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Review

A Review of Safety Valves: Standards, Design, and Technological Advances in Industry

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Abstract: This review synthesizes insights from the literature and incorporates computational and experimental analyses to explore various types of safety valves and their applications across industries such as oil and gas, chemical manufacturing, and power generation. Key areas of focus include global regulatory standards from organizations like the American Society of Mechanical Engineers (ASME), International Organization for Standardization (ISO), Deutsches Institut für Normung (DIN), and American Petroleum Institute (API), which ensure stringent design and testing requirements. This paper examines the historical development of safety valves, recent technological advancements such as smart valves with integrated sensors, and predictive maintenance capabilities, along with ongoing challenges in high-pressure and corrosive environments. Additionally, it highlights the role of computational tools like CFD and FEA in optimizing valve designs and ensuring reliability under demanding conditions. By presenting a streamlined analysis of standards, innovations, and future directions, this review underscores the indispensable importance of safety valve technology in ensuring operational safety across various industrial applications.

Keywords: review; safety valve; standards; design

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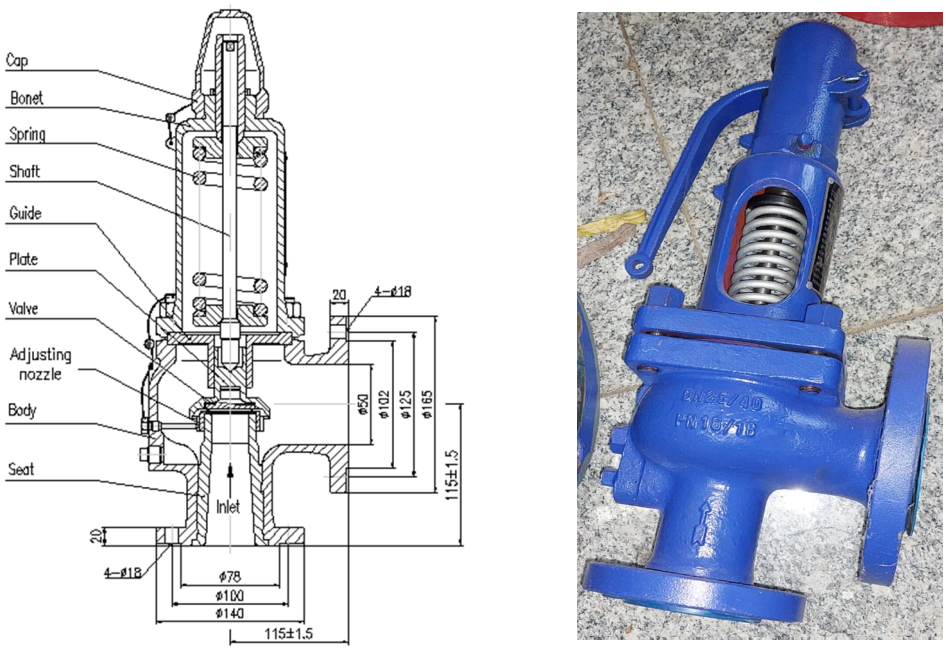
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1. Introduction

Safety valves are vital components in industrial systems, designed to prevent overpressure situations that could otherwise lead to catastrophic failures, equipment damage, and safety hazards [1–5]. Their role is very important in maintaining the integrity of processes across industries such as oil and gas, chemical manufacturing, power generation, and transportation [6,7]. According to the American Society of Mechanical Engineers (ASME), a safety valve is defined as a device that automatically releases a substance from a boiler, pressure vessel, or other systems when the pressure exceeds preset limits, ensuring operational safety and reliability (ASME BPVC, Section VIII). By acting as a pressure relief mechanism, these valves serve as the last line of defense in systems under pressure, protecting not only the equipment but also personnel and the environment from potentially dangerous failures.

In Figure 1 an example is presented of a pressure valve commonly used in the oil and gas industry and its main components.



(**a**) (**b**)

Figure 1. Example of pressure relief valve: (**a**) 2D drawing; (**b**) real shape [8].

Since both the sealing surface of the valve and the seat surface are coated with hard materials, the valve includes the valve body and plate, while the seat assembly comprises the seat body and adjusting nozzle. Figure 2 illustrates the assembly of these two components, which is typical for discharge valves.



(**a**) (**b**)

Figure 2. Components of the pressure valve: (**a**) plate assembly and (**b**) seat assembly [8].

An extensive range of the scientific literature [3,5,9–20] has been dedicated to the description and analysis of valve systems.

This review provides a comprehensive analysis of the different types of safety valves, including spring-loaded, pilot-operated, and other specialty valves and their application across various industries. This paper explores the major global standards that regulate safety valves, such as those developed by ASME, the American Petroleum Institute (API), and the International Organization for Standardization (ISO). Each of these standards imposes stringent requirements on the design, testing, and maintenance of safety valves to ensure they perform reliably under operational conditions. Additionally, this review

discusses the core principles of valve design, pressure settings, the materials used, and operating environments.

Technological advancements in safety valve design and operation present both opportunities and challenges. For instance, while traditional safety valves have evolved to handle high pressures and corrosive environments, modern industry demands even greater performance, particularly in terms of automation and predictive monitoring. Smart safety valves, equipped with sensors and integrated with artificial intelligence (AI), are becoming an essential part of Industry 4.0, allowing real-time monitoring and predictive maintenance capabilities [21,22]. Furthermore, advancements in materials, such as corrosion-resistant coatings and high-performance alloys, have significantly improved the longevity and reliability of safety valves under extreme conditions [15,23–29]. Despite these improvements, the ongoing challenge remains to balance operational reliability with the need for innovation, especially in industries requiring higher performance under demanding conditions such as high temperatures and corrosive or hazardous fluids.

For this review, an extensive search was conducted using the Web of Science (WOS) database, focusing on the keywords "safety valves" within the research area of engineering. The selection process involved filtering relevant studies published in English, covering key aspects such as safety valve design, materials, standards, and technological advancements. Studies were evaluated based on their methodological rigor, experimental or computational analysis, and relevance to industrial safety. The identified studies were then synthesized to address the gap in the literature regarding recent innovations and their practical applications in various industries. After finding the relevant papers (920 article types and 22 review articles), we performed a cluster analysis with VOSviewer version 1.6.20, as seen in Figure 3.

Figure 3a depicts the network of keywords associated with safety valves and related topics. The interconnected terms like "safety valve", "pressure valve", and "fluid dynamics" highlight the primary areas of focus, demonstrating the emphasis on valve performance and fluid safety. Figure 3b, with its heatmap visualization, reveals areas of higher research activity, such as "safety" and "valves", indicating well-explored domains. However, emerging topics like "fault diagnosis" and "smart technologies" appear underrepresented, suggesting critical gaps in addressing modern industrial challenges. Lastly, Figure 3c illustrates the temporal trends of these research themes, showing an increasing interest in areas like "simulation" and "reliability" but limited progress in adopting predictive maintenance and prevention techniques. These figures collectively highlight the need for more focused research on integrating advanced technologies and addressing operational limitations, which this review aims to explore comprehensively.

The evolution of safety valve technology has been instrumental in addressing industrial safety challenges. Early designs, such as weight-loaded valves, laid the groundwork for more sophisticated spring-loaded mechanisms developed in the 19th century, which resolved critical issues like tampering and operational reliability. These advancements enabled the widespread adoption of safety valves in steam engines, chemical plants, and other industrial applications. In recent decades, the transition toward smart safety valves equipped with sensors and predictive maintenance capabilities has further enhanced operational safety and reliability, aligning with the principles of Industry 4.0.

Although significant progress has been made, challenges persist in ensuring valve reliability under extreme conditions such as high pressures and corrosive environments. Furthermore, the potential of computational tools like CFD and FEA to optimize valve design and predict performance under complex operating conditions remains underexplored.

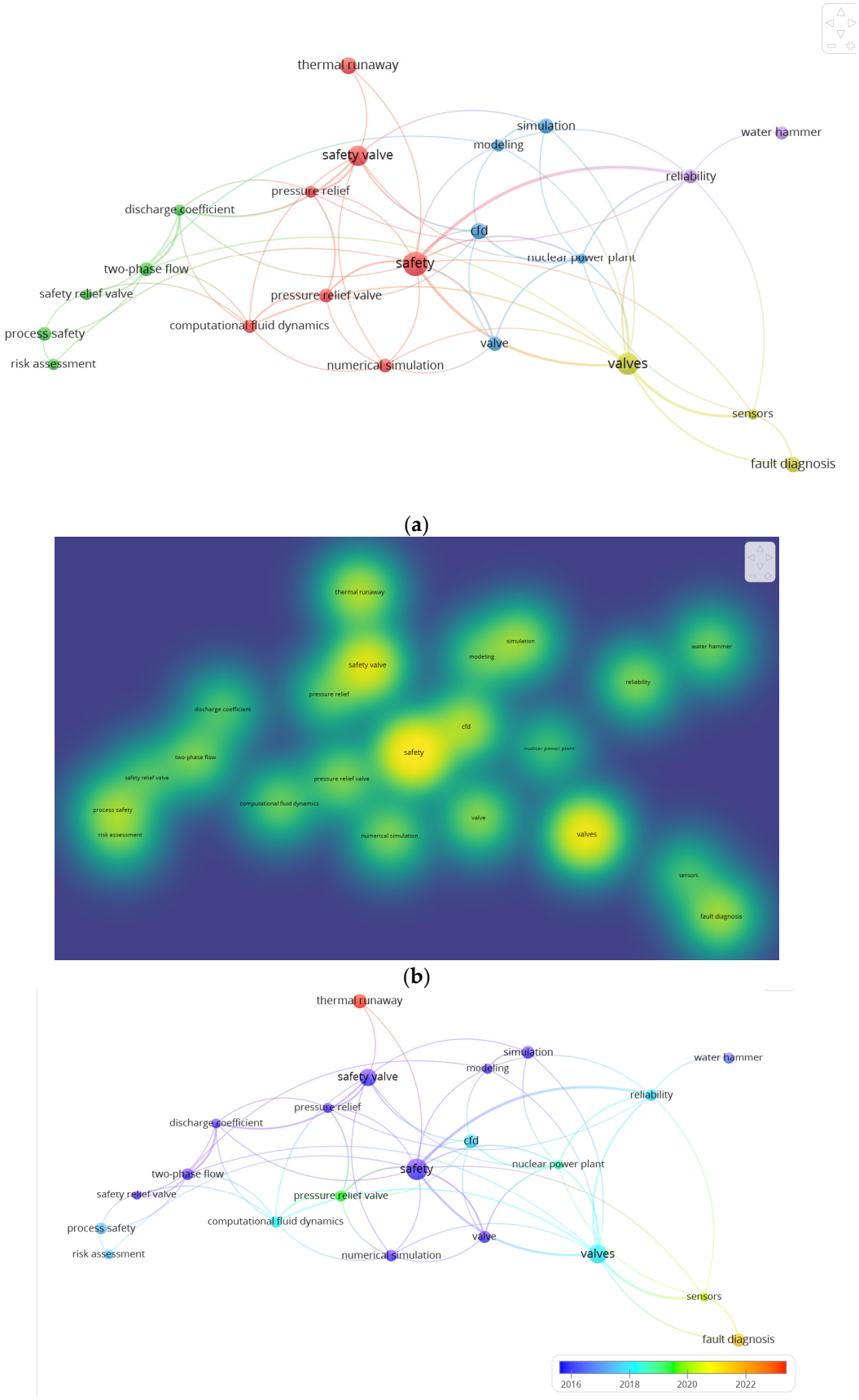


Figure 3. VOS viewer analysis results: (**a**) keywords co-occurrence network; (**b**) density visualization; (**c**) overlay visualization.

To address the gap in existing research, this review provides a distinctive contribution by synthesizing and analyzing key advancements and challenges in safety valve technology, with a focus on their evolving role in industrial applications. While previous studies have primarily focused on specific aspects such as design optimization, material selection, or compliance with regulatory standards, this paper adopts a comprehensive approach. It integrates discussions on global standards, historical developments, and emerging innovations such as smart safety valves and Industry 4.0 technologies. Furthermore, this review identifies critical challenges faced by safety valves in demanding environments, including high-pressure and corrosive conditions, and proposes directions for future research to address these limitations. By bridging the gap between traditional design principles and modern technological advancements, this study aims to provide a comprehensive perspective that informs both academic research and industrial practices.

The comparative and qualitative analysis of the information regarding the use of safety valves pursued the achievement of the following objectives. This set of objectives underscores the critical aspects that need to be addressed in a safety valve analysis review, leveraging insights from the contemporary literature and industry standards.

1. Performance evaluation: assess the performance of safety valves across a range of operating conditions to identify potential failure points and prevent incidents;
2. Operating condition assessment: analyze historical accidents and operational data to define the expected conditions under which the safety valves must function;
3. Proper selection criteria: develop guidelines for selecting safety relief valves by considering critical factors such as equipment type, fluid properties, operating temperature, set pressure, and required discharge capacity;
4. Accessibility analysis: ensure that all safety-critical valves are easily accessible for maintenance and inspection during the analysis phase;
5. Design variable influence: investigate how design variables affect the operational characteristics of pressure safety valves, particularly their opening and reclosing behaviors;
6. Optimal structural identification: identify the most effective structural designs for safety valves that deliver the best performance and reliability based on analysis results and industry benchmarks;
7. Test result review: conduct a thorough review of existing test results and empirical data to evaluate and compare the performance metrics of various safety valves;
8. Prototype applicability: assess the relevance and effectiveness of prototypical valve designs within specific systems to ensure they meet operational demands;
9. Reliability and efficiency assessment: determine the reliability and efficiency of safety valves in mitigating overpressure situations and protecting system integrity;
10. Improvement recommendations: formulate actionable recommendations for design modifications or operational changes aimed at enhancing the overall performance, reliability, and safety of safety valves.

This study focuses on evaluating the performance of safety valves under varying conditions, optimizing material selection for durability, and integrating IoT-based predictive maintenance systems to address current industry challenges.

2. Historical Background

The development of safety valves has a long and rich history, dating back to the early days of industrialization when the need to control pressure in steam engines and boilers became critical for safe operations. The first recorded use of safety valves can be traced to the 17th century, when Denis Papin, a French physicist and inventor, introduced a rudimentary form of the safety valve to control steam pressure in his pressure cooker invention in

1679 [30]. This early innovation laid the groundwork for the industrial applications that followed during the Industrial Revolution.

Around 1830, Timothy Hackworth developed an open-ended safety valve for the emerging steam trains and boilers of the time, marking the beginning of modern safety valve design. However, despite this innovation, steam installations did not significantly improve in safety with the early safety devices available [31].

In 1848, Charles Retchie invented the accumulation chamber, which increases the compression surface within the safety valve allowing it to open rapidly within a narrow overpressure margin [32].

Early safety valves were rudimentary, relying on weights to maintain steam pressure. However, these designs were prone to tampering or accidental release. In 1856, John Ramsbottom introduced a tamper-proof, spring-loaded safety valve, which quickly became the standard for railway applications and later for stationary installations [33].

The 19th century saw significant advancements in safety valve design, particularly with the rise of steam engines in locomotives and factories. Safety valves became essential for protecting boilers from dangerous overpressure, which could cause catastrophic explosions. By the late 19th century, safety valves were not only in widespread use in steam-powered machinery but were also being integrated into chemical and petrochemical industries, where managing volatile and pressurized fluids became essential.

As industrial processes grew in scale and complexity throughout the 20th century, the demand for more reliable and standardized safety valves intensified. This led to the establishment of various international standards, such as the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) in 1914 [31]. ASME played an essential role in shaping the modern standards for the design, testing, and use of safety valves, ensuring consistency and safety across industries (ASME BPVC, 1914). The ASME Boiler and Pressure Vessel Code, Section I, became a mandatory requirement in all states that acknowledged the necessity for legislation [31]. Additionally, the American Petroleum Institute (API) and the International Organization for Standardization (ISO) further developed specific regulations to address the needs of the oil, gas, and chemical industries, where extreme pressures and hazardous environments are common.

Throughout the 20th century, safety valve technology continued to evolve. Innovations in materials science, particularly the development of alloys and composites that can withstand high pressures and corrosive environments, significantly improved valve performance. These materials were essential for meeting the growing demands of industries operating under more extreme conditions, such as oil refineries, chemical plants, and power generation facilities. In parallel, advances in engineering design, such as pilot-operated and balanced-bellows safety valves, allowed for greater precision and reliability in valve operation [30].

In recent decades, the emergence of smart technologies and automation has further transformed the landscape of safety valve design. The introduction of digital monitoring systems, sensors, and artificial intelligence (AI) has enabled real-time tracking of valve performance and predictive maintenance, significantly reducing the risk of failures and improving operational efficiency [21,22]. This evolution reflects the broader trend toward Industry 4.0, where interconnected systems and data-driven technologies are reshaping industrial safety and maintenance practices.

3. Overview of Global Standards Governing Safety Valves

Safety and relief valves are strictly regulated by codes and regulations, with the two primary frameworks being ASME in the USA and PED in Europe. The main applicable standards for safety valves are shown in Table 1 [34].

Table 1. Safety valves applicable standards.

Region/Safety Valve Standards		
Europe		
PED 97/23/EC—Pressure Equipment Directive—Classifies pressure equipment into four categories (I, II, III, IV) [35]		EN4126—Safety devices for protection against excessive pressure [36]
USA		
ASME I—Direct fired pressure vessels [37]	ASME III—Nuclear power plants [37]	ASME IV—Heating Boilers [37]
ASME VIII—Unfired pressure vessels [37]	ANSI/ASME PTC 25.3—Performance test codes [37]	API 520—Sizing selection and installation of pressure relieving devices in refineries, Part 1 Design, Part 2 Installation [37]
API 521—Guide for pressure relieving and depressurizing systems [38]	API 526—Flanged-steel pressure relief valves [39]	API 527—Seat tightness of pressure relief valves [40]
Others		
Korea—KS B 6216 Spring-loaded safety valves for steam boilers and pressure vessels [41]		Japan—JIS B 8210—Steam boilers and pressure vessels—spring-loaded safety valves [42]
Australia—SAA AS 1271—Safety valves, other valves, liquid-level gauges and other fittings for boilers and unfired pressure vessels [43]		International—ISO 4126—Safety valves—general requirements [36]

Table 2 provides a concise summary of the key operational code requirements based on the current global standards [44].

Table 2. Main operational code requirements according to the current worldwide codes.

Set Pressure/Tolerance			
Pressure specification—ASME I		Pressure specification—ASME VIII	
2 psi (0.14 bar); 70 psi (4.76 bar)	3% above 70 psi (4.76 bar)	2 psi (0.14 bar); 70 psi (4.76 bar); 3% above 70 psi (4.76 bar)	
10 psi (0.68 bar); between 300 psi (20.4 bar); and 1000 psi (68.03 bar)	1% above 1000 psi (68.03 bar)		
Blowdown			
ASME I		ASME VIII	PED
<67 psi (4.62 bar) = 4 psi ≥67 psi (4.62 bar) and ≤250 psi (17.24 bar) = 6% >250 psi (17.24 bar) and <375 psi (25.86 bar) = 15 psi 4% above 375 psi (25.86 bar)		Gas/vapor: 7–10% Liquid: No requirement	No code requirement but 7–10% is the industry standard
Overpressure			
ASME I		ASME VIII	PED
2 psi (0.14 bar) or 3%, whichever is greater		3 psi (0.2 bar) or 10%, whichever is greater Multiple valves: 16% Fire case: 21%	10% above accumulation

Using the bibliography list, the following analysis was defined regarding the comparison between findings and recommendations in standards and the existing literature in the safety valve industry:

- ✓ Sizing methodologies: ASME outlines specific procedures for valve sizing, yet the literature indicates that dynamic effects, such as fluctuating flow rates, can lead to under-sizing in practical applications [10,14];
- ✓ Material specifications: standards specify acceptable materials for corrosion resistance, whereas the literature highlights new composites that may surpass traditional materials in corrosive environments [15,24];
- ✓ Operational testing: while standards mainly prescribe static pressure tests, research advocates for dynamic testing to better simulate real-life scenarios, leading to more accurate performance assessments [4,19];
- ✓ Failure analysis: standards may not adequately address the fatigue mechanisms that can lead to safety valve failures; studies emphasize the need to integrate these findings into quality assurance protocols [5,12];
- ✓ Installation requirements: installation standards suggest basic configuration guidelines, but the literature emphasizes the importance of system integration factors such as pipe layout and fluid dynamics [11,25];
- ✓ Performance under transient conditions: standards often focus on steady-state operation, while the literature discusses the significant impact of transient conditions on safety valve performance, advising for adaptive approaches [19,45];
- ✓ User training protocols: drawing from standards which focus on valve operation, the literature calls for enhanced training programs targeting user awareness to improve valve reliability and maintenance procedures [11,46];
- ✓ Emergency procedures: standards outline basic emergency response steps; however, the literature stresses comprehensive drills and scenarios for better preparedness in real incidents [26,47];
- ✓ Monitoring technologies: while standards describe basic monitoring techniques, the literature encourages the use of advanced data analytics and IoT technologies for predictive maintenance [21,48];
- ✓ Environmental compliance: standards include basic guidelines for emissions; the literature suggests comprehensive environmental impact assessments for safety valves, especially in chemical industries [6,49];
- ✓ Impact of backpressure: standards acknowledge backpressure considerations, but the literature suggests deeper analytical methods to quantify its effect on valve performance [50,51];
- ✓ Smart valve integration: standards may lack specifics for smart technologies, while the emerging literature proposes frameworks for integrating smart algorithms to enhance valve responsiveness [22,48];
- ✓ Validation of sizing methods: standards mention traditional sizing methodologies, but studies evaluate their adequacy and propose advanced metrics tailored to specific industry scenarios [14,52];
- ✓ Lifecycle assessment: standards do not typically cover the complete valve lifecycle, while the literature urges the adoption of lifecycle cost analysis for optimized maintenance planning [12,48];
- ✓ Cross-disciplinary approaches: standards emphasize mechanical design, whereas the literature argues for incorporating insights from fluid dynamics and materials science to enhance performance [51,53];

- ✓ Chatter prevention: standards provide basic guidelines, but the existing literature presents in-depth studies on valve behavior related to chatter and offers novel design solutions [18,54];
- ✓ Case studies of failures: standards may provide general guidelines for valve operation; the literature often includes detailed case studies and lessons learned from past failures to inform better practices [55,56];
- ✓ Customization needs: standards suggest generic valve specifications, while the literature highlights the growing need for customized solutions to meet specific operational demands in various industries [1,8];
- ✓ Simulation techniques: while standards offer basic testing procedures, the literature investigates complex simulation techniques that more accurately predict valve behavior [3,50];
- ✓ Regulatory updates: standards are frequently static; however, the literature advocates for agile approaches that incorporate ongoing research findings and technological advancements into compliance updates [18,30];
- ✓ Standard operating procedures: standards provide basic procedures for the operation of safety valves, while the literature emphasizes the need for specific guidelines tailored to individual operational contexts to ensure optimal performance [11,46];
- ✓ Assessment of system risks: standards may outline general safety assessments; however, the literature advocates conducting detailed risk analyses that consider system-specific variables and historical data [6,19];
- ✓ Energy efficiency considerations: standards often overlook energy consumption metrics; the literature discusses integrating efficiency guidelines into the design and operation of safety valves to minimize energy waste [21,22];
- ✓ Role of computational fluid dynamics [CFDs]: while standards indicate basic testing methods, the literature strongly promotes the use of CFD simulations to gain insights into fluid dynamics affecting valve performance [50,57];
- ✓ Temperature effects: OSHA and other standards typically address temperature limits but may lack thorough analysis; the literature reports that temperature fluctuations can significantly impact valve materials and performance, suggesting further study [1,51];
- ✓ Post-failure analysis: standards may lack guidelines on conducting thorough post-failure assessments, whereas the literature stresses the importance of such analyses to derive insights for preventing future incidents [55,56];
- ✓ Life cycle management: standards provide limited guidance on life cycle management of safety valves; the literature suggests a more proactive approach to evaluating long-term performance and maintenance needs [12,27];
- ✓ Public safety regulations: while standards focus on compliance, the literature advocates for a broader view encompassing public safety regulations and social responsibility in safety valve designs [6,49];
- ✓ User-friendly design: standards primarily focus on functionality; the literature suggests employing ergonomic designs that enhance user interaction to minimize operational errors [22,48];
- ✓ Collaboration with regulatory bodies: standards are often developed independently, but the literature suggests ongoing collaboration between industry experts and regulatory bodies to keep standards relevant and effective [18,30];
- ✓ Design specifications: standards typically provide minimum design specifications for safety valves, while the literature discusses advancements in design techniques that improve performance and reliability beyond minimum requirements [10,14];

- ✓ Installation guidelines: many standards outline general installation practices, yet the literature emphasizes the importance of site-specific factors—such as ambient temperature and system dynamics—that can significantly affect valve function [11,25];
- ✓ Failure mode analysis: while standards acknowledge common failure modes, the literature often presents detailed case studies that explore less frequent but critical failure scenarios, highlighting a need for broader failure analysis [55,56];
- ✓ Calibration frequencies: standards may dictate calibration frequencies based on general operational environments; however, the existing literature indicates that calibration needs should reflect specific operational conditions and historical performance data [6,19];
- ✓ Industry-specific regulations: occupational standards may offer generic guidelines; the literature often points out the necessity for tailored regulations that account for the unique challenges faced in specific industries, such as pharmaceuticals or nuclear power [12,19];
- ✓ Innovations in valve technologies: standards typically endorse existing technology, while the recent literature advocates for the exploration of innovative technologies like automated monitoring systems that collect data for predictive maintenance [21,48];
- ✓ Impact of design age: standards sometimes focus on modern systems, whereas the literature analyzes the performance of legacy systems, suggesting the need for updated evaluations and modifications to improve safety [1,5];
- ✓ Risk management approaches: standards might present basic risk management principles, while the literature emphasizes more sophisticated methodologies that integrate probabilistic risk assessments for better decision making [22,49];
- ✓ Hydraulic performance testing: though standards define testing protocols for hydraulic performance, the literature often highlights the limitations of these tests and suggests additional metrics for evaluating valve performance under diverse conditions [10,50];
- ✓ Post-maintenance validation: standards may require post-maintenance checks, yet the literature strongly advises for comprehensive validation procedures to ensure that safety valves remain functional after maintenance activities [55,56].

4. Types of Safety Valves

This section provides an overview of the different types of safety valves, focusing on their distinct designs, functions, and applications across various industries. Each type of safety valve—such as spring-loaded, pilot-operated, and balanced-bellows valves—offers unique advantages suited to specific pressure ranges, environmental conditions, and fluid types. Table 3 [54] and Figure 4 are presenting different types of safety valves according to the standards ASME [58], DIN 3320 [59], and EN ISO 4126 [60].

Table 3. Characteristics of different types of safety valves.

Safety Valve Type	Characteristics
ASME	
ASME I valve	It opens within 3% overpressure and closes within 4%.
ASME VIII valve	It opens within 10% overpressure and closes within 7%.
Low-lift safety valve	The discharge area of the valve is determined by the current position of the disc.
Full-lift safety valve	The position of the disc does not directly determine the discharge area.

Table 3. *Cont.*

Safety Valve Type	Characteristics
Full-bore safety valve	Without bore protrusions, it lifts to make the minimum area at or below the seat the controlling orifice.
Conventional safety relief valve	The spring housing is vented to the discharge side, meaning changes in backpressure directly impact the valve's operational characteristics.
Balanced safety relief valve	It includes a mechanism to minimize the impact of backpressure on its operational characteristics.
Pilot-operated pressure relief valve	The primary relieving device is integrated with and controlled by a self-actuated auxiliary pressure relief device.
Power-actuated safety relief valve	The primary relieving device is combined with and controlled by an externally powered device.
DIN 3320	
Standard safety valve (SV)	Upon opening, achieves the lift required to discharge the mass flow rate with a pressure rise of no more than 10%. This valve features a pop-type action and is also referred to as a high-lift valve.
Full-lift (Vollhub) safety valve	After starting to lift, it opens quickly to full lift within a 5% pressure rise, as limited by its design. The lift before rapid opening (proportional range) should not exceed 20%.
Direct loaded safety valve	The opening force beneath the valve disc is countered by a closing force, such as a spring or weight.
Proportional safety valve	It opens steadily in relation to pressure increases, avoiding sudden openings within a 10% lift range without a pressure rise. After opening, it reaches the necessary lift to discharge the mass flow with a pressure rise of no more than 10%.
Diaphragm safety valve	It uses a diaphragm to protect linear moving and rotating elements, as well as springs, from the effects of the fluid.
Bellows safety valve	Direct loaded safety valve. The sliding and (partially or fully) rotating elements, along with springs, are protected from fluid effects by a bellows designed to compensate for backpressure influences.
Controlled safety valve	Consisting of a main valve and a control device, it includes direct-acting safety valves with supplementary loading, where an additional force enhances the closing force until the set pressure is reached.
EN ISO 4126	
Safety valve	Automatically discharges a quantity of fluid, using only the energy from the fluid itself, to prevent exceeding a predetermined safe pressure. It is designed to re-close and stop further fluid flow once normal pressure conditions are restored. The valve may exhibit either pop action (rapid opening) or open in proportion (not necessarily linear) to the pressure increase above the set point.
Direct loaded safety valve	the loading from fluid pressure beneath the valve disc is countered solely by a direct mechanical loading device, such as a weight, lever and weight, or spring.
Assisted safety valve	It can be lifted through a powered assistance mechanism at a pressure lower than the set pressure, while still meeting all safety valve requirements outlined in the standard, even if the assistance mechanism fails.
Supplementary loaded safety valve	It utilizes an additional force to enhance the sealing force until the pressure at the valve inlet reaches the set pressure.

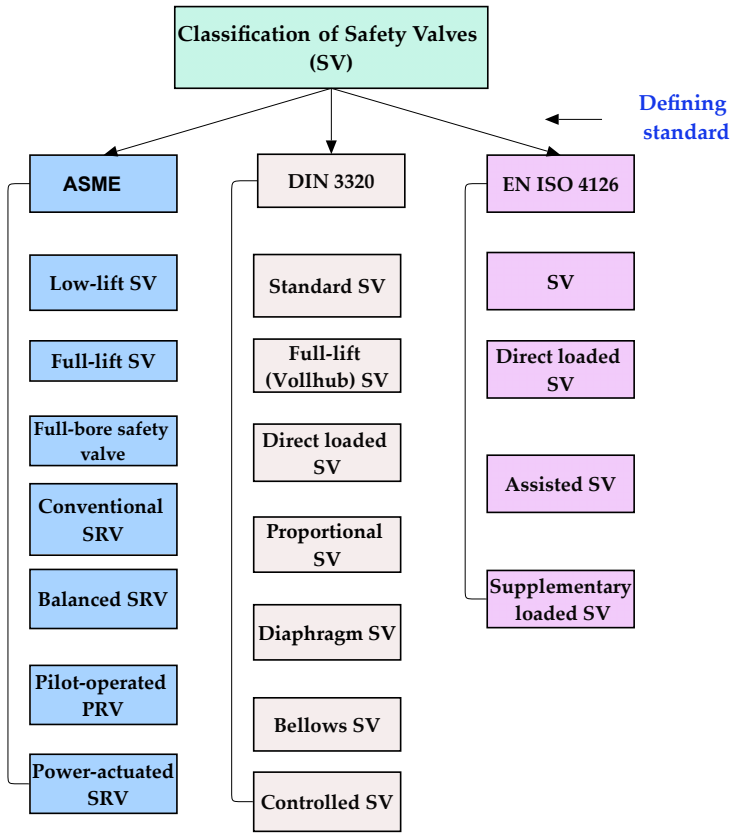


Figure 4. Classification of safety valves.

5. Design and Operation Principles

5.1. Discussion on the Working Principles of Safety Valves

Safety valves are critical components in various systems, especially in pressure vessels and boilers, ensuring safety by preventing overpressure; the working principles of safety valves are the followings:

1. Pressure monitoring: safety valves are designed to monitor the pressure inside a vessel or system. As the pressure rises, it is compared against the valve's set point for different conditions.
2. Spring mechanism: most safety valves employ a spring-loaded mechanism. The spring exerts a force that keeps the valve closed under normal operating conditions.
3. Set pressure: When the internal pressure exceeds a predetermined "set pressure", it overcomes the force exerted by the spring.
4. Opening Mechanism: once the set pressure is reached, the valve opens, allowing excess fluid (gas or liquid) to escape. This release of pressure prevents the system from reaching dangerous levels.
5. Full lift: as the internal pressure increases further, the valve will fully open, allowing maximum flow to disperse the excess pressure efficiently.
6. Closing mechanism: once the pressure drops back to a safe level (below the set pressure), the spring closes the valve again, sealing the system and restoring its normal operating conditions.
7. Types of safety valves: there are different types of safety valves based on their application, such as pop-off valves, balanced bellows valves, and pilot-operated valves, each having specific features to suit various system requirements.
8. Regular testing: safety valves should be regularly tested and maintained to ensure reliability and proper functioning. Table 4 provides a clear and organized overview of the

different types of safety valves, outlining their working principles, key components, and common applications [18,22,28,52,59–63].

Table 4. Working principles, key components, and common applications for common safety valves.

Working Principle	Key Components	Typical Applications
Check Valve		
Prevents backflow in a system. The valve opens when fluid flows in the desired direction and closes automatically to prevent reverse flow.	Disc, spring, seat, hinge, or lever	Water supply systems, sewage systems, pumps
Two-Way Valve		
Controls the flow of fluid in two directions. It can switch between sources or routes within a system based on operational settings.	Actuator, valve body, stem	HVAC systems, industrial pipelines
Pressure Regulating Valve		
Regulates downstream pressure by automatically opening or closing in response to upstream pressure changes.	Spring, diaphragm, adjustable set-point	Water distribution systems, gas distribution
Blow-off Valve		
Automatically releases excess pressure from a system to maintain balance without manual intervention.	Actuator, set pressure adjustment mechanism	Air compressors, pneumatic systems
Safety Relief Valve		
Combines features of relief and safety valves, opening to vent fluid when the set pressure is reached, and closes once normal pressure is restored.	Spring, disc, adjusting screw	Pressure vessels, oil and gas industries
Vacuum Relief Valve		
Opens to allow air into a system when a vacuum condition is detected, preventing collapse of vessels or piping.	Spring, disc, intake port	Storage tanks, pipelines subjected to vacuum
Standard Safety Valve		
Opens automatically when system pressure exceeds a set point, allowing rapid venting of fluid or gas.	Spring, disc, seat, adjustment mechanism	Boilers, pressure vessels, gas systems
Full Lift Safety Valve		
Opens fully at the set pressure to vent large volumes of fluid quickly, typically used in high-capacity situations.	Spring, disc, full-lift mechanism	Steam boilers, large pressure vessels
Direct Loaded Safety Valve		
Uses a direct application of pressure to overcome the spring force; the valve opens at set pressure without additional mechanisms.	Spring, disc, set lever or mechanism	High-pressure gas systems, industrial applications
Proportional Safety Valve		
Opens in proportion to the increase in pressure, allowing controlled venting as pressure varies.	Spring, piston or diaphragm, flow control device	Process control systems, natural gas pipelines
Diaphragm Safety Valve		
Utilizes a diaphragm to sense pressure and actuate the valve, providing good sealing and reliable performance.	Diaphragm, valve body, spring	Chemical processing, pharmaceutical industries
Bellows Safety Valve		
Has bellows that equalize pressure on both sides of the valve disc, minimizing the effect of back pressure.	Bellows, disc, seat	High-pressure steam systems, specialized chemical processes
Controlled Safety Valve		
Operated based on an external control signal (electrical or pneumatic) to modulate its opening and closing.	Actuator, control signals, feedback system	Automated systems, advanced manufacturing processes

5.2. Pressure Settings and Valve Response Under Different Conditions

Safety valves are vital safety devices commonly used to prevent overpressure in various applications such as boilers, pressure vessels, gas systems, and hydraulic systems. They consist of key components, including a body, spring, disc, seat, adjustment mechanism, and guide, designed to operate effectively under varying pressure conditions. Under normal operation, the internal system pressure remains below the valve's set pressure, keeping the valve closed due to the spring force. However, as pressure increases, it eventually overcomes the spring force, causing the valve to open and allowing excess fluid to vent, thereby reducing system pressure. This quick response and simplicity of design make spring-loaded safety valves reliable and compact, suitable for numerous applications. Once pressure falls back to a safe level, the valve re-seats to prevent leakage, ensuring the system is sealed. Various applications of spring-loaded safety valves include relieving pressure in boilers, protecting chemical processing equipment from dangerous overpressures, managing safe operation levels in gas pipelines, and preventing equipment damage in hydraulic systems.

To maintain their efficiency and safety, spring-loaded safety valves require regular testing to ensure they open at the correct set pressure and close fully afterward. Calibration of the spring tension is essential to maintain precise pressure settings. Additionally, thorough inspections should be conducted to identify any signs of wear, corrosion, or damage that could compromise functionality. Keeping detailed records of maintenance activities, testing, and any adjustments made can help track performance and ensure compliance with safety regulations. Understanding the design and operational principles of spring-loaded safety valves is crucial for engineers and maintenance personnel in managing pressure safely and effectively, as these valves act as essential protectors in various pressurized systems.

Operating principle: normal operation: under normal operating conditions, the pressure inside the system remains below the safety valve's set pressure, which is typically set at about 75–90% of the maximum allowable working pressure (MAWP). The force exerted by the spring keeps the valve closed, ensuring system integrity. For example, if the MAWP is 1034 kPa (150 psi), the set pressure might range from 775 to 930 kPa (112.5 to 135 psi). Pressure increase: as system pressure rises due to factors such as heating, fluid expansion, or operational anomalies, this increased pressure acts directly on the disc area of the valve. In steam systems, for instance, pressure could rise to over 1034 kPa (150 psi) under conditions of low water levels or high heat input. Opening point: when the internal pressure exceeds the predetermined set pressure (e.g., a safety valve may be set to open at 827 kPa (120 psi)), the force from the internal pressure acting on the disc surpasses the opposing spring force. This threshold is critical for activating the safety mechanism. Flow regulation: once the valve opens, it allows excess fluid (either gas or liquid) to escape, thereby reducing the pressure within the system. The amount of flow that escapes correlates with how far the valve opens. For example, a valve may be designed to allow a flow rate of several hundred to several thousand liters per minute, depending on its size and application. Re-seating: after the system pressure decreases back to a safe level, typically around 10% below the set pressure, the spring re-closes the valve. This action ensures that the system is sealed and can safely resume normal operations. The reliability of the spring's function is essential to prevent leakage, as any failure to re-seat could lead to pressure loss and operational inefficiency.

Detailed responses under specific conditions are presented in Table 5 [1,2,15,48,52,58,59,64,65].

Table 5. Responses under specific conditions for different safety valve types.

Condition Description	Response Description
Spring-Loaded Safety Valve	
A pressure boiler at 620 kPa experiences a pressure surge due to heating	Valve opens within milliseconds at 827 kPa to vent steam and prevent overpressure damage
Relief Valve	
An oil processing unit at 400 kPa faces a slow pressure buildup	Relief valve opens at 482 kPa, allowing oil to escape and stabilize the system without causing sudden pressure drops
Pilot-Operated Safety Valve	
A gas pipeline at 827 kPa faces a sudden pressure spike to 1034 kPa	Pilot valve detects pressure spike and opens the main valve to vent gas rapidly, reducing pressure quickly
Balanced Bellows Safety Valve	
A steam system at 690 kPa experiences a pressure increase due to water drop	Valve opens at 690 kPa to prevent pressure fluctuations, ensuring smooth operation
Fusible Plug Safety Valve	
A refrigeration unit operates normally but experiences overheating and reaches 130 °C.	The fusible material within the plug melts at 120 °C, opening the valve and allowing excess refrigerant to escape, thereby protecting the system from potential failure due to overheating.

5.3. Materials Used for Valve Components Based on Application

Table 6 provides a comprehensive overview of the materials used for different components in various types of safety valves [22,59–65]. The choice of materials is essential as it affects the valve's performance, durability, and compatibility with various fluids or gases.

Table 6. Common materials used for different safety valve components.

Components	Materials	Observations
Standard Safety Valve		
Spring	Stainless steel (e.g., 302, 316), Inconel, or carbon steel	Stainless steel is preferred for corrosion resistance.
Disc	Stainless steel, bronze, brass, or plastic (e.g., PTFE or PVC)	Materials chosen based on fluid compatibility.
Seat	Machined stainless steel, bronze, or hardened carbon steel	Should provide a good sealing surface.
Body	Cast iron, carbon steel, or stainless steel	Selection depends on pressure rating and application.
Full Lift Safety Valve		
Spring	Stainless steel (e.g., 316 or Inconel)	Must withstand high stress due to full lift operation.
Disc	Stainless steel or other alloys for high strength	High durability required due to full flow.
Seat	Hardened stainless steel or specialized alloys	Ensures tight sealing during operation.
Body	Carbon steel or forged steel	Dependent on pressure rating and environment.
Direct Loaded Safety Valve		
Spring	Stainless steel or Inconel	High fatigue resistance.
Disc	Stainless steel or other high-strength materials	Must be durable.
Seat	Stainless steel or plastic suitable for specific media	Should resist wear and corrosion.
Body	Carbon steel or stainless steel	Based on pressure ranges and service conditions.
Proportional Safety Valve		
Spring	Stainless steel or other high-grade materials	Selected for control and reliability.
Piston/Diaphragm	Nylon, PTFE, or rubber (e.g., EPDM, Viton)	Material depends on temperature and chemical compatibility.
Body	Stainless steel or brass	Chosen for strength and durability.

Table 6. *Cont.*

Components	Materials	Observations
Diaphragm Safety Valve		
Diaphragm	PTFE, rubber, or elastomer	Must be compatible with the fluid.
Spring	Stainless steel or Inconel	High strength and corrosion resistance required.
Body	Stainless steel or plastic	Resistant to corrosion and chemicals.
Bellows Safety Valve		
Bellows	Stainless steel (e.g., 316) or high-nickel alloys	Must withstand pressure and thermal cycles.
Disc	Stainless steel or high-strength alloys	Provide reliable sealing and durability.
Seat	Hardened stainless steel or specialized metal	Ensures a tight seal under varying conditions.
Body	Carbon steel or stainless steel	Selected based on operational pressure and environment.
Controlled Safety Valve		
Actuator	Aluminum, stainless steel, or plastic	Material choice based on application requirements.
Spring	Stainless steel or Inconel	Resistant to fatigue and environmental effects.
Body	Cast iron, carbon steel, or stainless steel	Sized for specific application needs.

In addition to the commonly used materials for safety valves (see Table 7 [15,18,33,58–60]), there are special materials that are utilized under specific conditions to ensure optimal performance, reliability, and safety.

Table 7. Special materials for safety valves to operate under extreme conditions.

Special Material	Applications and Notes
Special Condition: High-Temperature Environments	
Hastelloy, Inconel, Monel	Used for valves exposed to extreme temperatures (e.g., >400 °C). Hastelloy is known for its excellent oxidation resistance. Inconel and Monel provide high strength and corrosion resistance at elevated temperatures.
Special Condition: Corrosive Environments	
Tantalum, Zirconium, PTFE Lined	Ideal for applications involving aggressive chemicals, acids, or caustics. Tantalum and zirconium offer excellent chemical resistance, while PTFE lining provides non-stick and anti-corrosion properties.
Special Condition: Cryogenic Applications	
Austenitic Stainless Steel (e.g., 304L, 316L)	Suitable for low-temperature applications (e.g., liquefied gases) where ductility and toughness are essential at cryogenic temperatures.
Special Condition: Low-Pressure Applications	
Aluminum alloys	Used for lightweight valves in applications like air or steam systems where high strength is not as critical.
Special Condition: High-Wear Components	
Stellite, Hardened Steel	Employed in areas subject to frequent mechanical wear and erosion (e.g., valve seats, discs). Stellite is a cobalt–chromium alloy that resists wear and galling. Hardened steel provides extra toughness and wear resistance.
Special Condition: Severe Service Conditions	
Titanium, Carbon Fiber Reinforcements	Used in extreme operational conditions (e.g., high pressure combined with corrosive substances). Titanium offers a high strength-to-weight ratio and excellent corrosion resistance, while carbon fiber boosts load-bearing capabilities.
Special Condition: Pharmaceutical Applications	
316L Stainless Steel	Ensures high purity and cleanliness. Electropolishing decreases the surface roughness, reducing contamination risk and facilitating cleaning.
Special Condition: Hygienic Applications	
Food-grade materials (e.g., 304 or 316L Stainless Steel)	Used in food and beverage processing to comply with hygiene standards and prevent contamination. Special surface finishes (e.g., 3A sanitation standards) are often applied to enhance cleanliness.

6. Testing and Maintenance

Several significant industrial accidents have been attributed to the failure of safety valves, underscoring the critical importance of proper valve design, maintenance, and operational practices in ensuring safety in high-pressure environments. The "Piper Alpha disaster" in 1988, located in the North Sea, resulted in a catastrophic series of explosions and fires, leading to the tragic loss of 167 lives [55]. Investigations revealed that modifications to the platform had led to the failure of key safety relief systems, including improperly functioning safety valves, which exacerbated the situation by allowing pressure to build uncontrollably. Similarly, the "Bhopal gas tragedy" in 1984 remains one of the worst industrial disasters in history, where a catastrophic leak of methyl isocyanate (MIC) gas at the Union Carbide pesticide plant exposed more than 500,000 people to toxic substances [56]. The incident was significantly worsened by the lack of functional safety systems, including safety valves, which were inadequately designed and maintained, resulting in thousands of deaths and long-term health consequences for the affected population.

Another significant incident occurred at the "Chevron Richmond refinery" in California in 2012, where a fire erupted due to a corroded pipe that led to a failure in the safety valve mechanisms [66]. This incident not only resulted in injuries but also prompted a shelter-in-place order for nearby residents due to thick plumes of smoke. Additionally, a gas leak during maintenance work at "Hyundai Heavy Industries" in South Korea in 2012 led to multiple worker fatalities, primarily due to safety valves that were not properly calibrated or maintained, highlighting the need for better training and protocols in handling high-risk operations [67].

The infamous "Deepwater Horizon oil spill" in 2010, one of the largest marine oil spills in history, was linked to failures in blowout preventer (BOP) systems that include safety valves designed to prevent blowouts during drilling [68]. When these valves failed to operate effectively during a critical moment, it resulted in an explosive blowout that caused the tragic loss of 11 crew members and the release of approximately 4.9 million barrels of oil into the Gulf of Mexico, with devastating environmental impacts. Lastly, the "ExxonMobil Torrance refinery explosion" in 2015 was attributed to the failure of a safety valve that allowed for pressure buildup, resulting in a violent explosion that injured workers and caused extensive property damage and operational disruption [69].

These significant incidents highlight the dire consequences of inadequate safety valve performance and the essential need for rigorous testing, maintenance, and compliance with safety regulations across industries. They serve as poignant reminders of the importance of implementing robust quality assurance measures, adherence to regulatory standards, and a culture of continuous improvement in industrial safety practices to prevent similar tragedies in the future. The overarching lessons from these events stress the critical role that safety valves play in protecting workers, the environment, and the integrity of industrial operations.

To maintain their efficiency and safety, safety valves require regular testing. Guidelines suggest testing intervals can vary from annual to every five years based on the application and regulations. It is crucial that they open at the correct set pressure and fully close afterward.

Calibration of the spring tension is essential, typically adjusted in increments of 5 psi until the desired opening pressure is achieved. Additionally, thorough inspections should be conducted to identify any signs of wear, corrosion, or damage, which can impact functionality.

For example, visual inspections can be performed on a semi-annual basis, while more in-depth evaluations may be conducted annually.

Regular testing according to different standards ensures compliance and the effective functioning of safety valves in various applications, a comprehensive list of tests for safety valve reliability, along with specific names and their corresponding international standards is presented:

(a) Set pressure test:
- Purpose: verifies that the safety valve opens at the specified set pressure;
- Standard: ASME Boiler and Pressure Vessel Code (BPVC) Section I or VIII;
- Reference: ASME PTC 25 for testing methods;

(b) Leakage test:
- Purpose: ensures the valve does not leak when closed;
- Standard: API 527 (for blow-off and seat leakage tests);
- Reference: ISO 5208 (Industrial valves—Pressure testing of valves) for methods;

(c) Capacity test:
- Purpose: determines whether the safety valve can discharge the required flow rate;
- Standard: ASME PTC 25 or API 520/521;
- Reference: ASME BPVC Section I for setting capacity testing procedures;

(d) Re-seating test:
- Purpose: confirms that the valve properly closes after venting;
- Standard: ASME BPVC Section I and VIII;
- Reference: API 527 for guidelines on reseating tests;

(e) Functional test:
- Purpose: ensures the valve operates as intended under specified conditions;
- Standard: API 526 or ASME BPVC;
- Reference: ISO 4126 (safety devices for protection against excessive pressure);

(f) Cycle test:
- Purpose: assesses the durability and reliability of the safety valve through repeated cycles;
- Standard: ASME BPVC Section I or VIII;
- Reference: API 526 for testing protocols;

(g) Temperature test:
- Purpose: checks valve performance at specified temperature ranges;
- Standard: ASTM E1952 (standard guide for the testing of pressure relief valves);
- Reference: specific temperature ratings can reference ASME fittings or valve temperature classes;

(h) Vibration test:
- Purpose: evaluates valve performance under vibrational conditions typical in the operating environment;
- Standard: ISO 10816 (mechanical vibration—evaluation of machine vibration by measurements on non-rotating parts);
- Reference: API 610 for pumps may provide context for dynamic conditions, applicable to safety valves on pumps;

(i) Visual inspection:
- Purpose: identifies any visible signs of wear, corrosion, or damage;
- Standard: ASME B31.3 (Process Piping)—includes inspection requirements;

- Reference: NACE RP0188 for corrosion assessment;

(j) Documentation and traceability:

- Purpose: maintains records of pressure tests, repairs, and maintenance history;
- Standard: ISO 9001 (Quality Management Systems);
- Reference: API Spec Q1 (Specification for Quality Management System Requirements);

(k) Calibration check:

- Purpose: verifies that the pressure settings and indications are accurate;
- Standard: ISO 17025 (general requirements for the competence of testing and calibration laboratories);
- Reference: ASME PTC 19.1 (Test Codes);

(l) Dynamic response test:

- Purpose: evaluates how quickly and effectively the valve reacts to system pressure changes;
- Standard: IEC 61508 (functional safety of electrical/electronic/programmable electronic safety-related systems) for controlled systems;
- Reference: API 520 for guidelines.

Table 8 provides a comprehensive overview of the tests, the equipment used, and notable manufacturers of the equipment necessary for ensuring the reliability and performance of safety valves [1,22,33,58–61,63,65]. By combining this information, you can gain insights into the practical application of testing safety valves in real-world scenarios.

Table 8. Equipment and manufactures for testing safety valves.

Purpose	Equipment	Manufacturers
Set Pressure Test		
Verifies that the safety valve opens at the specified set pressure.	Pressure Calibration System, Hydraulic Test Pump, Pressure Gauge	Fluke (Pressure Calibrators), Ametek (Test Pumps)
Leakage Test		
Ensures the valve does not leak when closed.	Leak Detector, Hydraulic Press, Bubbler Test Equipment	Klein Tools (Leak Detectors), Parker Hannifin (Hydraulic Test Equipment)
Capacity Test		
Determines whether the safety valve can discharge the required flow rate.	Flow Meter, Pneumatic/Hydraulic Test Bench, Data Acquisition System	Endress + Hauser (Flow Meters), Emerson (Test Benches)
Re-seating Test		
Confirms that the valve properly closes after venting.	Pressure Test Setup, Flow Meter, Recording Gauge	Omega Engineering (Pressure Gauges), Wika (Pressure Measurement Equipment)
Functional Test		
Ensures the valve operates as intended under specified conditions.	Test Bench, Dynamic Pressure Controller, Data Logger	Siemens (Test Benches), National Instruments (Data Loggers)
Cycle Test		
Assesses durability and reliability through repeated cycles.	Automated Test Rig, Pneumatic Cylinder, Cycle Counter	Honeywell (Automated Test Rigs), Festo (Pneumatic Cylinders)
Temperature Test		
Checks valve performance at specified temperature ranges.	Environmental Chamber, Thermocouples, Temperature Data Logger	Thermo Scientific (Environmental Chambers), Omega Engineering (Thermocouples)

Table 8. *Cont.*

Purpose	Equipment	Manufacturers
Vibration Test		
Evaluates valve performance under vibrational conditions.	Vibration Testing System, Accelerometers, Dynamic Signal Analyzers	Bruel & Kjaer (Vibration Testing Equipment), PCB Piezotronics (Accelerometers)
Visual Inspection test		
Identifies visible signs of wear, corrosion, or damage.	Magnifying Glass, Borescope, Non-destructive Testing (NDT) Equipment	X-Rite (Borescopes), General Electric (NDT Equipment)
Documentation and Traceability		
Maintains records of tests, repairs, and maintenance history.	Quality Management Software, Document Control Systems	SAP (Quality Management Software), Seamless Docs (Document Control)
Calibration Check		
Verifies accuracy of pressure settings and indications.	Calibrated Pressure Gauges, Multifunction Calibrator	Fluke (Calibrators), Alexander & Associates (Calibrated Equipment)
Dynamic Response Test		
Evaluates reaction speed and effectiveness under pressure changes.	Dynamic Pressure Controller, Real-Time Data Acquisition System	Keysight Technologies (Dynamic Controllers), National Instruments (Data Acquisition Systems)

A well-structured maintenance plan for safety valves is essential to ensure their reliable operation and compliance with relevant standards and codes. A comprehensive overview of a maintenance plan, including recommended frequencies, procedures, and references to industry standards and codes must contain the following:

- Routine inspections. Frequency—at least annually or according to the manufacturer's recommendations and specific regulations applicable to the industry. Activities—visual inspection for signs of damage, wear, or corrosion. Check for proper valve identification and labeling. Inspect for leaks or signs of pressure loss around the valve. Standards/references—ASME Boiler and Pressure Vessel Code (BPVC) Section I for boilers and Section VIII for pressure vessels. API Recommended Practice 576 for inspection of pressure-relief devices;
- Operational testing. Frequency—annually or more frequently as required by specific applications or regulatory mandates. Activities—conduct a set pressure test to verify that the valve opens at specified pressure settings. Perform a leakage test to ensure the valve properly seals in the closed position. Operational tests to ensure the valve functions correctly under various conditions. Standards/references—API 526 for steam relief valves. ASME PTC 25 for performance testing of pressure relief devices;
- Calibration. Frequency—every 3 to 5 years or according to specific service demands and conditions. Activities—calibrate the valve's set pressure using calibrated test equipment. Document the calibration process and results in maintenance records. Standards/references—ISO 17025 for calibration and testing laboratory standards. ASME PTC calibration guidelines;
- Maintenance and repairs. Frequency—as required based on inspection or testing findings. Activities—repairs to seals, gaskets, or any damaged components should be performed as needed. For valves that have been removed for maintenance, perform checks for corrosion damage or wear. Reassemble and conduct functional checks after repairs. Standards/references—API 527 for repair procedures and guidelines for pressure relief devices. Manufacturer guidelines for specific maintenance practices;

- Documentation. Frequency—ongoing, with records updated after each maintenance activity. Activities—maintain records of inspections, tests, repairs, and calibrations. Document any changes made to the valve settings or configurations. Standards/references—ISO 9001 for maintaining quality management systems and documentation practices. API Recommended Practice 580 for risk-based inspection and management of equipment;
- Replacement. Frequency—as necessary or based on performance and age of the valve. Activities—evaluate the performance history and condition; if the valve routinely fails tests or shows excessive wear, consider replacement. Follow manufacturer guidelines for selecting and installing replacement valves. Standards/references—ASME BPVC for guidelines regarding the retirement of equipment. Industry best practices for the disposal of old valves and installation of new devices.

The standards and tools mentioned were chosen based on their global recognition, relevance to the diverse applications of safety valves, and their ability to address industry-specific needs effectively. For instance, the ASME Boiler and Pressure Vessel Code (BPVC) is widely adopted for its rigorous guidelines ensuring safety valve reliability across critical sectors like power generation and oil and gas. Similarly, ISO and API standards provide specialized testing protocols, such as ISO 5208 for leakage testing and API 526 for cycle testing, which address both general and niche operational requirements. These standards are prioritized because they ensure compliance with regulatory norms while supporting the safe and efficient functioning of safety valves under varying industrial conditions.

7. Technological Advancements in Safety Valves

7.1. Recent Innovations and Smart Safety Valves

Studies considered for analyzing the technological advancement themes collectively emphasize the development of advanced fault diagnosis methods, the application of machine learning techniques to enhance diagnostic accuracy, and the rigorous performance evaluation of these models. These advancements contribute significantly to improving the reliability and efficiency of various hydraulic and control systems. Smart safety valves represent a significant advancement in industrial safety and automation [21,70]. The SmOP system [71] involve valves integrated with sensors, control systems, and connectivity features that enable real-time monitoring, automatic adjustments, and predictive maintenance capabilities. The production of basic and specialty chemicals is foundational for nearly all commercially produced goods. These chemicals are synthesized in reactors, often involving hazardous reactants or solvents. Operational disruptions—such as cooling failure, incorrect reactant dosing, agitator malfunction, or premature catalyst activation—can lead to "runaway" reactions, where rising reactor temperatures significantly accelerate reaction rates. In exothermic processes, this can result in rapid energy release, causing potentially hazardous temperature and pressure increases. To safeguard equipment and maintain safe operating conditions, industries employ mechanical safety devices alongside safety-related programmable logic controllers (sPLCs) [47]. The following paragraph reveals a classification regarding their functionalities and benefits (Figure 5).

A. Real-Time Monitoring and Diagnostics

Smart safety valves continuously collect data on pressure, temperature, flow rate, and other critical parameters and can detect early signs of wear, leaks, or blockages, helping operators intervene before issues escalate. This real-time feedback loop allows for immediate adjustments to maintain safe and efficient operation.

B. Predictive Maintenance

With the integration of machine learning algorithms [61], smart safety valves can analyze historical and real-time data to predict potential failures, so this predictive capability reduces unplanned downtime by enabling scheduled maintenance before critical parts reach failure points, predictive maintenance also reduces maintenance costs and extends the lifespan of the valve, contributing to more sustainable industrial practices. As computing technology advanced, traditional machine learning methods like support vector machine (SVM), K-nearest neighbor (KNN), and random forest (RF) were introduced in valve fault diagnosis, as depicted in Table 9.

Table 9. Machine learning methods used valve fault diagnosis.

Machine Learning Methods		
Support Vector Machine (SVM)	K-Nearest Neighbor (KNN)	Random Forest (RF)
Synthetized Subjects Approached		
This paper proposes a non-intrusive solenoid valve fault diagnosis method that combines time–frequency and time–domain analyses of current signals for fault pattern recognition. The method uses the solenoid valve's driving end current and its second-order rate of change to extract time–domain parameters and frequency band energy as key diagnostic features [72]. To accurately identify fault types in EHSVs and address issues in traditional diagnostic algorithms, this paper develops a fault diagnosis model based on a simulated annealing particle swarm optimization (SA-PSO)-enhanced support vector machine (SVM). The SA-PSO-optimized SVM model uses static no-load flow, pressure, and internal leakage as input data, with a designated label as the output result. Compared with standard SVM and PSO-SVM models, this model demonstrates superior performance, achieving a classification accuracy of 99.3% and high stability [73]. In the [74] work, a multiple-kernel support vector machine (MK-SVM) algorithm is proposed for diagnosing simultaneous faults in a distillation column. The developed MK-SVM algorithm employs a multilabel approach with various kernel functions to classify these concurrent faults. Data for normal and faulty operations are generated through dynamic simulation of a pilot-scale distillation column using Aspen Plus.	The [75] study applied a discrete wavelet transform for time–frequency analysis of acoustic emission (AE) signals, followed by classification of valve conditions and flow rate estimation for faulty valves at 450–750 rpm. K-nearest neighbors (KNNs) and support vector machine (SVM) classifiers identified valve conditions, with flow rate predicted through a regression model, achieving 74.5% to 98.8% accuracy. Valve leakage loss was then estimated by comparing the flow rate of the faulty valve to a baseline using AE parameters. Multiple fault time-series samples [76] of the control valve at various openings were collected for fault diagnosis to assess the effectiveness of the proposed method. The impact of this method on missing data imputation and fault diagnosis was analyzed. When compared to random imputation and k-nearest neighbor (KNN) imputation, the accuracies of the MM-based imputation were improved by 17.87% and 21.18%, respectively, with under a 20.00% missing data rate with valve openings ranging from 10% to 28%.	An intelligent fault diagnosis method utilizing Dempster–Shafer (DS) theory [49] is proposed for the detection of multiple faults in hydraulic valves. This approach falls under ensemble learning within the framework of information fusion theory. Initially, signal segments containing fault information are selected to create sample sets. These sample sets are then simultaneously input into individual classifiers, including long short-term memory networks (LSTM), convolutional neural networks (CNNs), and random forests (RFs). The paper [77] presents a simulated annealing wrapped generic ensemble fault diagnosis strategy for common VRF system faults, including refrigerant charge amount (RCA) faults, valve faults, and compressor liquid return (LF) faults. The strategy employs a simulated annealing algorithm based on random forest (SA-RF) for feature selection, identifying optimal variables that effectively characterize fault states, thereby enhancing modeling efficiency and reducing data dimensionality.

C. Remote Control and Automation

Smart safety valves are often connected to centralized control systems, allowing operators to remotely adjust valve settings or shut down systems in emergencies.

Automated response protocols can be programmed into the system to close or open valves based on preset thresholds, minimizing human intervention and reaction time. This remote accessibility is particularly valuable in hazardous or hard-to-reach environments.

D. Enhanced Safety through Self-Diagnostics

Smart valves perform regular self-diagnostics, identifying issues such as incorrect positioning, sensor malfunctions, or software errors. They ensure that the valve operates within safe parameters, reducing the likelihood of catastrophic failures.

These diagnostics improve compliance with safety standards and reduce liability risks associated with equipment malfunction.

E. Integration with Industrial IoT (IIoT)

Smart safety valves are compatible with Industrial Internet of Things (IIoT) networks, allowing seamless integration with other smart devices and systems within a facility. This integration enables comprehensive data analysis across the entire plant, leading to optimized system performance and resource usage. IIoT connectivity also supports cloud-based monitoring, providing remote access to valve data and enabling advanced analytics [62].

F. Application Areas

- ✓ Oil and gas industry: smart valves enhance safety in high-pressure environments, preventing leaks [78] and blowouts;
- ✓ Chemical processing: they monitor toxic or corrosive materials, ensuring safe containment and handling;
- ✓ Water treatment plants: smart valves help regulate water pressure and flow, optimizing resource usage;
- ✓ Manufacturing: they support automation and quality control, ensuring precise control over production processes.

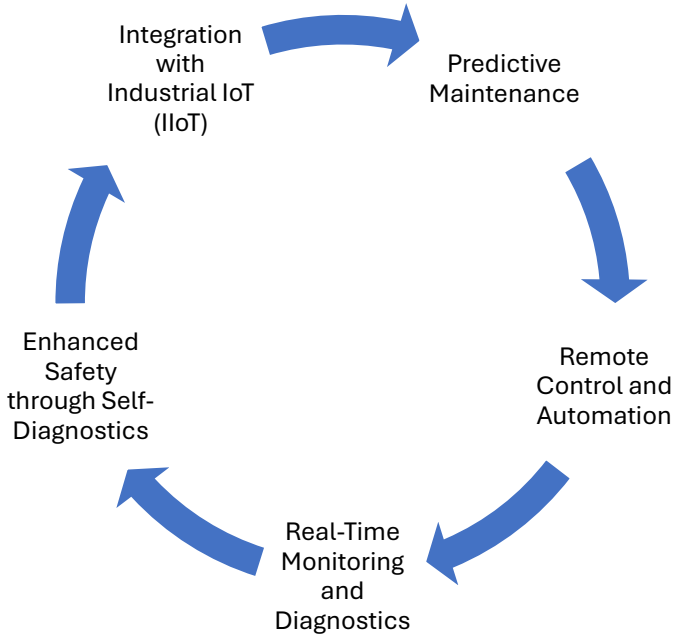


Figure 5. Recent innovations and functionality of smart safety valves.

7.2. Technological Innovations and Industrial Impacts

Chevron implemented smart safety valves equipped with real-time monitoring and control systems in their offshore drilling platforms. These valves reduce the risk of blowouts by detecting pressure anomalies early and enabling remote emergency shutdowns. This enhances operational safety and cuts costs associated with manual checks and downtime [46].

BP Deepwater Operations uses advanced safety valves integrated with predictive maintenance systems. By leveraging IoT connectivity, they reduced unplanned shutdowns by 15%, saving millions in operational costs annually [46].

BASF Chemical plants integrated automated safety valves with predictive maintenance algorithms in their production lines. This setup prevents chemical leaks by detecting early wear in valve seals, reducing environmental risks and avoiding penalties for non-compliance with safety regulations [64].

Siemens Energy installed smart safety valves in power plants to optimize steam flow management. The valves are connected to central control systems that automatically adjust operation parameters for peak efficiency, reducing energy consumption and maintenance costs [65].

Thames Water uses smart safety valves to regulate the flow of water and chemicals in treatment processes. These valves minimize resource waste, reduce operational costs, and enhance the reliability of water delivery systems [79].

In their manufacturing plants, Toyota implemented smart valves in pressurized systems for paint and coating applications. The valves' real-time feedback system reduced paint waste by 20%, resulting in significant material savings and environmental benefits [48].

These examples illustrate the diverse applications and tangible benefits of adopting modern safety valve technologies across industries.

The use of additive manufacturing (3D printing) has revolutionized the production of valve components. By allowing for the creation of complex geometries and reducing material waste, 3D printing enhances customization and reduces inventory costs. This technology not only speeds up production but also reduces costs related to storage and delivery [80].

The ongoing development in AI and machine learning could make smart safety valves even more autonomous, potentially handling complex decisions without human input.

Cybersecurity remains a key challenge, as connectivity increases vulnerability to cyber-attacks. Enhanced encryption and security protocols are essential.

Standardization of smart valve technology across industries will also be critical, as compatibility issues could limit widespread adoption. Table 10 presents key technical specifications of smart safety valves, including inflow and outflow rate volumes, dimensions, weights, energy consumption, and material choices. It highlights the suitability of these valves for various industrial sectors, with a particular focus on renewable energy infrastructure such as wind, solar, and biogas plants. Additionally, it covers the environmental and safety considerations relevant to each application.

Table 10. Specifications of smart safety valves for industrial and renewable energy applications.

Specification	Application	Correlation with Industry Sectors	Renewable Energy Suitability	Environment and Safety
Inflow Rate (m^3/h) 10–1000	Smart valves designed for monitoring and controlling flow.	Oil and Gas: Offshore platforms, pipeline systems, refineries. Water Treatment: Chemical dosing, filtration.	Biogas Plants: Gas flow control for anaerobic digestion. Hydropower: Water flow regulation in turbines.	Compliance with environmental regulations for waste discharge (e.g., EPA for water treatment).
Outflow Rate (m^3/h) 8–800	Smart control of liquids, gases, and steam.	Power Plants: Steam management, cooling systems, turbine regulation. Manufacturing: Chemical processing.	Solar Thermal Power: Steam valves for energy production. Wind Farms: Gas flow in lubrication systems.	Ensure proper venting systems to avoid environmental contamination.

Table 10. *Cont.*

Specification	Application	Correlation with Industry Sectors	Renewable Energy Suitability	Environment and Safety
Dimensions (mm) 100 × 50 × 200 to 500 × 300 × 1000	Smart valves in compact or large sizes based on system needs.	Aerospace: Space-constrained valves for fluid handling. Manufacturing: Custom sizes for specific applications.	Wind Turbines: Compact valves for lubrication systems. Hydropower: Large valves for water flow control.	Dimension specifications must meet regulatory standards for safety and installation space (e.g., OSHA).
Weight (kg) 5–150	Light- or heavy-duty smart valves for different applications.	Oil and Gas: Heavy-duty valves for high-pressure systems. Agriculture: Lightweight valves for irrigation systems.	Solar Farms: Lightweight valves for water or cooling systems. Biomass Plants: Lightweight, durable valves for solid fuels.	Valves must be made from eco-friendly materials that comply with recycling standards.
Energy Consumption (kWh) 0.1–2.5	Low-energy consumption for continuous monitoring.	Chemical Plants: Energy efficient valves for managing chemical reactions. Power Plants: Steam and heat management for optimal performance.	Solar Thermal: Energy-efficient valves for steam and heat management. Biogas: Low-energy valves for gas flow regulation.	Low energy consumption minimizes environmental impact. Compliance with energy-saving standards (e.g., ISO 50001).
Materials Stainless steel, brass, polymers, composites, alloys	Smart valves use advanced materials for durability, corrosion resistance, and low maintenance.	Oil and Gas: Corrosion resistant materials for harsh environments. Water Treatment: Chemicals-resistant materials.	Solar and Wind: Lightweight composites for corrosion resistance. Biogas Plants: Resistant polymers for handling corrosive gases.	Materials must meet RoHS, REACH, and sustainability standards for responsible sourcing and recyclability.
Suitability for Renewable Energy Smart valves designed for renewable energy infrastructure, offering efficiency and integration.	Smart valves control flow, optimize energy usage, and integrate with smart grids.	Wind Farms: Smart valves for hydraulic systems and lubrication. Solar Thermal: Steam flow control in solar thermal plants.	Geothermal: Smart control for steam and fluid regulation. Hydropower: Automated valve control for optimal water flow.	Ensures minimal environmental impact by integrating energy-efficient technology.
Pressure Rating (bar) 10–2000	Smart valves optimized for high- or low-pressure systems, with real-time monitoring and adjustment.	Oil and Gas: High-pressure smart valves for upstream and downstream operations. Power Plants: Steam pressure regulation.	Hydropower: Smart high-pressure control for turbines. Geothermal: Pressure control in deep wells and steam extraction.	Compliance with safety standards for pressure systems (e.g., ASME, API).
Flow Control Technology Manual, pneumatic, electric, hydraulic, IoT-enabled, smart control	Technology-driven control for automated, predictive maintenance and real-time adjustments.	Manufacturing: Automated control systems for efficiency. Oil and Gas: IoT-enabled smart valves for remote monitoring.	Wind Energy: IoT or smart control for regulating air or fluid flow. Solar Thermal: Automated flow for energy optimization.	Compliance with automation and control standards (e.g., IEC, ANSI).
Maintenance Requirements Low maintenance, predictive analytics for failure prevention, smart diagnostics	Continuous monitoring to predict and reduce down-time and improve lifespan.	Oil and Gas: Predictive maintenance to avoid unplanned shutdowns. Water Treatment: Automated diagnostics for optimal flow control.	Wind: Predictive maintenance to ensure long operational lifespans. Solar: Smart diagnostics to reduce maintenance needs.	Reduces environmental waste by extending valve life and minimizing downtime. Promotes sustainability through IoT maintenance systems.

Smart safety valves offer several advantages over traditional systems [22,53,78,81,82]. For instance, they respond much more quickly due to integrated sensors that detect pressure changes almost immediately, whereas traditional valves rely on mechanical mechanisms that are slower to react. Additionally, smart valves are equipped with predictive maintenance features, which continuously monitor performance and alert operators when maintenance is needed, reducing the risk of unexpected failures and minimizing downtime. In contrast, traditional valves often require manual inspections and are prone to undetected malfunctions. Furthermore, smart valves integrate seamlessly into automated control systems, allowing for real-time adjustments based on operational conditions, which enhances both safety and efficiency compared to traditional valves.

7.3. Practical Impact of Safety Valves in Various Industries

Oil and gas industry: pressure relief valves (PRVs). In oil refineries and natural gas processing plants, pressure relief valves are crucial for safety. They are strategically placed on vessels and pipelines to automatically release gases or liquids when pressure exceeds set thresholds due to equipment failure or operational changes. For instance, during an emergency shutdown or an unexpected chemical reaction resulting in a pressure spike, PRVs prevent catastrophic failures by safely releasing the excess pressurized fluid to a flare, where it is burned off safely.

Chemical manufacturing: rupture discs and relief valves. Chemical plants handle volatile substances that require precise pressure control. A rupture disc is a non-reclosing pressure relief device that acts as a safety barrier until an overpressure incident occurs, at which point it bursts open. This device is often used in tandem with relief valves, allowing for an immediate release that avoids the buildup of dangerous pressure levels. This setup is essential in chemical reactors or storage tanks containing reactive or hazardous chemicals, ensuring a secondary layer of protection.

Power generation: steam safety valves in boilers. Boilers in power plants operate under high pressure to generate steam for turbines. Safety valves are installed to open at predetermined pressures, permitting the discharge of steam into the atmosphere or a condensing unit. These valves are designed in accordance with stringent standards such as those set by ASME, which specify rigorous testing and material requirements. In the event of a failure in the control system preventing proper pressure regulation, these valves avert potential catastrophic explosions, protecting both equipment and personnel.

Pharmaceutical industry: aseptic safety valves. Cleanliness and pressure control are critical in pharmaceutical manufacturing, where contamination can render entire batches unusable. Aseptic safety valves are employed in systems handling sterile liquids or gases, ensuring any pressure relief maintains the sterile environment. Such valves are typically designed with smooth surfaces and minimal crevices to prevent bacterial growth and are integrated into sterilization-in-place and cleaning-in-place systems.

Food and beverage industry: vacuum relief valves in storage tanks. During processes such as cooling after pasteurization, the pressure inside storage tanks can change rapidly. Vacuum relief valves are installed to protect the structural integrity of these tanks by allowing air to enter if a vacuum condition arises due to a temperature drop. This prevents tank implosion and maintains product integrity. These valves are critical for maintaining hygiene standards and preventing mechanical failure.

Automotive industry: fuel tank safety valves. In vehicles, fuel tanks are equipped with safety valves to manage pressure variations caused by temperature changes or fuel expansion. These valves protect the tank from rupturing under high-pressure conditions, such as those generated by intense heat during driving or when parked in the sun. This

functionality not only ensures vehicle safety by mitigating burst risks but also helps in controlling evaporative emissions, making vehicles more environmentally friendly.

These detailed examples demonstrate how safety valves are integral to operational safety and efficiency across different industries, adhering to specific regulatory standards that ensure their reliability and effectiveness in preventing accidents.

7.4. Future Research Directions Associated with Safety Valves

Analyzing the available bibliography, the main recommendations for future research directions in the field of safety valves were extracted.

- ✓ Material innovations: investigate the development and application of advanced materials that can withstand extreme temperatures and corrosive environments, enhancing the longevity and reliability of safety valves;
- ✓ Enhanced pressure-release mechanisms: explore innovative designs for pressure-release mechanisms that can improve response times and accuracy in high-stress situations, thereby increasing overall safety;
- ✓ Integration of fail-safe features: study the implementation of fail-safe designs that ensure safety valves can still operate effectively even in the event of a primary system failure;
- ✓ Agile manufacturing practices: analyze how agile manufacturing methodologies can improve the production efficiency and customization of safety valves to meet evolving industry needs;
- ✓ Digital solutions and automation: research the impact of automation technologies and digital tools, such as IoT sensors, on monitoring safety valves' performance, facilitating real-time data analysis, and optimizing operational efficiency;
- ✓ Simulation and modeling advances: develop advanced computational fluid dynamics (CFDs) and modeling techniques to better predict the behavior of safety valves under varied operational conditions, enabling improved designs;
- ✓ Predictive maintenance techniques: investigate predictive maintenance methodologies that leverage data analytics and machine learning to forecast potential failures and minimize downtime in valve operations;
- ✓ Environmental impact assessments: conduct research into the environmental effects of safety valve materials and operations, aiming to enhance sustainability in manufacturing and product design;
- ✓ Integration of smart technologies: explore the integration of smart technologies, such as machine learning algorithms, for adaptive control of safety valves in response to changing operational parameters;
- ✓ Standardization of testing protocols: advocate for the development and standardization of testing protocols across manufacturers to ensure consistency in safety valve performance evaluation;
- ✓ User training and awareness programs: develop training programs that educate users and maintenance personnel on emerging technologies and best practices for safety valve management;
- ✓ Market trends and user needs: research market trends to align safety valve development with user needs and regulatory requirements, ensuring that innovations effectively address current industry challenges.

By delving into these areas, future research can contribute significantly to technological advancements and improvements in safety valve performance and reliability across various applications.

8. Finite Element Method and Experimental Analysis in Relief Valves Working Process

The finite element method, as a powerful computational tool, allows for detailed simulation and analysis of stress distribution, deformation, and flow dynamics in relief valve components under different operating conditions. Coupling FEM with experimental analysis enhances the accuracy and reliability of these simulations, providing valuable insights into valve behavior under high-stress scenarios. Experimental validation is essential to ensure that FEM models accurately replicate real-world performance, thereby informing design optimizations and improving the valve's reliability and safety across its operational lifespan. This section explores the integration of FEM with experimental approaches to capture a comprehensive understanding of relief valve functionality.

According to [3], the total force acting on the disk (F_x) is a result of the pressure on the upstream side of the disk at the nozzle exit (p_N), the backpressure on the downstream side of the disk (p_B), and the momentum transfer from the fluid stream impacting on the disk. The nozzle pressure (p_N) is related to the vessel pressure (p_0) through the fluid dynamics in the upstream piping (including friction loss, acoustic coupling inertia, and dynamic capacitance).

It is presented in studies [45,50] that the total force acting on the disk can be calculated by relation (1), where F_0 represents the pretension force.

$$F_x(t) = F_p(p) + F_m(x, p) + F_i(x) - F_0 \tag{1}$$

where p is the pressure acting on the disk, and x is the displacement, [MPa]. The other forces involved in relation (1) are presented below.

Pressure force: the force given by the static pressure difference Δp across the valve between the variable upstream pressure p and the downstream pressure p_0. It depends on the volumetric flow rate, and it generates a pressure force given by the relation (2):

$$\mathrm{F_p(p)} = \mathrm{A_p}\cdot\Delta\mathrm{p} = \mathrm{A_p(p - p_0)} \tag{2}$$

where A_p is the total area on the valve upon which the fluid pressure (p) acts, [mm^2] [50].

Impact force: the effect of impact at the lower and upper bounds x_1 and x_2 is modeled by a force term given by relation (3) [50,57]. According to these sources, the impact force models the repulsion during impact using a stiff spring constant $k_i = 10^9 \ldots 10^{10}$ N/m, much larger than the system stiffness ($k_i \gg k$).

$$F_i(x) = \begin{cases} -k_i(x - x_i) & , x \le x_1 \\ 0 & , x_1 < x < x_2 \\ -k_i(x - x_2) & , x \le x_2 \end{cases} \tag{3}$$

Momentum force: due to the redirection of the fluid jet by the valve surface, a momentum change is considered by the force given by relation (4) [50]:

$$F_m(x, p) = \frac{C_f \rho}{A_p}\left[A_v(x)\cdot C_{d,v}\sqrt{\frac{2p}{\rho}}\right]^2 \tag{4}$$

where C_f is an empirically determined momentum coefficient which controls the relative amount of transferred momentum. $C_{d,v}$ and $C_{d,b}$ are accurately chosen to reflect the transition from laminar to turbulent flow. The valve opening section $A_v(x)$ is a direct function of the flow perimeter of the valve and the displacement which gives a generated surface for

the flow given by relation (5) [50,57,83]. The flow proportionality coefficient α is used to adjust the actual flow area depending on the geometry.

$$A_v(x) = \alpha \pi d_v x \tag{5}$$

where d_v is the flow diameter of the valve, [mm].

For a constant driving force, the dynamic response of the system is described by the angular frequency which is given by the relation (6), regarding the undamped working conditions, and is expressed as follows:

$$\omega_n = \sqrt{k/m} \tag{6}$$

With respect to the units previously presented, the angular frequency is expressed as rad/sec.

Considering the real environment of the valve, and with any mechanical system having its own damping, the damp factor is given by the relation (7):

$$\nu = b/2m\omega_n \tag{7}$$

The valve is over-damped if $\nu > 1$, critically damped if $\nu = 1$, and will oscillate if $\nu < 1$. The valve opens when $F_x > F_0$ and closes when $F_x < F_0$, where F_0 is the force on the disk corresponding to the spring compression at the set pressure (x_0). Regarding relations (1) and (2), and according to [3,4], the displacement of one degree of freedom in the system describes a waveform modulated in amplitude.

When the disc oscillates slightly, the mass-spring system can be regarded as a linear system, and the principle can be used to simplify complex problems. Considering that the excitation force on the disk is described by the harmonic law (8), the differential equation of displacement can be put in form (9) [83].

$$F_x(t) = F\cos\omega t = kA\cdot\cos\omega t \tag{8}$$

$$m\ddot{x} + b\dot{x} + kx = kA\cos\omega t \tag{9}$$

where capital A refers to the equivalent displacement of the excitation force, [mm].

The solution of the Equation (9) can be put in the form given by (10) regarding the complex nature of problem.

$$x(t) = \frac{A}{\sqrt{\left(1-\frac{\omega^2}{\omega_n^2}\right)^2 + \left(2\nu\frac{\omega}{\omega_n}\right)^2}}\cos(\omega t - \theta) \tag{10}$$

where θ is phase shift of the oscillation given by relation (11), [rad].

$$\theta = \tan^{-1}\frac{2\nu\frac{\omega}{\omega_n}}{1-\left(\frac{\omega}{\omega_n}\right)^2} \tag{11}$$

Table 11 provides a summary of different studies that analyze the behavior and performance of safety relief valves using both computational and experimental techniques.

While the literature extensively addresses traditional safety valve designs and regulatory standards, emerging trends such as smart safety valves with integrated sensors and predictive maintenance capabilities remain underexplored. These technologies, aligned with Industry 4.0 principles, represent a transformative shift in industrial safety by enabling real-time monitoring and automated adjustments.

Table 11. Overview on safety valves experimental and numerical analyses.

Source	Analyses	Discussion and Results
[51]	In this study, a quadratic model using RSM, suggested by the software Design-Expert 8.05b, was used for design and data analysis. The reference pressure over all the domains was defined as the atmospheric pressure. The initial gauge pressure in the test vessel domain was set as 7.2 MPa, which is equal to the set pressure of the NPMS PRV. The inlet condition of the test vessel was set at a constant gauge pressure of 7.26 MPa (relieving pressure). The initial pressures in the other domains were set as 0 MPa. During the dynamic simulation, the inlet to the test vessel was changed from a constant pressure (7.26 MPa) condition to a wall condition.	The PRV with the backpressure chamber started to close at 7.001 MPa, which is 0.435 MPa higher than that in the case without a backpressure chamber. This is because steam accumulates in the backpressure chamber and generates a downward force on the moving parts of the PRV during discharge. The reseating pressures for the cases without and with the backpressure chamber were 5.895 and 6.801 MPa, respectively, indicating a decrease in blowdown from 18.13% to 5.50%. Because of this decrease, the ASME III PRV setting requirements are satisfied.
[84]	The k−ε two-equation turbulence model uses the gradient diffusion hypothesis to relate the Reynolds stresses to the mean velocity gradients and the turbulent viscosity. The average outlet pressure is equal to 1 bar (absolute). The inlet pressure ranges from 0.3 MPa to 1.3 MPa (0.3, 0.5, 0.7, 0.9, 1.1, and 1.3 MPa). The inlet temperature is equal to the saturation temperature for the inlet working pressure. The logarithmic wall function is used, and the profile is corrected to incorporate fluid compressibility effects, using an equivalent roughness of all internal surfaces equal to 0.2 mm according to the valve design. There is a symmetry boundary condition in the xz plane. Nozzle opening ranges from 3 mm to 18 mm (3, 6, 9, 12, 15, and 18 mm).	Although this CFD study has not been validated experimentally, numerical validation has been compared to extensive experimental data and a wide range of flow conditions. The CFD simulations showed that average normal disc force is about 19% lower than theoretical ASME force, which could prevent the valve oversizing. From the total opening (18 mm) up to 9 mm, there were no large variations in the maximum deviation; however, for 6 mm, it reached 5.07%, followed by the minimum statistical value (1.64%).
[85]	To model the flow, the transient form of the compressible Reynolds Averaged Navier Stokes (RANS) equations was used in conjunction with the Energy Equation. Turbulence effects were modelled using a two-equation k–e transport model. Standard wall functions were used to remove the need to grid the boundary layer. Air was used as the flow medium, and ideal gas properties were assumed. In the following sections, further details are given on mesh design and the justification for using the k–e model. For the valve model, typical values of the parameters for m, k, F_0, and Δt are as follows: m = 0.96 kg, k = 22.3 kN/m, F_0 = 0.96 kN, and Δt = 0.0001 s. A simulation of the vessel blowdown transient process was initiated by setting the initial valve upstream pressure to 7% above the set pressure. The Mach number, pressure distribution, and the vector plots of the velocity fields in the seat region are determined at four time instants (0.005 s, 1.001 s, 1.8801 s and 2.1008 s), respectively. The four time instants represent the opening stage, maximum lift stage, closing stage, and closure, respectively.	The use of the model suggests the following conclusions can be made: a. The proposed model with a transient CFD model and a single degree of freedom model for the disc can satisfactorily capture the main dynamic events of the opening and closing processes of a SRV mounted on a pressure vessel; b. The current CFD model based on the standard k–e turbulence model can predict valve blowdown to within 11% of actual results providing some confidence in the approach; c. Examination of several design and operational parameters, including the adjusting ring position, spring stiffness, and bellows and vessel volumes, has shown the versatility and effectiveness of the approach; d. The specific SRV studied opens or pops suddenly, which releases fluid quickly and minimizes over pressurization of the vessel; e. In addition to the effect of geometry and flow conditions, the blowdown is mainly dependent on the adjusting ring position, spring stiffness, and the balanced bellows; f. The blowdown can be decreased by increasing the adjusting ring and/or spring stiffness, but each of them has a limited effect, so proper design or selection of them both is critical; g. The volume of the pressure vessel has an evident effect on the vibration characteristics and the mass flow of the valve, especially during the opening and closing periods.

Table 11. *Cont.*

Source	Analyses	Discussion and Results
[86]	A steady simulation with a constant inlet pressure boundary condition of 0.3 MPa and a constant outlet pressure boundary condition of 0.04 MPa is used to verify the mesh independence for the grooved valve disc. Five different thicknesses of the first boundary layer are generated depending on the size of elements, such as 0.2, 0.1, 0.05, 0.025, and 0.01 mm. The turbulence model determines the pattern of flow, which influences the fluid forces on the valve disc. Therefore, five different turbulence models (standard k-ε model, RNG k-ε model, realizable k-ε model, standard k-ω model, and SST k-ω model) are discussed to determine the optimal turbulence model.	In this paper, based on the critical engineering problem of the lack of in-depth knowledge on the fluid forces acting on the valve disc of nuclear safety valves, the characteristics of the fluid forces of the valves were investigated in detail by combining CFD methods and supervised learning algorithms. First, a high-fidelity CFD model that captures the main flow characteristics inside the valve was employed. Based on the streamlines of the CFD model, we derived that most fluids in such valves with eccentric structures flowed toward the orifice close to the outlet, more unstable vortices were generated near the orifice far from the outlet.
[52]	A numerical valve model was validated to predict the discharge capacity and opening characteristics of high-pressure safety valves, in line with the EN ISO 4126-1 valve sizing standards. The model was developed in ANSYS CFX with the Soave–Redlich–Kwong real-gas equation of state, enabling calculations at pressures up to 3600 bar. A custom test facility was built for valve function and capacity tests using water and nitrogen at up to 600 bar.	For gas flows, numerical and experimental mass flow rates matched within 3%, while flow force deviations averaged 12%. Including fluid–structure interaction improved flow force predictions and offered insights into valve opening dynamics. For liquid flows, a cavitation model extension reduced overpredictions in mass flow by 2–20% at low disk lifts and cut flow force deviations from 35% to 7%. At higher disk lifts, cavitation effects diminished, yielding mass flow rates within 4% and flow forces within 5% of experimental values.
[87]	This study investigates the flow dynamics in an LNG safety valve designed to control pressure limits in LNG transportation lines. When pressure exceeds a set value, excess LNG discharges through the gap between the nozzle exit and valve sheet, with forces generated by LNG discharge and the valve spring. The complex flow involves vortices, flow separation, and shock waves, which contribute to noise and vibration. A two-dimensional, axisymmetric, compressible Navier–Stokes computational model simulates gas flow in the gap between the nozzle exit and valve sheet.	The simulation revealed that a specific distance exists between the nozzle exit and valve sheet where the thrust coefficient on the valve sheet rises sharply. This finding is critical as it indicates an operational threshold where dynamic forces intensify, potentially influencing valve performance and contributing to system noise and vibration. The study enhances the understanding of flow physics within LNG safety valves, providing insight into factors that may impact reliability and suggesting potential improvements to reduce adverse effects.
[88]	This study investigates how flow volume discretization fineness and turbulence model choice affect the accuracy of air mass flow rate predictions in two safety valves using ANSYS Flo® CFD software. Various levels of grid refinement were tested, and several turbulence models were compared, including the standard k−ω model and SST Menter modification.	Results show that grid fineness is the primary factor influencing calculation accuracy, with optimal reproduction achieved using grids containing at least two cells along the smallest edge. Turbulence model choice had a comparatively minor effect on accuracy, though the highest accuracy was obtained with the standard k−ω model and SST modification of Menter.
[89]	This study addresses the need for a real gas flow model in high-pressure safety valves with set pressures over 200 bar, typically used in applications like polyethylene and synthesis gas. The existing ISO 4126-1 standard only provides ideal gas equations and lacks guidance for calculating real gas factors and adiabatic exponents. A new equation for real gas critical mass flow through a nozzle was developed and compared with ISO 4126-1 models and experimental data. ANSYS-CFX numerical calculations were also conducted to evaluate discharge coefficients at high pressures.	The derived real gas flow equation showed good agreement with experimental results and the EN-ISO 4126-1 model, highlighting the need for an ISO-standard update to include real gas models for nozzle flow. Initial ANSYS-CFX results suggest that discharge coefficients measured at moderate pressures can be extrapolated to higher pressures if paired with a real gas nozzle flow model. However, further experimental validation on diverse valve types is recommended, and a high-pressure test facility was established by BASF in Ludwigshafen for ongoing research.

Table 11. *Cont.*

Source	Analyses	Discussion and Results
[90]	This study evaluates various literature models developed over the past 30 years to mitigate instabilities in gas-service safety valves. The instability sources during valve opening were identified, leading to model classifications: balance-based and pressure wave models. A sensitivity analysis was conducted on five models, considering factors like set pressure, inlet line diameter, specific heat ratios, and moving mass. Models were also validated against experimental data using various gases and pressures.	The results show that balance-based models and pressure wave models exhibit different trends in predicting instabilities, and no single model consistently matched experimental results. The "three percent rule" for predicting inlet line length was reliable in only 2 out of 5 cases. The measured trend of decreasing permissible inlet line length with increasing pressure was not predicted accurately by any model. Findings suggest that valve instability is influenced by factors not considered in the models, such as spindle friction and lubrication. Therefore, safety valve instability remains stochastic and requires additional lifecycle parameters for accurate modeling.
[61]	This study addresses the need for robust fault diagnosis models for pressure relief valves, particularly when these valves operate under harsh conditions. A novel diagnostic approach was developed, integrating the Elastic Weight Consolidation (EWC) algorithm with the Deep Residual Shrinkage Network (DRSN) to enhance diagnostic accuracy and prevent catastrophic forgetting in multi-task learning scenarios. The model was tested using time-series data from pressure relief valves subjected to hydraulic media with various contaminant particles.	Results indicate that the combined EWC-DRSN model achieved an average diagnostic accuracy of 98.8% and an average loss of 0.095, demonstrating high effectiveness for identifying clamping faults in pressure relief valves. The integration of EWC with DRSN provides a robust fault diagnosis framework that maintains diagnostic performance over multiple tasks. This approach is particularly beneficial for hydraulic systems requiring consistent and reliable operation, contributing to enhanced maintenance and fault management.
[91]	This study investigates the risk of erroneous opening of pressure relief valves (PRVs) in high-hydrostatic-pressure oil pipelines, particularly in mountainous regions, where such errors can lead to significant oil discharges and potential spilling-over of pressure relief tanks. The research focuses on a continuous undulating oil pipeline, particularly analyzing the B station. A simulation model of the pressure relief system for the B station was created using OLGA software, with model accuracy validated against historical accident data.	The simulation revealed that the maximum discharge rate reached 8284 m^3/h when the PRV mistakenly opened at the station's inlet and outlet, aligning closely with recorded accident data indicating a filling time of 200 s for the pressure relief tanks. The analysis of discharge velocity, flow rate, accumulated discharge volume, and ventilation volume of the vent valve indicated that discharge velocities exceeded safe limits, confirming a high risk of tank spilling. Furthermore, it was determined that the existing vent valve design was inadequate for meeting ventilation requirements during PRV failures. Based on these findings, the study recommends several improvements: increasing the number of vent valves, transitioning from manual to electrically operated valves, and implementing a security control interlock protection program to enhance the safety and reliability of the pressure relief system at the B station.
[63]	This study employs the Bondgraph simulation technique to analyze the dynamics of a direct-operated relief valve featuring directional damping. The research begins by deriving the governing equations based on the Bondgraph model, allowing for a comprehensive understanding of the valve's behavior. The pressure-flow characteristics of both the valve port and the damper unit are incorporated into the numerical solutions of the system equations.	The analysis identifies several key parameters influencing the valve's dynamic response, which can be adjusted to enhance its performance. These findings provide valuable insights into optimizing valve design and operation, particularly in applications requiring precise pressure regulation.

Table 11. *Cont.*

Source	Analyses	Discussion and Results
[92]	This study focuses on designing a digital pressure relief valve driven by a stepper motor, establishing a mathematical model of the cavitation flow field within the valve element. Using Fluent software, the research simulates and analyzes various configurations of the valve element's cavity volume and fillet rounding. The aim is to understand how these design parameters affect cavitation within the valve.	The simulation results demonstrate that increasing the valve element cavity volume effectively suppresses cavitation, as it correlates with a reduction in maximum turbulent kinetic energy, leading to decreased energy loss and lower pressure drops. Conversely, increasing the fillet radius of the valve element results in higher turbulent kinetic energy, increased energy loss, and a greater possibility of cavitation.
[93]	This paper presents the development of a three-dimensional computational fluid dynamics (CFDs) model integrated with dynamic equations to investigate the fluid characteristics and dynamic performance of a spring-loaded pressure safety valve (PSV). The model incorporates unsteady analysis and a moving mesh technique to accurately predict the flow field and assess the flow force acting on the valve disk over time.	The findings reveal that the innovative mesh generation and modeling techniques effectively enable the movement of the valve disk, thus eliminating common mesh errors associated with complex geometries in commercial CFD software (ANSYS CFX). The study systematically applied various constant inlet pressure loads to the model, producing response parameters such as disk displacement, mass flow rates through the valve, and the fluid force exerted on the disk. The response parameters were analyzed and compared against the behavior of the PSV under varying overpressure conditions.
[94]	This article discusses the function of pressure relief valves (PRVs) in providing surge relief and pressure protection within pipeline systems. The effectiveness of a PRV is influenced by the system's properties, the characteristics of the pressure surge, and the configuration of the valve's attributes and settings.	The analysis highlights the complexities associated with PRV design, emphasizing that while a well-designed PRV can safeguard systems against excessive pressures, improper application may exacerbate a system's transient response. The article presents general principles for PRV usage and selection, complemented by a sensitivity analysis of various PRV parameters. It concludes that understanding these principles is critical for effective system design. Additionally, the selection of a PRV should involve evaluating its viability and cost-effectiveness within specific systems, utilizing numerical simulation as a tool to inform this decision-making process.
[13]	This study conducted a comparative analysis of the expansion effects of different gases—air, argon, and ethylene—in safety relief valves, representing a range of specific heat ratios. Experimental testing on a $1/2'' \times 1''$ valve with a 10 mm orifice (API 526 designation D) showed significant reductions in disc lift and mass flow rate under nominal overpressure when operated with argon. To further investigate these effects, a numerical CFD model using a discontinuous Galerkin formulation was employed, validated initially with air on a 2″ J 3″ valve and later applied to argon and ethylene as thermally perfect gases.	Results showed that gases with a specific heat ratio greater than the one used during type testing (e.g., argon vs. air) can alter safety valve performance. Specifically, argon's lower specific heat ratio led to a reduced disc lift and mass flow rate under nominal overpressure, suggesting that gases with varying thermodynamic properties can impact valve operation differently.

Table 11. *Cont.*

Source	Analyses	Discussion and Results
[8]	This study employs CFDs to evaluate air/water flow behavior in a discharge valve across four seat–valve distances and three distinct nozzle positions. Parameters analyzed include velocity distribution, pressure profiles, tangential stresses, and turbulent kinetic energy (TKE) throughout the valve.	The CFD analysis highlights how different seat–valve distances and nozzle positions significantly impact fluid dynamics and valve efficiency. The observed peak velocity of 3210 m/s near the valve seat underscores the influence of seat-valve spacing on velocity profiles, potentially affecting wear rates and valve durability. High-pressure points, reaching 4.3 MPa on the valve plate, could contribute to structural stresses, emphasizing the importance of materials that withstand such extreme conditions. Tangential stress patterns, particularly on chamfered surfaces, indicate areas prone to erosion, while the randomized turbulent kinetic energy patterns suggest that nozzle positioning strongly influences flow stability.
[95]	This study introduces a simplified dynamic model (SDM) designed to predict the reclosing dynamics and blowdown of a conventional PRV. The SDM uses a one-degree-of-freedom motion equation, neglecting damping due to its minimal impact on reclosing time. The model uniquely integrates static CFD-derived lift force coefficients as inherent valve characteristics, enhancing accuracy.	The SDM offers a time-efficient, reliable method for predicting PRV blowdown, validated by case studies. Although it neglects oscillations and damping, the model effectively assesses blowdown and evaluates the effects of spring stiffness on the reclosing process.
[96]	This study emphasizes the significance of pressure safety relief valves in oil and gas production, where overpressure can lead to catastrophic failures. A buffer relief valve was designed using ANSYS, focusing on achieving optimal performance. Finite Element Analysis results were compared with experimental data to validate the model.	It was found that the valve, designed to operate at a pressure of 0.14 MPa, demonstrated a close correlation between ANSYS FEA and experimental results, achieving a response time of 4 s in simulation and 2 s experimentally. These results confirm the valve's reliability and safety under specified conditions, showcasing the efficacy of the design process and the model's applicability in ensuring safety and durability in pressure relief applications.
[97]	This study evaluates the dynamic performance of High-Temperature and High-Pressure (HTHP) PRVs, important for nuclear plant safety. Using CFD modeling, with domain decomposition (DDM) and Grid Pre-deformation (GPM) methods, the research assesses the effects of factors such as damping, superheat, and adjusting ring settings on a specific PRV (DWPRV). Experimental validation complements the CFD analysis.	Results indicated that the maximum flow rate occurs when the curtain area is 1.18 times the throat area. It was observed that superheat, up to 100 °C, has minimal impact on valve performance, despite changes in material properties. The reseating pressure rose linearly with increased distance between the upper adjusting ring and sealing face, while the lower adjusting ring had a minor impact. For the lift-to-throat diameter ratio, a value of 0.35 led to a higher blowdown, indicating specific design considerations to ensure reliable operation in nuclear settings.
[98]	This study presents a dynamic model for a two-stage pilot relief valve, examining how different design parameters influence system response. Non-linearities, such as orifice diameter and cone angle of the main spool, are considered. The study also analyzes the impact of pilot spring pre-compression and damping coefficients on stability.	The results highlight that modifications to the orifice diameter and cone angle significantly influence peak rise time and settling time, indicating that spool tip shape is very important for optimizing dynamic characteristics. Increasing pilot spring pre-compression was shown to extend the operating range of the valve, while damping coefficients are critical for system stability, though difficult to adjust in practice.

Table 11. *Cont.*

Source	Analyses	Discussion and Results
[99]	This study develops a mechanical model of a direct spring-loaded safety valve, specifically analyzing the flow force component using CFD simulations in ANSYS Fluent. The DN50/DN80 valve was tested at five fixed disc positions (1, 2, 5, 8, and 11.2 mm) with nine different inlet pressures (1.5–5.5 barg). Simulated flow force values were compared to experimental data for validation.	The results show strong alignment between simulated and measured flow forces, validating the CFD simulation method for pressures above 2 barg.

Additionally, a notable research gap exists in the application of advanced computational tools like CFDs and FEA for optimizing safety valve performance under extreme conditions, such as high-pressure and corrosive environments. Addressing these challenges through innovative materials and robust designs can significantly enhance reliability. In addition to the analyzed standards, the computational tools analyzed—ANSYS Flo® CFDs software, OLGA software, and Fluent software—were selected for their advanced capabilities in modeling and simulating fluid dynamics in complex systems. ANSYS Flo® is highly regarded for its precision in assessing valve performance under various flow conditions, OLGA excels in simulating transient multiphase flow scenarios relevant to the oil and gas industry, and Fluent offers versatile solutions for optimizing valve designs through detailed CFD analysis. These tools complement the standards by providing a robust platform for evaluating safety valve behavior, enabling a more comprehensive understanding of their performance under real-world conditions. Together, these standards and computational tools form a cohesive framework for ensuring the reliability and effectiveness of safety valves in diverse industrial applications.

Future research should focus on developing standardized frameworks for smart valve technologies and exploring novel materials capable of withstanding demanding environments. By bridging these gaps, the field can advance toward more efficient and sustainable industrial safety solutions.

9. Conclusions

This review comprehensively addresses the critical role, standards, and advancements associated with safety valves in industrial applications. Safety valves are indispensable for maintaining safe operational pressures across sectors like oil and gas, chemical manufacturing, and power generation, protecting systems from catastrophic overpressure events. The performed analysis includes an extensive overview of different valve types, such as spring-loaded, pilot-operated, and specialized valves, each adapted to specific industrial needs. Adhering to stringent standards set by regulatory bodies like ASME, API, and ISO, safety valves are subject to rigorous design, testing, and maintenance requirements to ensure optimal performance under diverse operational conditions.

Also, it explored the historical development of safety valves, from early mechanisms used in steam engines to contemporary designs that accommodate increasingly complex industrial demands. The introduction of advanced materials, including corrosion-resistant alloys and high-strength composites, has significantly improved the durability and reliability of valves, particularly in harsh environments with high pressures and corrosive fluids. These material advancements are essential for industries where extended operational lifetimes and minimal maintenance intervals are critical. A major focus of this review is the shift towards smart safety valves, a development that aligns with Industry 4.0 initiatives. Equipped with sensors and diagnostic systems, smart valves provide real-time data on pressure, temperature, and flow rate, enabling predictive maintenance and early detection

of potential failures. Integrated with machine learning algorithms, these valves can forecast issues based on historical and real-time data, reducing unplanned downtime and extending the equipment's lifecycle.

The review highlights several recent incidents, underscoring the importance of regular testing, rigorous maintenance, and adherence to safety protocols. Failures in safety valve performance have historically led to significant industrial accidents, such as the Piper Alpha disaster and the Bhopal tragedy. These cases emphasize the need for stringent quality assurance practices, including set pressure tests, leakage tests, functional tests, and cycle tests, which are integral to maintaining reliable safety mechanisms.

Furthermore, this review addresses ongoing challenges within the field, such as optimizing valve designs for high-performance settings, including cryogenic applications and extreme-temperature operations. Innovations like finite element modeling and computational fluid dynamics (CFDs) simulations are discussed as powerful tools for refining valve designs, enabling engineers to predict how valves will behave under various operational stresses. Experimental validation remains an essential step in confirming these simulations and ensuring that designs meet real-world demands.

Looking ahead, the development of smart safety valves with enhanced cybersecurity features will be essential as industrial systems become increasingly connected. The integration of safety valves into the Industrial Internet of Things presents new opportunities for comprehensive monitoring and control across plant systems, but it also introduces vulnerabilities that require robust security protocols.

The implementation of smart safety valves equipped with advanced technologies across various industries demonstrates significant advancements in operational efficiency, safety, and cost savings. Chevron's offshore drilling platforms utilize real-time monitoring valves to mitigate blow-out risks and enhance emergency responses, while BP's predictive maintenance systems in safety valves have led to a 15% reduction in unplanned shutdowns, saving millions annually. Similarly, BASF's automated safety valves prevent chemical leaks, reducing environmental risks and ensuring compliance with regulations. Siemens Energy optimizes steam flow management in power plants through smart valves, cutting energy consumption and maintenance costs. In water treatment, Thames Water's smart valves improve resource efficiency and system reliability, and Toyota's implementation in manufacturing plants has reduced paint waste by 20%, yielding significant material and environmental benefits. These diverse applications underscore the transformative impact of modern safety valve technologies. Furthermore, advancements in additive manufacturing have revolutionized valve production, enabling the creation of complex designs, reducing material waste, and cutting storage and delivery costs. Together, these innovations highlight the critical role of safety valve technologies and manufacturing advancements in driving industrial progress.

Future in the digital domain could significantly transform the functionality and effectiveness of safety valves across industries. Advanced sensors would enable continuous real-time monitoring of critical parameters such as pressure and temperature, allowing for immediate detection of anomalies. The integration of the Internet of Things would facilitate remote monitoring and control, offering a comprehensive view of system health and enhancing coordination across industrial sites. Predictive analytics and machine learning could analyze data patterns to foresee potential failures, enabling proactive maintenance strategies that reduce downtime and extend valve lifespan. Digital twin technology could simulate and test safety valve designs under various conditions, optimizing performance and enhancing resilience without physical risk. Enhanced automation would allow valves to react autonomously to sudden changes, improving both safety and efficiency. Additionally, blockchain technology could ensure secure data integrity and traceability

for compliance and maintenance records. Collectively, these advancements promise to transform safety valves into intelligent components within an interconnected industrial ecosystem, leading to improved safety outcomes and operational efficiency.

Safety can be classified based on their utilization across different domains as follows: Oil and gas industry (pressure relief valves: used to release excess pressure in pipelines, vessels, and storage tanks. Blowdown valves: specialized for drilling operations to control well pressure. Emergency shutdown valves: automatically actuated valves to isolate sections of a plant during emergency situations); medical industry (gas regulator safety valves: used in medical gas systems to ensure safe delivery of oxygen and other gases. Pressure relief valves in sterilizers: maintain safe pressure levels in autoclaves and sterilization equipment); agriculture (irrigation system relief valves: protect irrigation lines and pumps from pressure surges. Fertilizer applicator safety valves: ensure safe dispensing of liquid fertilizers by managing pressure levels effectively); military/army (fuel tank relief valves: protect fuel tanks from pressure fluctuations and potential ruptures. Explosive ordinance disposal valves: used in controlled practices to prevent accidental detonation from pressure changes); industrial manufacturing (control valves in chemical processing: for managing reactor and pipeline pressures to prevent leaks and explosions. Thermal relief valves: used in heat exchangers and boilers to control pressures due to thermal expansion); aerospace (cabin pressure valves: maintain safe pressure levels in aircraft cabins. Propellant vent valves: used in spacecraft to release propellant gases safely); food and beverage industry (vacuum relief valves: protect storage tanks during cooling processes following pasteurization. Pressure safety valves in beverage production: regulate pressure in carbonation processes). By categorizing safety valves based on their application in these key domains, we can better understand their specific roles in maintaining safety and operational efficiency across various industries.

While this review provides a comprehensive synthesis of current knowledge, it has certain limitations. The findings are based on secondary sources, without empirical data or experimental validation, which may limit the direct applicability of the conclusions. Furthermore, the diversity of industrial practices and standards across sectors poses challenges for generalizing the insights presented. Addressing these gaps through targeted empirical studies and sector-specific investigations would further strengthen the understanding of safety valve performance and advancements. Future research should prioritize experimental validation of safety valve designs under extreme conditions, such as cryogenic environments and high-temperature operations, to bridge the gap between theoretical models and real-world performance. Additionally, investigations into the integration of smart safety valves with advanced cybersecurity protocols are essential to address vulnerabilities introduced by Industrial Internet of Things (IIoT) connectivity. Specific studies could also explore the long-term reliability of new materials, particularly in corrosive environments, and the development of standardized frameworks for predictive maintenance algorithms adapted to various industrial settings.

Engineers can use the following practical recommendations, to enhance the safety and reliability of safety valves in various applications, ultimately leading to better overall system performance: regular maintenance: conduct routine inspections and maintenance on safety valves to ensure they operate correctly and reliably, following manufacturer guidelines and industry standards. Proper sizing: ensure that safety valves are appropriately sized for the specific application and system pressure to avoid overpressure conditions and ensure effective release when needed. Installation checks: verify that safety valves are installed according to provided specifications and guidelines, taking care to minimize the effects of backpressure and ensuring proper orientation. System testing: periodically perform testing of safety valves under operational conditions to confirm their functionality and response to

pressure changes. Use of appropriate valve types: choose the right type of safety valve (e.g., spring-loaded or pilot-operated) based on the specific application requirements, including the working pressure and fluid characteristics. Implement dual-unit systems: in critical applications, consider using a redundant safety valve setup to enhance reliability and mitigate risks associated with valve failure. Monitor pressure settings: regularly check and recalibrate the pressure settings of safety valves to ensure they respond accurately to overpressure conditions within the system. Fluid compatibility: select materials for safety valves that are compatible with the fluids they will handle, minimizing corrosion and fatigue issues over time. Avoid blind spots: position safety valves such that they are accessible for maintenance and inspection, avoiding placements in areas that may be difficult to reach. Educate personnel: train operators and maintenance personnel on the proper use, inspection, and maintenance of safety valves to ensure they are proficient in recognizing potential issues. Document maintenance activities: keep thorough records of all inspections, tests, maintenance, and repairs performed on safety valves to facilitate tracking of performance and compliance with regulatory requirements. Emergency response procedures: establish clear emergency response protocols relating to safety valve activation to ensure prompt and effective action in the event of an overpressure incident.

In conclusion, this review underscores the indispensable role of safety valves in industrial safety and efficiency. The ongoing advancements in materials, smart technology, and design methodologies contribute to improved safety performance and operational resilience. Future research should focus on enhancing valve performance in extreme conditions, advancing predictive maintenance capabilities, and developing standardized protocols for smart valve cybersecurity. By adopting these innovations, industries can improve safety, reduce operational risks, and support sustainable and efficient industrial practices.

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