the system.



Figure 1. A high-temperature high-pressure PSV experimental setup.

2.2. PSV in Industrial Process and Power Plants

Although the representative testing facility depicted in Figure 1 is simple, with few components involved, industrial process plants—including oil refining plants, thermal power plants, and nuclear power plants—are much more intricate. These plants are equipped with numerous systems and subsystems categorized as high-, medium-, and low-pressure. They require various types and numbers of PSVs. In these settings, PSVs serve as critical safety components, designed to prevent overpressure scenarios and safeguard personnel, equipment, and the environment. The quantity of these valves fluctuates based on the specific industry, plant design, and operational capacity.

In oil refineries, the number of PRVs can vary significantly based on the refinery's complexity and processing capacity [6]. Small- to medium-sized refineries typically have

between 100 and 500 PRVs. In contrast, larger refineries might incorporate anywhere from 500 to 2500 PRVs. Such variation arises from the plethora of processes in oil refining, from crude oil distillation to advanced hydrocracking and reforming units, with each process necessitating specific pressure controls.

Thermal power plants, which encompass coal, natural gas, or oil-fired plants, generally utilize fewer PRVs than oil refineries [2,3]. Smaller plants might be equipped with 50–200 PRVs, whereas larger facilities can have 200–1000 PRVs. The plant's design, including the number of turbines, boilers, and auxiliary systems, often determines this range.

Nuclear power plants introduce a different level of complexity due to diverse reactor designs. For standard designs, like the pressurized water reactor (PWR) or the boiling water reactor (BWR), the number can span from a few dozen to several hundred relief devices, including safety valves (SVs), relief valves, and rupture discs [31]. The reactor's design, safety protocols, and myriad auxiliary and support systems influence these numbers. Recently, small modular reactor (SMR) systems have emerged, where components such as the reactor pressure vessel (RPV), steam generator, and pressurizer are designed to be compact and integrated [21]. This approach minimizes pipe breaks and simplifies transportation from the factory to the operational site. Yet despite their compactness, SMR systems still need PSVs for overpressure protection. Indeed, their importance is accentuated by the innovative and condensed system design.

PSVs are designed such that if the fluid (i.e., liquid or gas) pressure increases to the point that it exceeds its setpoint pressure (i.e., the fluid pressure overcomes the spring force)—the PSV will begin to open. In this regard, the maximum pressure is defined as the amount of pressure needed to keep the PSV fully open throughout the fluid discharge. Blowdown is defined as the difference between the setpoint pressure at which a PSV opens and the pressure at which it closes. PSV operations should be as quick as possible, and PSVs should be optimally sized to release enough fluid during postulated overpressure conditions to return the system pressure back to normal and to automatically close once a designated pressure (i.e., the PSV reseat pressure) is reached.

Above all, it is essential to understand the monumental significance of PSVs in ensuring plant safety. The numbers provided are broad estimates based on industry norms and may vary based on specific plant designs and other factors. However, the meticulous sizing and calibration of PSVs are crucial for managing specific overpressure conditions, preserving the stability of operations, and protecting expensive and sensitive equipment.

2.3. Case Studies: Plant-Level Accidents Due to PSV Failure

PSV performance degrades, causing the valve to fail to operate as designed. PSV malfunctions or degraded operation can cascade into catastrophic failure of an overpressured system. The major causes of PSV performance degradation are cavitation and wear. The root cause can be a disruption in fluid flow distribution/dynamics; boundary-layer formation [32] and pressure drops across valve flow regions [33,34]; gas bubble formation and collapse [35,36]; variations in geometric configuration and the shape of components such as the poppet of the valve (i.e., chamfered conical, blunt, or spherical) [37]; nozzle tips [38]; inlet/outlet piping [39]; abrupt pressure fluctuations [40]; and acoustic resonance.

In addition, inlet/outlet piping, valve internal geometry, and type are related to PSV performance and flow stability. Researchers have shown how spring-loaded PSV performance and flow stability are impacted by (a) the inlet or upstream line, which creates expansion waves [41]; (b) dynamic instabilities [42]; (c) flow-induced vibrations resulting from vortex shedding at the base of the valve riser that amplifies the riser acoustics [43]; and (d) orifices in the inlet piping to improve valve stability [44].

There are several major plant-level accidents that have occurred—at high-pressure industrial complexes, such as oil refining, thermal power, and nuclear power plants—due to malfunctions or safety valve failure. These plants are equipped with numerous systems and subsystems categorized as high-, medium-, and low-pressure. They require various types and numbers of PSVs. A representative plant-level accident at the Three Mile Island

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(TMI) nuclear power plant, discussed below in more detail, is an example of an event that forced the nuclear industry to improve their safety standards and regulations.

The TMI Nuclear Generating Station in Pennsylvania, USA, faced a significant accident on 28 March 1979, due to a combination of a malfunctioning safety relief valve, misinterpretation of sensor data, and human error. A PRV in the plant's Unit 2 reactor's primary coolant system failed to close properly, resulting in coolant leakage. This led to a partial meltdown of the reactor's core. While a small amount of radioactive gas was released, there were no injuries or fatalities. The incident emphasized the importance of regular maintenance, meticulous valve inspections, and comprehensive training and safety procedures. It significantly influenced public opinion and brought about changes in the regulatory approach to nuclear power.

A randomly selected number of plant-level accidents—as environmental issues came to the fore in the 1980s and global warming issues in the 2000s—focused on fossil fuel refining and chemical process, as presented in Table 1, identified similar root causes related to PSV failure.

Table 1. List of process and petrochemical plant facility accidents related to valve failure or malfunctioning [45,46].

Facility and Location	Date	Incident/Accident Description	Key Root Causes
Petrochemical factory, Texas City, USA [47]	30 May 1978	An overpressure event in an LPG storage vessel during filling; the vessel cracked, resulting in an LPG leak. The leaked LPG ignited, creating a massive fireball. The explosion shattered the vessel and damaged two adjacent vessels.	A pressure gauge and a relief valve malfunctioned. This led to an overpressure event.
Petrochemical, Icmesa Chemical Company at Seveso [48]	10 July 1976	Explosion at a chemical process plant contaminated two square miles of crops and vegetables.	An overpressure event occurred, and the PSV on a reactor vented as a result.
Phillips explosion, Pasadena, Texas [49]	23 October 1989	Explosion, resulting in 23 fatalities. Primary causes of the accident included the (a) absence of process hazard analysis and human factor considerations and (b) insufficient operating and isolation procedures.	Incorrect connection of the actuating signal made the valve open when it should have been closed.
Petrochemical, Thunder Horse PDQ Tilting, Gulf of Mexico [49]	11 July 2005	The main cause of the incident was the uncontrolled water flow due to Hurricane Dennis. Water moved uncontrollably between several ballast tanks.	Incorrect valve positioning and operational mistakes triggered the event.
Petrochemical, T2 Laboratories Explosion in Jacksonville, Florida [49]	19 December 2007	The cooling system malfunctioned. This led to an uncontrolled chemical reaction while producing a gasoline additive.	The main issue was traced back to the poor design of the cooling and pressure relief systems.

These examples highlight the importance of regular maintenance, accurate sizing and selection, and qualified inspection and testing of the system structure and components (e.g., PSVs/PRVs). Inadequate maintenance, flawed system designs, or human error can result in system or component (e.g., valve) failure, leading to severe accidents that endanger life and the environment. In petrochemical industries, many accidents stemming from valve failure are related to overpressure events. A selection of plant-level accidents from process units and petrochemical facilities is presented in Table 1. Based on system safety engineering perspectives, accidents are caused by linear chains of failure events and can be explained with respective accident causality and causality models to identify the chain of events and the root causes [50].

3. Terminology and Factors Related to PSV

There are several terms for pressure relief safety valves, such as PRVs, PSVs, relief valves, and safety relief valves. Although these valve systems have some uniqueness, for the simplicity of this study, we use only PSV and pressure safety/relief valves as the general terminology [11,14,51,52]. The general descriptions of these valves are presented briefly below:

- Pressure Relief Valves: PRVs are spring-loaded devices—characterized by a rapid opening, often proportional to the pressure, due to overpressure—that open when excess pressure is present and close when normal conditions have been restored.
- Relief Valves: Relief valves are pressure relief devices that are actuated by static
 pressure at the inlet and raise gradually when the opening pressure is exceeded. This
 device is primarily used for liquid service, and it contains a spring enclosure for closed
 discharge systems.
- Safety Relief Valves: These valves are used for liquid or compressible fluids and exhibit features like rapid opening, popping actions, or opening proportionally to the increased pressure.

The design of a PSV differs. Based on the back pressure (i.e., releasing fluid in another pressurized line/system), two types of PSV design are common, namely, the (1) conventional and (2) balance bellows designs, as presented in Figure 2 [53]. The various parts of a PSV are also shown in Figure 2. The major parts are the disc, lifting device, nozzle, and seat. Other important parts of a PSV are the lock nut, adjusting screw, spring, spindle, bonnet, guide, gasket, lock screw, and valve body.



Figure 2. PSV cutaway view of (a) conventional and (b) balanced bellows designs [53].

Understanding the operational characteristics of PSVs/PRVs and the associated terminology is essential to ensure facility operational safety. A few of the important operational terms are discussed below:

 Blowdown: The pressure difference between the PSV's/PRV's popping and reseating pressure, expressed as a percentage or pressure units.

- Popping pressure: The inlet static pressure causing the PSV/PRV disc to move faster in the opening direction, applicable to compressible fluids.
- Set pressure: The pressure at which a PSV/PRV starts relieving fluid, displaying opening, popping, or start-to-leak characteristics.
- Reseating: The closing of a PSV/PRV after normal operating conditions is restored, requiring pressure to drop below the set point.
- Accumulation: The pressure increase over a PSV's/PRV's set pressure, expressed as a percentage. A normal accumulation is 10% of the set pressure, 10% for compressible fluids, 3% for high-temperature fluid (steam), and 16% for multiple PSVs.

The design of PSVs also differs based on nozzle and bonnet features—a full-nozzle or semi-nozzle type, as shown in Figure 3 [54], which differs based on the "wetted" inlet. Generally, open-bonnet designs are used for non-hazardous applications, while closed-bonnet designs are preferred for hazardous ones. Table 2 presents the benefits of each special design feature.



Figure 3. Special designs of PSVs: (**a**) full-nozzle; (**b**) semi-nozzle; (**c**) closed-bonnet; and (**d**) openbonnet designs [54].

Table 2. Special de	sign PSVs/PRVs based	l on the nozzle (i.e.,	full/semi) and bonr	net (i.e., open/close).
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Special Design Features	Applicability
Open Bonnet	If the process fluid has a high temperature and is non-hazardous, an open bonnet is generally used to prevent spring expansion.
Closed Bonnet	If process fluid is hazardous, a closed bonnet is used.
Full-Nozzle	This is suitable for high-pressure and corrosive fluid applications.
Semi-Nozzle	This design offers only the replacement of the seat instead of a full inlet.
Bellows	This is used when the back pressure of the process to PSVs is considered.

It is important to understand PSV operation, the fluid flow area through the valve, as presented in Figure 4, and the terminology for the fluid flow areas [14]. Three flow areas are associated with PSV operation: (a) the flow area that corresponds to the cross-sectional area between the inlet and the seat, (b) the curtain area, which is the cylindrical or conical discharge opening, and (c) the discharge area through the valve.



Figure 4. PSV (**a**,**b**) flow area [14] (**c**) operational procedure, and (**d**) functional curve of spring-loaded PSV [53].

The valve disc starts lifting in an inlet overpressure situation. However, the overpressure must be higher than the spring loading to keep lifting or holding, as shown in Figure 4. A shroud, skirt, or hood could be used around the disc for a full opening.

The selection of PSVs/PRVs entails the following steps [14,55]:

- Considering process data and parameters: The process data and parameters are prerequisites for selecting the valve type, orifice, and accessories. The required process parameters are the flow rate, pressure, temperature, fluid properties (such as density, viscosity, Cp/Cv), and service conditions.
- Orifice and valve selection: The selection of the orifice size is based on the minimum required flow rate using the valve capacity tables. Selection of the valve is based on the process temperature and pressure. Valve characteristics should be selected based on the required process control parameters.

• Options and accessories: Options and accessories like the rapture disc, rapture pin, and pilot-operated safety relief valve must be separately specified. In this study, safety relief valve sizing for vaporizing liquids (i.e., fire condition) is emphasized.

4. Sizing PSVs/PRVs for Vaporizing Liquids, Considering Fire Conditions

Several steps must be followed to estimate the required orifice area for PSVs/PRVs, as presented in Figure 5, to ensure the safety of the pressurized system. This calculation method considers the facility and fluid fire possibilities for simulating the worst case per code recommended practice [5–8,14]:



Figure 5. Flow chart of PSV selection and sizing.

- Determine the total wetted surface area: Table 3 presents the calculation steps, including the logic described in Figures 6 and 7, and the corresponding equations.
- Determine the total heat absorption and environmental safety factors: The calculation procedure and associated equations used to determine the total heat absorption and environmental safety factors are presented in Table 4.
- Determine the valve orifice size: The minimum area required is estimated, and the size of the orifice is selected from the manufacturer's valve capacity table. The steps for valve orifice size estimation and correction factors are presented in Table 5.

PV Geometry	Wetted Surface Area, $A_{wet} [ft^2]$	Parameters
Sphere	$A_{\rm wet} = \pi * E_s * D$	A wot. Total wetted area. $[ft^2]$.
H-cylinder with flat ends	$A_{\text{wot}} = \left(\frac{\pi * D * B}{180}\right) \left(L + \frac{D}{2}\right) - \left(\frac{D}{2} - E\right) \sin(B)$	<i>B</i> , Effective liquid level angle, degrees. <i>L</i> , Vessel end-to-end length, $[ft]$.
H-cylinder with spherical ends	$A_{\text{wet}} = \pi * D\left\{E + \frac{(L-D)*B}{180}\right\}$	E_s , Effective liquid level, $[ft]$. E_s , Effective spherical liquid level, $[ft]$.
V-cylinder with flat ends	If $E < L$, then : $A_{wet} = \pi * D\left(\frac{D}{4} + E\right)$	E_1 , Initial liquid level, $[ft]$. D, Vessel diameter, $[ft]$.
	If $E < L$, then : $A_{wet} = \pi * D\left(\frac{D}{2} + E\right)$	<i>K</i> , Effective total height of the liquid surface, [<i>ft</i>].
V-cylinder with spherical ends	$A_{wet} = \pi * E * D$	K_1 , Height of the liquid surface, feet.
	Effective liquid level angle, degrees $B = \cos^{-1} \left(1 - \frac{2*E}{D} \right)$	<i>H</i> , Vessel elevation, $[ft]$. <i>F</i> , Liquid depth in the vessel, $[ft]$.

Table 3. Steps to determine the wetted surface area, $A_{wet} [ft^2]$ [7].

Note: H—horizontal, V—vertical.



Figure 6. Pressure vessel (**a**) selection (considering fire cases) and (**b**) an effective liquid-level logic diagram [5–8,14].



Figure 7. Logic diagram for: (a) back pressure P_b correction factor and (b) orifice selection.

Table 4. Steps to determine the total heat absorption, Q[BTU/hr], environmental factor, *F*, and rate of vapor from liquid, W[lbs/hr], for certain conditions (prompt firefighting and adequate drainage options) [5,7].

Conditions (Prompt Firefighting and Adequate Drainage Options) Total Heat Absorption, Q[BTU/hr]		Parameters
Available	$Q = 21,000 * F * A_{wet}^{0.82}$	_ A_{wet} , total wetted area, $\left[ft^2\right]$
Not available	$Q = 34,500 * F * A_{wet}^{0.82}$	<i>Q</i> , total heat absorption, $\begin{bmatrix} BTU \\ hr \end{bmatrix}$ <i>F</i> , factor F based on vessel type
Vessel type	Environmental factor, F (IC)	
Bare vessel	1	<i>IC.</i> insulation conductance values.
Insulated vessel, with IC value 0.3 (4), 0.15 (2), 0.075 (1), 0.05 (0.67), 0.0376 (0.5), 0.03 (0.4), 0.026 (0.33)		$\left[\frac{BTU}{hr*ft^2*F}\right]$
Water application facilities, on bare vessels,	_	
Depressurizing and emptying facilities, F =	_	
Rate of vapor from liquid, W, $[lbs/hr]$ Determine the fluid mass flow converted to gas from the liquid, $W = Q * H_{vap}$		H_{vap} , latent heat, $\left[\frac{BTU}{lb}\right]$ W, rate of vapor from liquid $\left[\frac{lbs}{hr}\right]$

Table 5. Steps to determine the minimum required relieving area, $A[in^2]$ [5,7].

Orifice Area	A , $[in^2]$	Parameters
General	$A = \frac{W\sqrt{T*Z}}{C*K*P_1*K_b\sqrt{M}}$	Correction factors:
For gas or steam (kg/hr)	$A = \frac{1.3164*W\sqrt{T*Z}}{C*K*P_1*K_b\sqrt{M}}$	K_b , back pressure, K_{SH} , for superheated steam, K_w , back pressure for liquids,
For steam (kg/hr) For liquid (m ³ /h) For air (Nm ³ /h)	$A = \frac{W}{52.5*K*P_1*K_b*K_{SH}*K_N} \\ A = \frac{0.196*VL*\sqrt{G}}{K_1*K_w*K_0*\sqrt{1.1*P-P_b}} \\ A = \frac{V*\sqrt{T}}{1125*K*P_1*K_b}$	K_v , viscosity (for water, $K_v = 1$), K_p , for valves with uncertified, (for 10% o/v pr., $K_p = 0.6$; for 15% o/v , $K_p = 0.8$; and for 25% o/v pr. $K_p = 1$), and K_N , for Napier equation

Where *A* is the orifice area required, $[cm^2]$; *W* and *VL* are the required capacity, $\begin{bmatrix} kg \\ hr \end{bmatrix}$; *G* is the density of gas to air or liquid compared to water; *M* is the molecular weight; *Z* is the compressibility factor (if unknown, use *Z* = 1); *T* is the temperature, absolute; *C* is the gas constant; *k* is the specific heat ratio, and $k = C_p/C_v$ (if unknown, use k = 1.001); *K* is the flow factor (for gas/steam, K = 0.975; liquid, $K_1 = 0.701$; as per API 520, liquid $K_2 = 0.62$); and P refers to pressure, namely, P_1 is the relieving pressure, *P* is the set pressure, and P_b is the back pressure.

4.1. Calculate the Correction Factors

The correction factors for proper sizing and selection of pressure relief safety valves can be ensured by following the logic diagram below [5–8,11,14,55].

4.2. Selecting the Orifice Size and Valve Model

After calculating the required discharge area, select the next larger orifice size from Table 6. Using the manufacturer's valve orifice selection table and the valve operating curve with respect to the relieving temperature, select the valve model. Considering the back pressure, select either the conventional or balance bellows valve type. For multiple valve selection, use 16% instead of 10% accumulation. Other features, like the rupture disc, rupture pin, pilot-operated safety relief valve, and multiple valve type or valve accumulation value, may be selected considering the specific service condition.

Orifice Area	D	E	F	G	Н	J	К	L
Area (cm ²) Orifice Area	0.71 M	1.26 N	1.98 P	3.24 Q	5.06 R	8.3 T	11.86 V	18.41 W
Area (cm ²)	23.2	28	41.2	71.2	103	168	271	406

Table 6. PSV orifice area according to API 526 in cm².

4.3. Case Studies: PSV Selection

The sizing and selection of PSVs for the atmospheric distillation column for the petroleum oil refining process of Eastern Refinery Ltd., Chittagong, is considered a case study [11]. The design and operating data for the safety valve of the original PSVs and estimated PSV orifice size are presented in Table 7.

Table 7. Calculation for sizing and selection of PSV.

Relevant	Calculation	Parameters
Relieving pressure (absolute)	$P_1 = \text{set Pr.} + \text{over Pr.} + \text{atm. Pr.}$ $P_1 = 3.2 + (3.2 \times 16\%) + 1.013 \text{ Bar}$ = 4.725 Bar	Gas, relieving fluid W = 50,000 kg/hr, required relieving capacity (each valve)
Required number of PSVs is 3	So, over pressure= 16% of set Pr From Figure 8, back pressure correction factor, $K_b = 1$	M = 94 kg/k. Mole, molecular weight $Z = 1$, compressibility factor (If unknown, use $Z = 1$) $T = 473 K$, relieving temperature (absolute)
Orifice area for gas or steam (kg/h)	$A = \frac{1.3164 * W \sqrt{T * Z}}{C * K * P_1 * K_b \sqrt{M}} = 93.1665 \text{ cm}^2$	C = 344, gas constant (specific heat ratio, $k = 1.27$) K = 0.975, flow factor (for gas and steam, $K = 0.975$) P = 3.2 bar, set pressure
Next higher orifice size	from Table 6, $A' = 103 \text{ cm}^2$	$P_b = 0$, back pressure
Modified valve flow rate	A'/A × W = 55,277.4 kg/hr	 Use three PSVs for the application

Using the Serasin-RSBD valve manufacturer, we select the valve model for the R orifice, with an orifice size of 103 cm², a relieving temperature of 473K, and a set pressure of 3.2 bar as follows: The preliminary valve model: P68R1 6RB 150 lb; Dimensions: A (239.7), B (241.3); Inlet/outlet DN (6 in. \times 150 lb/8 in. \times 150 lb), Weight (215 kg), Valve type (conventional type because there is no back pressure). The final valve model is determined as P68R1 330





(b)

Figure 8. Cont.



Figure 8. Correction factors for (**a**–**c**) back pressure and (**d**) viscosity. (**a**): K_b , constant back pr., valve without bellows. (**b**): K_b , balanced bellows valve only, gas & steam at 10% overpressure. (**c**): K_w , variable back pr., balanced bellows valve on liquid service only. (**d**): K_v , viscosity correction factor.

5. Testing and Servicing Procedures

Pre-installation and post-service testing of PSVs/PRVs are required in the presence of professionals/safety inspectors. The general and recommended procedure for PSV/PRV disassembly, servicing, reassembly, and testing are discussed, as follows.

5.1. Procedure for PSV Disassembly

The recommended procedure to dismantle PSVs, as presented in Figure 9 [51], for servicing, if required by the PSV test results/preventive maintenance, is as follows:

- Step 1: Remove the valve cap, note the length of the adjusting screws, loosen the locknut, and adjust the screw to remove the bonnet, spring, and spring washers.
- Step 2: Remove the spindle, ball, disc, and bellow. Loosen and unscrew the adjusting ring. Invert the valve body and dismantle the nozzle using drift.

The valve parts and corresponding part numbers are shown in Figure 9.



Figure 9. SERASIN RSBD PSV with internal configuration.

5.2. Procedure for Servicing and Reassembly

Lapping the nozzle and disc seat surfaces can solve PSV leaks. However, lap operation requires skill and experience; otherwise, irreparable damage may occur. Lapping can be performed by hand or by machine without any pressure. This process requires several grade pastes to remove marks and create a uniform polish. Disc and nozzle lapping should be performed independently. New gaskets and clean bolts should be used for PSV reassembly. All parts must be lubricated before assembly, and the reassemble must be checked to ensure no moving parts. The steps in assembly are the opposite steps of disassembly.

5.3. Procedure for PSV Testing and Servicing

PSV testing requires a test bench that consists of an inlet pressure regulator, needle valve, inlet pressure indicator, and release valve, as shown in Figure 10, the design of which is similar to other test benches [56]. The outlet nozzle of the PSV should be attached to the release line through a water pot to count bubbles or observe blowdown performance.



Figure 10. Schematics of PSV test bench setup.

The steps in PSV testing and servicing are as follows:

- Step 1: Open the PSV from the process line with marking (e.g., inlet, outlet, blow line). Pre-test the PSV. If the first pre-test result is not satisfactory, test again.
- Step 2: Disassemble the PSV, clean, and service. Lap the nozzle. Assemble the PSV.
- Step 3: Test the PSV:
 - Gradually increase the inlet pressure in the test bench. Outlet (blow line of PSV) pressure is measured by bubble formation in water. When static inlet Pr. ≥ set Pr. => Pop action, PSV will operate. After the blow, PSV will stop within a short time.
 - If the operating pressure and set pressure differ, readjust the spring pressure/tension. If the operating point is the same in several test results and leakage is very low, the valve is ready for qualification testing.
 - Keep a record of the pre-test, test, set pressure, and operating pressure in the record book signed by the inspector. If the spring performance degrades, changing the spring is recommended.
 - In general, case $\pm 10\%$ accumulation is considered. For special PSVs, considering the process and test condition case, $\pm 3\%$ or $\pm 16\%$ accumulation is used.
 - Because there is no option for giving back pressure, the bellows type PSV has to allow higher leakages. This leakage is compensated by the back pressure.
 - After testing, PSVs should be sealed with the proper tag.

- Step 4: Seat tightness checking procedure:
 - Make sure that the valve is properly installed and all connections are tight.
 - Set the pressure at the valve inlet to the MAWP. Open the valve and allow it to discharge until the pressure drops to the set pressure. Repeat this process three to four times to ensure the valve has been fully exercised.
 - After exercising the valve, reduce the pressure to 90% of the set pressure. Close the outlet of the valve and measure the leakage rate for one minute.
 - If the valve has a metal seat, compare the leakage rate with the values given in Table 8 of API 527. The leakage rate should be within the desired value.
 - If the leakage rate is within the acceptable limits, the valve is considered to be seat tight. Otherwise, the valve should be disassembled and inspected for any damage or wear. The seat and disc should be replaced if necessary.
 - Reassemble the valve and repeat the seat tightness test. Once the valve passes the seat tightness test, it can be put back into service.

Set Pressure		Leakage Rate for Effective Orifice Size, A [in ²] (F Orifice) (Bubbles/min)	
PSI (G)	Kg/cm ² (G)	A <= 0.307 in ²	$A > 0.307 \text{ in}^2$
15-1000	1–70	40	20
1500	105	60	30
2000	141	80	40
2500	176	100	50
3000	211	100	60
4000	281	100	80
5000	352	100	100
6000	422	100	100

Table 8. Allowable leakage rate in bubble per minute as per API 527 [8].

6. Conclusions

Selecting a suitable PSV/PRV with an associated design feature is essential to ensure the safety and uninterrupted operation of the process plant. Though the manufacturer must always guarantee the final design, this study will significantly reduce the amount of upfront engineering effort. This study covers the following research and engineering areas of PSVs/PRVs and provides relevant guidance:

- Provides an overview of the PSV/PRV systems to support safety of the pressurized system.
- Defines and discusses the basic terminology related to PSV/PRV design and operation.
- Addresses the special design features and their pros and cons for specific process applications.
- Demonstrates standard procedures with associated equations and characteristic curves to size and select the suitable PSV/PRV for specific applications.
- Identifies that the major causes of PSV performance degradation are cavitation and wear, which are the root cause of disruption in fluid flow distribution/dynamics, boundary-layer formation and pressure drops across valve flow regions, gas bubble formation and collapse, variations in geometric configuration and the shape of components and inlet/outlet piping, and acoustic resonance.
- Examines a case study to show the correctness of the presented procedure to select and size a PSV/PRV with associated features that match with the original design model.
- Offers an outline of the servicing and testing of PSVs/PRVs, which is considered an industry standard and driven by proven practice.

Overall, this study provides standard calculation and selection procedures that are based on a prescribed method. However, it is recommended to follow the manufacturer's detailed guidelines for a specific design case. This study aims to provide simple and general guidelines for selecting the best suited PSVs/PRVs and ensuring their safe and efficient operation.

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Abbreviations

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ISO	International Organization for Standardization
MAWP	maximum allowable working pressure
MP	megapascals
PSEP	process safety and environmental protection
PSV	pressure safety valve
PRV	pressure relief valve
Variables	and Greek symbols
Α	flow area, [m ²]
Awet	wetted surface area, [ft ²]
В	effective liquid level angle, degrees
С	gas constant (Cp for constant pressure, and Cv for constant volume)
D	vessel diameter [ft]
Ε	effective liquid level [ft]
E_s	effective spherical liquid level [ft]
E_1	initial liquid level [ft]
F	liquid depth in vessel [ft]
F	environmental factor
G	density of a gas to air or liquid compared to water
Η	vessel elevation [ft]
H_vap	latent heat, [Btu/lb]
IC	insulation conductance values, [Btu/(hr.ft ² .F)]
Κ	effective total height of liquid surface [ft]
K_1	total height of liquid surface [ft]
Κ	flow factor (for gas/steam, $K = 0.975$, for liquid, $K_1 = 0.70$, for API 520, liquid, K_2 , = 0.62)
Κ	correction factor (K_b for constant back pressure and K_w for variable back pressure)
L	vessel end-to-end length [ft]

- M molecular weight
- P_1 relieving pressure (pr.) (abs) P_1 = set pr. + over pr.+ 1.013
- P set pressure
- Pr pressure
- *P*_b back pressure
- *Q* total heat absorption [Btu/hr]
- *T* relieving temperature, absolute
- *V* required capacity, [Nm²/hr]
- *VL* required capacity, [m³/hr]
- W rate of vapor from liquid [lbs/hr]
- Z compressibility factor, if unknown, use Z = 1
- *k* specific heat ratio, $k = C_p/C_v$, if unknown, use k = 1.001

Subscript: *b*-back pressure, *w*-variable break pressure, and *L*-liquid

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