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Reactor Pressure Vessel (RPV) Design and Fabrication: A Literature Review

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Abstract –*The general design follows the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code and fabrication processes used in different countries. Detailed knowledge of the design and fabrication information is necessary to assure long-term structural integrity and safe operation of the Pressure vessels. In this article, a brief overview has been presented to address the unique features of pressure vessels, such as material used for their preparation, design and construction along with various other relevant aspects of pressure vessel. About 32 published studies (1967-2009) are reviewed in this paper. It is marked from the literature survey articles that A516 are the most frequently studied and used material in designing and construction of pressure vessels.*

Keywords: Reactor Pressure vessel (RPV), fabrication, design, heat transfer enhancement, structural integrity

1.0 INTRODUCTION

This review gives an overview of Pressure vessels, steels used for pressure vessels, design and construction aspect of pressure vessels. A pressure vessel is defined as a container with a pressure differential between inside and outside. The internal pressure is usually higher than the external, except for some isolated situations. The fluid inside the vessel may undergo a change in state as in the case of steam boilers, or may combine with other reagents as in the case of a chemical reactor. Pressure vessels often have a combination of high pressures together with high temperatures, and in some cases flammable fluids or highly radioactive materials. Because of such hazards it is imperative that the design be such that no leakage can occur. In addition these vessels have to be designed carefully to cope with the operating temperature and pressure. It should be borne in mind that the rupture of a pressure vessel has a potential to cause extensive physical injury and property damage. Plant safety and integrity are of fundamental concern in pressure vessel design and these depend on the adequacy of design codes.

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Pressure vessels are used in a number of industries; for example, the power generation industry for fossil and nuclear, the petrochemical industry for storing and processing crude petroleum oil in tank farms as well as storing gasoline in service stations, and the chemical industry (in chemical reactors). Their use has expanded throughout the world. Pressure vessels and tanks are, in fact, essential to the chemical, petroleum, petrochemical and nuclear industries. The size and geometric form of pressure vessels vary greatly from the large cylindrical vessels used for high-pressure gas storage to the small size used as hydraulic units for aircraft. Some are buried in the ground or deep in the ocean, but most are positioned on ground or supported in platforms. Pressure vessels are usually spherical or cylindrical, with domed ends. Construction of pressure vessel is shown in Figure 1.

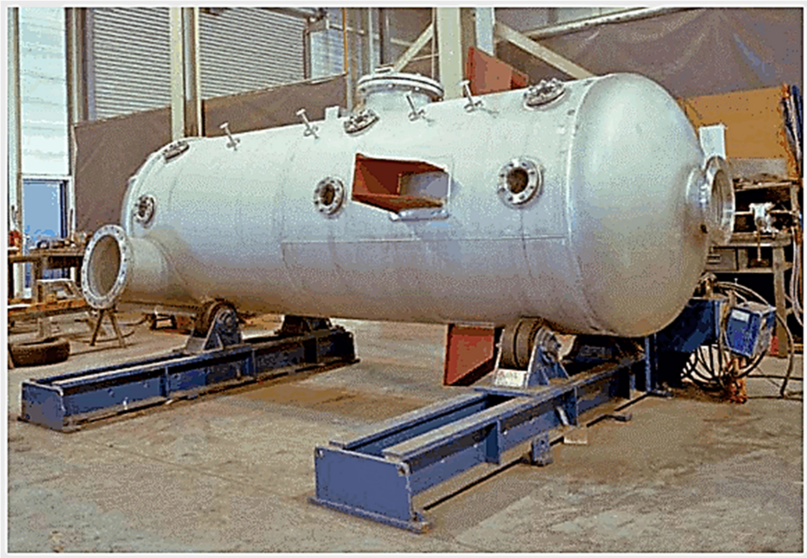

Figure 1: Construction of pressure vessel

The vessel geometries can be broadly divided into plate- and shell-type configurations. The plate-type construction used in flat covers (closures for pressure vessels and heat exchangers) resists pressure in bending, while the shell-type's membrane action operates in a fashion analogous to what happens in balloons under pressure. Generally speaking the shell-type construction is the preferred form because it requires less thickness (as can be demonstrated analytically) and therefore less material is required for its manufacture. Shell-type pressure components such as pressure vessel and heat exchanger shells, heads of different geometric configurations, and nozzles resist pressure primarily by membrane action.

Pressure vessels are made in all shapes and sizes, from a few centimeters (cm) in diameter to 50 meters (m) or more in diameter. The pressure may be as low as 0.25 kilopascals (kPa) to as high as 2000 megapascals (MPa). Modern petroleum refining and petro-chemical processing may involve operating conditions for ferritic steel pressure vessels extending to metal temperatures up

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to 565 ^{o}C (1050 ^{o}F) and pressure up to 28 MPa. Operating conditions for petroleum-refining pressure vessels ranges from as low as 205 ^{o}C temperature and 0.1 MPa pressure (hydrogen treating pressure vessel) to a maximum of 565 ^{o}C temperature and 3.1 MPa pressure (for catalytic cracking pressure vessel) [1,2]. Corrosive environment includes hydrogen, chlorine and sulfur etc. depending upon the operating conditions of pressure vessels.

2.0 STEELS FOR PRESSURE VESSELS

Pressure vessels are used in oil & gas and chemical processing plants for different chemical reactions, such as, catalytic cracking process, hydrocracking process, catalytic reforming and hydrogen treating process are often used in the temperature range 205-565^{o}C with the stresses about 15-30 MPa over design life of 25 - 30 years. Several commercially available steels, including SS316, SS304, A516, A508 etc., have been studied for applications in reactor pressure vessel [3-7]. Although these studies have contributed to better understanding of the microstructures of these welded joints, limited information is available in correlating the observed microstructures with the mechanical responses of the alloy over prolonged operating life. In thick-wall vessels operating in similar service environment, it is common to apply welded austenitic steel inlay to low carbon steels, thereby, taking advantage of the high strength and low cost of the base metal while retaining the superior corrosion resistance of the stainless steel weld inlay [2]. The low carbon steel and stainless steel inlay of the vessel is primarily constructed by welding resulting in different microstructures in the welded zone [4].

The microstructure of a fusion weld in a pipe is very complex and comprised of as many as seven distinct regions [8]. The welding thermal cycle produces peak temperatures and cooling rates that are highest at the fusion boundary. In a single-pass weld in ferritic steel, four distinct regions can be identified in the HAZ alone (Coarse-grain, Grained-refined, Inter-critical and Tempered HAZ region). The HAZ of multi-pass weld is even more complex, and as a result of multiple heat treatments, may contain more than four regions. The weldment is thus a composite material consisting of BM, three HAZ regions and the WM. Previous research found that most number of cracks is found in HAZ region of material [9,10]. Moreover, HAZ of 2.2Cr-1Mo steel weld exhibits inferior rupture strength to the BM [11] and formation of carbides in the HAZ results in deteriorated corrosion resistance as compared to the WM and BM [12]. This zone (HAZ) is a common source for defects such as hard inclusions, blisters by trapped gas and micro-cracks that develop during fast cooling of the welded joint.

In the petrochemical industry, environmental factors, such as, sulfur, chlorine and particularly those associated with hydrogen constitute over 25% of service failures[13]. Hydrogen induced pressure vessel steel fractures can occur in chemically hostile environments in the presence or absence of an applied stress. Hydrogen-induced cracking and hydrogen attack predominantly occur in low strength steels with yield stresses below 560 MPa (80 ksi) [14,15]. While low strength steels have been considered immune to hydrogen-assisted cracking (HAC), the presence of inclusions is known to promote stress oriented hydrogen induced cracking (SOHIC) or step wise

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cracking [16-18]. Earlier research has investigated hydrogen embrittlement in low strength steels (Yield Strength: 300-400 MPa), for example, hydrogen crack initiation at U-notch or at defects [19] and the effects of microstructure on hydrogen cracking [18,20], with much less emphasis being placed on crack propagation in steels with yield strength below 480 MPa.

Pressure vessels, such as, hydrogen treating pressure vessel in petroleum-refineries, operating over 15 psig (0.1 MPa) are designed in accordance with ASME Section VIII Div 1, 2 or 3, or an equivalent foreign country code. However, these codes do not address service conditions. American Petroleum Institute (API) produces the relevant high temperature hydrogen guideline, API Publication 941. API Publication 579 – "Fitness for Service" (American Petroleum Institute (API), 2000) is relatively recent code dedicated to addressing post fabrication issues of equipment. As most of the problems encountered in heavy-section piping occur at welded joints, damage-assessment techniques need to be focus on these regions rather on the base metal [9,21]. Since existing ASME Boiler & Pressure Vessel (B&PV) code rules do not adequately consider the high-temperature creep failure modes that can arise as a function of geometry, loading and material combination [22], an experimental research, establishing the processing, heat treatment-structure-properties relationship focused on the weldments of the alloy, is therefore necessary. The results are essential in generating relevant failure data and quantifying factors that can explain fracture mechanism for both static and fluctuating load at elevated temperatures and in corrosive environment.

Exposure to absorbed hydrogen and thermal aging can cause deleterious effects including the formation and propagation of brittle cracks. Hydrogen embrittlement (HE) is one of the most serious problems in high strength steels [23,24]. Moreover fatigue crack growth (FCG) behavior is enhanced in hydrogen environment for many structural steels [25,26]

The continued and prolonged use of pressure vessels for power generation, nuclear or chemical reactions, industrial processing, and storage requires them to withstand severe conditions of pressure, temperature, and other environments. Such environmental conditions include corrosion, neutron irradiation, hydrogen embrittlement, and so on. During service, these pressure vessel steels, especially 2.25Cr–1Mo steel, are susceptible to temper embrittlement and/or hydrogen damage [27]. Several types of hydrogen damage such as hydrogen embrittlement, and hydrogen attack are commonly occurring at the pressure vessel material. Some vessels are designed to carry noncorrosive fluids while others are designed to withstand harsh corrosive and highly radioactive materials.

The materials commonly used for pressure vessel construction include:

1. Low alloy steels with stainless steel liners for chemical processing plants.
2. Special metals such as titanium and zirconium. Sodium hydroxide and chlorine dioxide plant pressure vessels are constructed using solid, lined or cladded titanium for different chemical processing plants.

3. Nonmetallic materials, such as plastic and composites. One of the end uses of composites is to develop the natural gas vehicle (NGV) tank for automobile industry.
4. Concrete for industrial waste and sewage storage

The properties of the materials that are of general interest include:

1. Yield strength for the limit of elastic design
2. Ultimate strength for brittle fracture consideration
3. Reduction of area as a measure of ductility and energy absorption
4. Fracture toughness for the limit against brittle catastrophic fracture
5. Resistance to corrosion in dry and wet conditions

In pressure vessel steel, carbon is of prime importance because of its strengthening effect. It also raises the transition temperature, lowers the maximum energy values and widens the temperature range between completely tough and completely brittle behavior. Pressure vessel steel generally contain less than 0.25 wt % C or in other word, those steel are categorized in low carbon steel. ASTM A516 Grade 70 steel is one of the most commonly used materials in the fabrication of low temperature pressure vessels. Steel used in the fabrication of pressure vessel steel are of two kinds, carbon steel and alloy steel.

3.0 DESIGN AND CONSTRUCTION ASPECTS

In the design of pressure vessels safety, is the primary consideration, especially for nuclear reactor pressure vessels, due the potential impact of a possible severe accident. In general however, the design is a compromise between consideration of economics and safety. The design factor used in the ASME Boiler and Pressure Vessel Code [28] is intended to account for unknown factors associated with the design and construction of the equipment. The design formulas and the stress analysis methods are generally approximate and have built-in assumptions. Typically it is assumed that the material is homogeneous and isotropic. In the real world the material has flaws which tend to deviate from this assumption. Figure 2 shows general steps involved in design of pressure vessel.

Thick-walled reactor pressure vessels are the hearts of the processing units in refineries. These large vessels range more than 905 tons in weight and some have wall thickness up to 305 mm. If a pressure vessel is intended to operate in corrosive environment such as hydrogen sulfide (H2S), material selection as per ASME B&PV codes is done, which is based on pressure vessel operational and functional limitations. These thick-walled reactors are intended to operate in corrosive environment, H2S (operational requirements) and is desired to function properly (functional requirements) throughout its design life.

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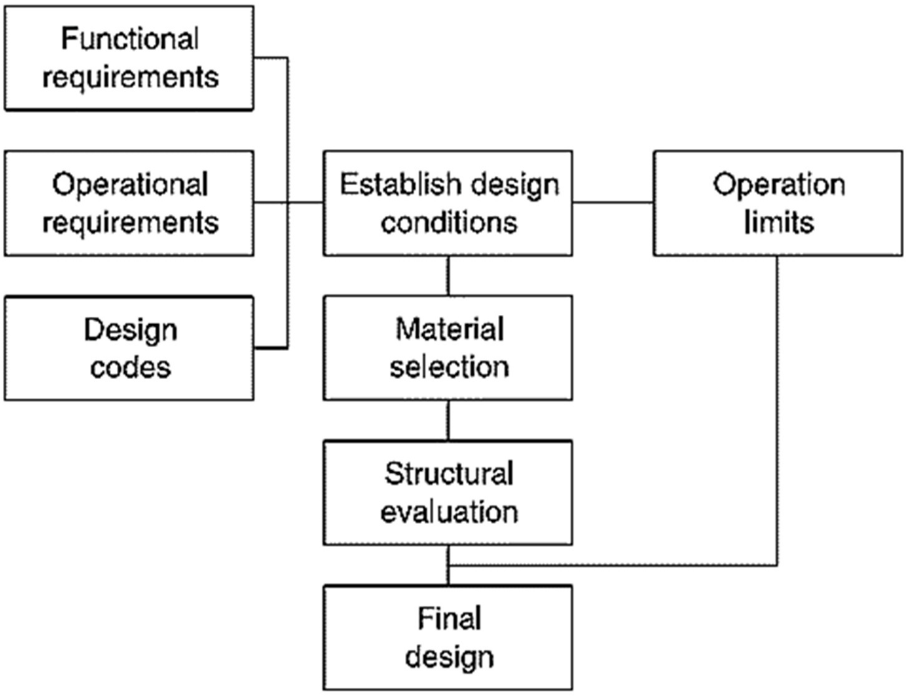

Figure 2: General aspects of design of Pressure Vessel

When two or more parts of pressure vessel steel are welded together, the properties of the metal in weldment vary significantly. Weldment here are composed of three microstructural regions, base metal (BM), weld metal (WM) and heat affected zone (HAZ). Properties in those regions are different due to high heat input during welding, slag inclusions, and disproportionate heat or cooling rate. During welding, a weldment undergoes complex temperature changes that cause transient thermal stresses, and non-elastic strain in regions near the weld. The majority of service failures of industrial equipment made of Cr-Mo steels have been reported to occur in critical parts such as welds, mainly due to the microstructural changes, due to the composition of the alloy in use and to the thermal fields produced by the welding process, which give rise to marked variations in the material properties [29].

Submerged arc welding (SAW) process is commonly employed in the fabrication of pressure vessels. The SAW is an arc welding process in which coalescence of metals is produced by heating them with an arc between a bare consumable electrode and the work piece, with the arc being shielded by a blanket of granular, fusible material placed over the welding area. In the welding process, flux closest to the arc melts and form slag on the surface of the weld, thus protecting the molten metal from reacting with the air. It's a common practice to assemble pressure vessel using fusion welding processes (Figure 3) as gas metal arc welding [30]

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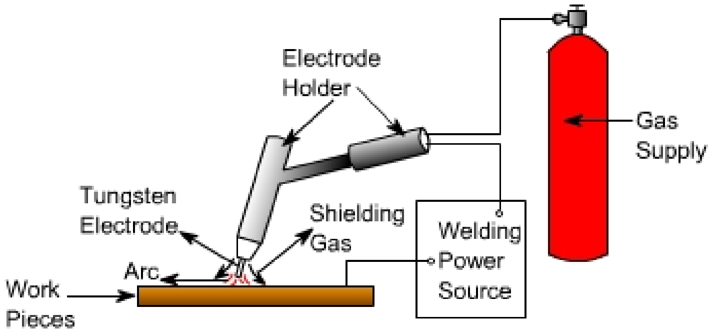

Figure 3 Fusion welding processes as gas metal arc welding [30]

SAW will results in a weld joint having good ductility and uniformity. Good impact strengths are obtained when specific procedures and techniques are evaluated in combination with the electrode and flux. A proper selection of the electrode and flux provides good corrosion resistance depending upon the requirement, and ensures mechanical properties at least equal to that of the base metal [31].

A post weld heat treatment (PWHT) is needed to reduce the internal stresses that have developed due to the welding process to an acceptable level. Post weld heat treatment could be defined as heating to a suitable temperature (recrystallization temperature); holding long enough to reduce residual stresses, and then cooling slowly enough to minimize the development of new residual stress. Heating and cooling must be done slowly and uniformly, usually at 150^{o}C/h.

This treatment has a bearing on the quality of weld or the integrity of the finished weldment, and control of temperature may be rigidly specified. However, the residual stresses in a structure subjected to PWHT still do not reduced to zero [30].

Figures 4 show the effects of PWHT on the longitudinal residual stresses at different location on the weldment. The residual stresses in the welded plate subjected to PWHT were reduced to a much lower value, but not completely removed. Also PWHT smoothed out the concentrated residual stress into a wider area. So the high peak values were distributed more uniformly around the welding area, and the effects of high changes of stress in a small area were reduced.

Residual stresses at HAZ are higher as compared to WM and BM. PWHT reduces the residual stresses considerably as shown in Figure 2.4. Relatively high residual stresses at HAZ rendered this zone as a common source for defects such as hard inclusions, blisters by trapped gases and micro-cracks.

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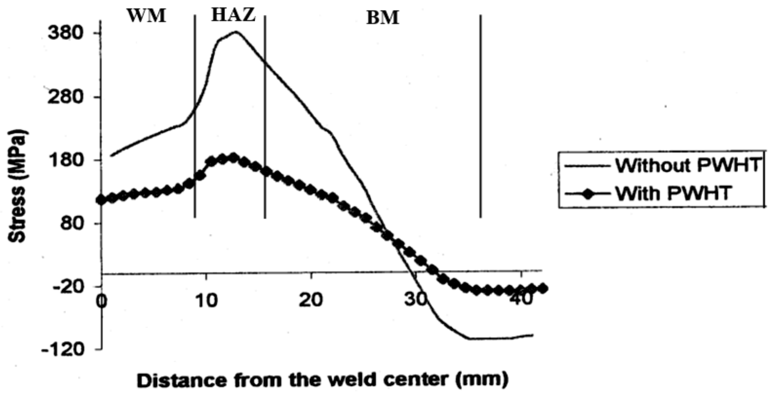

Figure 4: Longitudinal Residual stresses at weld after PWHT [30]

In the 1940's, Nelson collected data regarding the operation- experience in petroleum and petrochemical industry were published. He developed a set of curves, known as "Nelson curves" as shown in Figure 5. Nelson curves are useful in designing and fabrication of pressure vessels and pumping at moderate temperatures (yet greater than 205 ^{o}C) and hydrogen pressure (greater than 690 KPa). The Nelson curves have been accepted by the American. In 1949, the original version of the Nelson Diagram was published by the American Petroleum Institute (API). The Nelson Diagram is a collection of equipment successes and failures in regards to high temperature hydrogen attack (HTHA) over a wide range of temperatures and hydrogen partial pressures. The various modes of attack (i.e. surface decarburization, fissuring and material decarburization) on the equipment data points are distinguished. The Nelson Diagram consists of a curve for each of the following materials: carbon steel, 0.5Mo steel, 1.0Cr-0.5Mo steel, 1.25Cr-0.5Mo steel, 2.25Cr-1.0Mo steel, 2.25Cr-1Mo-V and 3.0Cr-1Mo steels (same curve), and 6.0Cr-0.5Mo steel. These curves provide operating limitations for specific steels in high temperature hydrogen service. Below and to the left of the curve is considered as a safe operating region. For a hydrogen partial pressure of 300 lb/in^2, Figure 2.5, safe operating temperature(s) is 550 ^{o}F for carbon steel, 675 ^{o}F for 0.1 Mo steel, 780 ^{o}F for 0.25 Mo steel and 840 OF for 0.5 Mo steel. Operating above these temperatures will result in surface decarburization, fissuring, and decarburization. A review of the fallacy of the 0.5Mo curve, recently made by Prescott [32], indicated the wide ranging effects on 0.5Mo material of varying heat treatment and impurity levels.

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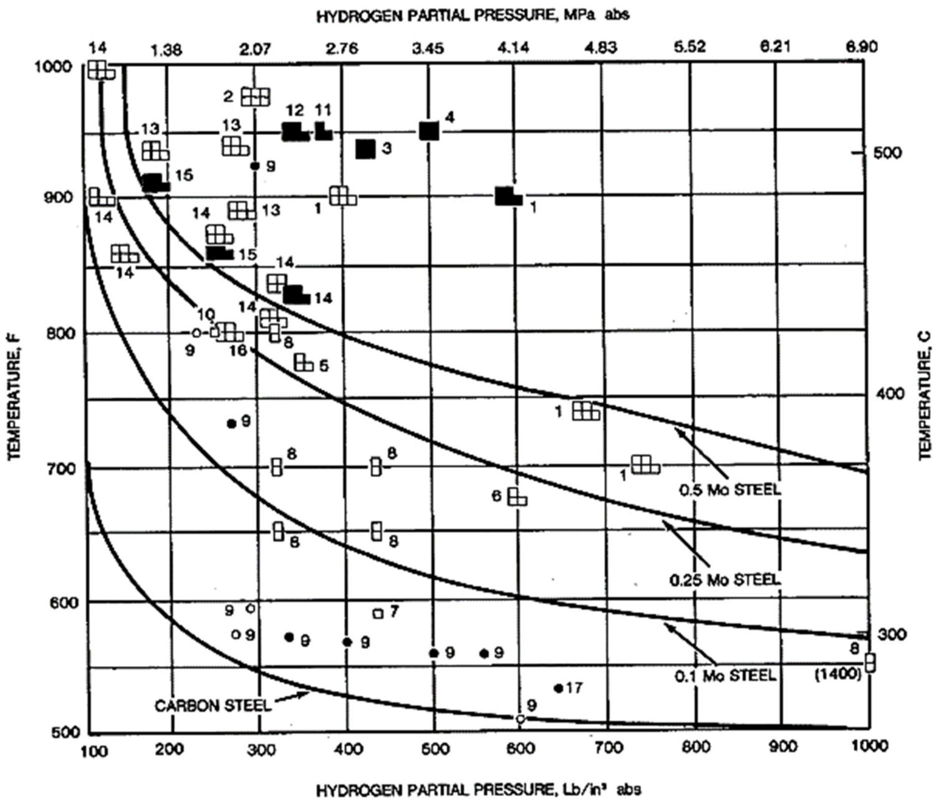

Figure 5: Nelson curves showing operating limits for C-Mo steels

4.0 CONCLUSIONS

The design of pressure vessel is initialized with the specification requirements in terms of standard technical specifications along with other numerous requirements. It is observed that all the pressure vessel components are selected on the basis of available ASME standards and the manufactures also follow the same standards during manufacturing process. Many pressure vessels are made of steel especially A516. To manufacture a pressure vessel, rolled and forged parts are welded together. Some mechanical properties of steels, achieved by rolling or forging, could adversely be affected by the welding process, unless special precautions are taken. In addition to adequate mechanical strength, current standards dictate the use of steel with a high impact resistance as well. During welding, material undergoes complex temperature changes that cause transient thermal stresses and non-elastic strain in regions near the weld is observed. The majority of service failures of industrial equipment have been reported to occur in the weld area.

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