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Kolmetz Handbook Of Process Equipment Design

PRESSURE VESSEL SELECTION, SIZING AND TROUBLESHOOTING

(ENGINEERING DESIGN GUIDELINE)

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INTRODUCTION

Scope

Vessels are a vital part of the operational units in the process industries. A vessel is a container in which materials are processed, treated, or stored. Without this type of equipment, the process industries would be unable to create and store large amounts of Product. Pressure vessels used in industry are leak-tight pressure containers, usually cylindrical or spherical in shape, with different head configurations.

The process engineer should have some knowledge of the mechanical design of vessels. For example, the process engineer may have to make a preliminary design of vessels for a cost estimate. A vessel consists of a cylindrical shell and end caps, called heads. For safety, vessel design is governed by codes. An example is the ASME (American Society of Mechanical Engineers) Boiler and Pressure Vessel Code.

In all the major industrialized countries, the design and fabrication of thin-walled pressure vessels is covered by national standards and codes of practice. The Code design criteria consist of basic rules specifying the design method, design load, allowable stress, acceptable material, and fabrication-inspection certification requirements for vessel construction.

This guideline covers several things in designing pressure vessel. Starting from the material, allowable stress, welding, corrosion and sizing equipment

General Design Consideration

Vessels are a vital part of the operational units in the process industries. A vessel is a container in which materials are processed, treated, or stored. Without this type of equipment, the process industries would be unable to create and store large amounts of Product. Vessels are used to carry out process operations such as distillation, drying, filtration, stripping, and reaction. These operations usually involve many different types of vessels, ranging from large towers to small additive and waste collection drums. Vessels are also used to provide intermediate storage between processing steps. They can provide residence time for reactions to complete or for contents to settle.

For handling such liquids and gases, a container or vessel is used. It is called a pressure vessel, when they are containers for fluids subjected to pressure. They are leak proof containers. They may be of any shape ranging from types of processing equipment. Most process equipment units may be considered as vessels with various modifications necessary to enable the units to perform certain required functions, e.g. an autoclave may be considered as highpressure vessel equipped with agitation and heating sources.

Pressure vessels used in industry are leak-tight pressure containers, usually cylindrical or spherical in shape, with different head configurations. They are usually made from carbon or stainless steel and assembled by welding. Early operation of pressure vessels and boilers resulted in numerous explosions, causing loss of life and considerable property damage.

Some 80 years ago, the American Society of Mechanical Engineers formed a committee for the purpose of establishing minimum safety rules of construction for boilers. In 1925 the committee issued a set of rules for the design and construction of unfired pressure vessels. Most states have laws mandating that these Code rules be met. Enforcement of these rules is accomplished via a third party employed by the state or the insurance company.

In all the major industrialized countries, the design and fabrication of thin-walled pressure vessels is covered by national standards and codes of practice. In most countries it is a legal requirement that pressure vessels must be designed, constructed, and tested in accordance with part or all of the design code. The primary purpose of the design codes is to establish rules of safety relating to the pressure integrity of vessels and provide guidance on design, materials of construction, fabrication, inspection, and testing. The standard used in North America (and most commonly referenced internationally) is the ASME Boiler and Pressure Vessel Code (the ASME BPV Code).

The Code design criteria consist of basic rules specifying the design method, design load, allowable stress, acceptable material, and fabrication-inspection certification requirements for vessel construction. The design method uses design pressure, allowable stress, and a design formula compatible with the geometry of the part to calculate the minimum required thickness of the part. This procedure minimizes the amount of analysis required to ensure that the vessel will not rupture or undergo excessive distortion. In conjunction with specifying the vessel thickness,

A. Design Pressure

A vessel must be designed to withstand the maximum pressure to which it is likely to be subjected in operation. For vessels under internal pressure, the design pressure (sometimes called maximum allowable working pressure or MAWP) is taken as the pressure at which the relief device is set. This will normally be 5 to 10% above the normal working pressure, to avoid spurious operation during minor process upsets. When the design pressure is decided, the hydrostatic pressure in the base of the column should be added to the operating pressure, if significant.

Vessels subject to external pressure should be designed to resist the maximum differential pressure that is likely to occur in service. Vessels likely to be subjected to vacuum should be designed for a full negative pressure of 1 bar, unless fitted with an effective, and reliable, vacuum breaker.

B. Design Temperature

The strength of metals decreases with increasing temperature, so the maximum allowable stress will depend on the material temperature. The maximum design temperature at which the maximum allowable stress is evaluated should be taken as the maximum working temperature of the material, with due allowance for any uncertainty involved in predicting vessel wall temperatures. The minimum design metal temperature (MDMT) should be taken as the lowest temperature expected in service.

C. Materials

Pressure vessels constructed in such a manner that, a sudden change of section producing a notch effect is present, are usually not recommended for low temperature range operations. The reason is that, they may create a state of stress such that the material will be incapable of relaxing high-localized stresses by plastic deformation, therefore, the materials used for low temperature operations are tested for notch ductility.

The materials to be used in pressure vessels must be selected from Code-approved material specifications. This requirement is normally not a problem since a large catalogue of tables listing acceptable materials is available. Factors that need to be considered in picking a suitable table are:

- Cost
- Fabricability
- Service condition (wear, corrosion, operating temperature)
- Availability
- Strength requirements

Pressure vessels are constructed from plain carbon steels, low and high alloy steels, other alloys, clad plate, and reinforced plastics. Selection of a suitable material must take into account the suitability of the material for fabrication (particularly welding), as well as the compatibility of the material with the process environment.

Carbon steels can be used down to 60 degree C. Notch ductility is controlled in such as materials through proper composition steel making practice, fabrication practice and heat treatment. They have an increased manganese carbon ratio. Aluminium is usually added to promote fine grain size and improve notch ductility. Embrittlement of carbon and alloy steel may occur due to service at elevated temperature. This inhibited by addition of molybdenum and also improve tensile and creep properties.

Two main criteria in selecting the steel elevated temperature are metallurgical strength and stability. Carbon steels are reduced in their strength properties due to rise in temperature and are liable to creep. Therefore, the use of carbon steel is generally limited to 500^{o}C.

One of the most widely used steel for general purpose in the construction of pressure vessel is SA-283, Grade C. This steel has good ductility and forms welds and machines easily. It is also one of the most economical steel suitable for pressure vessels. The SA-283 steels cannot be used in applications with temperatures over 340 °C. For vessels having shells of grater thickness. SA-285 Grade C is most widely used Hi moderate pressure applications. The SA-285 steels cannot be used for services with temperature over 482 °C. However, both SA-285 and SA-285 SA-212 steels have very low allowable stress, at higher temperature.

Plain carbon and low alloy steels plates are usually and where service condition permit because of the lesser cost and greater availability of these steels. Such steels may me fabricated by fusion welding and oxygen cutting if the carbon content does not exceed 0.35%.vessels may be fabricated.

The important materials generally accepted for construction of pressure vessels are indicated here. Metals used are generally divided into three groups as.

1 Low cost Cast iron, Cast carbon and low alloy steel, wrought carbon and low alloy steel.
2 Medium cost - High alloy steel (12%chromium and above), Aluminum, Nickel, Copper and their alloys, Lead.
3 High cost - platinum, Tantalum, Zirconium, Titanium silver.

Vessels with formed heads are commonly fabricated from low carbon steel wherever corrosion and temperature considerations will permit its use because of the low cost, high strength, ease of fabrication and general availability of mild steel. Low and high alloy steel and non-ferrous metals are used for special service.

Several typical pressure vessel materials for a noncorrosive environment and for service temperatures between 50 F and 1000 F are shown below

Table 1. Acceptable Pressure Vessel Materials

Temperature Use Limit (F)	Plate Material	Pipe Material	Forging Material
Down to -50	SA-516 All grades	SA 333 Gr. 1	SA 350 Gr. LF1, LF2
+33 to +775	SA-285 Gr. C SA-515 Gr. 55, 60, 65 SA-516 All grades	SA-53 SA-106	SA-181 Gr. I, II
+776 to +1000	SA-204 Gr. B, C SA-387 Gr. 11, 12 Class 1	SA-335 Gr. P1, P11, P12	SA-182 Gr. F1, F11, F12

D. Maximum Allowable Stress (Nominal Design Strength)

The allowable stress used to determine the minimum vessel wall thickness is based on the material tensile and yield properties at room and design temperature. For design purposes, it is necessary to decide a value for the maximum allowable stress (nominal design strength) that can be accepted in the material of construction. This is determined by applying a suitable safety factor to the maximum stress that the material could be expected to withstand without failure under standard test conditions. The safety factor allows for any uncertainty in the design methods, the loading, the quality of the materials, and the workmanship.

At temperatures where creep and stress rupture strength do not govern the selection of stresses, the maximum allowable stress is the lowest of

1. The specified minimum tensile strength at room temperature divided by 3.5;
2. The tensile strength at temperature divided by 3.5;
3. The specified minimum yield strength at room temperature divided by 1.5;
4. The yield strength at temperature divided by 1.5.

At temperatures where creep and stress rupture strength govern, the maximum allowable stress is the lowest of

1 The average stress to produce a creep rate of 0.01%/1000 h;
2 F times the average stress to cause rupture at the end of 100,000 h, where F¼0.67 for temperatures below 15008F (8158C)—see the code for higher temperatures;
3 0.8 times the minimum stress to cause rupture after 100,000 h.

Typical maximum allowable stress values for some common materials are shown in below.

Table 2. Typical Maximum Allowable Stresses for Plates

Material	Grade	Min Tensile Strength (ksi)	Min Yield Strength (ksi)	Maximum Temperature (°F)	Maximum Allowable Stress at Temperature °F (ksi = 1000 psi)				
					100	300	500	700	900
Carbon steel	A285 Gr A	45	24	900	12.9	12.9	12.9	11.5	5.9
Killed carbon steel	A515 Gr 60	60	32	1000	17.1	17.1	17.1	14.3	5.9
Low alloy 1¼ Cr, ½ Mo, Si	A387 Gr 22	60	30	1200	17.1	16.6	16.6	16.6	13.6
Stainless steel 13 Cr	410	65	30	1200	18.6	17.8	17.2	16.2	12.3
Stainless steel 18 Cr, 8 Ni	304	75	30	1500	20	15	12.9	11.7	10.8
Stainless steel 18 Cr, 10 Ni, Cb	347	75	30	1500	20	17.1	15	13.8	13.4
Stainless steel 18 Cr, 10 Ni, Ti	321	75	30	1500	20	16.5	14.3	13	12.3
Stainless steel 16 Cr, 12 Ni, 2 Mo	316	75	30	1500	20	15.6	13.3	12.1	11.5

E. Welded-Joint Efficiency and Construction

The use of a welded joint may result in a reduction in strength of the part at or near the weld. This may be the result of metallurgical discontinuities and residual stresses. A joint efficiency depends only on the type of joint and on the extent of examination of the joint and does not depend on the extent of examination of any other joint

The strength of a welded joint will depend on the type of joint and the quality of the welding. Four categories of weld

1 A Longitudinal or spiral welds in the main shell, necks or nozzles, or circumferential welds connecting hemispherical heads to the main shell, necks, or nozzles;
2 B Circumferential welds in the main shell, necks, or nozzles or connecting a formed head other than hemispherical;
3 C Welds connecting flanges, tube sheets, or flat heads to the main shell, a formed head, neck, or nozzle;
4 D Welds connecting communicating chambers or nozzles to the main shell, to heads, or to necks.

The possible lower strength of a welded joint compared with the virgin plate is usually allowed for in design by multiplying the allowable design stress for the material by a joint efficiency E. The value of the joint efficiency used in design will depend on the type of joint and amount of radiography required by the design code.

F. Corrosion Allowance

The corrosion allowance is the additional thickness of metal added to allow for material lost by corrosion and erosion, or scaling. Corrosion is a complex phenomenon, and it is not possible to give specific rules for the estimation of the corrosion allowance required for all circumstances. For carbon and low-alloy steels, where severe corrosion is not expected, a minimum allowance of 2.0mm should be used; where more severe conditions are anticipated, this should be increased to 4.0 mm. Most design codes and standards specify a minimum allowance of 1.0 mm, Design Loads

A structure must be designed to resist gross plastic deformation and collapse under all the conditions of loading. The loads can be classified as major loads, which must always be considered in vessel design, and subsidiary loads

Major Loads
1. Design pressure: including any significant static head of liquid.
2. Maximum weight of the vessel and contents, under operating conditions.
3. Maximum weight of the vessel and contents under the hydraulic test conditions.
4. Wind loads.
5. Earthquake (seismic) loads.
6. Loads supported by, or reacting on, the vessel.

Subsidiary Loads
1. Local stresses caused by supports, internal structures, and connecting pipes.
2. Shock loads caused by water hammer or by surging of the vessel contents.
3. Bending moments caused by eccentricity of the center of the working pressure relative to the neutral axis of the vessel.
4. Stresses due to temperature differences and differences in the coefficient of expansion of materials.
5. Loads caused by fluctuations in temperature and pressure.

Minimum Practical Wall Thickness

There will be a minimum wall thickness required to ensure that any vessel is sufficiently rigid to withstand its own weight and any incidental loads. As a general guide the wall thickness of any vessel should not be less than the following values ; the values include a corrosion allowance of 2 mm:

Table 3. Minimum Practical Wall Thickness

Vessel diameter (m)	Minimum thickness (mm)
1	5
1 to 2	7
2 to 2.5	9
2.5 to 3.0	10
3.0 to 3.5	11

Table 4. The corrosion allowance for vessels

Service	Material	Corrosion allowance
general process	carbon steel and low-alloy steel	4 mm
non-corrosive or very mildly corrosive (e.g. steam, dry compressed air, LPG, LNG and dry natural gas)	carbon steel and fine grain carbon steel	1 mm
Service in which the operating temperature is always below 0 °C	fine grain carbon steel, 3.5% Ni steel and 9% Ni steel	1 mm
	aluminium and stainless steel	none

Table 5. The corrosion allowance for removable internals

Item	Corrosion allowance
Stainless steel internals	None
Heavily-loaded components (catalyst grids, etc.) in non-clad equipment made from carbon or low-alloy steel	50% of the corrosion allowance specified for the vessel shall be applied to each surface of the internal

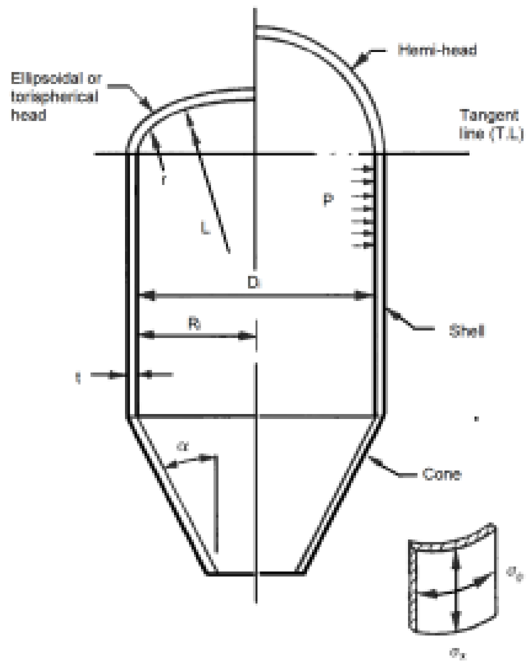

Figure 1. General configuration and dimensional data for vessel shells and heads.

DEFINITION

American Society of Mechanical Engineers (ASME)—organization that provides laws of regulation for boilers and pressure vessels

Average stress and minimum stress - stresses determined from published or manufacturer's data on the subject material.

Baffle - A partial restriction, generally a plate located to change the direction, guide the flow or promote mixing within the equipment in which it is installed.

Boiler - A closed vessel in which water is heated, steam is generated, steam is superheated, or any combination thereof, under pressure or vacuum by the application of heat from combustible fuels, electricity, or nuclear energy. The term does not include such facilities of an integral part of a continuous processing unit but does include fired units of heating or vaporizing liquids other than water where these units are separate from processing systems and are complete within themselves.

Buckling - localized failure caused by overstress or instability of the wall under compressive loading.

Collapse - a general failure of the entire cross section by flattening due to external pressure

Code - The complete rules for construction of pressure vessels as identified in ASME Boiler and Pressure Vessel Code, Section VIII, Division 1, Pressure Vessels.

Construction - The complete manufacturing process, including design, fabrication, inspection, examination, hydrotest, and certification. Applies to new construction only.

Corrosion - The wasting away of metals as a result of chemical action usually cause by the presence of O_2, CO_2, or an acid.

Corrosion allowance - Any additional thickness specified for corrosion during the vessel service life.

Column Davit - A hoisting device attached by means of a socket to the top of fractionation columns. Used for handling relief valves, bubble trays, bubble caps, etc.

Conical Head - Head formed in the shape of a cone.

Coupling - A fitting welded into the vessel to which the piping is connected either by screwing or welding. This type of fitting is generally used for pipe sizes 1% in. and smaller.

Density - The density of a homogeneous substance is the ratio of its mass to its volume. The density varies as the temperature changes and it is usually expressed as the mass per unit volume at a specified temperature.

> **Absolute Density** – The mass of a substance per unit volume at a specified temperature.
>
> **Relative Density** - The ratio of the mass of a given volume of fluid to the mass of an equal volume of pure water at the same temperature and pressure. Relative density replaces the term “specific gravity”.
>
> **Relative Density At 60°** - Fluid relative density measured against water with both materials at 60 degrees F and reference pressure of 14.696 psia (or equilibrium pressure). Equivalent to “RD 60/60”

Design metal temperature - The lowest temperature considered in the design, which, unless experience or special local conditions justify another assumption,

Design Pressure - The pressure used in the design of a vessel component for the most severe condition of coincident pressure and temperature expected in normal operation.

Design thickness - The thickness necessary to satisfy tension and compression strength requirements, in the absence of such expressions, by good and acceptable engineering practice for specified design conditions, without regard to construction limitations or corrosion allowances

Expansion joint - The joint to permit movement due to expansion without undue stress. A type of joint used in piping. It usually contains a telescoping section or a bellows to absorb strain caused by expansion or contraction due to changes of temperature or other forces.

Flange A circular metal plate threaded or otherwise fastened to an end of a pipe for connection with a companion flange on an adjoining pipe. Also that part of a boiler head (dished or flat) which is fabricated to a shape suitable for riveted or welded attachment to a drum or shell

Flanged and Dished (Torispherical) Head - Head formed using two radii, one radius called crown radius, and another called knuckle radius, which is tangent to both the crown radius and the shell.

Flat Head (or Cover Plate) - Flat plate welded or bolted to the end of a shell.

Guaranteed tensile strength - the minimum tensile strength for the base material, deposited weld metal and weldments, as guaranteed by the vessel fabricator.

Guaranteed yield strength - the minimum yield strength (0.2% offset) for the base material, deposited weld metal and weldments, as guaranteed by the vessel fabricator.

High strength materials - those materials having a minimum yield strength at room temperature greater than 70,000 psi (485 MPa).

Head - The end closure of a vessel.

Hemispherical Head - Head formed in the shape of a half sphere.

Insulation Rings - Rings made of flat bar or angle attached around the girth (circumference) of vertical vessels. Used to support the weight of the vessel insulation.

Lapjoint - A joint between two overlapping members. An overlap is the protrusion of weld metal beyond the bond at the toe of the weld.

Lining - An internal coating that consists of an applied liquid material which dries and adheres to the substrate, or a sheet material that is bonded to the substrate. It is designed for immersion service or vapor-space service. A lining can be reinforced or unreinforced.

Longitudinal stress - The average stress acting on a cross section of the vessel.

Manhole - As access opening to the interior of a boiler, elliptical and 11 in. by 15 in. or larger or circular 15-in. diameter or larger. An opening in a vessel that permits entry for inspection and repair

Manhole Hinges or Davits - Hinges or davits attached to manhole flange and cover plate which allow cover plate to swing aside from the manhole opening

Maximum Allowable Pressure (MAP) - It refers to the maximum permissible pressure based on the weakest part in the new (uncorroded) and cold condition and all other loadings are not taken into consideration.

Maximum Allowable Working Pressure (MAWP) - the maximum permissible pressure at the top of the vessel in its normal operating position at a specific temperature, usually the design temperature. It is the least of the values calculated for the MAWP of any of the essential parts of the vessel, and adjusted for any difference in static head that may exist between the part considered and the top of the vessel.

Maximum design temperature - The highest temperature considered in the design, equal to or greater than the highest expected operating temperature during the servke life of the tank.

Nominal thickness -f The ordered thickness of the material. This thickness includes any corrosion allowance. and is used for determination of P\NHT requirements, weld spacing, minimum and maximum thickness limitations

Nozzle - A short flanged or welded neck connection on a drum or shell for the outlet or inlet of fluids; also a projecting spout for the outlet or inlet of fluids; also a projecting spout through which is fluid flows.

Operating Pressure - The pressure at the top of the vessel at which it normally operates. It shall be lower than the MAWP, design pressure, or the set pressure of any pressure relieving device.

Operating Temperature - The temperature that will be maintained in the metal of the part of the vessel being considered for the specified operation of the vessel

Oxygen cutting - A group of cutting processes wherein the severing of metals is effected by means of the chemical reaction of oxygen with the base metal at elevated temperatures. In case of oxidation-resistant metals, the reaction is facilitated by the use of a flux.

Pressure - The amount of force exerted on a unit of area by a fluid.

> **Absolute Pressure** - The pressure referenced to a perfect vacuum as zero pounds per square inch absolute.
>
> **Atmospheric Pressure** - The pressure exerted by the atmosphere. Although this pressure varies with altitude, barometric pressure and humidity, the atmospheric pressure can be defined in custody transfer contracts, or by state and federal authorities. Atmospheric pressure is most often stated as 14.696 pounds per square inch absolute.
>
> **Back Pressure** - The operating pressure level measured upstream from a control valve.
>
> **Gauge Pressure** - That pressure measured relative to atmospheric pressure as zero, usually designated psig.
>
> **High Vapor Pressure** - A fluid which, at the measurement or proving temperature, has a vapor pressure that is equal to or higher than atmospheric pressure.
>
> **Low Vapor Pressure** - A fluid which, at the measurement or proving temperature, has a vapor pressure that is less than atmospheric pressure.
>
> **Reid Vapor Pressure (RVP)** - The vapor pressure of a fluid at 100 degrees Fahrenheit as determined by test method ASTM D 323-58. RVP is one of the important specifications for gasoline and solvents. It is a measure of the vapor pressure of a sample at 100°F (38°C), in the presence of air. A test is made in a bomb, and the results are reported in pounds per square inch absolute.

Static Pressure - The pressure in a fluid that is exerted normal to the surface. In a moving fluid, the static pressure is measured at right angles to the direction of flow.

Pressure vessel - A closed vessel or container designed to confine a fluid at a pressure above atmospheric. A leak-tight pressure container, usually cylindrical or spherical in shape, with pressure usually varying from 15 psi to 5000 psi.

Reinforcing Pad - Plate formed to the contour of shell or head, welded to nozzle and shell or head.

Seperator - A tank-type pressure vessel installed in a steam pipe to collect condensate to be trapped off and thus providing comparatively dry steam to connected machinery

Shell - The cylindrical portion of a pressure vessel.

Skirt - Cylinder similar to shell, which is used for supporting vertical vessels.

Skirt Access Opening - Circular holes in the skirt to allow workers to clean, inspect, etc., inside of skirt.

Skirt Fireproofing - Brick or concrete applied inside and outside of slart to prevent damage to skirt in case of fire.

Skirt Vents - Small circular holes in the skirt to prevent collection of dangerous gases within the skirt.

Sludge - The material that settles to the bottom of crude tanks and which cannot be removed by normal pumping means.

Spherical tank—a type of pressurized storage tank that is used to store volatile or highly pressurized material; also referred to as “round” tanks

Steam - Water vapor produced by evaporation. Dry saturated steam contains no moisture and is at a specific temperature for every pressure, it is colorless. The white appearance of escaping steam is due to condensation at the lowered temperature, it is the water vapor that shows white.

Stress concentration - Local high stress in the vicinity of a material discontinuity such as a change in thickness or an opening in a shell.
The *vessel jacketed* - the inner and outer walls, the closure devices, and all other penetrations or parts within the jacket which are subjected to pressure stresses.

Support Legs - Legs made of pipe or structural shapes that are used to support vertical vessels.

Toriconical Head - Head formed in the shape of a cone and with a knuckle radius tangent to the cone and shell.

2:l Semielliptical Head - Head formed in the shape of a half ellipse with major to minor axis ratio of 21.

Vessel thickness - the thickness required for strength of the pressure vessel shell, including corrosion allowance, but excluding weld overlay, lining, integral cladding or non-integral parts.

Weld efficiency factor - A factor which reduces the allowable stress. The factor depends on the degree of weld examination performed during construction of the vessel.

Welded joint - A union of two or more members produced by the application of a welding process.

NOMENCLATURE

An	Area of nozzle wall (mm^2)
Ar	Area of nozzle hole (mm^2)
As	Area of connecting region (mm^2)
ca	Corrosion Permeability (mm)
Di	Internal Shell Diameter (mm)
Dn	External Nozzle Diameter (mm)
dn	Internal nozzle diameter (mm)
Do	External Shell Diameter (mm)
ds	Diameter of nozzle on tank wall (mm)
E	Joint Efficiency
h	Head High (mm)
Ln	Nozzle Length (mm)
L_{sehll}	Shell Length (mm)
M	mass (kg)
p	Internal Pressure (Mpa)
ph	Maximum Pressure at the Head (MPa)
Ps	Maximum Pressure on Vessel Shell (MPa)
r1	Knuckle Radius (mm)
Rc	Internal Spherical Radius (mm)
S	Permissible Material Stress (MPa)
th	Required Head Thickness (mm)
$t_{knuckle}$	knuckle thickness (mm)
Tn	Actual nozzle thickness (mm)
tn	Required Nozzle Thickness (mm)
Ts	Actual body thickness (mm)
ts	Required thickness of tank (mm)
ts	Vessel Shell Thickness (mm)
V_{head}	Volume head (cm^3)
$Vl_{iquid\ head}$	Volume liquid in head (cm^3)
$V_{liquid\ shel}l$	Volume liquid in Shell (cm^3)
V_{nozzle}	Volume of nozzle (cm^3)
V_{shell}	Volume Shell (cm^3)

ρ_{liquid} Liquid density (g/cm^3)

$\rho_{material}$ Density of Material (g/cm^3)

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