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A critical review and analysis of pressure vessel structures

Abdolreza Toudehdehghan* and Tan Wai Hong

Faculty of Engineering and Quantity Surveying, INTI International University, Jalan BBN 12/1, Bandar Baru Nilai, 71800 Nilai, Negeri Sembilan. Malaysia

*Corresponding author: abdolreza.toudehdehghan@newinti.edu.my

Abstract. This paper provides an overview of the pressure vessel, starting with its background and a brief history. Then, the geometry, main components, classification, applications, materials and fabrication process of the pressure vessel are also discussed. When designing or performing optimization on the vessel, it is crucial for the designers to familiar with the types of failures and loadings, to select appropriate analytical methods to analyse the vessel. As well as the design parameters such as thickness, design pressure or allowable stresses, which can alter the performance, efficiency and safety of the vessel. Since the design of the pressure vessel is governed by the codes and standards, some of the commonly used codes are presented, with more details included for the ASME pressure vessel code.

1. Introduction

In the year 1495, Leonardo da Vinci has documented his pressure vessels design in the book, Codex Madrid I with the concept of pressurized air containers lifting the heavy weights underwater. Without the initiative to generate steam in boilers that spur an industrial revolution in the 1800s, vessels which resemble what can be seen today will never come true [5]. Pressure vessels are designed to carry, store and receive process fluids, gases, and liquids under required temperature and pressure limit [3]. They are often subjected to constant or cyclic internal/external pressure loading, with the difference between the operating pressure and ambient pressure. Due to the difference in operating pressure, the state of the fluid present in the vessel will undergo changes [2]. A ruptured pressure vessel can be hazardous, possibly leading to poison gas leaks, fires or explosions which may cause significant losses of human lives and property. To counteract this problem, the local providences and some states began enacting rules, which made it tedious for the manufacturers as the rules lack uniformity and differ from one location to another. Thus, American Society of Mechanical Engineers (ASME) took the initiative and established the standard specifications and design formulation for the pressure vessels. In the year 1911, the first edition of pressure vessel code was developed and then released in 1914, which is now known as ASME Boiler and Pressure Vessel Code (BPVC).

The code eventually developed over time and is presented in eleven sections, with multiple subdivisions, parts, subsections, mandatory and non-mandatory appendices. Many countries such as Japan, Australia, Britain, Canada, and Europe follow the BPVC as their official code or even developed their own [6]. It is impossible to eliminate the accidents completely, however, by studying the behavior of the pressure vessels, the likelihood of accidents can be reduced or prevented [12]. With that, the design of a vessel needs to achieve a balance between the safety as well as economics. To accomplish this task, it requires the understanding of parameters affecting the pressure vessel due to varying loads, pressure and thickness. Fortunately, the established engineering standards have resulted in the recent



advancements in the pressure vessels engineering such as material breakthrough with increased strength, durability, corrosion resistance and new joining methods (explosion welding, friction stir welding, etc.) that allows the design of vessels to be safer and more reliable.

On the other hand, pressure vessel can be made of any shape, but in the industry, spherical, cylindrical and conical pressure vessels are often employed. Ideally, the spherical shape can hold the internal pressure with evenly distributed stresses on the surface both internally and externally. It is advantageous in term of structural strength when compared to a cylindrical pressure vessel made of same wall thickness. However, the spherical shape may present manufacturability and costs concern. Thus, the cylindrical shape is more commonly used due to lower manufacturing costs and the ability to use the space efficiently. To overcome the structural weakness, few types of rounded or hemispherical ends will be fitted. The geometry of the vessel ultimately depends on the type of applications. Nonetheless, regardless of the types of the pressure vessel, a vessel should consist of closure heads, shell, openings, some functional attachments, a combination of nozzles and supports [9], as illustrated in Figure 1 which shows the vertical and horizontal vessel arrangement with the components labeled. The functions for each of the components are summarized as below:

- Shell - primary component consists of different plates welded together with a common rotational axis to contain the pressure [1]. It may be of different thickness or materials.
- Closure heads - heads can be either curved or flat to close off the ends of the vessel. The heads can also be placed inside the vessel to allow separation of the vessel into sections [9]. The most common ASME heads are ellipsoidal, hemispherical and torispherical [13].
- Openings - hand size hole openings for inspection, instrumentations or drainage. With an increase in the size, it can then be used as manway [3].
- Nozzles - cylindrical component which penetrates specific locations of the vessel to help relief the pressure. In certain designs, it can act as inlet or outlet for the fluid flow [25].
- Supports - non-pressurized part of the vessel which bears loads of vessel. Various types of supports are available, such as saddles, skirt, leg, ring, and lug [9].

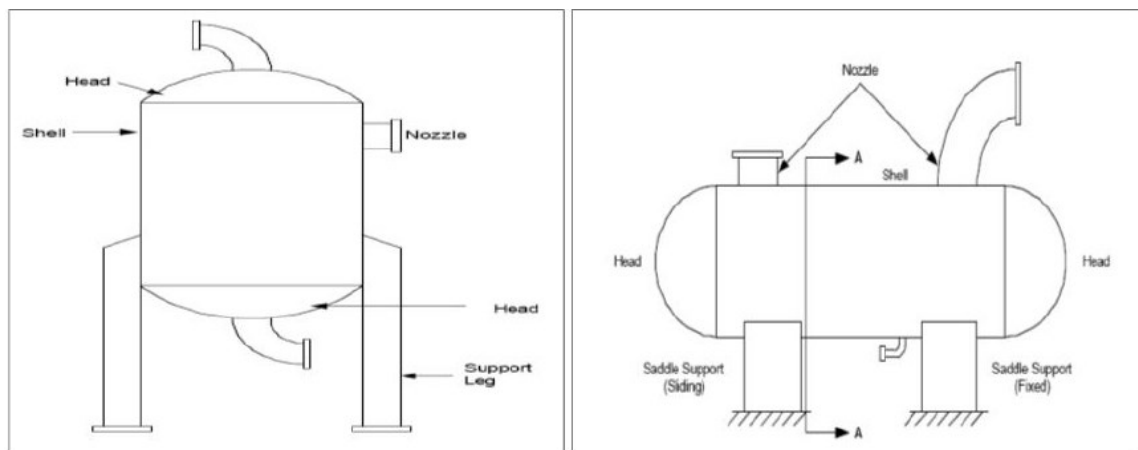


Figure 1. Vertical and horizontal vessel arrangement with labeled components [13]

2. Classification of the pressure vessel

Pressure vessels tend to vary in term of the design attributes. Although many designs are available in the industry, they always correspond to these two types. Solid Wall Vessel and Multi-layered Vessel. Pressure vessels can also be further categorized based on criteria such as manufacturing methods, materials, orientation, pressure-bearing situation, technological processes and usage mode [14].

2.1. Solid Wall Vessel

A solid wall vessel (monobloc pressure vessel) consists of only the cylindrical shell with closed ends and sealed finishes, characterized by the ratio of diameter to wall thickness. This ratio is a standard to categorize the vessel shell into a thick walled cylinder or thin walled cylinder [18].

2.2. Multi-layered Vessel

Basic multilayer vessel is formed by shrinking two or more layers into a core tube with different diametric differences, consist a mix of homogeneous material and isotropic materials. To make use of this multilayer design of vessel effectively, proper techniques of multi-layering and volume requirement must be known, otherwise, it would be a total waste of material and investment [23].

In Figure 2, the pressure vessel is classified into solid wall vessel and multi-layered vessel. The solid wall vessel can be of thin shell or thick shell, which is governed by the shell thickness or the internal fluid pressure.

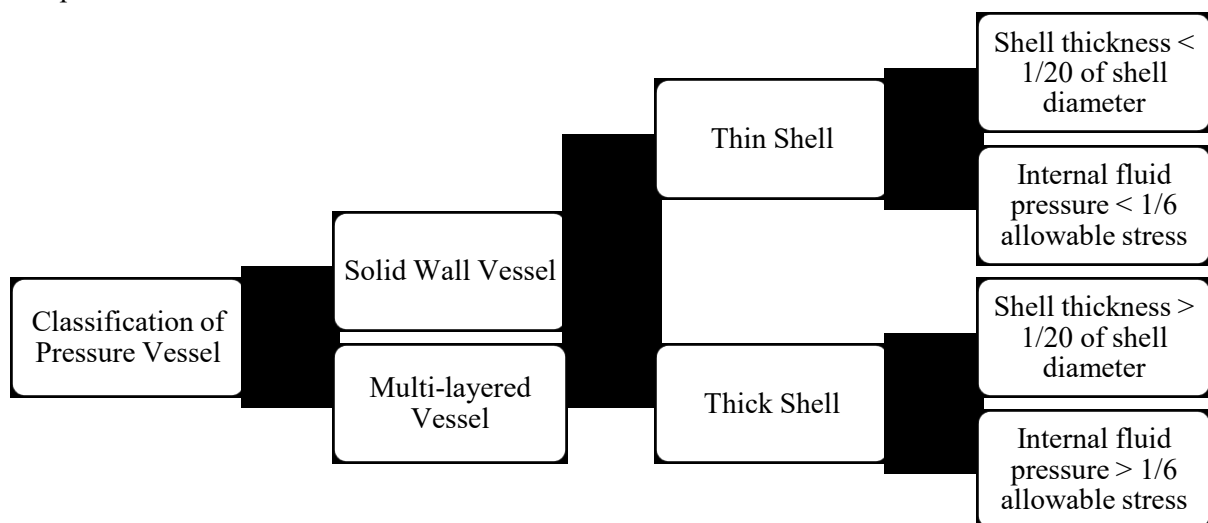


Figure 2. Classification of pressure vessel [16]

3. Applications of the pressure vessel

Figure 3 below shows some of the applications of the pressure vessel in both the industries and private sectors. As applications of pressure vessel are wide, thus, impossible to include all of them here.

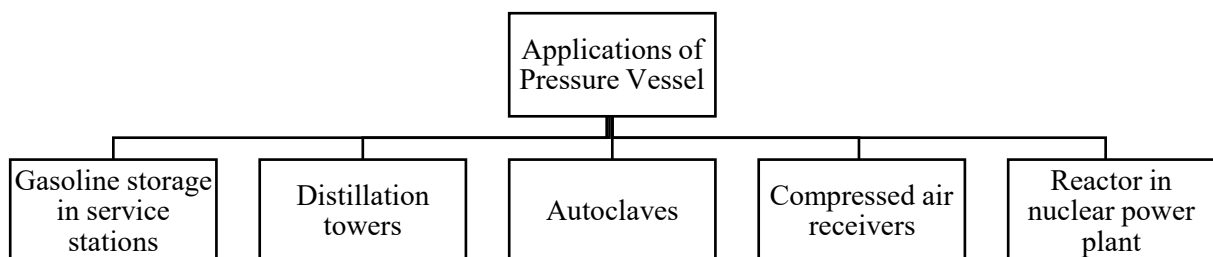


Figure 3. Application of pressure vessel [5]

The pressure vessel is part of the pressurized equipment playing a significant role in many industries, especially for storage purpose. As the manufacturing technology advances, their uses have expanded rapidly throughout the world [11]. With a breakthrough in the material, application of vessel will continue to expand in the future.

4. Materials of the pressure vessel

Choosing the right material for pressure vessel will yield benefits in term of performance, efficiency, and safety. However, designers must familiar with several factors that can influence material selection [19]:

- Strength, including creep – strength determines the minimum required thickness of vessel should be, to withstand the imposed loads or stresses. Ultimate tensile strength, yield strength, creep and rupture strength are among the elements used to determine the overall strength of the material.
- Resistance to corrosion – chemical actions or change in environmental chemistry can deteriorate the metals over a long period of time, where this single factor is sufficient to influent the material selection.
- Fracture toughness – the capability of a material to hold out against conditions that can lead to brittle fracture, characterized by the lack of deformation or yielding before the component fails completely when exposed to a combination of low temperature, high stress, and critical size defects.
- Fabric ability – sufficient ductility of the material to permit the rolling process of the plate for ease of construction of pressure vessel. Plate material should be weldable to assemble the individual segments.

5. Factors to be considered when designing the vessel

In order for the designers to be able to design a pressure vessel, there are some factors as summarized in Figure 4 below, that require consideration.

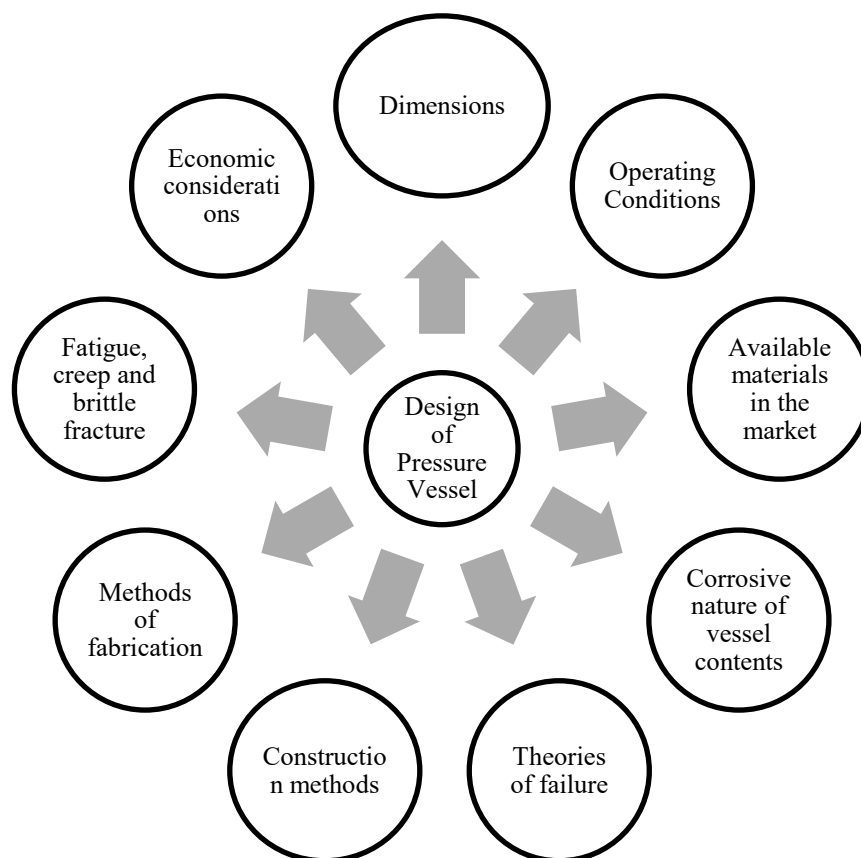


Figure 4. Design of pressure vessel [20]

6. Fabrication of pressure vessel

As pressure vessels consist of many components, various methodologies that conform to the requirements of the ASME Code are adopted to manufacture. Nonetheless, the basic manufacturing process of the pressure vessel is summarized in Figure 5 below.

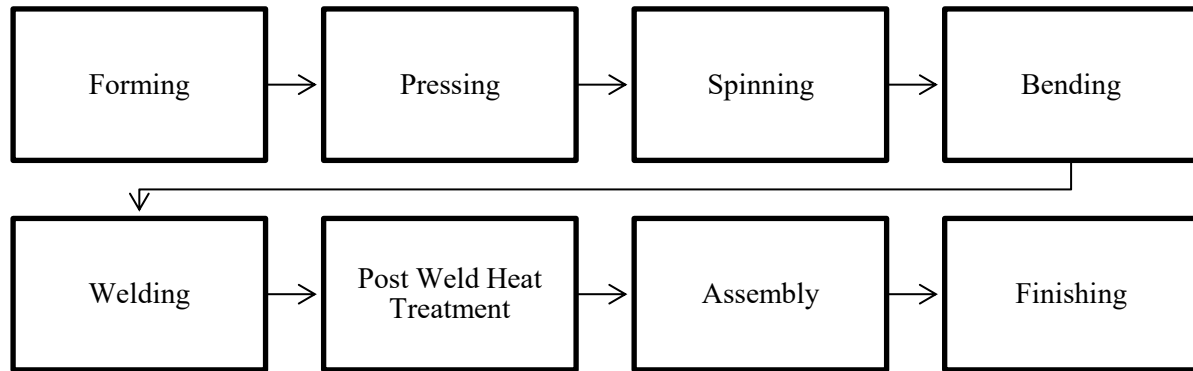


Figure 5. The sequence of Typical Manufacturing Process of Pressure Vessel [17] [10] [8] [24]

7. Failures in the pressure vessel

Energy stored in the vessel increases as the vessel size increases, indicating a higher extent of damage or danger. To prevent the rupture of the vessel, it is necessary to identify the different types of failure that can occur in the vessel [15]. Figure 6 provides examples of the failures of the vessel based on the perspective of materials, design, fabrication, and service. Whereas, Table 1 describes the types of failure that the vessel will encounter during its service life.

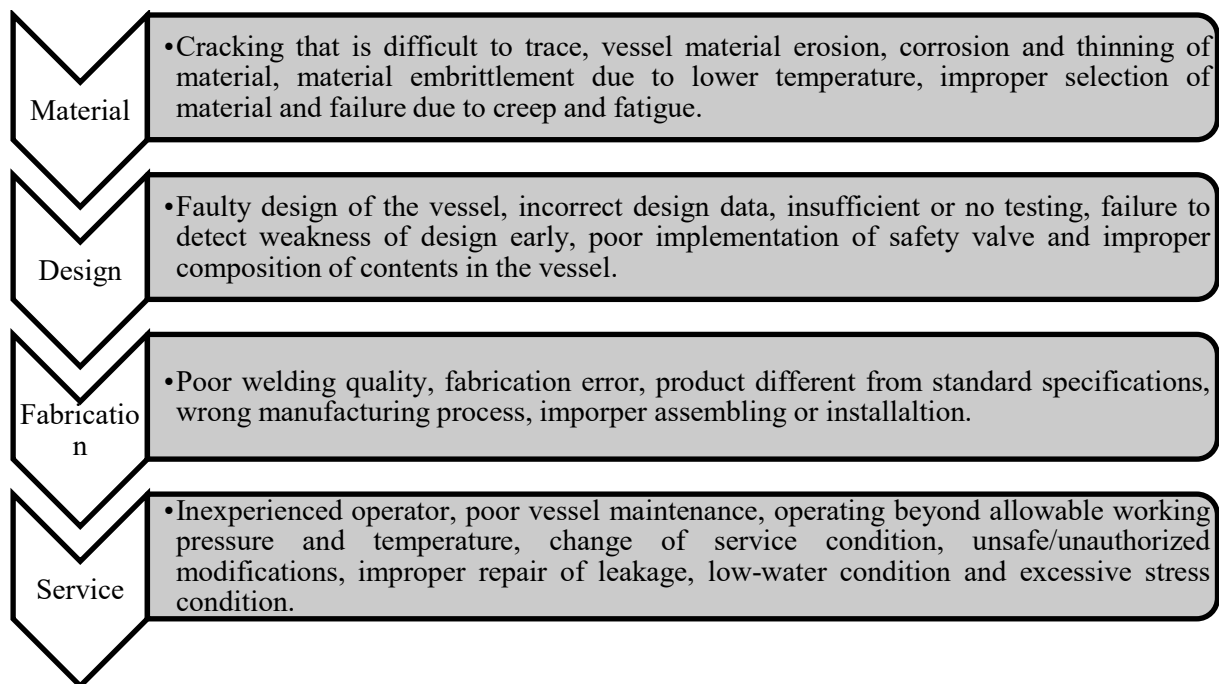


Figure 6. Failures in the pressure vessel

Table 1. Types of Failures

Types of failures	Description
Elastic deformation	Elastic instability or elastic buckling which can occur in the material, thus properties such as stiffness is essential to protect against buckling.
Brittle fracture	Occur at low or intermediate temperature, during the hydrostatic test where minor flaw can exist.
Excessive plastic deformation	To prevent excessive plastic deformation of the vessel, there is a stress limit guide specified in ASME manual.
Stress rupture	Creep deformation which happens because of the cyclic loading (fatigue), i.e. progressive fracture.
Plastic instability	Cumulative damage or cyclic deformation which causes instability of vessel due to plastic deformation.

8. Loadings in the pressure vessel

The main cause of stresses in a pressure vessel is the loadings which are applied over a large portion or only at the localized region. Figure 7 illustrates the categories of loadings according to general loads and local loads with examples.

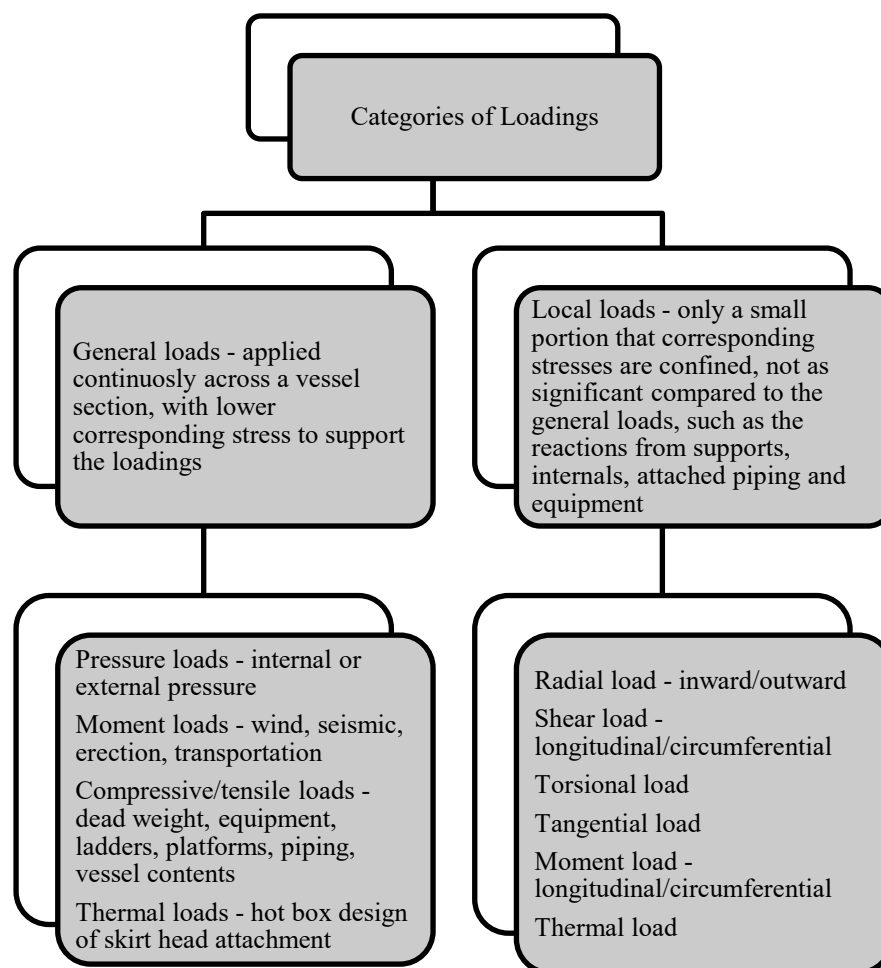
**Figure 7.** Categories of loadings [7]

Figure 8 on the other hand, illustrates the types of loadings that can be expected in a vessel according to steady loads and non-steady loads.

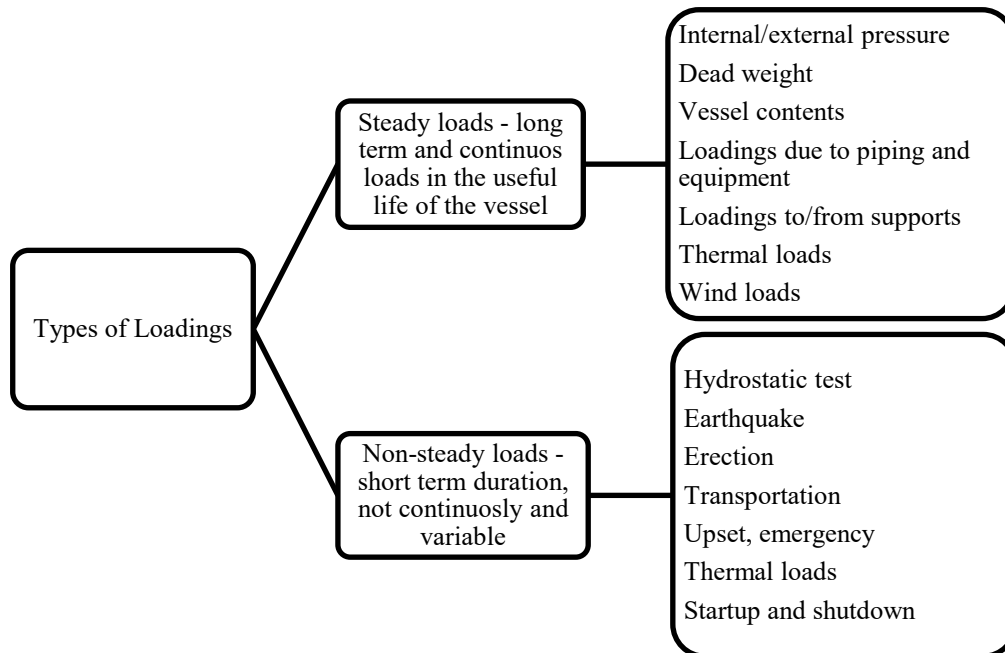


Figure 8. Types of loadings [7]

9. Design parameters of the pressure vessel

The following will briefly discuss some essential design parameters of the pressure vessel, which must be taken into consideration. The design of the pressure vessel begins by specifying each of the items discussed below. ASME requires the pressure vessel to be designed based on the most severe conditions that the vessel is subjected to, including during the start-up, normal operation, possible deviations, and shut-down. Other possible loading conditions or service factors should also be included during designing.

9.1. Operating Pressure

When designing the pressure vessel, the maximum internal or external pressure that can be expected in a vessel during its service is set as the operating pressure. The operating pressure is set with some factors taken into consideration. Such as [3]

- Effects due to ambient temperature
- Operational variations which may be encountered during its service
- Pressure variations due to the change of state of fluid
- Shut off pressure due to pump or compressor
- Static head due to the liquid level in the vessel
- Drop in the system pressure
- Pre-operating conditions

9.2. Design Pressure

When designing the pressure vessel, the maximum internal pressure set in a vessel is known as the design pressure [25]. In the vessel design, consideration is taken such that the design pressure is always higher than the operating pressure. To specify the design pressure, Turton et al. suggested the design pressure is to be greater than the maximum allowable working pressure (MAWP) for about 5% or 10% [22]. Based on the more severe design condition, an additional margin that is appropriate for a particular application should be included, especially for pressure vessel with both internal and external pressure

acting at different times. This margin would also help to prevent the safety relief valve from opening unnecessarily. On the other hand, the ASME Code requires the hydrostatic test to be conducted on the vessel before putting it into operation to give the final confirmation of the integrity and strength of the pressure vessel. Where equations to calculate design pressure and hydrostatic test pressure are given by [25]

$$\text{Design Pressure} = 1.1 * \text{Operating Pressure} \quad (1)$$

$$\text{Hydrostatic Pressure} = 1.3 * \text{Design Pressure} \quad (2)$$

9.3. Operating Temperature

Operating temperature is set according to the maximum and minimum metal temperatures that the pressure vessel will encounter during its service life.

9.4. Design temperature

The maximum fluid temperature which occurs under normal operating conditions is the design temperature. It is also known as temperature that corresponds to the design pressure. For the vessel to operate safely, there is a requirement for the minimum design temperature and the lowest expected service temperature in the vessel [21]. Generally, the design temperature of the vessel under external pressure should be less than or not exceed the maximum temperature. The reason is that the maximum allowable stresses are dependent on the temperature. Metals not only tend to weaken as the temperature increases but also become more brittle as the temperature drops. For a temperature ranging between -30 to 345°C, Turton et al. suggested 25°C additional allowance to be included to maximum operating temperature [22]. Whereas, Towler & Sinnott suggested an inclusion of maximum allowance of 10°C above maximum operating temperature and 36.67°C below the minimum operating temperature [21]. Any temperature which is higher than this range should use higher design allowance.

9.5. Allowable stress

To ensure the safe design of pressure vessels, the stresses imposed by the loadings are limited to the maximum allowable stresses specified in ASME Code for different materials, which is a function dependent on temperature [19]. The maximum allowable stresses also include a safety margin between stress level in components imposed by loads and stress level that causes failure. For vessels conforming to ASME Standard, allowable stress can be calculated based on the ultimate tensile strength with F.O.S of 3 (High pressure vessels) or 4 (Low pressure vessels).

9.6. Corrosion Allowance

When the vessel has operated for a long period of time, thinning can occur at the inner wall of the vessel, which leads to shorter lifespan or hazards of the vessel [25]. The corrosion can happen due to the reasons below:

- Chemical reaction or attack by the reagents on the vessel's inner wall surface
- Rusting of the material due to the presence of atmospheric air or moisture
- Oxidation that occurs with the increase in temperature
- At high flow velocities of the reagent over the wall surface that cause erosion

To counteract the issues, appropriate corrosion allowance (additional thickness) or addition of alloy elements could be considered. However, the general guidelines for the corrosion allowance are:

1. No additional thickness required if previous service experience shows no sign of corrosion or is of only a superficial nature as per UG-25.

2. For cast iron, carbon steel and low alloy steel vessel parts, about 1.5mm of corrosion allowance is provided except for those vessels operating in chemical industries, where 3.0 mm corrosion allowance is recommended.
3. For high alloy steel and non-ferrous vessel parts, corrosion allowance is optional and not necessary since the material itself is corrosion resistant.
4. For cylinder wall with thickness more than 30.0 mm, corrosion allowance is optional or not needed.

10. Codes and standards of the pressure vessel

There are many engineering standards and codes which provide information about the design, construction, welding, testing, marking, operation, certification, inspection and repair of the pressure vessel. These standards may vary from country to country, however, Figure 9 sums up the codes that are commonly used worldwide.

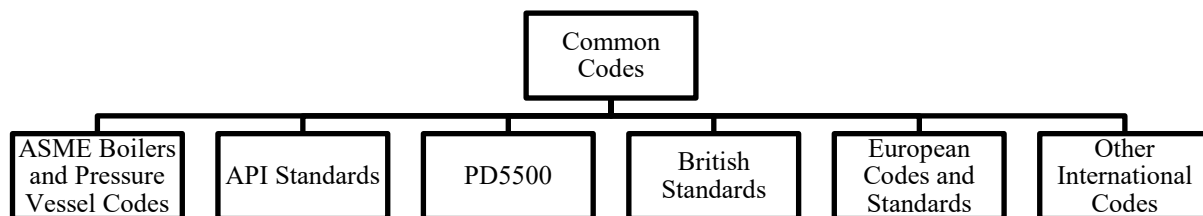


Figure 9. Commonly used codes [12]

Once the manufacturer decided on a code, it must be followed and complied throughout the whole process and not based on multiple standards. In Malaysia, the American Society of Mechanical Engineers (ASME) Code is normally followed when designing the pressure vessel. The ASME design criteria consist of the rules which address the detailed requirements such as design method, design loads, allowable stress and materials. Each Code Sections are listed as below: [3-4]

- I. Power Boilers
- II. Materials
- III. Rules for Construction of Nuclear Facility Components
- IV. Heating Boilers
- V. Non-destructive Examination
- VI. Recommended Rules for the Care and Operation of Heating Boilers
- VII. Recommended Guidelines for the Care of Power Boilers
- VIII. Pressure Vessels
- IX. Welding and Brazing Qualifications
- X. Fiber-Reinforced Plastic Pressure Vessels
- XI. Rules for In-service Inspection of Nuclear Power Plant Components
- XII. Rules for Construction and Continued Service of Transport Tanks

ASME Section VIII itself consists of the rules for fired and unfired pressure vessel, that can be further divided into three divisions according to the pressure limit. The information regarding the division 1, 2 and 3 are briefly described in Table 2 below.

Table 2. Details of ASME Section VIII [3-4]

ASME Section VIII (fired and unfired pressure vessels)		
Division 1	Division 2	Division 3
Requirements regarding design, fabrication, inspection, testing, and certification of pressure vessels operating at either internal or external pressures exceeding 15 psi.	Alternative rules regarding design, fabrication, inspection, testing, and certification of pressure vessels operating at either internal or external pressures exceeding 15 psi.	Alternative rules regarding the construction of high pressure vessels, as well as requirements of design, fabrication, inspection, testing, and certification of pressure vessels operating at either internal or external pressures above 10,000 psi.

11. Conclusions

Conclusively, pressure vessels have made an impact in the industry where their use will not diminish but continue to expand throughout the world with further research and development. Although fatal accidents may have occurred in the history of their development and operation, with efforts such as standards and codes to establish good safety practice, the likelihood of accidents can be reduced significantly. By understanding the parameters affecting the pressure vessel due to varying loads, pressure and thickness, the balance between safety and economics could be achieved. On the other hand, selection of components plays important role in design of pressure vessel rather than designing the individual components. A slight change in the selection could result in a different pressure vessel that will sway from what is aimed to be designed. Nowadays, with the components manufactured based on the standards, this would reduce the development time for a new pressure vessel and leaves more time for inventing new solutions. Such as material breakthrough, design optimization, new safety features, and economically-viable option.

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