普通高等教育“十二五”规划教材

Pressure Vessel System and Design

压力容器系统与设计

龙飞飞　赵俊茹　王维刚　编著

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Headline

It is a bilingual textbook. Based on the education goal of Process Equipment and Control Engineering major, the main contents are stated in detail, including the requirement, classification, material, fabrication, inspection and the principle, performance, structure of several typical unit equipments. The mechanics theory of thin monoblock revolution shell is introduced. Then based on which, the minimum required thickness formulas are introduced for typical pressure vessel structures. Also, the problems and solution method are illustrated for the equipments in service.

The main target is to train the ability of analyzing and understanding in professional field. Also the book can be used to train the ability of reading and communicating in specialty region. It is the textbook of bilingual education for Process Equipment and Control Engineering students, and can be used for reference by concerning foreign affairs designers, maintenance engineers on import equipments, etc.

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Preface

Pressure vessel systems have an extremely broad range of application, from simple storage vessels to complicated chemical reactor systems. It is the author's intent to show some common features of these vessel systems in order to develop an organized approach in judging whether a system is reasonably safe to operate. This requires a review of some metals that are most often used in pressure vessel systems, in order to refresh the reader's knowledge of the properties of materials, how they are affected in manufacturing and use.

Pressure vessel systems are too often taken for granted once the design and installation to nationally recognized standards have been completed. Unfortunately, materials degrade with usage, hidden flaws from fabrication make their appearance in service, and plant upsets cause unforeseen problems to arise in the pressure vessel system. It is by periodic review of the condition of the vessels that wear and tear can be detected. Once this deterioration is detected, plant people who operate pressure vessel systems need to go further, namely, to determine if the vessel can continue to be operated at the same pressure.

The intent of the author is to emphasize a total system approach to pressure vessel safety in order to consider the many risks and hazards, such as fire, chemical reactions, vapor-cloud explosions, lethal substance release, loss of production, adverse environmental effects, and possible legal and liability actions.

ASME code material selection is stressed, as are the many welding procedure and operator-qualification requirements. Nondestructive testing is an important part of quality control in the pressure vessel industry; therefore, some material on the different types of NDT is presented in the text.

The basics concerning the strength of materials are reviewed in order to lay the groundwork for stress analysis and code equations that are applied to determine safe working pressures. Also, the methods to calculate the minimum required thickness of typical vessel parts are introduced in the book. The user of this book should be advised that any code formulas or references should always be checked against the latest editions of codes, Le. , ASME Section VIII, Division 1, Uniform Building Code, arid ASCE 7-95. These codes are continually updated and revised to incorporate the latest available data.

We must thank Mi Guangzhu, Xu Guangyun, Li Cunxiu for drawing figures. Also, we are grateful to all those who have contributed information and advice to make this book possible, and invite any suggestions readers may make concerning corrections or additions.

Long Feifei

Contents

Chapter 1

Introduction

All structures with shapes resembling curved plates, closed or open, are referred to as shells. In pressure vessel design pressure vessels are closed containers for the containment of pressure. Pressurized equipments are required in a wide range of industrial plants for storage and manufacturing processes, such as petrochemical, offshore oil and gas rigs. Some of them are used in chemical process, but some are not. In the vessels and equipments used in chemical process, some are pivotal and the others are accessorial. But no matter what they are, key, secondary vessels or not used as chemical vessels, they have their own tasks to ensure the whole equipment would run a long period without accident.

1.1 Basic Requirements

There are some basic requirements for pressure vessels.

1.1.1 Reliable Mechanics Performance

It is the principal performance for pressure vessels. If it is trustless, equipments would not be used in process, or they would fail. There are a lot of pressure vessels failure accidents in domestic or overseas plants, some of them are even catastrophic. To satisfy requirements of mechanics performance, there are several elements for process equipments.

(1) ***Strength***

Strength is the failure resistance of pressure vessels under loads. Each vessel, including its shell and its components, should be provided with enough strength, or it can not be operated in gear and protect the safety of operators. On the other hand, the FS can not be too large for economical factor. Often, the chosen equivalent stress of a vessel is little less than the allowable stress of construction material. To design of components, designers may as well obey equal strength rule.

(2) ***Rigidity***

Rigidity is a term representing a component's ability to keep original figure against loads. If rigidity is not sufficient, vessels would collapse under external pressure. To shells and parts, criterion for assessing mechanical reliability always is rigidity, but not intensity. For example, if rigidity is not sufficient, vessels under external pressure would fail even if intensity is not sufficient.

(3) ***Tightness performance***

Pressure vessels and chemical equipments often are containers for fluid mediums, which may be combustible, explosive, poisonous and high corrosive. If the joints of openings and covers are not tight enough, the mediums would escape and pollute environment, at the same time, they even may hurt operators. Furthermore, the leakage self is a great loss. To vacuum vessels, if it is not airproof, air will enter the vessels and destroy vacuum condition. This is not allowable. Tightness performance is very important for chemical vessels. Evermore, the seals of high pressure vessels are paid more attention to, while those of middling, low pressure vessels are neglected, so in them, many types of leakage often appear. So attention must be paid to tightness performance of all pressure vessels except atmosphere vessels.

(4) ***Wear***

The wear of pressure vessels and chemical equipments is based on their employed life. The fixed number of year of them is currently 10 ~ 20 years, but actually exceed. The wear of chemical equipments mostly lies on the medium corrosiveness, especial carbamide, acid and alkali equipments. For the vessels under cycle loads, high temperature and fluid vibration, their lives also depend on many factors, such as fatigue, creep , vibration wear, and so on.

1.1.2 High Unit Throughput

Unit throughput of pressure vessels and chemical equipments is material quantity processed in unit time and in unit equipment volume (or area). For example, unit throughput of vitriol absorption tower is vitriol quantity processed in pounds per hour and per cubic meter. To chemical equipments, the requirements include not only high materials quantity processed, but also high efficiency. But there is contradiction between them. Actually unit throughput is a synthetical guide line of processed quantity and equipments efficiency.

1.1.3 Low Wasting Coefficient

Wasting coefficient is the consumed materials and energy when outputing unit weight and unit volume product, i. e. , materials, fuel, water, power, steam, compressed air, etc. . Wasting coefficient of vessels and equipments is related to the process, also to the design of equipments. For example, in ammonia synthesizing tower, the bigger the resistance when gases go through catalyzer bed, the bigger the falling quantity of the pressure, the bigger the power waste. It is better that the wasting coefficient is small.

1.1.4 Easy to Fabricate

Vessels and equipments must be designed to be easy to fabricate. For example, to thick wall cylindrical vessels, the less deep hoop welds, the better. In fabrication, if weld can be used, the best way is welding. In addition, to the best of the designer's abilities, standard components should be used.

1.1.5 Transport and Installation

Almost all pressure vessels and equipments need to be transported to erection site form shop. So they should be easy to transport. If they need to be assembled in field, they also should be easy to install. In addition to common information, such as conveyances dimensions, unit high-point weight, dock condition, many other items of information are necessary and must be recorded. The largest sling length is to be given to calculate the length of equipments. If the conveyances need to pass tunnels, the dimensions of which are needed. To the transportation of spherical tanks, proper fixed devices are needed.

1.1.6 Operation Performance

① convenient to operate, no noise and vibration;
② can be operated continuously, high automatization and easy to maintain;
③ convenient to take apart and examine;
④ experiments can be carried out on and monitored;
⑤ parts can be replaced with standard parts.

Some conditions above are related and complementary, but some may be incompatible each other. In order to get a optimal scheme, abortive analysis is necessary to find out main contradiction and its core in each design.

1.2 Pressure Vessel Classification

Pressure vessels are made in all sizes and shapes. The smaller ones may be no larger than a fraction of an inch in diameter, whereas the larger vessels may be 150 ft or more in diameter. Some are buried in the ground or deep in the ocean; most are positioned on the ground or supported on platforms; and some actually are found in storage tanks and hydraulic units in aircraft.

The internal pressure to which process equipment is designed is as varied the size and shape. Internal pressure may be as low as 1 in. water gage pressure to as high as 300000 psi or more. The usual range of pressure for monoblock construction is about 15 to about 5000 psi, although there are many vessels designed for pressure below and above that range. The ASME Boiler and Pressure Vessel Code, Section Ⅷ, Division 1, specifies a range of internal pressure from 15 psi at the bottom to no upper limit. (But if the internal pressure exceed 3000 psi, special design considerations are necessary).

On function, pressure vessels are varied too. They can range from storage tanks in which a gas or liquid is stored under pressure to large chemical reactor vessels where with pressure, and perhaps temperature, chemical changes take place among the fluid or gases confined under pressure in the vessel system. In this book, according to the functions of vessels, a simple classification could be:

(1) ***Storage vessels***

These include air tanks, ammonia tanks, water tanks, and similar tanks in which a gas or liquid is stored under pressure to be used when needed.

(2) ***Heat exchangers***

They are equipments primarily for transferring heat between hot and cold streams. They have separate passages for the two streams and operate continuously.

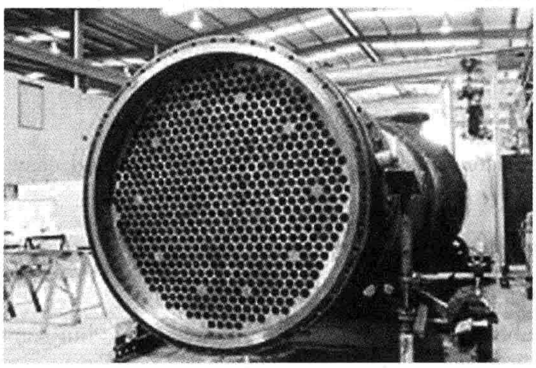

Fig. 1. 1 Heat Exchanger

(3) ***Chemical reactors***

Almost every kind of holding or contacting equipment has been used as a chemical reactor at some time, from mixing nozzles and centrifugal pumps to the most elaborate towers and tube assemblies such as those found in large chemical and petrochemical processes.

(4) ***Rotating pressure vessels***

These types of vessels usually use steam inside of them so that drying of a product will occur as it passes over the rotating roll's surface. They are used to dry clothing, paper, and plastic materials.

(5) ***Cookers***

Digesters, creosoting vessels, vulcanizers, and rendering tanks are included in this classification. These pressure vessels (cooking, rendering, etc., are performed under pressure) cause a physical change to take place to the contents and don't involve serious chemical reactions. Thus, in a digester, wood chips or rags are cooked with steam to make a pulp that is used in the manufacture of paper.

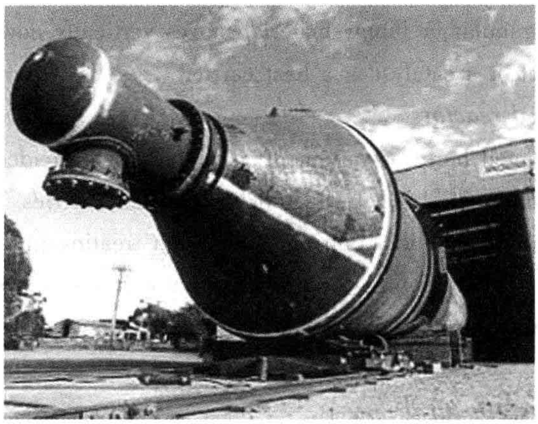

Fig. 1. 2 Digester Tank

1. 2. 1 Types of Reactors

In the above, the quantity of chemical reactors are enormous, also, they play very important roles in industry. They can be subdivided as:

(1) ***Stirred tanks***

Stirred tanks are the most common type of batch reactor. Stirring is used to mix the ingredients initially, to maintain homogeneity during reaction, and to enhance heat transfer at a jacket wall or internal surfaces. Sometimes they also can be used in continuous processing.

(2) ***Tubular flow reactors***

The ideal behavior of tubular flow reactors (TFR) is plug flow, in which all nonreacting molecules have equal residence times. Any backmixing that occurs is incidental, the result of natural turbulence or that induced by obstructions to flow by catalyst granules or tower packing or necessary internals of the vessels. As a result of chemical reaction, gradients of concentration and temperature are developed in the axial direction of TFRs.

(3) ***Gas-Liquid reactors***

Except with highly volatile liquids, reactions between gases and liquids occur in the liquid phase, following a transfer of gaseous participants through gas and liquid films. The rate of mass transfer always is a major or limiting factor in the overall transformation process. Naturally the equipment for such reactions is similar to that for the absorption of chemically inert gases, namely towers and stirred tanks.

(4) ***Fixed bed reactors***

The fixed beds of concern here are made up of catalyst particles in the range of 2 ~ 5 mm dia.

(5) ***Moving bed reactors***

In such vessels granular or lumpy material moves vertically downward as a mass. The solid may be a reactant or a catalyst or a heat carrier.

(6) ***Fluidized bed reactors***

The term is restricted here to equipment in which finely divided solids in suspension interact with gases. Solids fluidized by liquids are called slurries. Three phase fluidized mixtures occur in some coal liquefaction and petroleum treating processes. In dense phase gas-solid fluidization, a fairly definite bed level is maintained; in dilute phase systems the solid is entrained continuously through the reaction zone and is separated out in a subsequent zone.

(7) ***Kilns and hearth furnaces***

These units are primarily for high temperature services, the kilns up to 2500℉ and the furnaces up to 4000℉. Usual construction is steel-lined with ceramics, sometimes up to several feet in thickness.

The reactions taking place in chemical reactors are quite numerous and may include some of the following:

(1) ***Distillation***

A process for the separation of different compounds from a mixture, such as alcohol from water, where by the substance having the lower boiling point is vaporized and thereby driven off from the remainder of the mixture. It is usual practice to condense the vapor and thus retain the substance vaporized. The vessels in which the process is carried out are commonly referred to as "stills".

(2) ***Extraction***

A process in which a substance is removed from a mixture by the use of a solvent in which the substance will dissolve, such as in practice to reclaim the substance so dissolved by distillation or evaporation of the solvent. The vessels in which the process is carried out are commonly referred as "extractors".

(3) ***Hydrogenation***

A process in which gaseous hydrogen is chemically combined with an organic compound. It is the process used in making shortening compounds, butter substitutes, and many other forms of "solidified oils". The vessels in which the process is carried out are commonly referred to as "hydrogenators" or "reactors".

(4) ***Cracking***

A process which is sometimes referred to as destructive distillation, in which organic compounds are subjected to heat in such a manner that different organic compounds are formed, as in the cracking of certain petroleum oils to form gasoline. The process may be carried out in a chemical digester, or it may occur in pipe coil commonly referred to as a "cracking coil".

(5) ***Oxidation***

A process in which oxygen is added to a substance or hydrogen is removed by the use of an "oxidizer", such as air, oxygen, potassium permanganate, or potassium chlorate. Some of the chemicals formed by the oxidation process are formaldehyde, acetic acid, camphor, and indigo. The process is carried out in chemical digesters or chemical reactors.

(6) ***Amination***

A process in which an organic compound is treated with ammonia or one of its compounds to form what are known as "amines". Amines are used in the manufacture of dyes, and as insecticides, antiseptics, and medicines. The process is carried out in chemical digesters or chemical reactors.

(7) ***Reduction***

A process in which oxygen is removed in some degree from a compound by the use of a reagent such as hydrogen, carbon, or a hydrocarbon. Reduction is usually accomplished by the treatment of the substance with hydrochloric, sulfuric, or acetic acid and a metal such as zinc or iron in finely divided form. The process is carried out in chemical digesters or chemical reactors.

(8) ***Polymerization***

A process in which heat and pressure are applied to lightweight hydrocarbons in such a manner as to change them to heavy hydrocarbons. It is a process used in the manufacture of synthetic rubber, synthetic resins, and gasoline. The process is carried out in chemical digesters or chemical reactors.

(9) ***Sulfonation***

A process in which a compound of sulfur, oxygen, and hydrogen, such as sulfuric acid, is chemically combined with an organic compound to produce "sulfonic acids" or "sulfonated oils". The former are used in the manufacture of dyes, while the latter are used in the glue, paper, leather, textile, and soap industries. The vessels in which the process is carried out are commonly referred to as "sulfonators".

(10) ***Nitration***

A process in which a compound of nitrogen and oxygen, such as nitric acid or sodium nitrate, is chemically combined with organic compounds to form so-called nitro compounds, which are used principally in the manufacture of medicines, dyes, and explosives. The vessels in which the process is carried out are commonly referred to as "nitrators".

(11) ***Depolymerization***

A process whereby heat and sometimes pressure are applied to heavy hydrocarbons in such a manner as to change them to lightweight hydrocarbons; an example would be decomposition by heat of certain synthetic resins to recover more usable substances. The process is carried out in chemical digesters or chemical reactors.

(12) ***Diazotization***

A process in which a selected type of organic compound is combined with nitrous acid, the products of which are used principally in the manufacture of dyes.

(13) ***Amidation***

A process very similar to amination but in which the organic compounds formed are known as "amides". Amides are used in organic synthesis for the manufacture of commercial products. The process is carried out in chemical digesters or chemical reactors.

Chemical reactors can operate at very high pressures and therefore often require multilayer wall construction. These vessels may also require stainless-steel liners owing to the corrosiveness of the contents or, in the case of a gas such as hydrogen, because of the peril of carbon steel's becoming embrittled, and thus posing the potential for a disastrous cracking failure. The possibility of a runaway chemical reaction on these types of vessels also requires consideration.

1.2.2 Cryogenic Storage Tanks

The term "cryogenic" refers to a process that uses temperatures below -100 ℉. Special construction materials must be used, as many carbon-steel materials become brittle at temperatures below -20 ℉, and thus subject to possible sudden cracking failures.

Among the most economically and technically important physical reactions using cryogenic temperatures are the cooling and liquefaction of gases and the distillation and fractional condensation of liquefied gas mixtures to yield pure-component streams. Cooling and liquefaction are the bases of every cryogenic process.

Gases with low boiling points are used as a working medium in cooling and liquefaction. For production of ultralow temperatures, helium is used, but below 2 K (−272℃, or −443.6 ℉), liquid helium has a very low vapor pressure so that adiabatic demagnetization must be employed to reach temperatures close to absolute zero. Economically significant cryogenic processes do not occur at such extremes.

Because of the contraction in volume of gases with decreasing temperatures, cryogenic facilities are smaller than standard process facilities and must be well insulated for energy conservation. This sometimes creates the impression that maintenance is more difficult than for warm plants. Mechanically moving parts can be designed and installed with ready access for easy maintenance. However, equipment behind the heavy insulation may require thawing out and purging of gases before repairs can be made.

Cryogenic liquid storage tanks are usually located outdoors, because indoor leakage of any gas may result in fire, explosions, asphyxiation, and even possible toxic effect. Cryogenic tanks are, thus usually installed outdoors on reinforced concrete pads; they use low-voltage-powered pumps and may require a heating medium for liquid vaporization, as in natural gas line for distribution or plant use. Pressure regulation is usually by the use of the stored gas, and not by use of air or pneumatic regulators. This prevents instrument lines from freezing owing to moisture in the air.

1. 2. 2. 1 Construction materials for cryogenic tanks

Low-temperature service requires careful consideration of the metals to be used for the storage tanks and piping connected to the system. Some metals become extremely brittle below a certain point called the "transition temperature" and can crack very abruptly from a shock load or through a stress concentration point. According to ASME code requirements, only notch-touch materials, including welding materials, should be used, especially with ferrous metals. This should be remembered when performing any repairs to vessels in cryogenic service. There is a problem in using nonferrous metals, such as copper and aluminum alloys. These may be less susceptible to brittle fracture but are more likely to fail in a fire, because of their lower strength at elevated temperatures in comparison with ferritic material. Some broad temperature limits and the corresponding metals that may become brittle are shown in Table 1. 1.

Table 1. 1 Transition Temperature for Selected Metals

Material	Lowest permissible Operating temperature/°F
Carbon steel	−28
Aluminum killed steel	−64
2% nickel steel	−82
3% nickel steel	−154
9% nickel steel	−373
18 − 8 stainless steel-monel	−422

1. 2. 2. 2 ASME code requirements

The ASME code should be consulted for allowable stresses at low temperatures and for the testing required of the material to ascertain if it is suitable for low-temperature